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Geological, geomorphological and geophysical investigations of areas prone to clay slides: Examples from Buvika, Mid Norway

Thesis for the degree philosophiae doctor

Trondheim, May 2007

Norwegian University of Science and Technology
Faculty of Engineering Science and Technology
Department of Geology and Mineral Resources Engineering

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Abstract

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Large areas prone to clay slides are present in Canada, Sweden and Norway. Traditionally, mainly geotechnical approaches have been used to solve clay-slide issues. However, there is great potential to utilise interdisciplinary studies in order to prevent or reduce possible slide damage. The present study combines geology, morphology and geophysical investigations, with geotechnical data. The purpose is to better understand landscape development, formation of quick clay and sliding in clay.

Thick, marine clay deposits in valleys along the Norwegian coast are occasionally subjected to large landslides involving quick clay. The development of quick clay is closely related to the deglaciation history of the coastal parts of Norway. During and after the last ice age, up to several hundred metres of glaciomarine and marine deposits accumulated in Norwegian fjords. These sediments were subsequently exposed on land due to glacioisostatic rebound. Leaching of salt from the marine clay by groundwater resulted in the development of quick-clay layers or pockets, which completely liquefy when remoulded.

The study area of this thesis is the small valley Buvika, located in the Trondheimsfjorden area, Mid Norway. Buvika is characterised by its undulating terrain with numerous slide scars and ravines. There are thick occurrences of quick clay in the subsurface.

The existing geotechnical and geophysical data, combined with sedimentology, structural geology, morphology, geophysical results, and ^{14}C-datings, have given input to the understanding of the landscape development of the study area. From this, a deglaciation history has been deduced, indicating at least one, and possibly two, minor glacier re-advances in Late Allerød/Early Younger Dryas time. This implies that there have been more and larger ice-front oscillations in the study area than earlier documented.

The lowered relative sea level led to incision by rivers accompanied by numerous slides involving quick clay. The erosion pattern of a valley filled with glaciomarine and marine deposits can be quite complex, but careful analyses have helped outlining the interplay between river and ravine incision, groundwater erosion and sliding. The study of sediments and structures in large excavated sections have resulted in the detection of slide material from old flake-type slides, where only a thin layer of quick clay acted as a slide plane. Younger slide scars cutting into theses older slide deposits show further quick-clay development. Mapping of the morphology in Buvika has identified numerous slide scars and ravines. A relative chronology of slide events has been established based upon the slide scars' position in the terrain and/or results from ^{14}C-datings of terrestrial organic material. Most of the historical slide scars are located in the northern part of the valley.

Detailed mapping of the quick-clay extent is of great interest for planning and protection purposes, as the position of quick clay within slopes has a major impact on the landslide risk. In this study, the resistivity method is found to be potentially well suited for outlining quick-clay occurrences since quick clay has a slightly higher electrical resistivity (10-80 Ωm) than intact unleached clay (1-10 Ωm). This is due to a higher salt content in the latter. These relationships are supported by pore water salt content measurements. The resistivity profiles that were acquired show good correlation with other geophysical data and geotechnical drillings. However, the resistivity method must be combined with other investigations, since both leached, non-quick clay and silty, non-sensitive material may give resistivity values of the same range as quick clay.

The stratigraphy of an area strongly influences the landscape development. It determines the morphology, such as ravine development, and size, shape and distribution of slides. To the east of Buvika, thick and frequent layers of sand and gravel in the dominant clay deposits drain the slopes, leading to development of deeply incising ravines. To the south and north, thinner layers of coarse material in the clay lead to pore-pressure build-ups and quick-clay development, resulting in numerous slide scars.

Preface and acknowledgements

This PhD project started fall 2003 with initiative from Prof. Kåre Rokoengen at the Department of Geology and Mineral Resources Engineering (IGB), NTNU. He applied for financial support for my study from four different contributors: the Geological Survey of Norway (NGU), the International Centre for Geohazards (ICG), the Norwegian Water Resources and Energy Directorate (NVE), and the Norwegian University of Science and Technology (NTNU). I am thankful to all these contributors for the financial support: without you it would not have been possibly to carry out this project.

The working title of my project was relatively wide (Geological conditions and stability investigations related to clay slides), and at first we planned that different areas in Trøndelag should be used for field investigations. Buvika was chosen as the first study area, due to the large on-going road project there. Eventuality we felt that we could not leave Buvika, due to the large amount of existing data and opportunities for new exciting discoveries. I therefore have to give an extended thanks to Skanska Norge AS, Statens Vegvesen (the Norwegian Public Roads Administration) and Rambøll Norge AS who have provided a considerable number of geotechnical reports and maps. I must also thank Skanska that dug out all the marvellous cuts in clay ‘for me’ and gave me access to them.

I want to address sincere thanks to my main supervisor Prof. Kåre Rokoengen who worked hard to give me the opportunity to start this PhD study. He has also inspired and encouraged me these years and read numerous manuscripts. My second supervisor, Louise Hansen, at the Geological Survey of Norway (NGU), is given warm thanks for assistance during fieldwork, all support, inspiration and for giving very constructive comments on my manuscripts.

My other co-authors are thanked for useful comments on two of the papers: Harald Sveian (NGU), Lars Olsen (NGU), Rolf Sandven (NTNU), Jan Steinar Rønning (NGU), and especially Einar Dalsegg (NGU) for measuring all my resistivity profiles. John Dehls (NGU) and Stephen Lippard (NTNU) are thanked for improving and correcting the English language. Thanks are given to NGU that provided an office for my disposal, and to all my colleagues at the ‘Skred’-group and ‘Landskap og klima’-group at NGU for inspiration and support. I will also thank friends and colleagues at IGB for many inspiring talks.

Finally, I want to thank my family and the Solberg family for all support. Special thanks go to my beloved husband Ole Vegard, for being patient, enthusiastic and encouraging during these years. You never stopped believing that I could complete this PhD.

Trondheim, May 2007

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PAPERS

ENCLOSURES

Note on contributions

Paper I: Landscape development and deglaciation history of fjord-valley deposits in Buvika, Mid Norway

Louise Hansen and I carried out fieldwork with structural and sedimentological analyses of excavations. I wrote the article, and Kåre Rokoengen and Louise Hansen gave input on the manuscript, text and organisation. Harald Sveian (NGU) and Lars Olsen (NGU) gave input on the manuscript, mainly concerning the deglaciation history.

Paper II: Distribution of clay slides in fjord-valley deposits and their role in valley development, example from Mid Norway

I wrote this article, with input on the manuscript and the organisation from Louise Hansen and Kåre Rokoengen. They also participated in some of the fieldwork. Two anonymous reviewers also gave input on the manuscript (Paper accepted for The 1st North American Landslide Conference).

Paper III: Large, prehistoric clay slides revealed in road excavations in Buvika, Mid Norway

Louise Hansen and I carried out fieldwork with structural and sedimentological mapping of excavations. The article was written by Louise Hansen and myself. Louise Hansen wrote parts of the descriptions and interpretations of Section A-F, and together with Kåre Rokoengen, gave input on the rest of the manuscript.

Paper IV: Resistivity measurements as a tool for outlining quick-clay extents and valley-fill stratigraphy: feasability study from Buvika, Central Norway

I wrote this article with the following input from the co-authors: Jan Steinar Rønning (NGU/NTNU) organised the measurements and gave input on the interpretation of the results and on the manuscript. Einar Dalsegg (NGU) measured the resistivity profiles, inverted the data and helped interpret the results. Louise Hansen prepared data for 3D visualisation, and together with Kåre Rokoengen, gave input on the manuscript. Rolf Sandven (NTNU) gave input on the manuscript, especially the geotechnical part. Two anonymous reviewers and the associate editor also gave input on the manuscript (Paper accepted for Canadian Geotechnical Journal).

INTRODUCTION

Background

Geological background

In Norway, marine clay has its greatest extent in Trøndelag (Fig. 1) and Østlandet, but there are also areas with marine clay in Northern Norway, Vestlandet and Sørlandet. Deglaciation, deposition of glaciomarine and marine deposits, and the subsequent glacioisostatic rebound, have led to the emergence of large areas with marine deposits along the coast of Norway. The isostatic rebound during the Holocene was most rapid in Preboreal and Boreal time (Kjemperud 1981). Due to the depression, the relative sea level was locally much higher than it is today. In the selected study area, Buvika, Mid Norway (Figs. 1, 2), the marine limit (ML) after the last glaciation was about 175 m above present sea level (Reite 1983b).

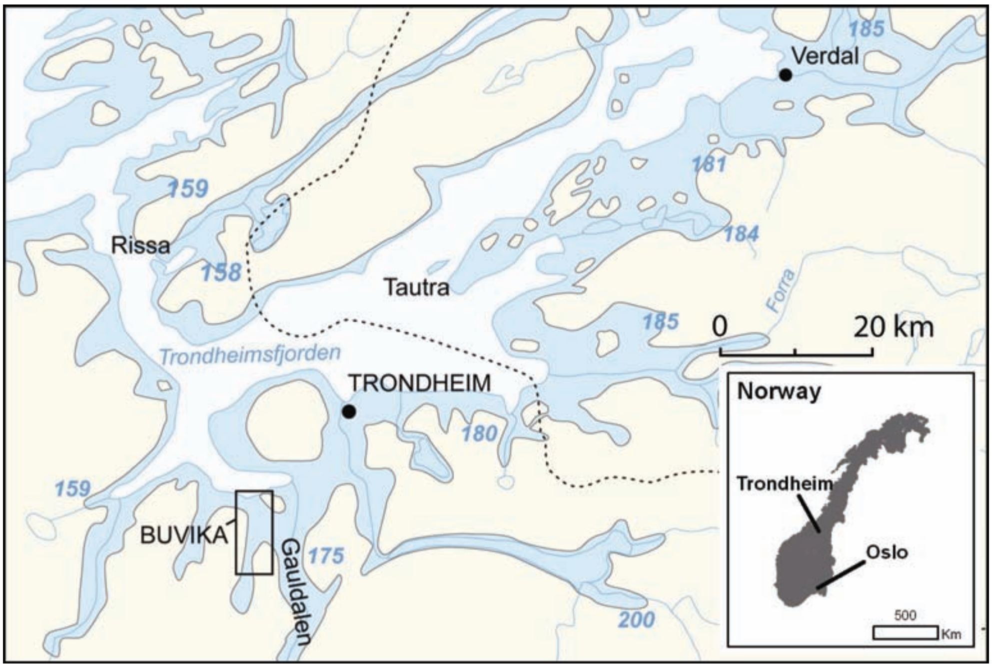

Fig. 1. The maximum extent of the sea during deglaciation in parts of the Trøndelag region. Blue: areas that have been seabed after the last glaciation. Numbers: Marine limit in different areas in metres above present sea level. Tautra is the locality that has given name to the most significant ice-marginal deposits in the Trøndelag (from Early Younger Dryas). Several large quick-clay slides have occurred in the Trøndelag region, e.g. Verdal (1893) and Rissa (1978), and a combined flood and slide disaster in Gauldalen (1345). Buvika is the study area of this thesis. The figure is modified after Sveian & Solli (1997).

Sweden and Canada are, in addition to Norway, the areas in the world with most postglacial, elevated marine and glaciomarine sediments (e.g. Lebuis *et al.* 1983; Hilmo 1989; Rankka *et al*. 2004). Even though there are slight differences in properties or composition of the deposits, all areas are exposed to severe landslides involving remoulding of quick clay.

The natural salt content in seawater is generally 35 g/l. When clay deposited in seawater is leached by fresh groundwater due to isostatic rebound, the salt content in the pore water is reduced. Marine clay where the salt content in the pore water is below 5 g/l may be sensitive/quick (Rosenqvist 1953; Bjerrum 1954). When the remoulded shear strength (s_r) is less than 0.5 kN/m^2 the clay is characterised as quick. The clay has high sensitivity when the ratio between undrained, undisturbed shear strength (s_u) and s_r is above 30 (NGF 1975). Some parts of the subsurface are known to be favourable for developing quick clay in pockets and/or layers: near bedrock, near the surface, where the groundwater flux is large (e.g. in slopes), and where clay is interfingered with silt/sand/gravel layers (e.g. Janbu *et al.* 1993). All these conditions give good influx of water to the generally impermeable clay.

When quick clay is remoulded, it completely liquefies. Every year small quick-clay slides occur in Norway, and occasionally very large slides result in severe damage to life and infrastructure. Many people live in areas with marine deposits, and a lot of construction work on these sediments meets severe challenges. Small initial slides do not necessarily involve quick clay, but can trigger much larger slides if quick clay is present (e.g. Gregersen 1981; Karlsrud *et al.* 1985).

Quick-clay slides in Trøndelag, Mid Norway

Large damaging slides involving remoulding of the quick-clay deposits are relatively infrequent. Nevertheless, in historic time at least 1150 people have died in Norway as a consequence of clay (and soil) slides, and very large clay slides seem to have a frequency of 2-3 per century (Furseth 2006). Slides can be triggered naturally, but human activity is often an important factor. An example is when the clay below a small fill collapsed and triggered the Rissa quick-clay slide in 1978. This slide event is probably the best known and described in Norway (Gregersen 1981; Løfaldli *et al*. 1981; NGI video). Several large natural disasters have occurred in the Trøndelag region

(Fig. 1). The slide and the following flood in Gauldalen in 1345, with 500 people assumed killed, is the largest recorded in Norway (Helland & Steen 1885; Rokoengen *et al.* 2001). The quick-clay slide in Verdal, where a total of 116 people perished in 1893, is well documented both geologically (Friis 1898; Sveian 1989) and historically (Walberg 1993). These are some of the largest events, but only a small extract of the large number of quick-clay slides in the Trøndelag region (e.g. Sveian 1989; Reite *et al.* 1999; Sand 1999; Furseth 2006).

Mapping of areas prone to clay slides

There are different approaches that may be used to study landslide issues. Today GIS-based tools give many opportunities to map morphologies like slide scars and ravines. Digital terrain modelling, combined with vertical aerial photographs and Quaternary geological maps, are used to identify areas where new slides could be a problem. This may, together with other data, lead to zonation of areas on different levels: e.g. susceptibility maps, hazard maps, consequence evaluations and risk analyses (Table 1). These approaches are often quantitative methods (e.g. Fell *et al*. 2005; Glade *et al*. 2005). Hazard maps, consequence maps and resulting risk maps have been made for several clay-slide prone areas in Norway, including Buvika (see later) (Gregersen 1988; Gregersen 2002; www.skrednett.no). Even though the temporal aspect is included in the hazard definition (Table 1), this aspect is generally not covered in the hazard map of quick-clay zones, possibly due to the difficulties in predicting quick-clay slides (e.g. Karlsrud *et al*. 1985). Susceptibility would possibly be a better term than hazard for these maps, since this term includes the current stability of areas. The risk maps from the zonation of quick clay in Norway are based on the definition of risk as being equal to the product of hazard and consequence (Gregersen 2002).

Although many of these methods are quantitative, risk-based qualitative approaches are used in many applications, including management of landslide risk and land-use planning (Fell *et al*. 2005). Mapping of different types of clay slides has been carried out in Scandinavian and Canadian areas, which may have both quantitative and qualitative approaches (e.g. Lebuis *et al.* 1983; Viberg 1984; Carson & Geertsema 2002; Robitaille *et al.* 2002).

In the present study, there has been an extended use of some of the background data for the hazard maps (like geotechnical drillings). An interdisciplinary, mainly qualitative approach is used by combining geology, morphology and geophysical methods with geotechnical data to get a more detailed picture of the subsurface. One aim is to give an extended understanding of the landscape development based on the valley-fill stratigraphy.

Table 1. Some definitions used in risk assessment (after ISSMGE TC32 2004 and Glade *et al.* 2005)

Term	**Definition**
Danger (Threat)	The natural phenomenon that could lead to damage, described in terms of its geometry, mechanical and other characteristics. The danger can be an existing one (such as a creeping slope) or a potential one (such as rock fall). The characterisation of a danger or threat does not include any forecasting.
Probability	A measure of degree of certainty. This measure has a value between zero (impossibility) and 1.0 (certainty). It is an estimate of the likelihood of the magnitude of the uncertain quantity, or the likelihood of the occurrence of the uncertain future event.
Hazard	Probability that a particular danger (threat) occurs within a given period of time.
Vulnerability	The expected degree of loss to a given element or set of elements at risk resulting from the occurrence of a natural phenomenon of a given magnitude. It is directly but inversely related to the resilient qualities at the elements at risk (e.g. building standard).
Susceptibility	The propensity of an area to undergo landsliding. It is a function of degree of inherent stability of the slope (as indicated by the factor of safety or excess strength) together with the presence of factors capable of reducing excess strength and ultimately triggering movement.
Consequence	In relation to risk analysis, the outcome or result of a hazard being realised.
Risk	Measure of the probability and severity of an adverse effect to life, health, property, or the environment. Quantitatively, Risk = Hazard x Potential Worth of Loss This can also be expressed as “Probability of an adverse event times the consequences if the event occurs”. Risk analyses may be qualitative or quantitative.

Relatively few morphological analyses have been made of clay terrains in Norway. A study in Romerike, southern Norway, differentiates erosion into zones associated with the geomorphology of the area (Foster & Heiberg 1971). Mapping of slides with different geological parameters has been done in Målselv, Northern Norway (Danielsen *et al.* 1992; Hansen *et al.* 2002). Other examples are Hansen *et al.* 2007 and Eilertsen *et al.* (in press) that connect valley-fill stratigraphy and clay-slide occurrences.

A series of Quaternary geological maps with descriptions has been made for Norway, including the areas with marine clay, which give a relatively detailed overview of the surface material. The scale and scope of the map determine the focus, and sometimes the map lacks indications of morphological elements such as slide scars and ravines (e.g. Reite 1983b). Reite (1983a) and Sveian (1989) are examples of Quaternary geological maps from the Trøndelag region where slide scars are included. The maps may give limited indications of the sediments deeper in the stratigraphy or depth to bedrock. Bargel (2003) discusses such maps and their use in more detail.

Some Canadian studies discuss the relationships between sliding and Quaternary valley-fill sequences, for example in Ontario (Fransham & Gadd 1977) and in British Columbia (Clague & Evans 2003). Mapping of landslide prone areas has also been carried out in Canada (e.g. Lebuis *et al.* 1983; Robitaille *et al.* 2002). Viberg (1984) and Carson & Geertsema (2002) discuss different factors relevant to clay slides, such as geology, topography, hydrology and geotechnics, in both Scandinavia and Canada.

It is important that the investigations on properties, formation and occurrence of quick clay continue in order better to understand the sliding processes, and prevent sliding and damage caused by sliding. Also the influence stratigraphy will have on the distribution of slide scars and ravines, and on landscape development, is important. There is a great potential for combining approaches for geological, geophysical and geotechnical investigations, for example to outline sensitive material, where both stratigraphy and material properties are important.

Objectives

The objectives of this thesis are to:

- Contribute to the deglaciation history and valley-fill stratigraphy of Buvika.
- Outline the stages of landscape development after the deglaciation, which is essential for understanding long-term erosion processes and further valley development.
- Increase the knowledge of the geomorphology and erosion pattern in areas prone to clay slides.
- Understand the connection between stratigraphy and the development of sensitive sediments (quick clay); where slides occur; and the formation of ravines.

- Study the internal structures of clay-slide deposits in order to better understand processes and deformation history.
- Perform and evaluate the resistivity method’s ability to outline the extent of quick clay in Norwegian marine deposits, by comparing the results with other geophysical and geotechnical data.
- Use resistivity measurements and other data to outline the general geological and stratigraphical distribution of sediments in the study area, which is important for formation of quick clay.
- Evaluate the resistivity method’s ability to outline groundwater drainage patterns and areas that may act as barriers to limit the extent of a potential quick-clay slide.

Organisation of the thesis

This thesis consists of introductory chapters where the background and objectives for the study are defined, the choice of study area and methods presented, and the papers described shortly. This first part of the thesis also includes a discussion that focuses on topics at the interface between the subjects of the papers in this PhD study. The main conclusions for the thesis are also listed, followed by suggestions for further work.

The four papers are arranged according to the content. The deglaciation history, Paper I, constitutes a basis for the development of the landscape. Paper II shows the development of the valley after deglaciation with main emphasis on sliding activity. Paper III focuses on stratigraphy and deformation structures of old slide deposits. Resistivity measurement is a relatively new and promising method for outlining quick-clay extents, and is the subject of Paper IV. The layouts of the papers are in accordance with the journals they are accepted by or submitted to.

Finally, in the back of the thesis, enclosures present abstracts and posters published during the PhD study with the candidate as the main author (Enclosure 1) and a complete list of publications where the candidate has participated during the PhD period (Enclosure 2). In addition there is a list of all the geological, geotechnical and geophysical reports from Buvika that have been used in the study (Enclosure 3), and larger version of three selected figures from the papers (Enclosure 4).

Choice of study area

The Trondheimsfjorden region was a natural choice in order to select a study area, due to the large areas of former seabed, the presence of quick-clay zones, and numerous slide events through history (Fig. 1; www.skrednett.no). The chosen study area Buvika is a relatively small valley, but is considered representative for fjord-valleys filled with glaciomarine and marine deposits (Fig. 2).

Buvika is located in Skaun municipality, in Sør-Trøndelag County, Mid Norway, about 25 km southwest of the city of Trondheim (Fig. 1). Buvika is a hanging fjord-valley to the south of Gaulosen fjord. The area is characterised by undulating terrain with numerous ravines and slide scars, surrounded by 300-400 m high hills of bedrock (Fig. 2). Vigda is the main river in Buvika, originating in Lake Ånøya. Lake Ånøya (149 m a.s.l.) is located eight km south of Vigda's outlet in the Gaulosen, which is a part of Trondheimsfjorden. East of Buvika lies the large Gauldalen valley (Figs. 1-3). Glaciomarine and marine clay sediments dominate the valley fill. Figure 2 shows the Quaternary sediment distribution, and a subdivision of the study area into Southern, Eastern, Central and Western Buvika. Figures 4 and 5 show examples of the morphology and different landscape elements in Buvika.

In the years 2003-2005 a new highway was built in Buvika (E39), in addition to the upgrading of a county road (Fv 802) (Figs. 3, 4a, 4e). Before and during the construction of the roads, different companies carried out numerous geotechnical investigations, documented in reports. These data, in addition to some refraction seismic data, constituted a solid basis for further investigations (Enclosure 3). The area was therefore well suited to evaluate the resistivity method and its ability to outline the extent of quick clay. The profile locations were chosen to maximise spatial coverage and understanding of the ground conditions, and additionally to make use of all the information that was already available in the area. The construction of the roads also gave unique opportunities to study sediments and structures of the valley fill in several large excavated sections. This increases the understanding of the stratigraphy and processes like glacier fluctuations and sliding activity.

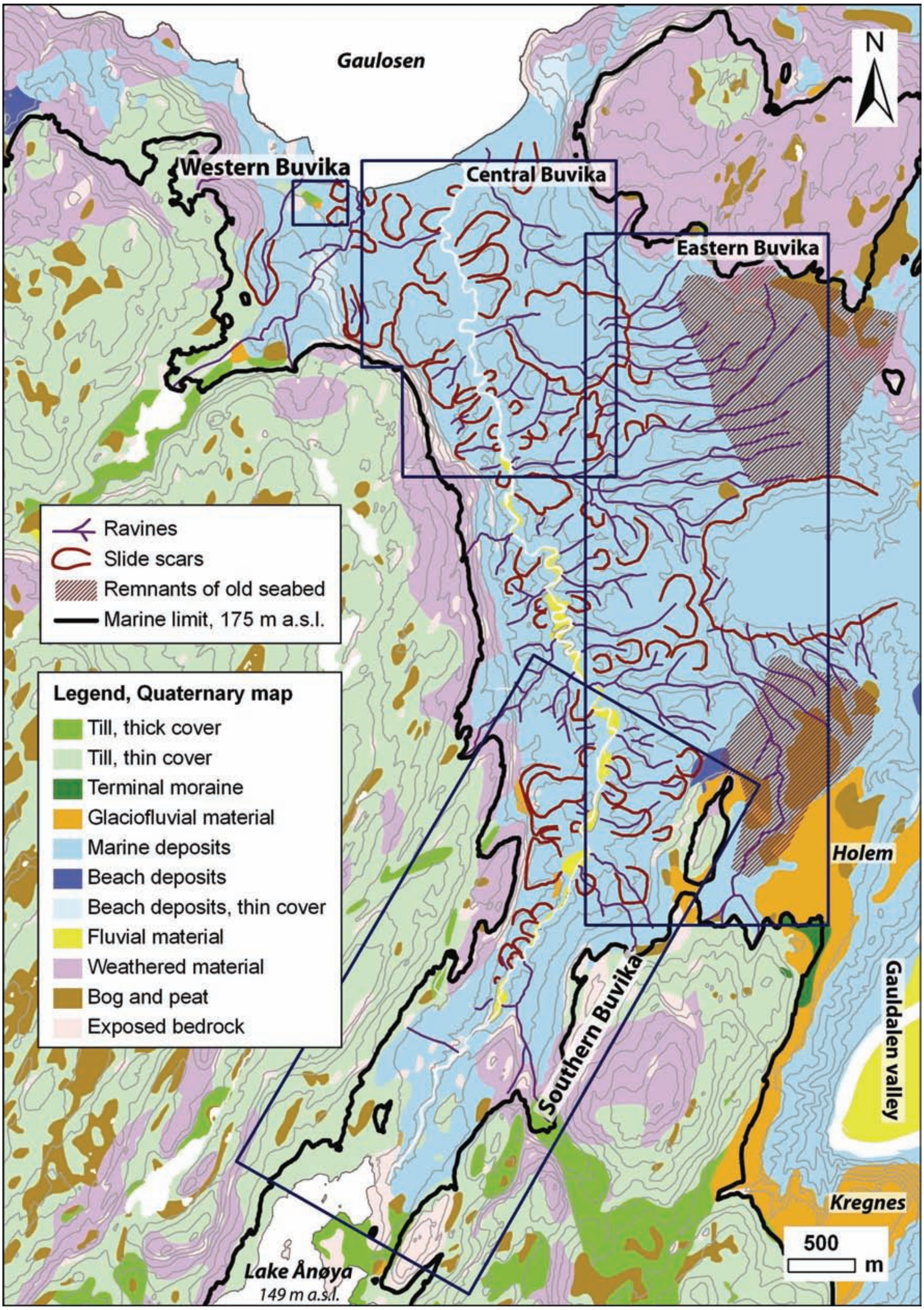

Fig. 2. Quaternary geological map showing surface material (modified from Reite 1983a, 1983b). Ravines and slide scars are also shown. The study area is divided into Southern, Eastern, Central and Western Buvika. Contour lines: 25 m (The map is slightly modified from Paper I).

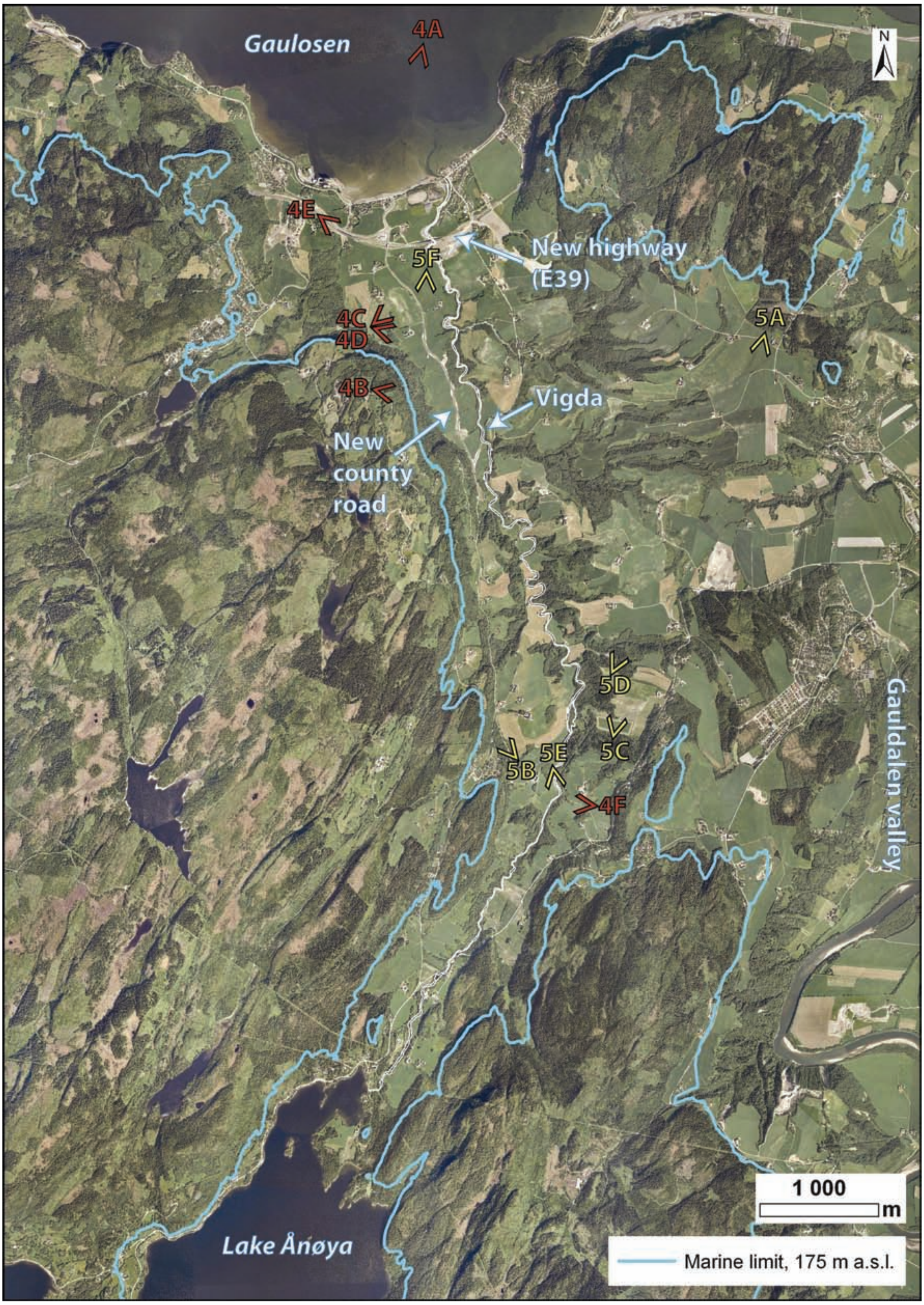

Fig. 3. Orthophoto from the study area Buvika (www.norgeibilder.no). Notice the wooded ravines along the eastern margin of Buvika. 4A-4F and 5A-5F show the view angle for the pictures with details of morphology and landscape elements in Figs. 4 and 5.

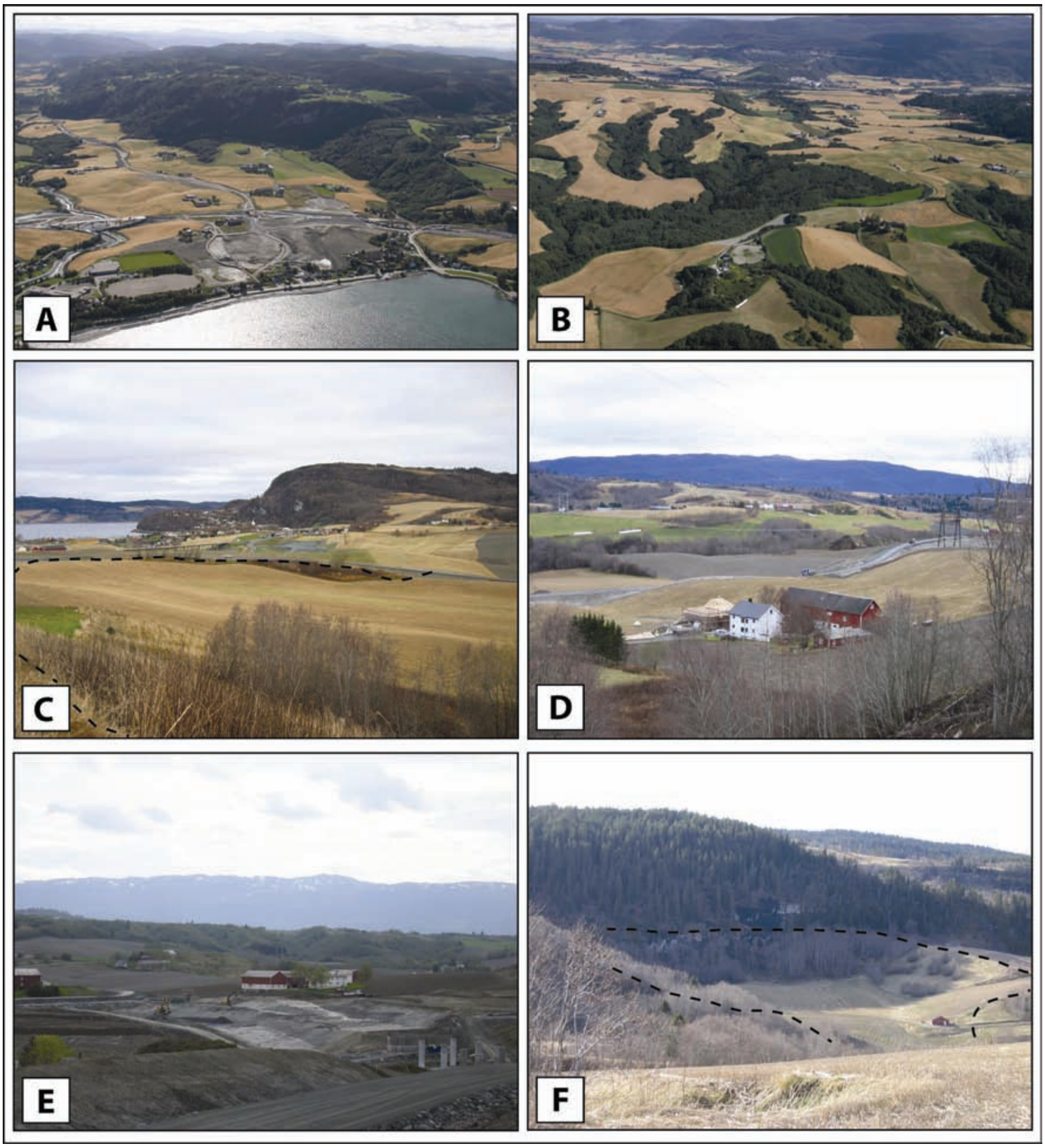

Fig. 4. Morphology of Buvika. See Fig. 3 for photo views. **A** Central Buvika towards south, during construction of the new highway (E39) (Photo: NVE). **B** Ravine terrain towards east (Photo: NVE). **C** and **D** View of the Saltnes slide scar, from the back scarp. **E** Excavations in clay due to the construction of the new highway. **F** A large slide scar in the southern part of Buvika.

Fig. 5. Landscape elements and field work in Buvika. See Fig. 3 for photo views. **A** Remnants of the old seabed, towards south. **B** Coarse fan material deposited from a hanging valley west in Southern Buvika. **C** Erosion in a ravine head. **D** Surficial scar/shallow slope failure in a ravine wall. **E** Stones and boulders in Vigda. **F** Resistivity measurements in Buvika.

Methods

In this study, field mapping is combined with geophysical investigation and study of geotechnical data. The methods used were mainly chosen during the study, based on the opportunities in the field area during the road construction. The methods are described in each paper, but a summary of the methods follows:

1. Mapping and interpretation of geomorphology of the landscape using vertical aerial photographs (Fig. 3), shoreline displacement curves, topographical maps, Quaternary geological maps (Fig. 2) and historical records. Fieldwork consisted of geomorphological mapping including slide scars, ravines, observations along the river, as well as detailed sedimentological and structural studies of road cuts (Figs. 4, 5).

2. Marine mollusc shell samples and samples of terrestrial organic material were collected for species determination and ^{14}C-dating with the AMS and conventional techniques. Sediment samples for grain size analysis (Grimstvedt 2004) and microfossil analysis were collected. A single fabric analysis was carried out, in addition to orientation measurements on striated bedrock and on folds in clayey deposits.

3. 2D resistivity measurements were carried out along thirteen profile lines (Fig. 5f). Four active cables were used with the Wenner electrode array (Fig. 6). The steel electrode separations were 2, 5 and 10 m. Induced polarisation (IP) was measured in five profiles. Recorded resistivity and IP were inverted using the computer program Res2Dinv (Loke 2004). A 1 km long refraction seismic line, and six ground penetration radar (GPR) profiles were also carried out for this study. Results from the geophysical measurements are gathered in Dalsegg *et al.* (2006) (also available from www.ngu.no).

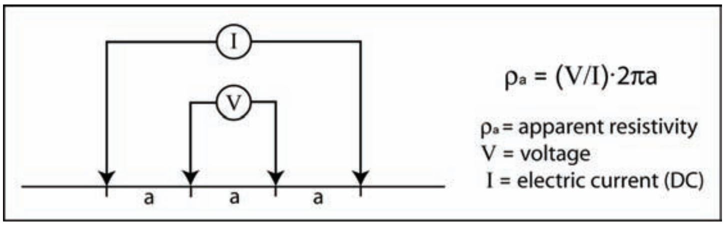

Fig. 6. Principle drawing of the Wenner electrode array (modified from Telford *et al.* 1990).

4. Bathymetric and seismic data have been acquired using interferometric sonar and boomer outside the Buvika shoreline. Details on the sonar data are presented in Hansen *et al.* (2005). The boomer results are unpublished data from the Geological Survey of Norway.

5. The software tool ESRI's ArcGIS (version 9.1) was used in creating maps and 3D visualisation. Rockworks (version 2006) was used to visualise interpreted drilling profiles in 3D.

6. Studies and interpretations of geotechnical reports from more than 700 drilling locations produced by different companies during 1966-2006 (Enclosure 3): Statens Vegvesen (the Norwegian Public Roads Administration), Rambøll Norge AS, NGI (the Norwegian Geotechnical Institute) and NTNU (the Norwegian University of Science and Technology). A short description of the main geotechnical drilling methods is given in Table 2. Also reports on refraction seismic investigations have been studied (Enclosure 3).

Table 2. The main geotechnical investigation types used in Buvika, with short method description and information type (based on Sandven 2002; Paper IV).

Investigation type	**Description**	**Information type**
Cone Penetration Test Undrained (CPTU)	The rod system with a probe is continuously pushed into the subsurface, and values of cone resistance, friction and pore pressure are registered continuously.	Sediment stratification, soil type indication, mechanical soil parameters.
Rotary Pressure Sounding	The rod system with a purpose-made tip is forced into the subsurface with both rotation and static downward pressure. The rotation and penetration rate is constant.	Indicated sediment stratification, occasionally soil type and depth to bedrock (not verified).
Total Sounding	Conventional Rotary Pressure Sounding combined with bedrock drilling, including rotation, ramming and flushing modes.	Indicated sediment stratification, occasionally soil type and verified depth to bedrock.
Core sampling	Generally a ϕ54 mm piston sampler is used to give undisturbed samples in clays for subsequent laboratory testing.	Sediment stratification, shear strength, deformation properties, index properties, permeability.

SHORT PRESENTATION OF THE PAPERS

Paper I

Solberg, I.L., Hansen, L., Rokoengen, K., Sveian, H. & Olsen, L. (subm): Landscape development and deglaciation history of fjord-valley deposits in Buvika, Mid Norway. Submitted to Boreas May 2007.

The paper has two main focuses. Firstly, the deglaciation history of Buvika is deduced from study of sedimentology, stratigraphy, structural geology, morphology and ^{14}C-datings of marine molluscs. The study gives implications on glacier fluctuations and indicates at least one, and probably two, minor glacier advances during the late-glacial period. The sedimentation in different parts of the study area during deglaciation is also presented. Secondly, results from the first focus are used to show how the varying stratigraphy influences the morphology and the erosion pattern in different parts of the study area. To the east, thick and frequent layers of sand and gravel in the dominant clay deposits drain the slopes, leading to development of deeply incised ravines. To the south and north, thinner layers of coarse material in the clay lead to pore-pressure build-ups and quick-clay development, resulting in numerous slide scars.

Paper II

Solberg, I.L., Hansen, L. & Rokoengen, K. (in press): Distribution of clay slides in fjord-valley deposits and their role in valley development, example from Mid Norway. The 1st North American Landslide Conference, June 3-8 2007, Vail, Colorado.

This paper shows the development of the valley after deglaciation with a division into three stages. During the Early stage (last part of the Pleistocene to 10 000 years BP), the sea level was lowered from 175 m to 150 m above present sea level. The stage is characterised mainly by sedimentation from suspension. In the Intermediate stage (the next 3500 years), the sea level was lowered by 110 m. The accumulation continued, but to a lesser degree than earlier. River incision and sliding activity increased during this stage. The Recent stage (the last 6500 years) had a sea level lowering from 40 m down to present sea level. This is a solely erosional stage on land in Buvika, with several small and large slides and continued ravine erosion. The paper shows the distribution of most of the slide scars in Buvika, and they are given approximately maximum ages mainly based on their position in the terrain.

Paper III

Solberg, I.L., Hansen, L. & Rokoengen, K. (subm): Large, prehistoric clay slides revealed in road excavations in Buvika, Mid Norway. Submitted to Landslides May 2007.

This paper is a study of excavated sections showing slide deposits from large, prehistoric clay slides. Folds, shearing and internal slide planes have been recorded in some of the sections, inferring sliding and rotating of blocks on a thin layer of remoulded quick clay. The slide-scar morphologies in the vicinity are diffuse or absent for most of the deposits. One section cuts through a slide block left behind during a more classic quick-clay slide. Varying results from ^{14}C-datings of organic material in the deposits only give maximum ages of the slide events. The style of sliding reflected in several sections differs from slides known from historical records, since these younger slide events seem to be characterised by collapse and remoulding of thicker quick-clay layers. The study of the slide deposits shows that the gradual formation of quick clay influences the long-term landscape degradation and the character of the present-day landscape.

Paper IV

Solberg, I.L., Rønning, J.S., Dalsegg, E., Hansen, L., Rokoengen, K. & Sandven, R. (in press): Resistivity measurements as a tool for outlining quick-clay extents and valley-fill stratigraphy: feasability study from Buvika, Central Norway. Canadian Geotechnical Journal.

This paper evaluates the resistivity method and its ability to outline the extent of quick clay in Norwegian marine deposits, by comparing resistivity results with large amounts of existing geotechnical and geophysical data. The study shows that the resistivity method is potentially well suited for outlining zones of quick clay. Quick clay has a slightly higher electrical resistivity (10-80 Ωm) than intact unleached clay (1-10 Ωm), due to a higher salt content in the latter. In the paper the role played by the salt content in pore water is considered, as well as the influence of bedrock on the measurements. The conformity between intersecting profiles is also discussed. In addition, the results of the study are used to interpret groundwater drainage patterns and the method's ability to outline areas that may act as barriers to limit the extent of a quick-clay slide. The general geological and stratigraphical distribution of sediments in the study area is discussed, especially the importance for development of quick-clay.

DISCUSSION

This section discusses the significance of the stratigraphy for quick-clay development, sliding and ravine formation. Some special issues related to slide scars; slide deposits and detection of quick clay are also discussed. The discussion of each topic is not exhaustive, but emphasis is put on topics at the interface between the subjects from the papers in this PhD study. In the following, the papers (number I-IV) will be referred to, where the different subjects are treated.

Stratigraphy - implications for quick-clay development, sliding and ravine formation

The relationship between stratigraphy and clay slides may be important for hazard evaluations. Clague & Evans (2003) discuss the connection between sliding and Quaternary valley-fill sequences in British Columbia. Other Canadian studies emphasise the importance of understanding the geological conditions related to groundwater flow and stability of slopes (La Rochelle *et al.* 1970; Hodge & Freeze 1977; Lafleur & Lefebvre 1980; Carson 1981). In Sweden, studies have been made on geology and stratigraphy important for quick clay development and slope stability (e.g. Stevens & Hellgren 1990; Stevens *et al.* 1991). There are relatively few detailed investigations on stratigraphy and clay slides in Norway, examples are Feyling-Hansen (1954) and new studies such as Hansen *et al*. 2007 and Eilertsen *et al*. (in press).

The stratigraphy in Buvika is highly influenced by the deposition of a large glaciofluvial delta at Holem in the neighbouring valley deposited at the deglaciation phase at the end of the last ice age (Figs. 2, 7) (Paper I). Coarse material interfingering clay was deposited into Buvika. The area closest to this delta has several coarse layers interfingering clay, below a top layer of more homogeneous clay. Distal to the delta, the coarse layers get thinner and less frequent. This distribution seems to have influenced the landscape development. Thick and frequent layers of sand and gravel drain the slope leading to seepage erosion, especially since many of the layers probably reach surface contact in both ends. This ravine development followed the incision of the main river-valley. The seepage erosion in thick coarse layers probably also led to vertical

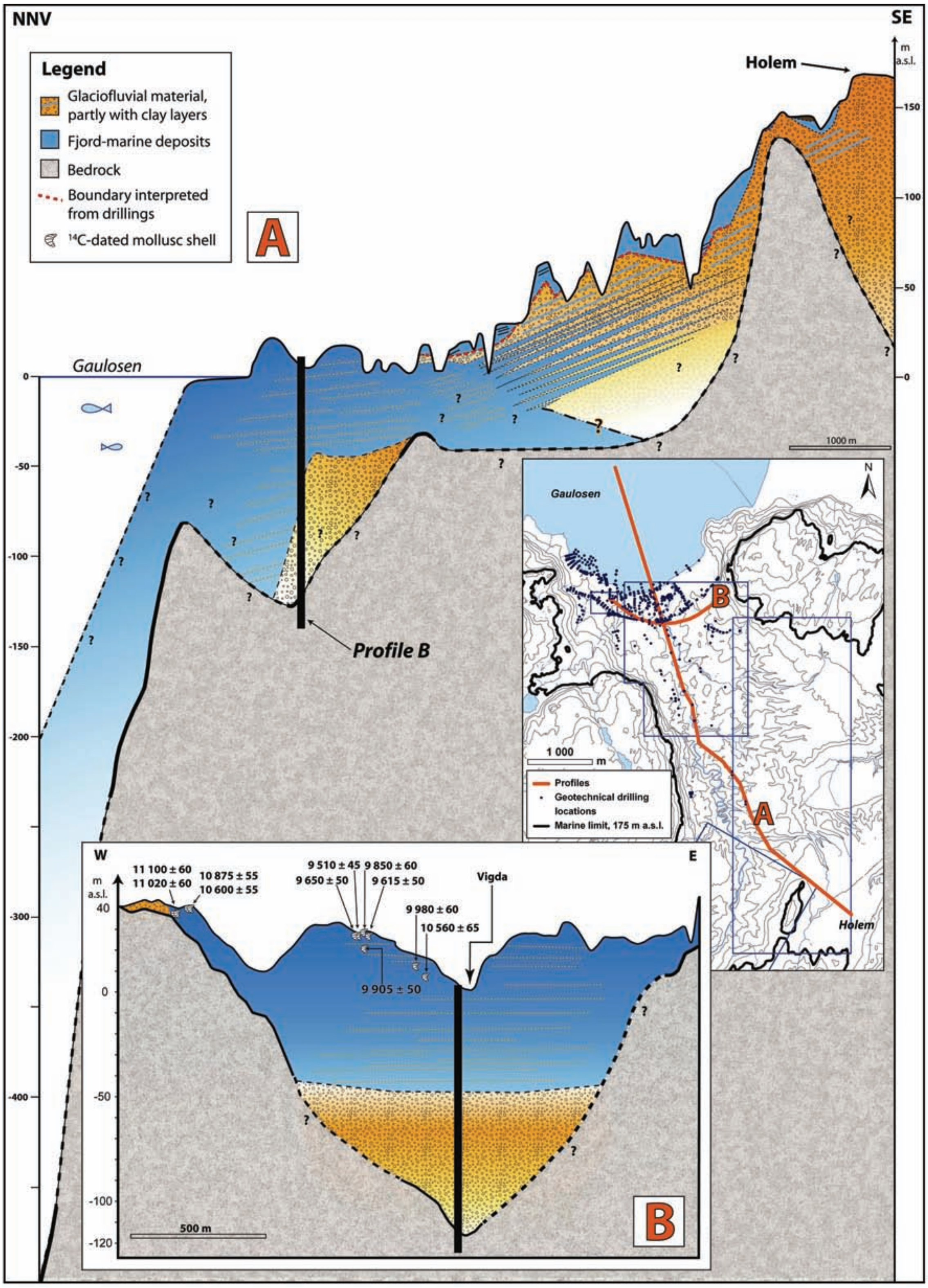

Fig. 7. Principle sketches of the stratigraphy along two profiles in Buvika (Paper I). **A** Profile along the valley, about 17x vertical exaggeration. **B** Profile across the valley, about 8x vertical exaggeration. The ages of mollusc shells are in ^{14}C-years BP.

settlements in the ravine head, which can be difficult to separate from slide scars. In addition to slide scars and slope failures, surficial scars were discovered in different levels of the ravine slopes, probably due to groundwater erosion (Figs. 5c, 5d). The surface erosion results in overturned trees, which makes the ravine impassable. Due to the lack of vegetation cover in the scars the slopes are vulnerable to accelerated erosion (Paper II).

The input of coarse material interfingering clay in the eastern part of Buvika gave rise to a stratigraphy that facilitated ravine erosion during isostatic rebound. Another example, from the western margin in Buvika, shows a similar stratigraphy, in a smaller area and scale. This area has traces of relatively large slides. During deglaciation, coarse sediments were deposited distally to a relatively small glaciofluvial fan in front of a hanging valley, interfingering clay deposited from suspension (Figs. 2, 5b) (Paper I). The coarse layers were most likely relatively thin, and sedimentary gravity flows probably did not reach as far as where Vigda incised the sediment. As a result, the layers pinching out in the clay led to an increased pore pressure and enhanced leaching of the clay.

Areas without a source for coarse material input nearby have very few sand layers. Thin sand or silt layers, together with increased groundwater gradient due to sloping of the terrain, have resulted in relatively slow development of quick clay in the deposit. This occurs in Central Buvika, near the sea (Fig. 7). In such areas, the formation of quick clay has initially been limited to thin layers. The slide planes of the large flake-type slides in Central Buvika were likely such thin quick-clay layers (Paper III). Continued leaching has produced more quick clay, which explains why this northern part of Buvika is one of the most slide-active areas of the valley today. Resistivity measurements suggest that almost all the clay above the river level is leached, and that intact salt marine clay occurs as pockets or layers – often below the river level (Paper IV).

Figure 8 summarises the preconditions for quick-clay development with regard to coarse layers interbedded with clay. The figure is only a guideline, and exceptions and transitional forms exist.

In addition to the stratigraphy, the topography of the bedrock, both covered and uncovered by sediments, will influence the formation of quick clay. A steep and high hill of fractured bedrock will supply the unconsolidated deposit in the valley with water at higher artesian pressures than in a relatively flat and low terrain. A large high-lying, drainage area in bedrock will probably give rise to the highest pressures. The Saltnes slide (see later), in addition to observations and measurements at other locations in the

	Relative number of layers	Dominating process	Relative rate of quick-clay formation	Early phase	Possible slide type or development of other landscape elements
THIN SAND / GRAVEL LAYERS IN CLAY	Few	Leaching	Slowly	Thin layers of quick clay	Flake type slides, relative thin layer of remoulded quick clay acting as slide plane
	Many/ frequent	Leaching	Fast	Thicker layers or pockets of quick clay	Classical bottle-neck quick clay slide, with remoulding of thick layer of quick clay
THICK SAND / GRAVEL LAYERS IN CLAY	Few	Drainage/ seepage. Leaching	Moderate	Thicker layers or pockets of quick clay?	Both ravine development and sliding activity
	Many/ frequent	Drainage/ seepage	Moderate/ Slowly	Thicker layers or pockets of quick clay?	Ravine development, often small/surficial slides connected to the ravine walls. Slides may occur between ravines.

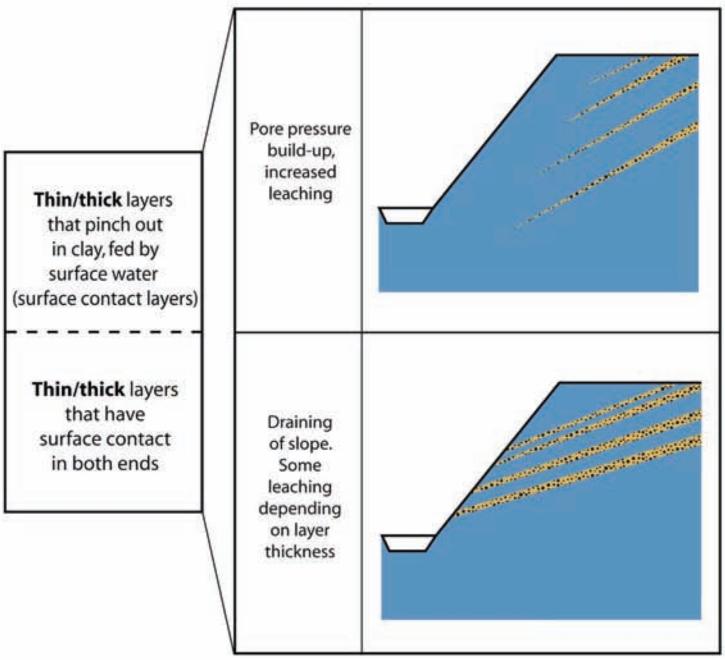

Fig. 8. Conceptual diagram showing preconditions for development of quick clay, leading to different slide types. Transitional forms also exist. Note: some ground-water gradient is assumed, but not examined in detail (Paper I).

valley (e.g. Berg & Hove 2001a, 2001b), shows that artesian conditions facilitate formation of quick clay. Increased artesian pore pressure may also directly trigger slides (Carson 1981). Undulating sediment-covered bedrock topography will often lead to quick-clay development, since the groundwater gradient is partly directed upward above a peak in the bedrock surface (e.g. Lebuis *et al.* 1983; Janbu *et al*. 1993; Rankka *et al*. 2004).

Distribution of clay slides and ravines, and their relative age

The undulating terrain of Buvika is formed by numerous slides and ravines through time (Figs. 2, 3). The slide scars are u-shaped or have the more classical shape of a quick-clay slide, with a slide gate that is narrower than the widest part of the scar (bottleneck shape) (e.g. Fig. 4f). Most of the slides terminate at the Vigda river-valley or in ravines, but for a few slides the debris went directly into the fjord (Fig. 2).

Traces of different slide types from small slumps to large quick-clay slides dominate the landscape, in addition to ravines (Figs. 2, 4a-4d, 4f). The mapping and dating of the slide scars in the vicinity of Vigda indicates that most of the slides are younger than 3000 years BP, and the youngest slides are mainly located in Central Buvika. With one exception, all the slides referred to in historical records are situated here (Paper II).

Scars from old quick-clay slides will likely dominate the landscape for a very long time, but even these scars may be removed by later erosion. In modern time traces of some old slide scars have been partly erased due to cropland levelling.

The eastern margin of Buvika is intersected by numerous deep ravines that end in the Vigda river-valley (Figs. 2, 3, 4b). The ravines deepened as the sea level was lowered, both through incision and slope failures. Some ravines occur in the relative flat bottom of a slide scar, indicating a younger age of the ravine relative to the slide event. The ravines that terminate in a slide scar may have been there before the slide, but since slides often occur between ravines (Mollard 1977; Lebuis *et al.* 1983; Robitaille *et al.* 2002; Geertsema *et al.* 2006), they may have been created afterwards. According to Carson & Geertsema (2002) ravines act to limit the spatial extent of high pore pressures in the deposits at depth, hence maintaining higher shear strength. The relatively low groundwater level will also lead to development of thicker and stronger dry crust clay. However, small ravines seem to have less effect on slide dimensions than larger ones.

Some small slide scars are located in the rear part of the ravines in Eastern Buvika, and they are probably a part of the ravine formation, due to groundwater/seepage erosion and subsequent settlement (Paper I).

Clay-slide triggers in Buvika

River erosion has probably been the most common triggering factor of the clay slides in Buvika (Paper II). Other erosion factors are important prerequisites – and some of them can trigger slides directly (Fig. 9). Initial slides are often triggered by river erosion that may lead to larger quick-clay slides. Increased river/ravine erosion is often connected to rapid snowmelt or heavy precipitation.

Groundwater indirectly leads to sliding due to the development of quick clay by leaching, but a more direct triggering influence is by seepage erosion and pore pressure build-up.

At least two clay slides in Buvika were probably initiated by rock falls (Paper II, III). Large earthquakes are not common in Norway, but cannot be excluded as a triggering factor for older slides (Bøe *et al.* 2003). In addition to these natural factors, human influence is a common triggering factor in areas vulnerable to clay slides (Paper II).

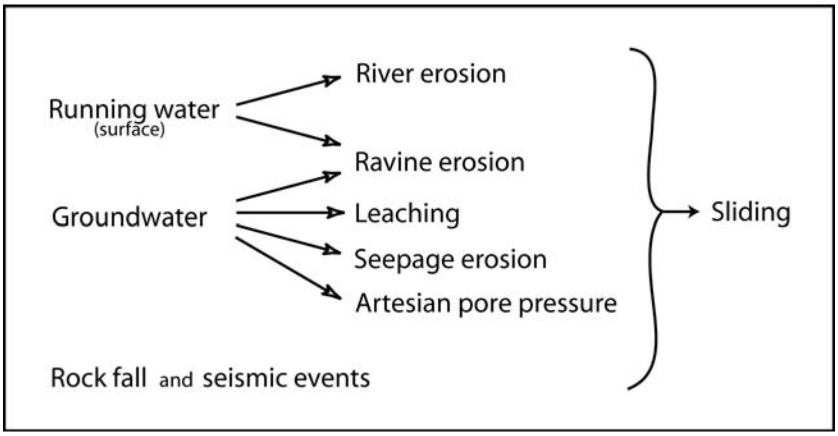

Fig. 9. Basic factors for natural sliding activity in areas with glaciomarine and marine deposits (Paper II).

Prerequisites for increased pore-pressure and quick-clay development

A quick-clay slide that leaves behind a more or less empty slide scar with a narrow gate requires the presence of thick quick-clay layers or zones. In areas where the formation of quick clay has been fast, such slides probably occurred relatively early after the deposits emerged above the sea level and the river incised the deposits. An example of this is the Saltnes slide in Central Buvika (Figs. 4c, 4d), which is dated to ca. 3000 ^{14}C-years BP (Paper II, Paper III). The bottom of the slide scar is 20-25 m a.s.l., but the slide plane was some metres lower. The sea level was about 11 m above present sea level at the estimated time of the event, and with a similar river gradient as now, this means that the riverbed was about 17 m above present sea level at the location for the Saltnes slide. The slide plane, therefore, was near the former riverbed level.

Resistivity measurements indicate a thick coarse deposit that thins out towards east and north, situated stratigraphically between bedrock and clay-slide deposits in the Saltnes slide scar (Fig. 10) (Dalsegg *et al.* 2006; Paper IV). Ground penetration radar (GPR) was used in order to verify this coarse material. The electrical properties of the subsurface, including dielectricity, electrical conductivity and magnetic permeability, determine the spread of the GPR pulses. Penetration depth for electromagnetic waves decreases with increasing electrical conductivity in the subsurface. The signals are strongly attenuated in conductive material such as clay and salt water (Mauring *et al.* 1995). The penetration of GPR in Buvika was rather limited (3-7 m), probably due to clay slide deposits, which have relatively good conductivity. Since these data did not give any information on stratigraphy at greater depths, they were not included in any of the papers.

Geotechnical drilling performed later partly confirmed the coarse material since sand came out of the drill hole together with artesian water. This coarse deposit is located about 16 m above present sea level, below clay in the slide scar. The clay deposit before the slide had some sand layers, as shown in a cut through a slide block, and from drillings inside and outside the slide scar.

Water from the steep rock face west and south of the scar was stored in the coarse deposit generating a local artesian pressure, which likely accelerated comprehensive leaching and increased the pore pressure in the clay deposit prior to sliding. This is supported by the fact that an artesian spring is present in the bottom of the slide scar. River erosion may have triggered the slide, possibly in combination with high pore-pressures in the quick-clay deposit. According to Carson & Geertsema (2002), a thick clay deposit will take some time to leach, even when buried aquifers exist. Nevertheless, the leaching will be faster than in similar clay deposits without an underlying aquifer. The massive clay deposit should be more prone to flow-sliding where the underlying

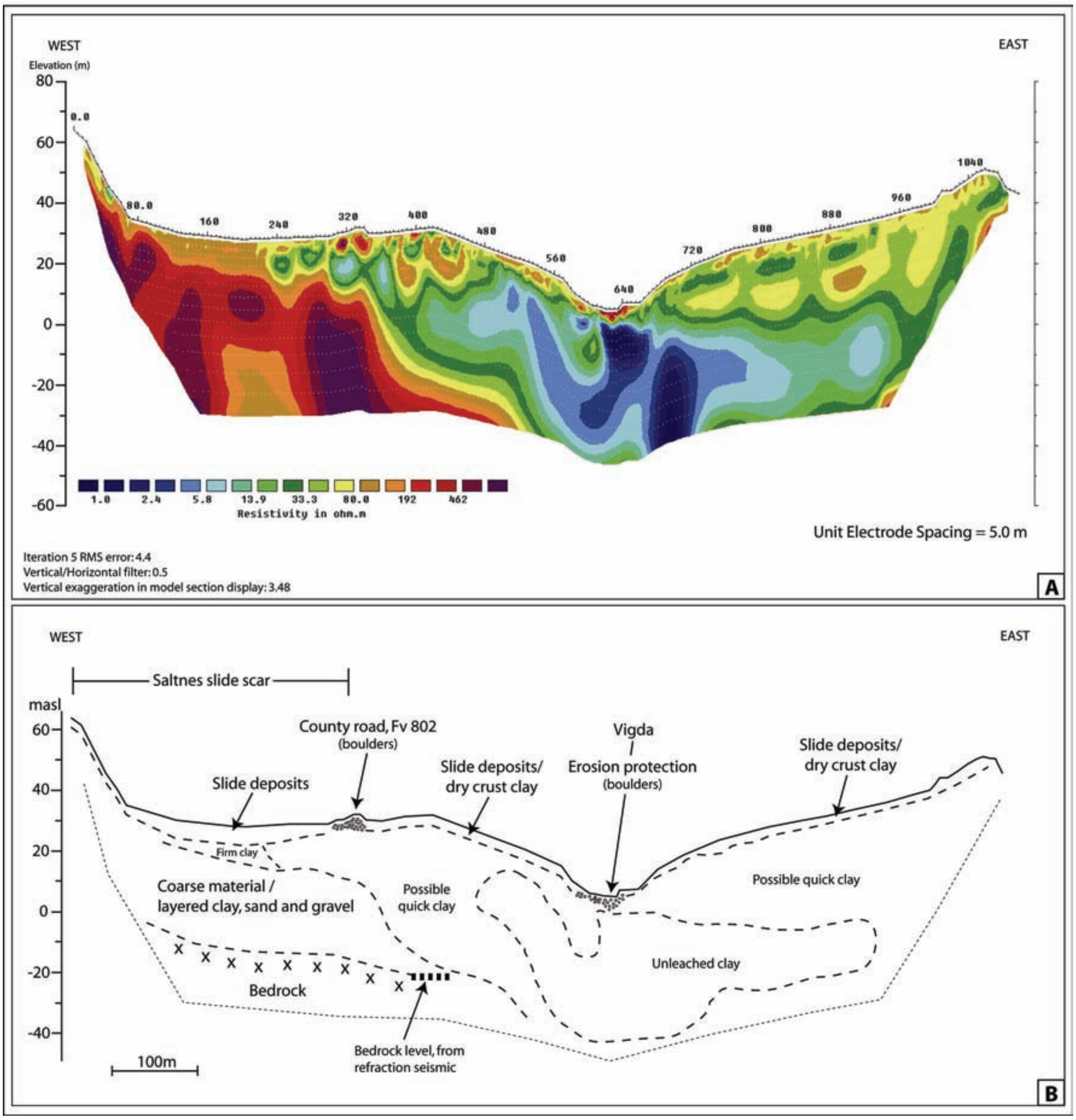

Fig. 10. A Resistivity profile 8 in Buvika that partly is located in the Saltnes slide scar (see Paper IV for location). **B** Interpretation with regard to sediment types and clay properties based on resistivity measurements and refraction seismic investigations (partly modified from Paper IV).

bedrock or aquifer is not too far below the valley floor level. This is also the situation for the Saltnes slide (Fig. 10). A comparable study in Quebec in Canada shows that strong hydraulic gradients associated with high pore pressure accelerate leaching of salt, and might directly trigger mass movement Carson (1981).

Recognition of slide deposits

Slide deposits may be difficult to recognise in the terrain, but morphology and sections will give information to help outline the landscape development and stratigraphy. Deformation structures in marine clay deposits may be interpreted as the results of terrestrial or submarine slides, or as glaciotectonic activity. Human influence may also disturb the original stratigraphy – and these deposits can in some cases be difficult to interpret as anthropogenic.

Morphology

Slide debris in Buvika that accumulated in the river-valley temporarily raised the river bottom, and incision into these deposits locally produced terraces. Such terraces of slide deposits are also described in Foster & Heiberg (1971), and here the terrain above an aggressive front of mass removal in the ravine heads is interpreted as virgin terrain (i.e. the old seabed). However, the studies from Buvika show that it can be difficult to distinguish slide deposits from *in situ* sediments, especially if distinct slide scars in the vicinity of slide deposits are absent. In particular, high-lying terrain or interfluve areas may be considered as composed of undisturbed material. Also in Buvika, some areas are interpreted as remnants of the old seabed (virgin terrain) (Fig. 5a) – and such interpretations should be based on a reconstruction of the entire seabed using, for example, geomorphology, the local sea-level curve and pre-consolidation calculations (Solberg *et al.* 2006).

In Buvika, undulating terraces in the vicinity of slide deposits discovered in road excavations indicated the source area for the slide(s). These deposits represent one or more flake-type slides with at least one slide plane (Paper III). A study of a modern slide in Canada, and the Storegga slide offshore Mid Norway, show that flake-type slides may have several slide planes (Haflidason *et al.* 2004; Geertsema *et al.* 2006).

Flake-type slides have probably occurred many times in prehistoric time, as a part of the degradation of the landscape. Regardless of the amount of remoulded quick clay, deposits both from numerous classical bottleneck slides and from flake-type slides most likely accumulated on the sea bottom outside the shoreline of Buvika (Fig. 7).

Excavated sections and geotechnical drillings

The study of long excavated sections in Buvika shows that there are far more signs of slide activity than solely indicated by slide scars, also in the relatively high-lying parts of the valley fill (Paper III). These deposits are difficult or impossible to identify by geotechnical drilling, unless drilling samples show terrestrial organic material. If the deposits are remoulded quick clay, where most of the excess pore water has escaped, the material will probably be interpreted as dry crust clay in drilling profiles. Some of the sections in Buvika, on the other hand, showed slide material that was not remoulded during sliding, except for a thin layer of quick clay, acting as the slide plane. The geotechnical drilling profiles, which were carried out before the excavations, indicate a slide plane as a transition into material with less drilling resistance. The top layer of slightly higher drilling resistance would normally be interpreted as dry crust clay. As the material properties may be similar to stable clay, these old slide deposits will not necessarily influence stability considerations in these particular locations. On the other hand, for the geological aspects and the understanding of how the landscape develops with regard to sliding, these discoveries are important. Younger slide scars cutting into these old slide deposits show continued quick-clay development.

Interpretation of deformation structures in clay

Large, continuous road cuts give much more information than small excavations in sediments, such as those made by a shovel. However, large sections in clayey deposits have rarely been investigated and documented. In Buvika the sections revealed (apparently) intact, moderately deformed or heavily deformed clayey sediments. To interpret these phenomena, careful records and analyses were made in most of the sections. The position and elevation in the terrain, and the presence of modern terrestrial organic material, also helped the interpretation. Still, it can be difficult to determine what caused deformations in a clayey deposit, and structures must be put into a geological context including considerations of the fossil content (Fig. 11).

Most of the excavated sections that showed deformed material in Buvika were interpreted as slide deposits (Paper III) (Enclosure 4). They were recognised through structures such as folds, faults, water-escape dykes, and terrestrial organic material in buried soil layers or mixed with clay. Since many of the sections mainly showed deformed and not totally remoulded clay, it is assumed that sliding took place on a thin layer of liquefied quick clay.

Another road cut in Western Buvika (Fig. 2) showed highly folded clayey silt in parts of the section (Paper I) (Enclosure 4). This was interpreted to be a glaciotectonised deposit, due to its position, the ages of marine molluscs, the fold axis direction and the structural interpretation.

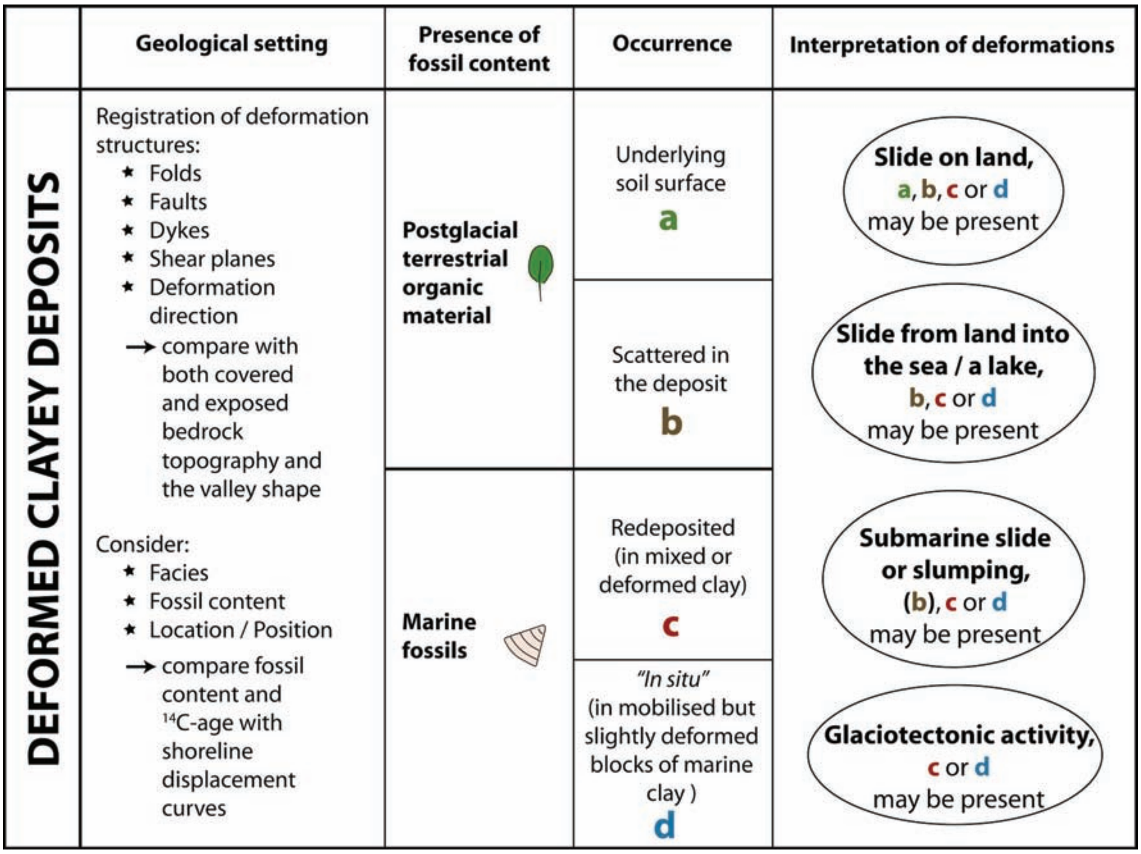

Fig. 11. Conceptual diagram for interpretation of deformed clayey deposits based on geological setting and possibly presence of fossil content. Deformation structures in clay deposits may be interpreted as terrestrial or submarine sliding activity, or as glaciotectonic action. For fill material from, for example cropland levelling, a-c may also be present, and these deposits will most likely be structureless.

Outlining quick clay

According to Karlsrud *et al.* (1985) the position of quick clay in slopes, in addition to *in situ* pore pressures, stresses and stress history, control the landslide risk. Traditionally, geotechnical drilling has been used to outline quick-clay zones or layers in the subsurface. Laboratory testing of core samples is the most reliable method of confirming the existence of quick clay. Still, this method is expensive and time-consuming, and it only gives information at individual points within the investigated area. Electrical resistivity imaging is a relatively cost-effective geophysical method; it is non-destructive, and gives a continuous image of the subsurface.

The results from the resistivity measurements in Buvika were compared to the geotechnical data in the vicinity of the profiles (Paper IV). Many of the geotechnical profiles were interpreted and inserted together with he resistivity profiles into a 3-D model in ArcScene (ArcGIS version 9.1) for comparison (Fig. 12). The use of resistivity measurements as a tool for outlining geotechnical properties of clay is strengthened by the present study, since a classification of possible quick clay (approximately 10-80 Ωm) complies with results from Canadian and Swedish investigations (e.g. Calvert & Hyde 2002; Leroux & Dahlin 2003).

The resistivity profiles cannot give high-resolution information on layering of the subsurface, since the resolution in the resistivity profiles often is lower than the thickness of the coarse layers. In this respect, some of the geotechnical test methods, such as the CPTU (Table 2), give local but detailed overview of the stratigraphy and the soil conditions. In addition, depth to bedrock may be difficult to determine precisely with the resistivity method. Here, refraction seismic investigations may be more reliable. The resistivity method will be less suitable in urban areas due to buried cables and other conductive materials that will disturb the measurements. Despite weak points in all these methods, together they may give a detailed picture of the subsurface with regard to material properties, stratigraphy and geology.

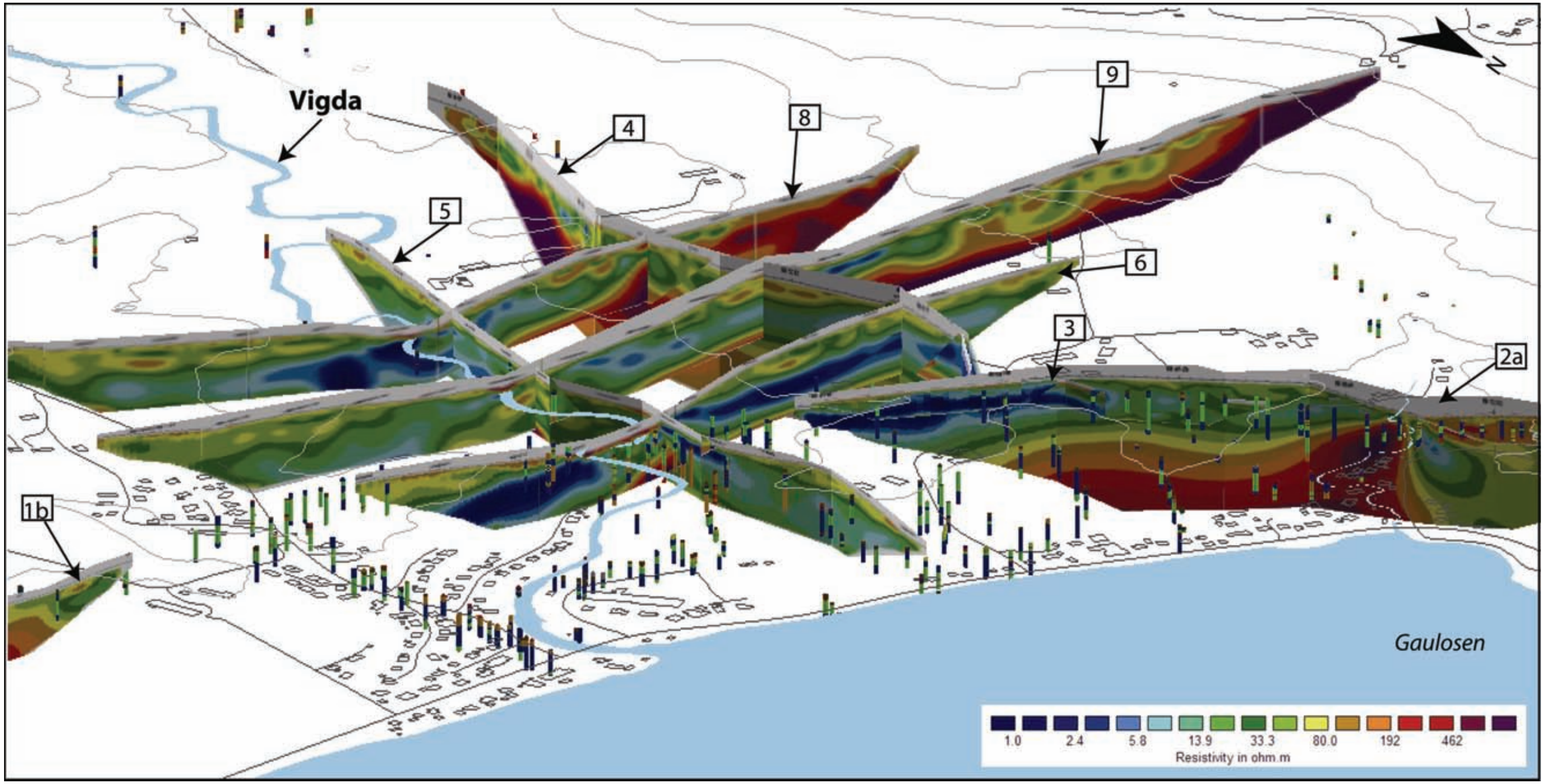

Fig. 12. Resistivity profiles visualised in ArcScene together with some interpreted geotechnical drilling profiles for comparison of the two methods (Data from Dalsegg *et al*. 2006 and Enclosure 3). For more on profile locations, see paper IV.

Hazard assessment, mitigation measures and valley development in Buvika

Hazard assessment

Mapping of areas for potential quick-clay slides is based on studies of Quaternary geological conditions, evaluation of topography and interpretation of some geotechnical field investigations (Gregersen 1988; Gregersen 2002). The hazard factors are based on the conditions in each area, and they are given score and a predetermined weighting. This results in a classification as low, medium or high probability for a slide to occur (Fig. 13). A lower limit for area involved in a potential slide is set to 10 000 m^2.

Hazard	Weight	Score for hazard			
		3	2	1	0
TOPOGRAPHY					
Earlier Sliding	1	Frequent	Some	Few	None
Height of slope, H	2	>30 m	20-30 m	15-20 m	<15 m
Slope inclination	3	1:3	1:4	<1:4	<1:6
GEOTECHNICAL CHARACTERISTICS					
Overconsolidation ratio (OCR)	2	1.0-1.2	1.2-1.5	1.5-2.0	>2.0
Pore pressure conditions [i] - In excess (kPa) - Under-pressure (kPa)	 3 -3	 > + 30 > - 50	 10-30 -(20-50)	 0-10 -(20-0)	 Hydrostatic Hydrostatic
Thickness of quick clay layer	2	>H/2	H/2-H/4	<H/4	Thin layer
Extent of quick clay	2	large	medium	small	None
Sensitivity, S_t	1	>100	30-100	20-30	<20
NEW CONDITIONS					
Erosion [ii]	3	Active/sliding	Some	Little	None
Human activity - Worsening effect - Improving effect	 3 -3	 Important Important	 Some Some	 Little Little	 None None
Maximum possible weighted score		51	26	18	0
% of cases with maximum weighted score		100%	79%	31%	0%

Low: **Score $\leq$ 18**
Medium: **26 > Score > 18**
High: **Score $\geq$ 26**

Low: Favourable topography and soil conditions; extensive site investigations; no erosion; no earlier sliding; no planned changes, or changes will improve stability.
Med.: Less favourable topography and soil conditions; limited site investigations; active erosion; important earlier sliding in area; planned changes give little or no improvement of stability.
High: Unfavourable topography and soil characteristics; limited site investigations; active erosion; extensive earlier sliding in area; planned changes will reduce stability.

Fig. 13. Evaluation and classification of hazard (based on Gregersen 2002; Nadim 2006).

The hazard map for Buvika is shown in Figure 14. Each zone shows the assumed maximum area that may be included in a quick-clay slide. The zones do not include considerations on outflow distance or influence on areas downstream from the zone (Gregersen 1988). A similar map has been made for consequences of clay slides. Risk is defined as the product of hazard and consequence (Table 1), and risk maps covers the same areas as the maps for hazard and consequence (Gregersen 2002). One purpose of the classification is to help prioritise resources for the further mitigation measures in slide-prone areas. In the present study, the investigations and understanding of the landscape development may be related to hazard or susceptibility zonation.

Mitigation measures in Buvika

The hazard zones with high and medium probability for slides in Central Buvika indicate that new construction in the area should be performed without decreasing the stability. Therefore, during the construction of the new highway E39 in Buvika (Fig. 3), Skanska Norge AS and Norwegian Water Resources and Energy Directorate (NVE) carried out several stability-increasing actions. Terrain levelling was performed in order to lower slope heights (Figs. 4a, 4e). Along the shore, relatively large boulder fills were placed in order to give a counterweight to the sloping terrain towards the sea (Fig. 15a). The riverbed was elevated by about 2 m along an approximately 2 km long section of Vigda (Fig. 15c), as well as in parts of a ravine. This acts as a counterweight towards the river/ravine slope, and as erosion protection. In addition, lime-cement pillars were made before some of the sections were excavated (Fig. 15b). Some of the pillars were 17 m deep and covered relatively large areas (B. Haavardsholm, pers. comm.). All these actions have increased the stability in Central Buvika, which is reassuring since large amounts of quick clay are detected there (Paper IV).

Landscape development in Buvika

All areas that have marine deposits can potentially develop quick-clay zones, and may be exposed to sliding. Construction or other interventions in such areas should therefore be carried out carefully. Regardless of mitigation measures in an area, future slides that potentially occur upstream may cause great damage to downstream areas, for example due to possible damming and following flooding.

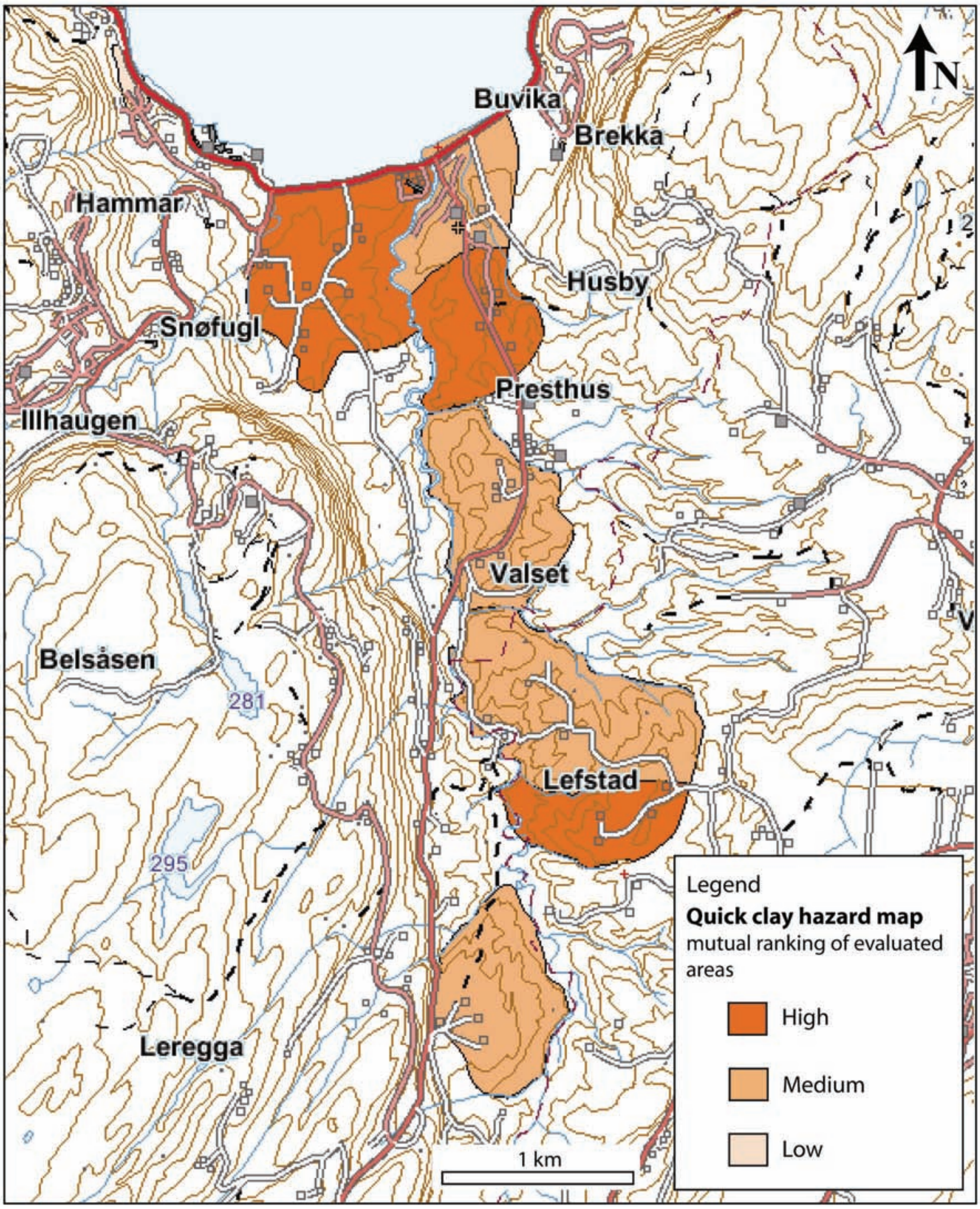

Fig. 14. Quick clay hazard map for Buvika (www.skrednett.no). See Fig. 13 for details on classification.

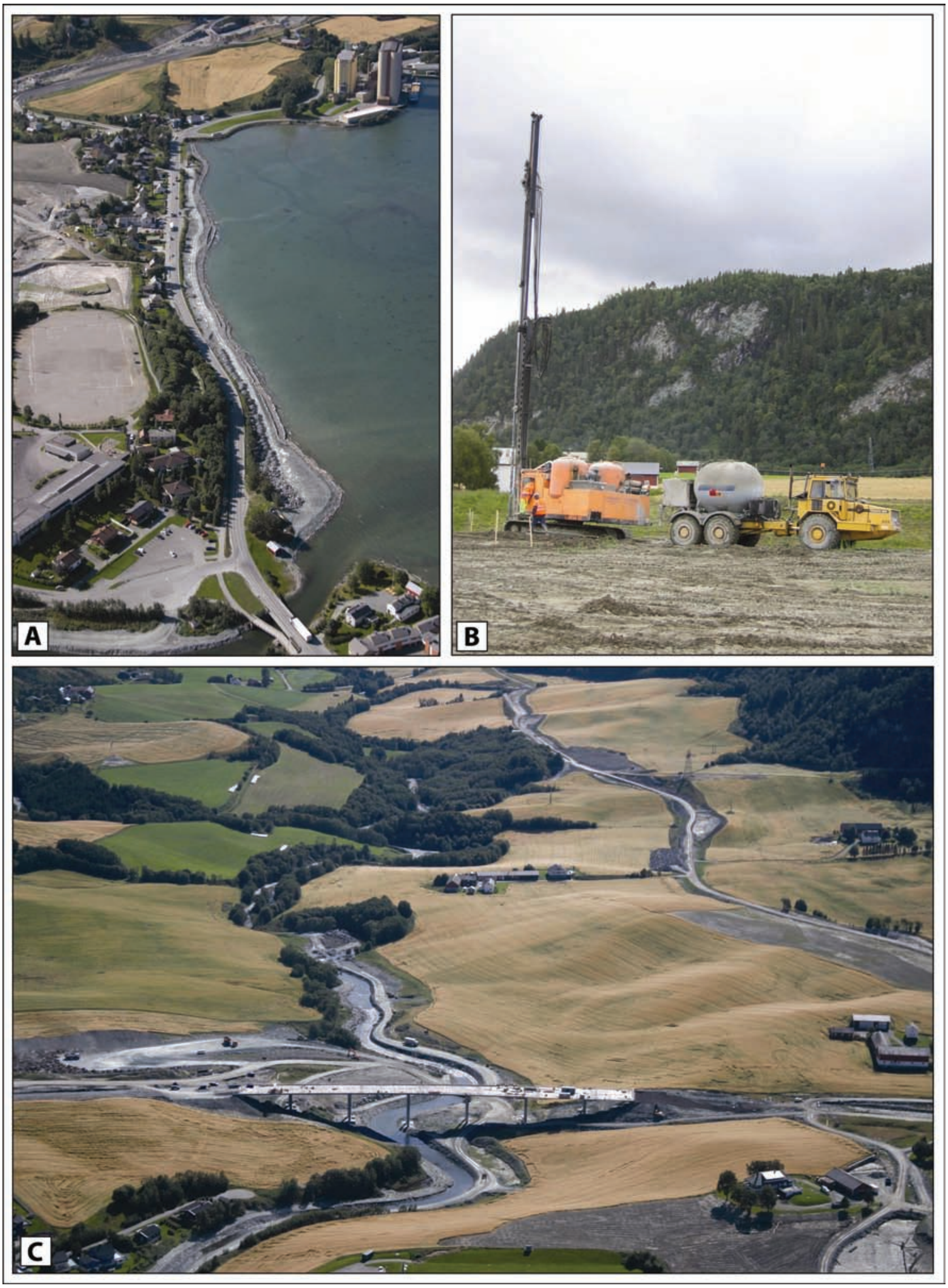

Fig. 15. A Shoreline protection against wave erosion and as counterweight to the sloping terrain towards the sea. **B** Lime cement piling. **C** Erosion protection along Vigda, which also acts as counterweight towards the slopes (Photos A and C: NVE).

The area in the vicinity of the new highway in Buvika has been thoroughly investigated with regard to geotechnical properties of the deposits. Other areas have scattered or lack geotechnical data, but numerous slide scars indicate that quick clay has been and may still be present (e.g. Fig. 4f).

The northern part of Buvika has been the most slide-active in historic time (Paper II), but other parts of the study area have also been exposed to relatively young slides. One example is a slide in 1864, involving about 400 000 m^3 clay deposits, which resulted in the deaths of four people (Helland 1896; Paper II). The river Vigda was dammed for some time afterwards. The slide scar is located in the southernmost hazard zone in Buvika, which has medium hazard degree (Fig. 14). Areas with steep slopes and quick clay present should be paid attention to in the future.

Along the eastern margin of Buvika, several ravines deeply incise the terrain (Figs. 2, 3, 4b). Surface erosion and small slides occur in the ravines, continuing to develop them (Figs. 5c, 5d). There are also erosion scars along Vigda in this area (Paper I; Gregersen 1988). Even though large slides involving several ravines probably not will occur (see earlier) (Paper I, II), slides between the ravines and smaller slides in the ravines may cause damage to cropland and buildings. The area has low to high hazard degree (Fig. 14).

The present study shows that geophysical methods, such as resistivity measurements, may potentially be used for susceptibility mapping together with geotechnical data and morphological studies. This may expand or reduce the present hazard (susceptibility) zones. A relatively detailed knowledge of the stratigraphy connected to the overall valley in-fill history increases the understanding of the morphology and erosion pattern in different parts of an area, and may be an indicator of future activity.

Despite detailed studies in clay areas, it is very difficult to predict quick-clay slides (e.g. Karlsrud *et al.* 1985). However, more interdisciplinary studies will increase the understanding and predictability of processes and development in clay areas in order to prevent slides or reduce the damage.

MAIN CONCLUSIONS FOR THE PHD THESIS

The main conclusions reached in this thesis are:

- Sedimentological, stratigraphical and structural analyses of road cuts in fine-grained marine deposits in Buvika, combined with ^{14}C-dating, indicate at least one, and maybe two, minor glacier oscillations during the late-glacial period.
- Sand layers interfingering clay in Eastern Buvika were probably deposited in the distal part of a large ice-marginal glaciofluvial system at Holem in the neighbouring Gauldalen valley.
- The valley development may be divided into three stages: Early, Intermediate and Recent. While the Early stage was dominated by sedimentation from suspension, the processes in the Intermediate stage were accumulation, river incision and sliding activity. The Recent stage is characterised by continued sliding activity, river and ravine incision, shaping the present landscape.
- The sedimentological stratigraphy in Buvika has highly influenced the erosion pattern and landscape development in different parts of the valley.
- Thick and frequent layers of sand and gravel seem to drain the slope and facilitate ravine development. Thinner layers of coarse material in clay lead to quick-clay development, resulting in numerous slide scars.
- Sand layers that pinch out into the clay increase the groundwater pore-pressure during, for example, heavy rainfalls. In addition to intensify the leaching of clay, increased pore-pressures may trigger slides.
- Slide events that include collapse and remoulding of thick quick-clay layers are dependent on massive quick-clay development, and in Buvika they mostly seem to represent relatively young slide events.
- Where fairly old bottleneck-shaped quick-clay slides are present, the conditions must have been favourable for relatively fast quick-clay development.
- The source area for old flake-type slides may be difficult to outline exactly, due to later landscape erosion.
- The long-term development of quick clay has an important impact on landscape degradation and on the character of the present day landscape. The study shows that

younger slide scars cut into older slide deposits after continued quick-clay development.

- Excavations in clayey deposits reveal structures such as folds, faults, water-escape dykes and terrestrial organic material in buried layers or mixed with clay. The deposits are interpreted to represent large clay slides, sliding on a thin layer of remoulded quick clay.
- The most common natural clay-slide triggers are river erosion and groundwater erosion, but rock falls have also triggered slides.
- The study shows that the resistivity method is useful for detecting sections of possible quick clay in the subsurface. However, the method cannot verify the presence of quick clay since both leached, non-quick clay and silty, non-sensitive material can give resistivity values of the same range (10-80 Ωm). Still, the indications are important in selecting areas for further investigations and for refining the interpretation of the subsurface.
- In addition to giving input on the general geological and stratigraphical distribution of sediments in an area, the resistivity profiles can give indications of barriers that may limit the extension of a potential quick-clay slide. Groundwater drainage patterns can potentially be interpreted from the resistivity profiles since increased groundwater drainage can be associated with leaching and subsequent formation of quick clay.

SUGGESTIONS FOR FUTURE WORK

Stratigraphy, quick-clay slides and deformation structures

The importance of the stratigraphy for formation of quick clay and landscape development have been emphasised in this study (Paper I). There is a potential for further and more studies on, for example, layer thickness, material types and ground-water gradients in relation to quick-clay development, drainage pattern and seepage erosion. In addition geotechnical properties could be compared to sedimentological facies, in order to extract more information about the sediments. An example of this may be correlating certain stratigraphical levels with geotechnically weak layers, as done by Hansen *et al.* (2007).

Regarding quick-clay slides, there are several interesting subjects that could be treated further and that potentially will refine susceptibility mapping of an area: The amount of clay that is left behind in the scar or deposited just outside the scar, how much is deposited downstream and how the out-flowing quick clay will influence the areas downstream. This could be done by studying old slide scars, different river systems and the morphology of terrains with quick-clay. Laser scanning (LIDAR) could be used in order to obtain a higher resolution terrain model. This would allow for more detailed mapping and analysis of the terrain, independently of vegetation. The better understanding of properties, formation and occurrence of quick clay in order to outline the sliding processes, may lead to methods to prevent sliding and reduce damage caused by sliding.

In the future, it could be interesting to study the deformation of clay caused by glacial tectonics and sliding in even more detail, for example, deformed material in small scale. This can be done by studying thin sections from the deposits (in microscope), and will potentially increase the understanding of various deformation processes.

It is the intention of this study that the methods and results obtained can be used to understand the development of other areas with marine deposits. A combination of geological, geomorphological, geophysical and geotechnical investigations will be important in future studies.

Enhanced use of resistivity measurements

As the resistivity method is shown to have great potential in outlining the extent of quick clay, it should be used in more areas for further testing of marine clays in Norway. Experience from Sweden and Canada also shows promising results (e.g. Calvert & Hyde 2002; Rankka *et al.* 2004; Dahlin *et al.* 2005). This study has tested the method by comparing the results with geotechnical data. However, results could be further tested and used in connection with landslide hazard mapping. Maps of hazard, consequence and risk have already been made for several areas prone to clay slides in Norway (see earlier and www.skrednett.no). However, hazard (or susceptibility) maps could be further developed by the use of the resistivity method in order to expand or reduce the hazard zones. Hazard maps today are mainly based on geotechnical data, which in many places are rather sparse. In addition, these maps only consider consequences for the areas that are directly affected by the slide, and not areas downstream from this area, which also should be paid attention to.

Resistivity profiles can also give indications of barriers that may limit the extension of a potential quick-clay slide. Carson & Lajoie (1981) discuss some examples they call "aborted retrogression", where till, bedrock or non-sensitive material limited a slide's size. A barrier should be large enough to remain stable, even if the support disappears during a hypothetical slide. Indications of thick coarse-grained deposits on bedrock, or the bedrock alone, will help to classify areas as relatively stable.

Inversion of the raw resistivity data may be done in a more advanced way than in this study (Paper IV). There are possibilities for inserting data in the program (Res2Dinv, Loke 2004), which will limit the number of uncertain values by incorporating boundaries of known layers. One example is the depth to bedrock, obtained from other methods (e.g. seismic, drilling). There is also a potential for synthetic modelling of different geological features, in order to better understand and interpret complex resistivity results.

The Wenner electrode array (Wenner-α) (Fig. 6) was chosen for this project because it is well suited for a layered subsurface (Reynolds 1997). The method gives a poorer resolution than some other arrays, but it has a higher signal-to-noise ratio. Other electrode arrays could be tried in order to compare how quick clay and other material will appear with various arrays. Dipole-Dipole and Schlumberger may give better lateral resolution than Wenner, but these methods are more time consuming and can produce more noise in the results (Dahlin and Zhou 2004).

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Paper I: Landscape development and deglaciation history of fjord-valley deposits in Buvika, Mid Norway

Solberg, I.L., Hansen, L., Rokoengen, K., Sveian, H. & Olsen, L. (subm): Landscape development and deglaciation history of fjord-valley deposits in Buvika, Mid Norway. Submitted to Boreas May 2007

Landscape development and deglaciation history of fjord-valley deposits in Buvika, Mid Norway

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Abstract

Solberg, I.L., Hansen, L., Rokoengen, K., Sveian, H. & Olsen, L.: Landscape development and deglaciation history of fjord-valley deposits in Buvika, Mid Norway. Submitted to Boreas May 2007.

Thick deposits of glaciomarine clay and silt overlain by Holocene marine sediments in Norwegian fjord-valleys have been, and still are, subjected to erosional processes such as river incision, ravine formation and slide activity. In Buvika, Mid Norway, these landforming processes are found to be highly influenced by the valley-fill stratigraphy. Glaciomarine and marine clay sediments dominate this eight km long hanging valley south of the Gaulosen fjord. Locally, and also deep in the stratigraphy, coarser-grained glaciofluvial sediments occur. Careful studies of sediments and structures in road excavations together with ^{14}C-datings indicate at least one, possibly two, minor glacier re-advances in Late Allerød/Early Younger Dryas time. This implies a more dynamic ice-sheet with more minor ice-front oscillations than earlier documented. The valley-fill emerged and was exposed on land due to glacioisostatic rebound. Leaching of salt from the marine clay resulted in the development of "quick clay" in certain layers or zones, especially where thin layers of sand/gravel feed the clay deposit with groundwater. The relative sea-level lowering led to incision by rivers accompanied by numerous slides involving quick clay, which completely liquefies when remoulded. Variations in the stratigraphy have influenced the morphology of different parts of the valley. To the east permeable layers of sand and gravel dipping NW mostly originate from the Holem ice-marginal delta near Melhus. These relatively thick and frequent layers of sand and gravel in the dominant clay deposits drain groundwater in the slopes, leading to the development of deeply incised ravines. To the south and north, thinner layers of coarse material in the clay lead to pore-pressure build-ups and quick-clay development, resulting in numerous slide scars.

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Introduction

The glacial and postglacial history of the Trondheim region has been investigated and described during the last century; see references in Reite (1994), Olsen *et al.* (2001a, 2001b) and Rise *et al.* (2006). Quaternary geological maps on scale 1:50000 cover the study area Buvika and surroundings (Reite 1983a, 1983b, 1984, 1985). Most studies on deglaciation history are based on sediment distribution, morphology, observations in gravel pits and other sections, marine geology, ^{14}C-datings and shoreline elevations. Studies of structures in large clay excavations indicating glacier fluctuations are relatively rare.

Deglaciation and deposition of glaciomarine and marine sediments, and the following glacioisostatic rebound, have led to the emergence of large areas with marine deposits along the coast of Norway. Subsequent leaching by groundwater has reduced the salinity of the pore water and developed parts of the marine clay into quick clay. Every year small quick-clay slides occur in Norway, and occasionally really large slides cause severe damage to life and infrastructure.

Knowledge of the morphology, stratigraphy and erosion pattern of areas prone to formation of quick clay is important in order to understand the landscape development and evaluate risk areas. Relatively few morphological analyses have been made of clay terrains in Norway. A study in Romerike, southern Norway, differentiates erosion into zones associated with the geomorphology of the area (Foster & Heiberg 1971). Other examples are Hansen *et al*. 2007 and Eilertsen *et al*. (in press) that connect valley-fill stratigraphy and clay slide occurrences. Also some Canadian studies discuss the relations between sliding and Quaternary valley-fill sequences, e.g. in Ontario (Fransham & Gadd 1977) and in British Columbia (Clague & Evans 2003). In Sweden studies have been made on geology and stratigraphy important for quick clay development and slope stability (e.g. Stevens *et al*. 1991).

The first purpose of the present study is to describe and interpret the stratigraphy and properties of the valley fill based on the available data. These results will be used to elucidate the implications for glacier fluctuations at the end of the last glaciation, the deglaciation history and valley-fill stratigraphy of Buvika. The second purpose is to describe the geology and stratigraphy of the deposits and discuss their significance for the erosion pattern. Emphasis is put on the development of material sensitive to collapse and sliding, where slides occur, and the formation of ravines.

Fieldwork in Buvika, combined with the extraction of data from large amounts of geotechnical reports from the area, means that the small valley has been thoroughly investigated. Numerous highway excavations have given access to local, high-resolution datasets in clay deposits that are rarely included in stratigraphical studies. We hope that the results will be useful also for future studies of areas with similar geology both in and outside the Trondheim region. Special features from Buvika are treated in more detail in other papers: clay slide distribution (Solberg *et al.* in press,a), quick-clay distribution and resistivity measurements (Solberg *et al.* in press,b) and stratigraphy of slide deposits exposed in road cuts (Solberg *et al.* subm).

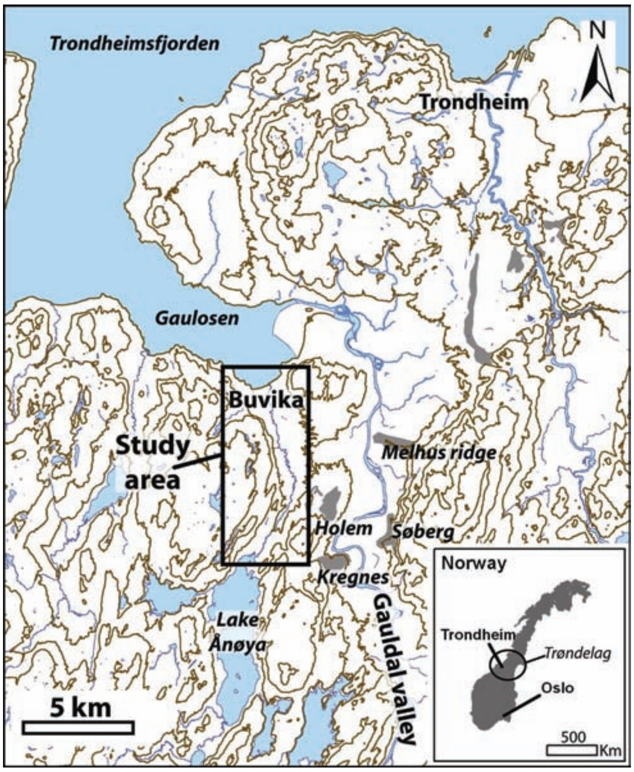

Fig.1. Location of the study area SW of the city of Trondheim. Shaded areas are ice-marginal deposits (ridges or deltas) of Early YD age. Contour lines: 100 m.

Setting

Location

Buvika is located about 25 km southwest of the city of Trondheim in Sør-Trøndelag County, Mid Norway (Fig. 1). The study area is a small fjord-valley characterised by its undulating terrain with numerous ravines and slide scars, surrounded by 300-400 m high hills of bedrock. Vigda is the main river in Buvika, originating in Lake Ånøya (149 m a.s.l.). The lake is located eight km south of Vigda's outlet in the Gaulosen bay, which is a part of the main fjord Trondheimsfjorden (Figs. 1, 2). East of Buvika lies the large Gauldalen valley (Figs. 1, 3).

A new highway (E39) through Buvika was finished in 2005. During the construction of the road several cuts were made revealing the sedimentology and structural geology of marine and glaciomarine deposits (Figs. 2, 4).

Bedrock

Metasedimentary and volcanic rocks of Late Precambrian to Silurian age dominate the study area, which is strongly influenced by the Caledonian orogeny (ca. 500-400 mill. years ago). The study area lies in the Trondheim Nappe with rocks like mica schist and green schist (Wolff 1979, Sigmond *et al.* 1984). West in central Buvika there are phyllites with graphite (Dalsegg *et al.* 2006).

The bedrock is jointed in a NE-SW direction. In addition there is a jointing in NNW-SSE to N-S direction, which influences the morphology. Most of the rivers and small streams follow these directions. There is possibly a NNW-SSE fault that extends from the Gaulosen fjord through Buvika, to part of the Gauldalen valley to the SE. Its presence is supported by a refraction seismic cross-section in central Buvika that shows a zone of lower velocity in bedrock in the deepest part of the valley, indicating a weakness zone (Pedersen 2003).

In the middle of Gaulosen outside Buvika the depth to bedrock is about 500 m, which makes Buvika a hanging valley on the southern flank of the fjord (Rise *et al.* 2006).

Fig. 2. Buvika seen towards the north. See Table 1 for ^{14}C-ages from samples 1-11 (Photo: the Norwegian Water Resources and Energy Directorate, NVE).

Deglaciation history of the Trondheim region

The main movement of the continental ice sheet during the last glacial maximum (LGM) in the southern Trøndelag area was towards NW, probably little influenced by the topography (Reite 1994; Bargel *et al.* 1999). Locally, the younger ice movements changed to westerly and northerly directions. During deglaciation the topography strongly influenced the glacier movement, which contributed to the erosion of the characteristic valley landscape, e.g. in Buvika (Reite 1983a, 1983b, 1984).

Radiocarbon datings from different parts of Central Norway indicate that coastal and outer fjord areas were deglaciated in Late Bølling/Early Allerød, partly due to calving (Kjemperud 1981; Reite 1994; Sveian & Solli 1997). The calving process was rapid in the deeper fjord basins, especially when the glacier was floating and the glacier retreated to bedrock thresholds, which gave the ice front a temporary standstill (Kjenstad & Sollid 1982). The retreat was interrupted by several such standstills or in

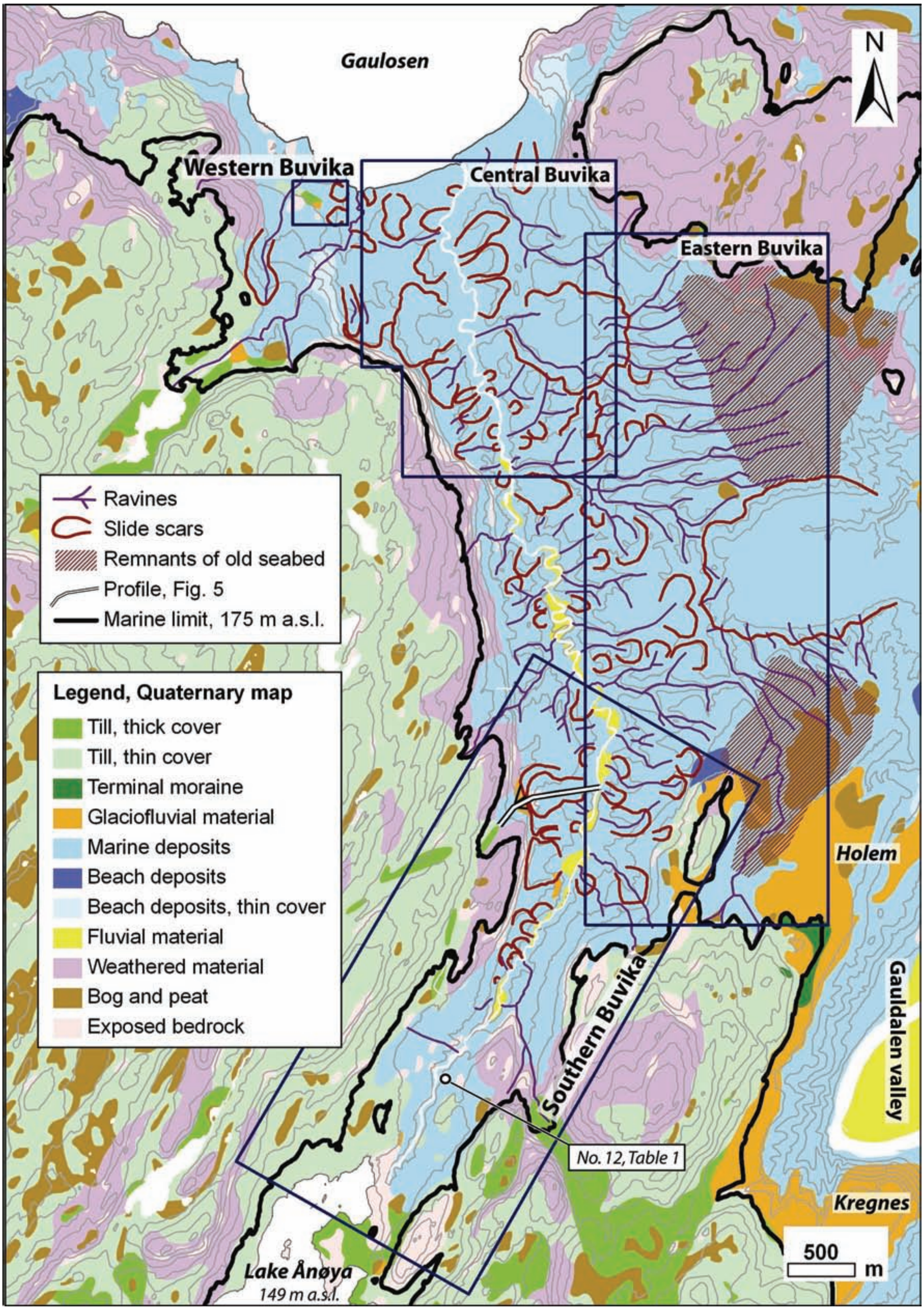

Fig. 3. Quaternary geological map showing surface material (modified from Reite 1983a, 1983b). Ravines and slide scars are also shown. The study area is divided into Southern, Eastern, Central and Western Buvika. Contour lines: 25 m.

some periods even by re-advances. The debris transported to the glacier-front formed more or less continuous ice-marginal deposits like moraines, deltas and ridges, and there are several remains of such deposits in the Trondheim region. Not all of these are dated, but they are used to reconstruct a deglaciation history for the area. The most significant ice-marginal deposits in the Trøndelag area have been dated to Early Younger Dryas (Early YD), and are called the Tautra Moraines (Reite *et al.* 1982; Reite 1983a).

Four lines of correlative ice-marginal deposits have been reconstructed for the outer and central Trøndelag area (Reite *et al.* 1982; Reite 1994; Sveian 1997). The moraines were deposited through major still-stands or re-advances of the retreating ice-fronts: 1) Outer Coastal Moraines 12400-12000 years BP (earlier set to ca. 12500 ^{14}C-years BP (Reite 1994)), 2) Tautra Moraines (Early YD, 10800-10500 ^{14}C-years BP), 3) Hoklingen Moraines (Late YD, 10400-10300 ^{14}C-years BP) and 4) Vuku Moraines (YD/Early Preboreal, 10000-9900 ^{14}C-years BP). In addition, two younger stages (Preboreal) are later included for the Nord-Trøndelag area (Sveian 1997).

According to established ice recessional chronology, Buvika was deglaciated in Mid to Late Allerød (Reite 1983b; Reite 1994; Rise *et al.* 2006). The sedimentation of thick glaciomarine clay and silt deposits mainly took place in Late Allerød and Early YD. The study area is located only a few km distally to the Tautra sub-stage line. The exact ages of the ice-front deposits in Gauldalen are, however, still quite uncertain due to lack of good ^{14}C-datings. Recent studies indicate larger and more rapid Allerød - YD fluctuations of the ice front position, with fjord-ice advances (Ottesen *et al.* 1995; Feragen 1997; Olsen *et al.* 2007).

Remains of two large glaciofluvial deltas are located in Gauldalen valley, southeast of Buvika: Holem and Kregnes-Søberg (Figs. 1, 3). Due to river erosion, only small parts of the former large Kregnes-Søberg glaciofluvial delta are left in Gauldalen. The elevation of the delta surface is ca. 170 m a.s.l., and the surface at Kregnes is rough due to eolian dunes (Reite 1985). Radiocarbon datings from several samples in the Kregnes-Søberg delta are not conclusive, but suggests an age of about 10300 years BP, which corresponds to the age of the Hoklingen sub-stage (Nemec *et al.* 1999). However, this is a too young age according to morpho-stratigraphy and other datings along the Hoklingen sub-stage line, which is located many km south of Kregnes (e.g. Reite 1994).

Today, we suggest, from shorelines and a review of all the data in the Trondheim region, that the Kregnes-Søberg delta most likely belongs to a late phase of the Tautra sub-stage (~ 10600). The Holem delta and the Melhus ridge are assumed to correspond to an early phase of the Tautra sub-stage (Reite *et al.* 1982; Reite 1983a). The presence of till on top of the Holem delta shows a glacier push after the deposition of the delta (Fig. 3) (Reite 1983a).

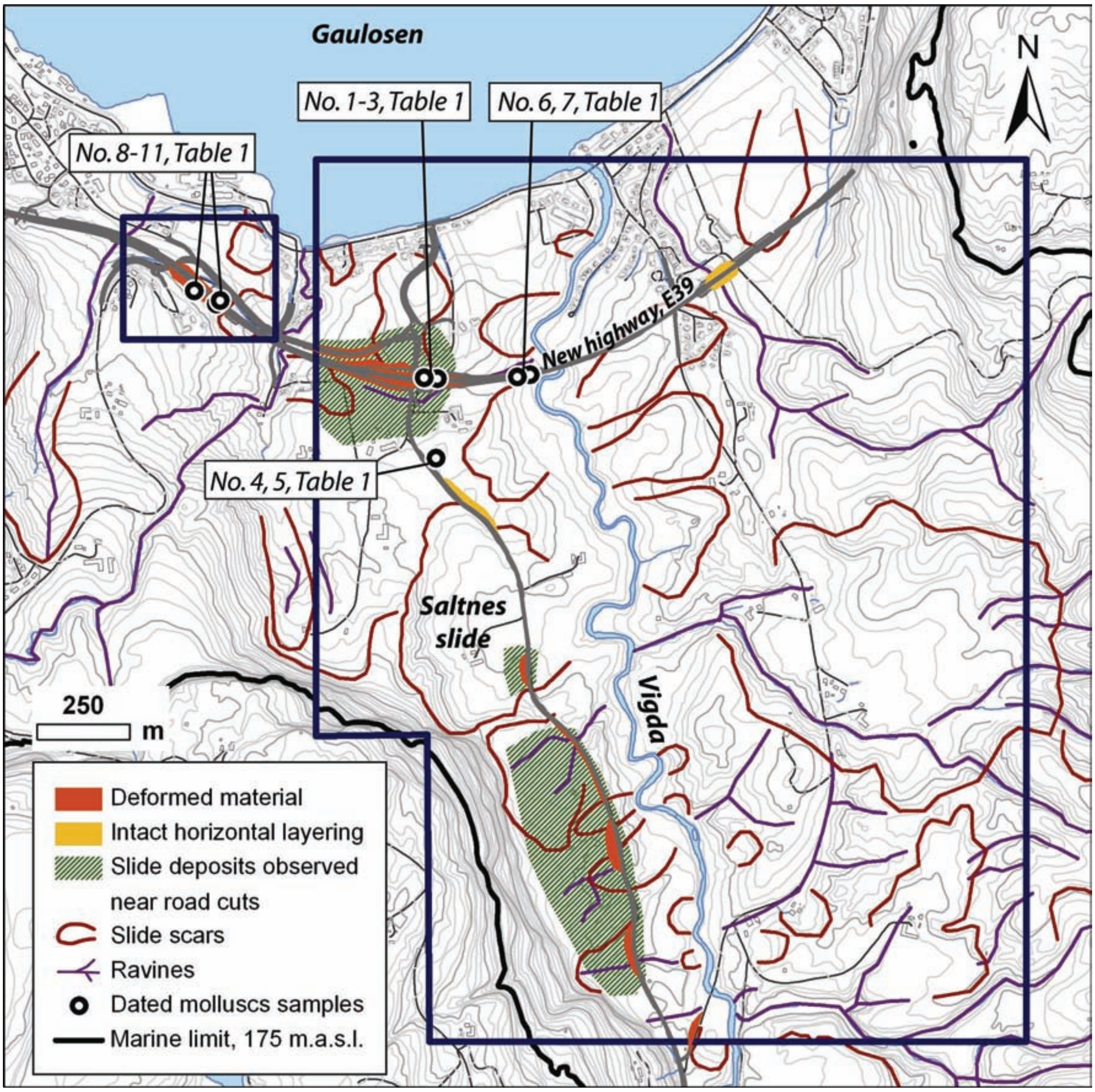

Fig. 4. Western Buvika and Central Buvika: road cuts with slide deposits and deformed material (red), and with intact horizontal layering (orange). Slide scars and mollusc sample locations are also shown (See Table 1 for details on samples 1-11). Contour lines: 5 m.

Shoreline displacement and Quaternary deposits

The high marine limit at Buvika (ML, 175 m a.s.l, Reite 1983b) is caused by the isostatic rebound after depression of the Earth's crust during the maximum glaciation and the eustatic sea-level rise due to melting glaciers. The rebound was initiated as soon as the ice started to melt, and during the Holocene it was most rapid in Preboreal (about 6 m per 100 years, Kjemperud 1981). The shoreline displacement in Allerød and early YD is not thoroughly investigated in the study area, but is supposed to have been about 2 m per 100 years in average (Reite 1983b). The shoreline displacement curves from Frosta and Verdal in Nord-Trøndelag are applicable for the study area (Kjemperud 1981; Reite 1983b; Sveian & Olsen 1984; Reite *et al.* 1999).

Above the ML in the study area there is mainly a sparse cover of till, exposed bedrock or weathered material. Below ML glaciomarine and marine deposits dominate, partly with sand or silt layers. Coarser materials, like glaciofluvial sediments and tills, also occur especially in the ice-marginal deposits. There are few bedrock outcrops below ML, except along the steep valley sides (Fig. 3).

Formation of quick clay

The natural salt content in seawater is generally 35 g/l. When marine clay is leached by fresh groundwater due to isostatic rebound, the salt content in the pore water is reduced. Marine clay where the salt content in the pore water is below 5 g/l can be sensitive/quick (Bjerrum 1954). When the remoulded shear strength (s_r) is less than 0.5 kN/m^2 the clay is characterised as quick. The clay has high sensitivity when the ratio between undrained, undisturbed shear strength (s_u) and s_r is above 30 (NGF 1975).

Some parts of the subsurface are known as favourable for developing quick clay in zones and/or layers: near bedrock, near the surface, where the groundwater flux is large (e.g. in slopes), and where clay is interfingered with silt/sand/gravel layers (e.g. Janbu *et al.* 1993). All these conditions give good influx of water to the generally impermeable clay. When quick clay is remoulded, it completely liquefies.

Methods

The basis data used in this study is acquired from: historical records, vertical aerial photographs, shoreline displacement curves, topographical maps and Quaternary geological maps. The study area is covered by the Quaternary map sheets 1521 I Orkanger, 1521 II Hølonda, 1621 III Støren and 1621 IV Trondheim (scale 1:50000), with descriptions in Norwegian (Reite 1983a, 1983b, 1984, 1985).

Fieldwork consisted of geomorphological mapping of slide scars, ravines, terraces and river channels as well as sedimentological/structural geological studies of road cuts. Fabric analysis was carried out in Western Buvika according to the method of Krüger (1994). In Western Buvika strike and dip measurements were carried out on fold structures in clay, and plunge and plunge directions were measured on striations on a bedrock outcrop. Microfossil analysis has been carried out on ten sediment samples (Western Buvika). Grain size analyses were carried out on 25 sediment samples (by the use of Coulter LS 200, Grimstvedt 2004). Classical geotechnical soil classification is used (e.g. NGF 1975).

Mollusc shells were collected, and the Radiological Dating Laboratory, NTNU, prepared the mollusc fragment samples for ^{14}C-dating with the AMS technique at Uppsala University (e.g. Bowman 1990). The samples were collected in cuts and drilling samples, and the resulting ages in Table 1 are ^{14}C-years BP (Before Present: before AD 1950). A standard marine reservoir age of 440 years has been subtracted.

Resistivity measurements and refraction seismic investigations have been carried out in the area (Dalsegg *et al.* 2006; Solberg *et al.* in press,a). Boomer data were collected from the seabed just outside Buvika using equipment from GeoAcoustics. Depth converting was made with an average sound velocity of 1500 m/s in water and sediments.

Geophysical reports and numerous geotechnical drilling reports produced by different companies have been used: Statens Vegvesen (the Norwegian Public Roads Administration), Rambøll Norge AS, NGI (the Norwegian Geotechnical Institute) and NTNU (the Norwegian University of Science and Technology) during the period 1963-2006. These reports contain information from more than 700 drilling locations, which give extended input for understanding the stratigraphy of the subsurface.

Table 1. ^{14}C-datings of mollusc fragments from road cutting samples and geotechnical drilling samples. Dating type is AMS, and 440 years correction for reservoir effect is used. Determination of species made by S. Funder and Ø. Stokland.

No.	Lab. Ref.	Location	Altitude m a.s.l.	Mollusc type	Sediment	^{14}C-age	Comments	Fig. No.
1	TUa-5166	Central Buvika	27	*Mytilus edulis*	Clay, rich in clasts	9510±45	Resedimented	2, 4, 6
2	TUa-5167	Central Buvika	27	*Arctica islandica*	Clay, rich in clasts	9615±50	Resedimented	2, 4, 6
3	TUa-5169	Central Buvika	27	*Mytilus edulis*	Clay, rich in clasts	9650±50	Resedimented	2, 4, 6
4	TUa-5130	Central Buvika	28	*Yoldiella lenticula*	Clay	9850±60	From drilling	2, 4, 6
5	TUa-5131	Central Buvika	21	*Bathyarca glacialis*	Clay	9905±50	From drilling	2, 4, 6
6	TUa-4574	Central Buvika	12	*Bathyarca glacialis*	Silty clay	9980±60	Pits for bridge pillars	2, 4, 6
7	TUa-4573	Central Buvika	7	*Portlandia arctica*	Silty clay	10560±65	Pits for bridge pillars	2, 4, 6
8	TUa-4575	Western Buvika	42	*Portlandia arctica*	Clayey silt rich in clasts	10600±55	Unit D	2, 4, 6-8
9	TUa-4576	Western Buvika	35	*Portlandia arctica*	Clayey silt rich in clasts	10875±55	Unit D	2, 4, 6-8
10	TUa-4572	Western Buvika	37	*Spirorbis species*	Clayey silt rich in clasts	11020±60	Unit C	2, 4, 6-8
11	TUa-4571	Western Buvika	37	*Portlandia arctica*	Clayey silt rich in clasts	11100±60	Unit C	2, 4, 6-8
12	TUa-5168	Near Lake Ånøya	127	*Mya truncata*	Silty clay	11285±60		3

Descriptions

The study area is divided into four parts: Southern, Eastern, Central and Western Buvika (Fig. 3). The landscape is dominated by erosion by Vigda and a lot of slide scars in the southern and central part (including Western Buvika), and by ravines in the eastern part of Buvika (Figs. 3, 4).

Morphology, sedimentology, structural geology and ^{14}C-datings in Southern, Eastern and Central Buvika

Southern Buvika

Southern Buvika, located north of Lake Ånøya, is the upper and narrowest part of the Buvika valley. There are two bedrock thresholds along Vigda just north of the lake, in addition to several other bedrock outcrops (Figs. 3, 5).

The course of the Vigda is relatively straight in the southern part and the river gradient is higher here than further downstream (~2.9º and ~0.6º respectively) (Solberg *et al.* in press,b). Along Vigda slide material is detected at several places, and erosion scars in ravine slopes and riverbeds are observed. Some large slide scars among several small ones are present, in addition to short ravines. One of the large slide scars lies below a coarse-grained deposit (ca. 90-140 m a.s.l.) in a small hanging valley in the western hillside (Figs. 3, 5). The material consists of rounded boulders, gravel and sand, and in the upper part of the deposit there is a thin layer of fine-grained material. This is also shown in a geotechnical report from the upper part of the deposit (Tautra & Musum 1977). Small streams have eroded the deposit making relatively shallow ravines.

The sediments in the area are mainly marine deposits, as shown on the Quaternary geological map (Fig. 3). Near Lake Ånøya the sediment thickness is limited, but it increases northwards. Close to Lake Ånøya mollusc fragments were sampled in apparently undisturbed silty clay for ^{14}C-dating (Fig. 3; Table 1: sample 12). According to the result the material was deposited in Late Allerød. Geotechnical drilling data in the northernmost part of Southern Buvika reflects clay draped over layered material i.e. clay interfingered with sand and/or gravel (Fig. 6A) (Lefstad 2006). About 2.5 km north of Lake Ånøya there is a relatively small, coarse-grained deposit below clay (Fig. 3). Downstream of this deposit, boulders are observed in and around the river.

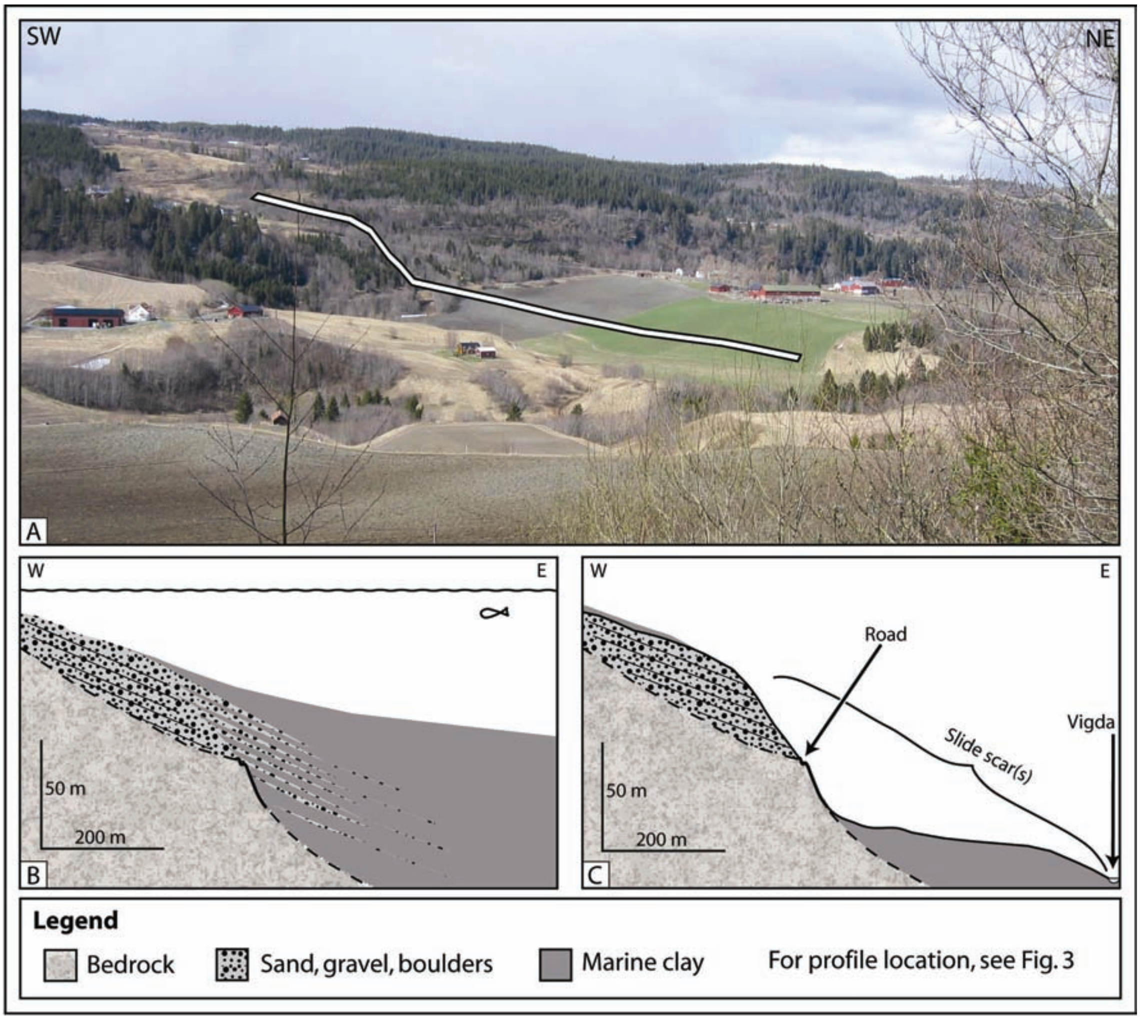

Fig. 5. A. Undulating terrain in front of a glaciofluvial deposit in the western hillside in Southern Buvika. For location, see Fig. 3. B. Principle sketch along the profile. Sedimentation of coarse material from a small hanging valley in the western hillside, interfingering clay from suspension during the deglaciation. C. Today the most distal part of the glaciofluvial fan is cut by clay slides.

Eastern Buvika

Along the eastern margin of the valley, between Buvika and the Gauldalen valley (Fig. 1), there is a gently inclined, dissected sediment platform (Fig. 3). It lies at 130 to 155 m a.s.l., and slopes towards Buvika. The gradient of the platform is 0-5º, except for the areas where deep ravines have modified and increased the gradient.

Numerous ramified, deep ravines incise the terrain east of Vigda. The length of the ravines is relatively short in the slope between Vigda and the back scarp of a huge slide scar (ca. 1.4 km^2) that occurred in the neighbouring Gauldalen valley (Fig. 3). Other ravines, to the north and south, are considerably longer. The relief is very steep in

Eastern Buvika, mainly due to the ravine erosion. There are surficial scars in the walls in different height/levels of the ravines.

Some slide scars are present in this part of Buvika. They are mainly located in the ravines, in the ravine walls or in the head of the ravines. Some of the scars are relatively shallow, especially the ones at the head of the ravines.

The surface sediments in Eastern Buvika are mainly marine sediments, with some coarser-grained deposits in the southern part (Fig. 3). The subsurface is mainly known from geotechnical drilling profiles, and the profile along the valley in Figure 6A is partly based on these drilling profiles (in addition to drilling profiles from Central Buvika). Almost all the drillings in Eastern Buvika are rotary pressure soundings, and the material characterisation is therefore only indicative. The drillings here are up to 34 m deep and show clay interbedded with sand and/or gravel in the deepest part of the profiles (Lefstad 2002; Lefstad & Eggereide 2002b; Lefstad 2006). Near Vigda the layered material lies deeper than 15-20 m a.s.l., while the profiles towards SE show layered material as high as 82 m a.s.l.. The uppermost part of the drilling profiles shows mainly clay with sporadic thin coarse layers. The drilling profiles towards north (towards Central Buvika) show more sporadic and thin layers of coarse material (Berg & Hove 2000; Lefstad & Eggereide 2002a; Helle 2004).

Central Buvika

The Quaternary geological map shows marine clay in Central Buvika with a lot of slide scars, many of them with a “bottle-neck” shape. Some slide scars cuts into older generations of slide deposits (Figs. 3, 4) (Solberg *et al.* subm). The historical slide events in the study area are mainly from Central Buvika (Solberg *et al.* in press,b).

In Central Buvika there is a large slide scar called the Saltnes slide (almost 200000 m^2) (Figs. 2, 4), dated to ca. 3000 ^{14}C-years BP (Solberg *et al.* in press,b). The slide scar is located just north of a buried bedrock threshold, revealed by refraction seismic measurements (Dalsegg *et al.* 2006). The depth to bedrock is here 50-70 m. Below the Saltnes slide scar, resistivity measurements and a sound drilling indicate a thick deposit of coarse material like sand and/or gravel overlying bedrock, and the deposit thins out towards east and north (Dalsegg *et al.* 2006, Solberg *et al.* in press,a). This coarse

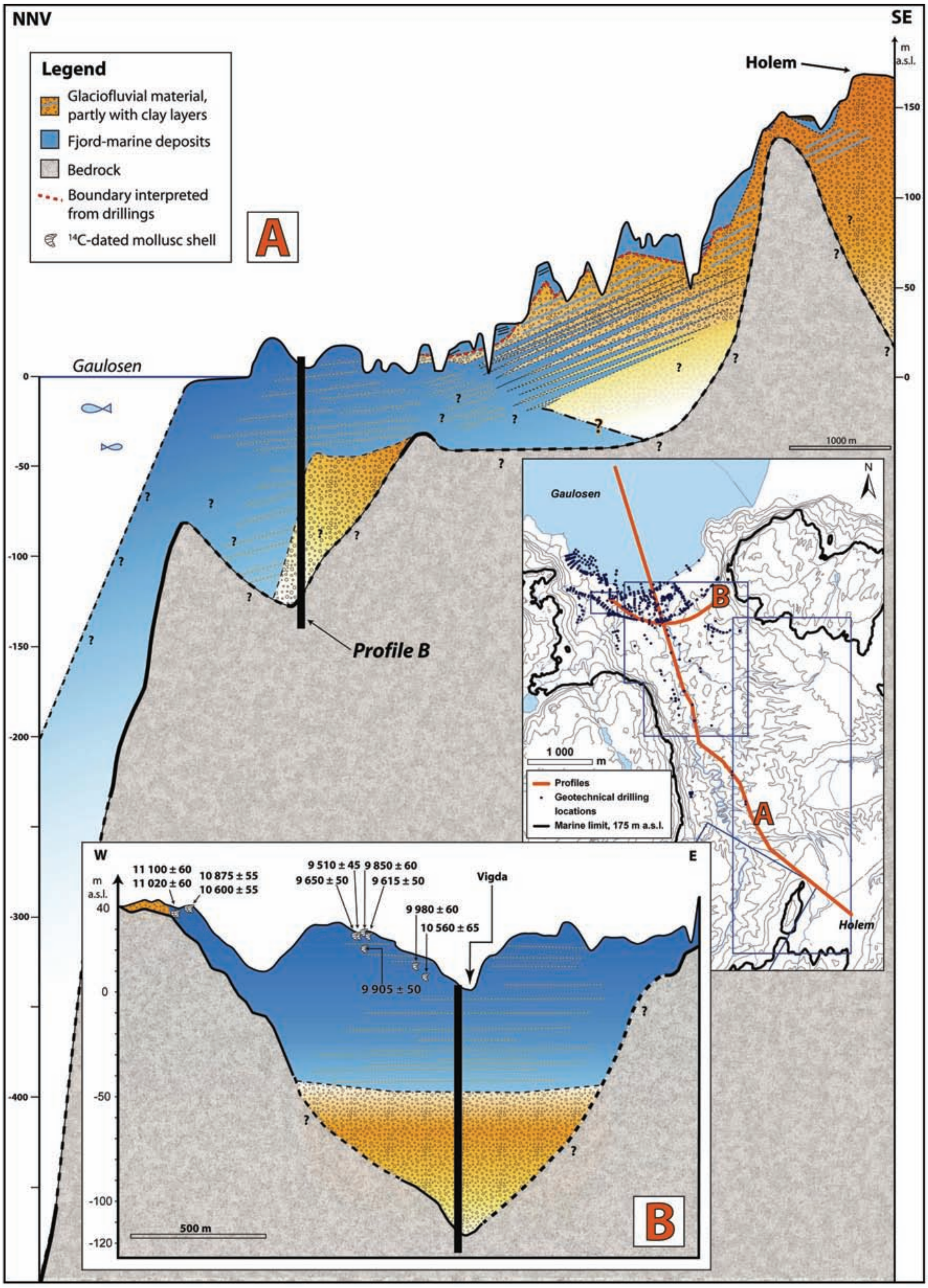

Fig. 6. Principle sketches of the stratigraphy in Buvika. A. Profile along the valley, about 17x vertical exaggeration. B. Profile across the valley, about 8x vertical exaggeration. The ages of mollusc shells are in ^{14}C-years BP.

deposit is covered by clay, partly with sand layers, as shown in a cut in a slide block, and from drillings inside and outside the slide scar (Solberg *et al.* (in press,a) and unpublished data from Rambøll AS). There is an artesian spring in the bottom of the slide scar.

Refraction seismic investigations and boomer data show that there are two buried bedrock thresholds in Central Buvika, before the bedrock surface falls steeply into the Gaulosen basin (Fig. 6A) (Rye & Lefstad 1987; Pedersen 2003; Dalsegg *et al.* 2006; Rise *et al.* 2006; unpublished boomer data from Geological Survey of Norway). The depth to bedrock below Vigda in Central Buvika is at least 120 m (Fig. 6B). The seismic velocity is apparently the same in all the sediments overlying bedrock, and indicates clay in the whole profile (1500 m/s). Still, coarser material with lower velocity than clay may be hidden below a thick clay deposit (Pedersen 2003). The geotechnical drillings are generally 40 m deep at the most in this area, and show mainly marine deposits (clayey silt), even though the lowest parts often contain coarse layers (e.g. Berg & Hove 2001). Coarse material between bedrock and clay is also indicated on a resistivity profile from the same area (Dalsegg *et al.* 2006).

In addition to geotechnical drilling profiles, road cuts gave detailed information about the sediments in Central Buvika. Undisturbed horizontal lamination in clay or silty clay dominate in some of the cuts (Fig. 4), and two ^{14}C-datings of mollusc samples in a drilling from an area of assumed *in situ* silty clay, gave Late Preboreal age (Figs. 2, 4; Table 1: samples 4, 5).

Relatively thin layers of sand and/or gravel also occur in road cuts, drilling samples and drilling profiles (e.g. Berg & Hove 2001; Helle 2004). The drillings generally show more coarse layers along Vigda, and here are also terrestrial organic material detected in drilling samples (Lefstad 2002; Helle 2004).

Just west of Vigda, along the alignment for the new road, there were two pits for bridge pillars (Fig. 2). These cuts showed horizontally laminated silty clay, with scattered mollusc shells and mollusc fragments. ^{14}C-dating of two mollusc samples here gave Mid YD and Late Preboreal ages (Figs. 2, 4; Table 1: samples 6, 7).

Some road cuts showed more or less folded and deformed clay deposits (Fig. 4) with elements of gravel and/or organic materials (terrestrial and marine) (Solberg *et al.* subm). Three ^{14}C-dated samples of mollusc fragments, sampled in clast-rich, deformed clay, gave Mid Preboreal age (Figs. 2, 4; Table 1: samples 1-3). The deposits are interpreted as slide material, and the samples are therefore not in their original stratigraphical position, but probably at a slightly lower elevation (Solberg *et al.* subm).

Sedimentology, structural geology and ^{14}C-datings in Western Buvika

Marine deposits dominate in Western Buvika as shown from the Quaternary geological map (Fig. 3). Coarse-grained material and bedrock outcrops are also present. Two large road cuts were made in this area during the construction of the new highway (Figs. 2, 4, 7, 8). The cuts make together a trough, and are about 200 m long, showing parallel sediment exposures on each side of the new road (Figs. 7, 8). The SW exposure is 10 m at the highest, and the NE exposure is maximum 5 m. The inclination of the cut slopes is about 25-30º. The bottom of the trough lies about 32 m above present sea level. A few slide scars are present in Western Buvika, and one of them limits the exposures towards SE (Figs. 3, 4).

The terrain in the area slopes towards the sea, as does the bedrock surface beneath the sediments (Hillestad 1963; Rye & Lefstad 1987; Berg & Hove 2001). The deposits on the NE cut are correlated with the upper part of the SW cut (Fig. 7). The sediments in the road cuts are divided into four litostratigraphical units: A, B, C and D (Figs. 7, 8).

Unit A

Unit A consists of a greyish, relatively well-graded, massive diamicton overlying striated bedrock (Fig. 7). There is less than 70 % sand and gravel in the unit, and the amount of clay and silt increases towards NW (Berg & Hove 2001; Grimstvedt 2004). The clasts in Unit A were angular to sub-angular. Geotechnical drillings indicate that the coarse deposits of unit A continues, but thins out, ~300 m further NW along the alignment for the new road, and is covered by gradually thicker marine clay (Berg & Hove 2001). Most of Unit A is structureless, but the upper part on the SW cut is banded. Clast fabric was measured in the diamict sediment of Unit A (Fig. 8). The data were scattered, but show low plunge with a preferred N-S direction. Unit A is interpreted as a till, deposited by a glacier on ice-scoured bedrock.

Fig. 7. The two road cuts in Western Buvika, located at ca. 32 m a.s.l.. For structure details, see Fig. 8. Notice the glacial striation towards NW on the bedrock surface and the lee-side of the bedrock exposure in the foreground.

Unit B

Unit B consists mainly of brownish diamicton in massive beds, which rests partially upon striated bedrock. There is over 80 % sand and gravel in the unit (Grimstvedt 2004). Unit B appears more coarse-gained than Unit A. Some laminated beds of fine and medium sand are present locally, especially near the boundary to Unit A. There is some deformation and tilting of these layers. In the upper part of Unit B (SW cut) there is a partly deformed sediment clast of laminated clay (~14 m^2) (Fig. 8), with some lamina of silt or fine sand.

The boundary between A and B is gradational and dips towards SE. Unit B lies partly over Unit A. A ~1 m^3 large boulder was detected in the boundary zone between

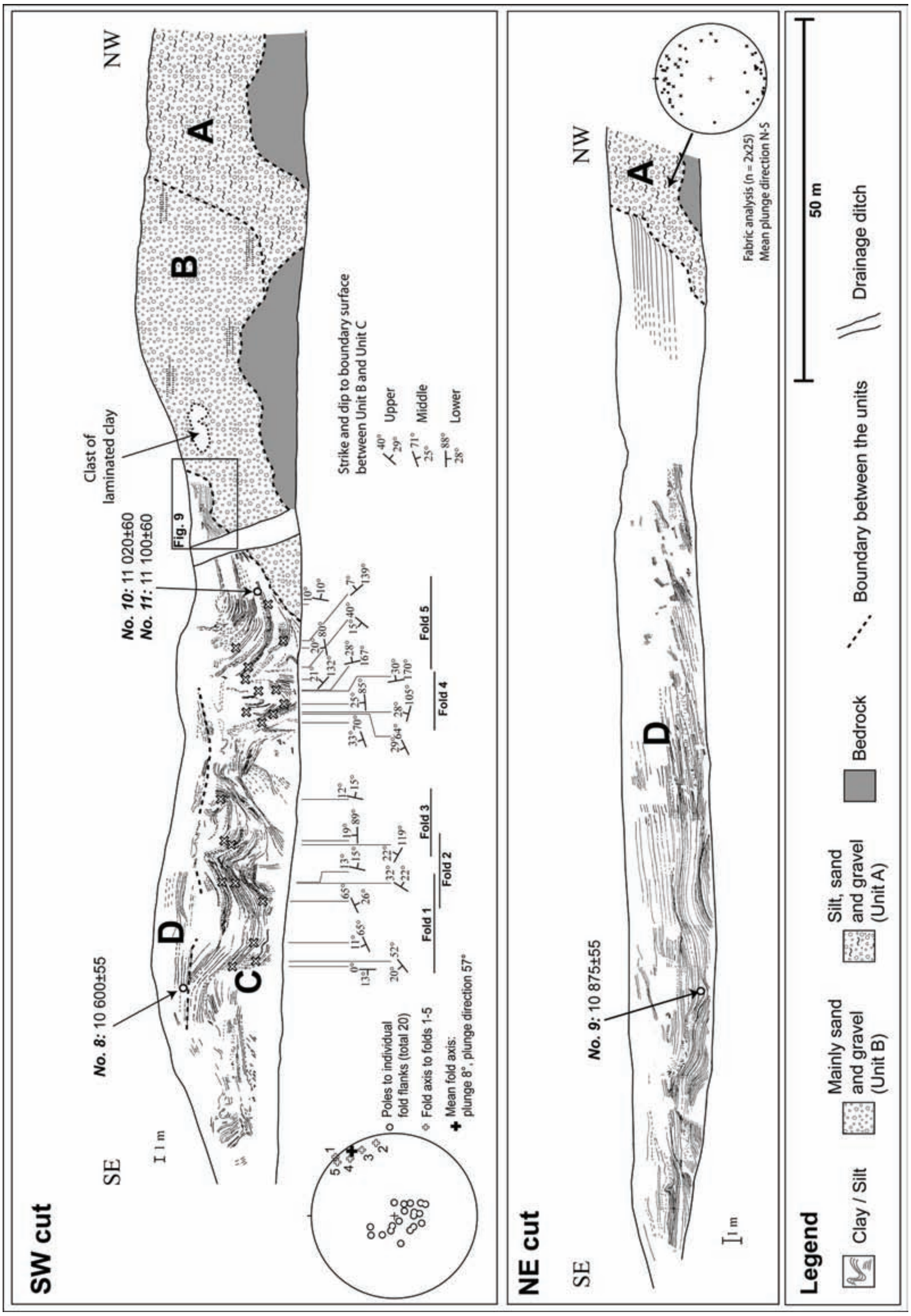

Fig. 8. The two cuts in Western Buvika, shown in Fig. 7. Units A and B: mainly coarse-grained material with indicative layering in Unit B, Units C and D: mainly fine-grained material. Structures in the blank areas in Unit C and Unit D were difficult/impossible to outline. Sample locations and results from ^{14}C-datings of mollusc fragments, in years BP (Table 1) are shown. For location, see Figs. 2-4.

Unit A and B. The bedrock outcrops below Unit A and B are whaleback-shaped and dip 4º towards SE. Both the shape and the striations (~152º) show the same direction.

The better-sorted materials in Unit B, and the laminated beds, indicate a deposition by currents where the fine material has been washed away. Unit B (and A) was deformed after deposition as shown by the presence of the deformed clay clast and the relatively steep, inclined boundary between Unit A and Unit B.

Unit C

Unit C consists of laminated clayey silt, silt and sandy silt (Grimstvedt 2004). Clayey silt dominates and the lamination appears in different nuances of grey. Scattered clasts of coarser material occur occasionally in the laminated beds. Locally there are a few layers or lenses of fine to medium sand, or with sand and gravel. Some layers of fine to very fine silty sand are normally graded, with an erosional lower boundary. These layers also contain clay clasts.

Mollusc fragments are scattered in the unit, and they seem to dominate near the boundary to Unit B. Most fragments occur in connection to clay-supported sand/gravel or grain-supported clayey gravel. The mollusc samples gave a ^{14}C-age of Late Allerød (Figs. 2, 4, 6B, 7, 8; Table 1: samples 10, 11).

Microfossil analysis in sediment samples from Unit C showed very few or no dinoflagellate cysts, possibly due to high sedimentation rates of clay. The registered dinoflagellate cysts are characteristic for arctic waters (K. Grøsfjeld, pers. comm.).

The material in the SW part of Unit C (about 30 m of the cut) is very compact, with both structureless parts and parts with deformed bedding (Fig. 8).

Unit C is open to tightly folded and the mean fold axis has a plunge of ~8º towards NE (~57º), with relatively little variation between the different folds (Fig. 8). The deformation structures are mainly folds, but truncations are also present.

The boundary between Unit C and Unit B is sharp and dips towards south (Fig. 8). Unit C is concordantly overlying Unit B, in the lower part with small-scale irregularities. In the upper part the boundary is more regular, although trough-shaped at a larger scale (Figs. 8, 9). In the upper part of Unit C, near the boundary to Unit B, horizontal layers/lamina are truncated by steeply dipping layers of clayey silt with layers and lenses of fine sand (Fig. 9).

Unit C was deposited primarily from suspension of clay and silt. Small turbidity currents deposited normally graded layers of fine sand. Debris flows also contributed to sand and gravel deposition. Scattered stones are probably dropstones (IRD) from icebergs indicating a relatively close-lying glacier. Later the whole unit was deformed from SE or NW.

The presence of laminated fine-grained deposits inclined at different angles to each other with an erosional contact, indicates a synsedimentary deformation (Figs. 9, 10). See later discussion.

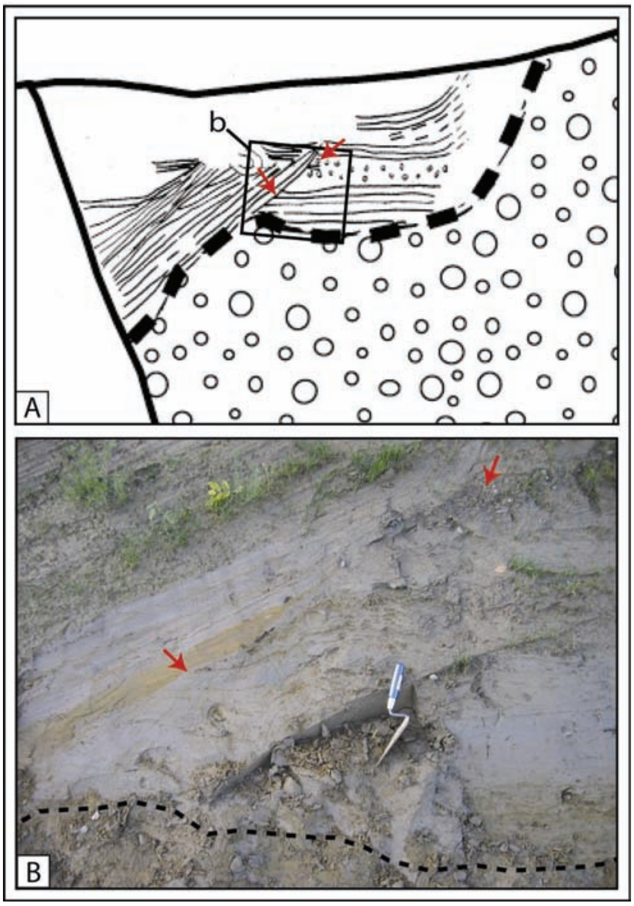

Fig. 9. Detail from the SW cut in Western Buvika (see Fig. 8). A. The structures represent two deformation events; see Fig. 10D-10G for details. B. Detail of structures and sediments.

Unit D

Unit D is present in both the SW and NE cuts, and consists of horizontally to sub-horizontally laminated clayey silt. Layers of silt, sandy silt and sand are also present. Flutes were detected at the base of a sand lamina. As in Unit C, scattered clasts of coarser material occur in the laminated beds.

Mollusc fragments are scattered in Unit D and one of the samples was collected in a clayey silt layer rich in clasts, in the SW cut just above the boundary to Unit C. The other mollusc fragments were sampled in a filled channel-structure of clayey silt rich in clasts, in the lower part of the NE cut. The ^{14}C-dating of the molluscs gave ages from Early and Mid YD (Figs. 2, 4, 6B, 7, 8; Table 1: samples 8, 9).

Small troughs, internal deformations and slumps occur in up to 30-40 cm thick layers in the clayey silt layers, some of which contain sand, gravel and pebbles. The deformed layers are draped, but truncations and filled-in troughs occur as well. Unit D concordantly overlies unit A on the NE cut, where Unit B is not exposed (Fig. 8).

Unit D is draped over Unit C, which is truncated. The boundary is relatively sharp in parts of the SW cut. In the NE cut it is possible that some of the lower parts of Unit D represent Unit C, but this is difficult to outline exactly.

The geotechnical drilling profiles from Unit D (and C) show relatively firm clay with some thin layers of coarser material (Berg & Hove 2001).

Unit C was originally deposited from suspension from melt-water plumes. Debris flows contributed to sand and gravel deposition. Small-scale synsedimentary slumping and sliding folded and deformed some of the material.

Valley in-fill history of Buvika

Deglaciation

Deposition of Unit A and Unit B in Western Buvika

Unit A was deposited directly on the ice-scoured bedrock and is tentatively interpreted as till since it is generally unsorted, including all grain sizes from clay to boulders. Unit A was possibly deposited near the terminus of the glacier as it retreated towards SE (Fig. 10A). Glaciotectonic activity probably caused the deformation of the unit, as discussed later. One fabric measurement in Unit A may reflect a rotation from the NW-oriented whaleback-shaped bedrock, to a more northerly glacier movement. This indicates a later and probably topography-influenced movement parallel to the valley axis. However, it cannot be excluded that Unit A is partially of gravity-flow origin, as banding also may indicate deposition by debris flows or gravity flows (Powell 1984).

The younger Unit B is interpreted as a proglacial outwash deposit, due to its better sorting compared to Unit A, with less clay and silt (Fig. 10B). The sediments were deposited from melt-water entering the fjord at the margin of a retreating glacier, indicated by local laminated beds of fine and medium sand. Most of the finer material (clay and silt) was probably carried away as suspension load. The clay clast in Unit B is apparently disconnected from Unit C/D, and reflects deformation likely caused by glacier activity.

Units A and B were deposited in Allerød according to the ^{14}C-dating of the mollusc fragments in Unit C (Table 1). The sea level in this period was probably close to ML (175 m a.s.l) (Kjemperud 1981; Reite 1983b).

Suspension sedimentation and glacier fluctuations

After glacier retreat, silt and clay in parts of Unit C were deposited upon Unit B (and A) (Fig. 10C). Lenses and troughs of fine sand show that the glacier was relatively close. At this time the glacier possibly stayed temporarily on the threshold south in Central Buvika, depositing the coarse material below the Saltnes slide scar. A resistivity profile here, across the valley, shows this deposit in the west, which seems to follow the deepening bedrock topography towards the east (Dalsegg *et al.* 2006). The thickness of this deposit may differ across the valley, due to variations in sedimentation. Also the coarse-grained deposit in Southern Buvika, interpreted as an ice-marginal ridge (Reite 1983b), was deposited during a standstill, contemporarily with an overall retreat.

Both the diamicton (Units A and B) and the fine material (Unit C) thereafter were subsequently rotated and somewhat deformed (Fig. 10D). This could be the result of iceberg ploughing, sliding/slumping or a short-lived ice-advance. The rotated sediments were subsequently eroded, possibly caused by turbidite currents (Fig. 10E). Suspension sedimentation continued, in addition to deposition of coarser material in troughs and lenses (still Unit C) (Fig. 10F). Afterwards the glacier possibly retreated further southwards (Fig. 11A).

The *main* deformation of the sediments in Western Buvika then followed shortly after (Fig. 11B). The fold axis in Unit C is consistent and the plunge is semi-parallel or parallel to the bedrock slope. Unit C/D lies partly over Unit B, and the boundary between Unit B and C/D is too steep to be of primary sedimentary origin (Figs. 9, 10G). The deformation was therefore towards NW and is interpreted as glacial tectonism, made by a glacier advancing from the Gauldalen valley (from the SE). The fold

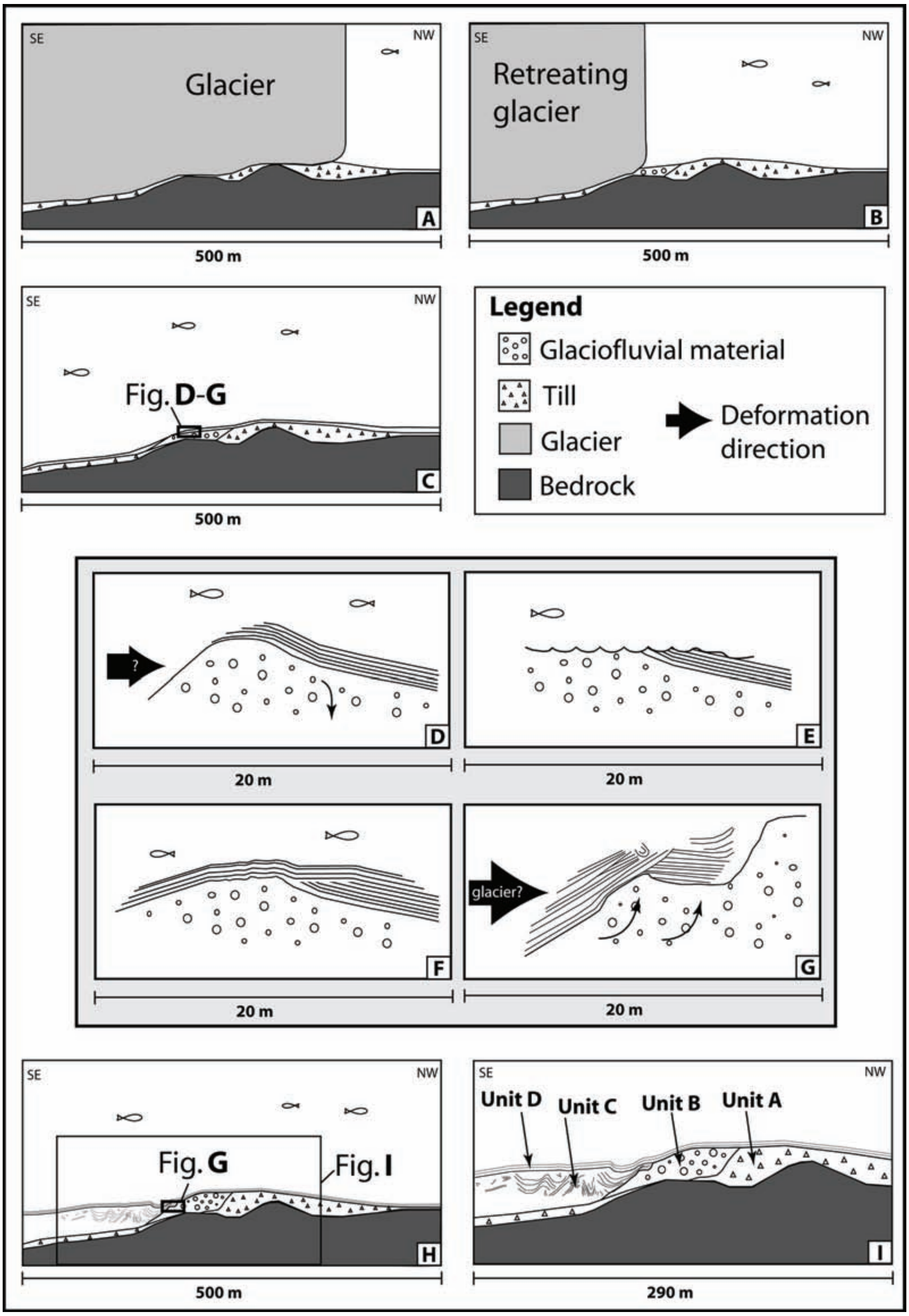

Fig. 10. Interpretation of events during sedimentation in Western Buvika. A. Deposition of till (Unit A). B. Deposition of glaciofluvial sediments (Unit B). C. Suspension sedimentation (parts of Unit C). D-F. Detail of a small deformation of Unit C and Unit B, followed by erosion and suspension sedimentation. G. Detail of the *main* deformation of Unit C and Unit B (See also Fig. 9). H. Suspension sedimentation (Unit D). I. The SW cut with the units shown in Figs. 7 and 8.

structures in Western Buvika have comparable appearance as some of the slide deposits in other road cuts in Buvika, but with absence of terrestrial plant material (Solberg *et al.* subm). However, the structures in Western Buvika are interpreted as glacier-influenced, due to the consistent deformation direction. The interpretation is strengthened by the indication of synsedimentary deformation derived from careful analysis of sediments and boundaries in the cuts of Western Buvika (Figs. 10D-10G). In addition, the deformation seems to be independent of the locality's topography. An alternative interpretation is that a giant, submarine slide from SE involving all Buvika occurred in Early YD. Glaciotectonic deformation is the preferred explanation here, however, a submarine slide cannot be completely ruled out. Glaciotectonic vs. iceberg-generated deformations are discussed later.

The dated sediment near Lake Ånøya (Fig. 3; Table 1) has about the same age as the samples in Unit C in Western Buvika (Late Allerød). The glacier had therefore retreated from Buvika during Late Allerød or earlier (Fig. 11A). This location near Ånøya lies leeward of the hills just east and has possibly been protected from subglacial erosion of a glacier advancing from SE (Fig. 11B), since the deposit seems undisturbed. During this period other data indicate that a glacier extended further to the outer part of Gaulosen (Olsen *et al.* 2007).

Coarse sediment input

Gauldalen is the large neighbouring valley east of Buvika (Figs. 1, 3), and the platform between Buvika and this valley is interpreted as a remnant of the old seabed (Solberg *et al.* 2006). The glaciofluvial deposit at Holem was possibly a fan-type delta, probably deposited during the main YD advance in Trøndelag (10800-10000 years BP) (Fig. 11C). Coarse material like sand and/or gravel must have been deposited in this period in Buvika, interfingering with finer material like clay and silt (Fig. 6). This is also indicated on the geotechnical drilling profiles located in the eastern margin of Buvika. The drilling profiles in Central Buvika, more distal to the glaciofluvial deltaic formation, show more sporadic and thin layers of coarse material. These areas have also been influenced by other, but smaller, sources for coarse input. Both sediment amounts, volume of discharge and in some cases the depositional direction varied during the

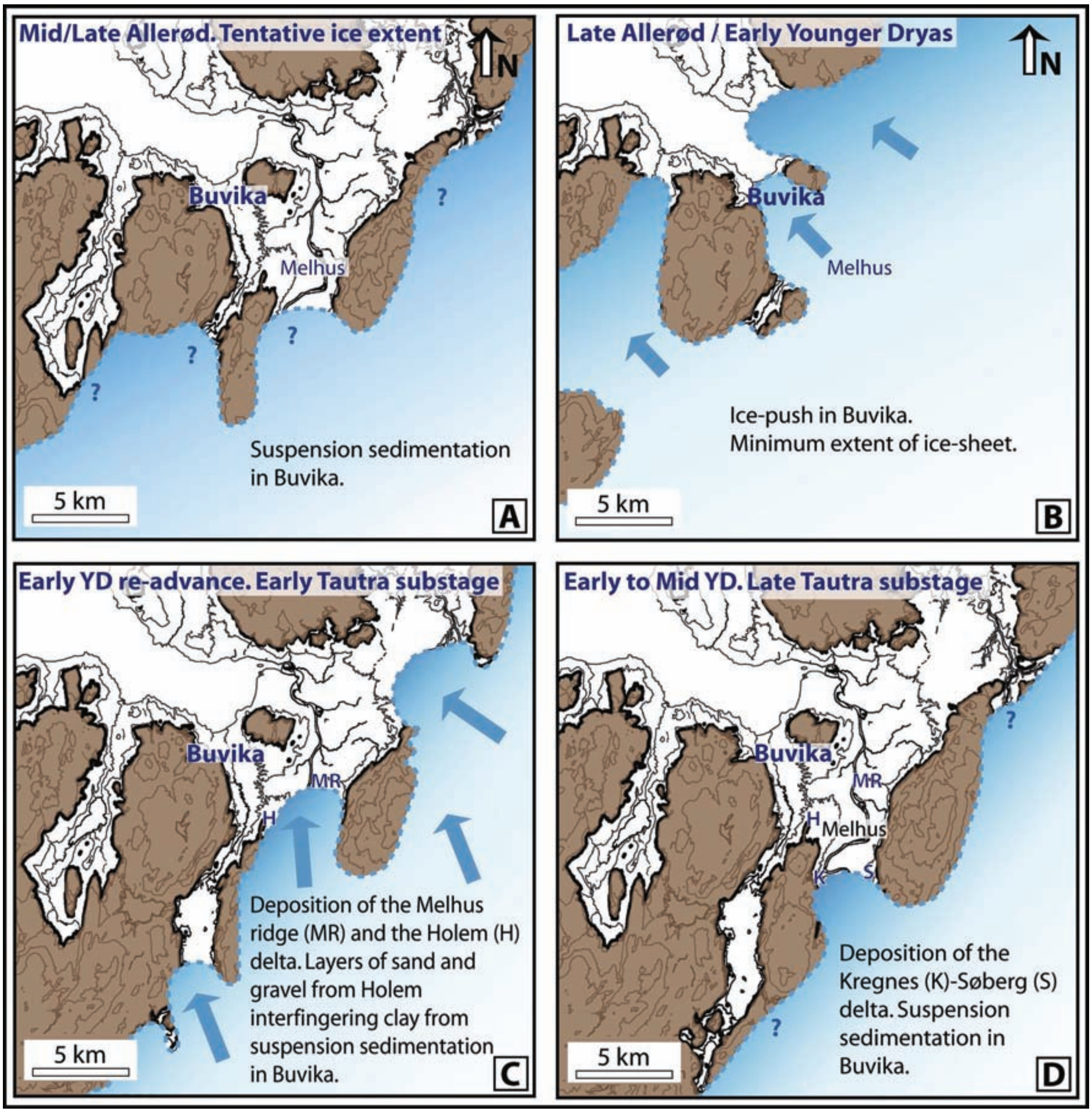

Fig. 11. Reconstruction of glacier dynamics in and near the study area. Blue: ice-sheet, shaded brown: dry land, thick black line: marine limit (ca. 175 m a.s.l.). Contour lines: 100 m. A. Mid/Late Allerød ice retreat. B. Late Allerød/Early YD ice-push with *main* deformation of the sediments in Western Buvika (Fig. 9G). C. Readvance, main Tautra sub-stage in Early YD. D. Stationary ice front, probably a late phase of the Tautra sub-stage in Early/Mid YD.

sedimentation. The Kregnes-Søberg delta probably belongs to a late phase of the Tautra sub-stage (~ 10600) (Fig. 11D).

The coarse-grained deposit on the western hillside in Southern Buvika is interpreted as remnants of a glaciofluvial fan, deposited by lateral melt-water drainage from south in a small hanging valley to Buvika. The location of the fan suggests that it interfingers with clay in the main valley (Figs. 3, 5). It is likely that there have been a minor input of coarse sediments from the other hanging valleys in the western margin of Buvika as well, but this is not observed at the land surface.

Final retreat of the glacier and continued sedimentation

After the final retreat of the glacier in Buvika, the top of Unit C was eroded by e.g. turbidite currents as shown by truncation. Unit D was deposited mainly from suspension in a glaciomarine environment (Figs. 10H, 10I). The bedding is mostly intact and subhorizontal. Still, some beds have internal deformation and there are some truncations, probably due to submarine slumping and sliding. ^{14}C-dating of mollusc fragments from Unit D shows an age of Early/Mid YD (Table 1).

In the southern part of Unit C/D (the SW cut) the material is more compact than the rest of the unit. One reason could be that it was compacted by a glacier. However, recent sliding activity may have altered the sediments, e.g. shown by a slide scar just SE of the cuts (Fig. 4).

Clay and silt was deposited by suspension in Buvika, and datings from Central Buvika indicate a continued infilling of the fjord-valley by glaciomarine sediments. Based on morphological interpretation of the old seabed and the local sea-level curve, a possible reconstruction of the entire seabed has been made (Solberg *et al.* 2006).

Problems related to the ^{14}C-datings

The mollusc types sampled in Buvika have different suitability when it comes to dating by the ^{14}C-method. The suspension and/or filter feeders *Mytilus edulis*, *Arctica islandica*, *Mya truncata* and *Bathyarca glacialis* generally are good species for dating. According to Mangerud *et al*. (2006) *Yoldiella lenticula* (sub-surface deposit feeder) should be avoided for dating, since it may be contaminated by much older material. This also applies for the sub-surface deposit feeder *Portlandia arctica*, which can show a too old age, especially in areas of carbonate-rich bedrock. In one location (Unit C) both *Portlandia arctica* and *Spirorbis species* are dated. *Spirorbis species* is a worm often living on seaweed or bedrock and should be good for dating (Ø. Stokland, pers. comm.). Since the dating results from these two species overlap in Western Buvika, dating of *Portlandia arctica* seems to work well. However, it cannot be excluded that some of the other datings in Buvika give too old ages, due to contamination.

Glacier-made vs. iceberg-made deformation structures

From the above discussion there seems to have been at least one, maybe two, minor glacier oscillations in Buvika in Late Allerød/Early YD. The ages of the mollusc fragments in the undeformed Unit D indicate that the folding of the sediments in Unit C must have occurred during or before the transition Late Allerød/Early YD. This advance was possible rapid and no diamicton from a longer stay is observed in Western Buvika, only deformed clayey silt. It is likely that the glacier at this stage was partly floating, and did not remove the sediments underneath it. A comparable situation is discussed in Fernlund (1988), where a glacier did not erode or deposit till, but only deformed older sediments.

Iceberg scouring has given rise to intense deformation of sediments on the Norwegian shelf (e.g. Lien 1983). In the Romerike area (SE Norway) iceberg scours, iceberg gravity craters and iceberg-deformed sediments from the last deglaciation are connected to a flood caused by the drainage of a large ice-dammed lake (Longva & Thoresen 1991). The maximal flood depth was about 35 m, with icebergs' thicknesses of maximum 39 m.

Iceberg drift was probably extensive both in inner and outer parts of the Trondheimsfjorden area during Allerød. Still, the deformed sediments in Western Buvika lie 30-45 m a.s.l. and when the deformation occurred (Late Allerød/Early YD) the sea level was probably about 175 m above present sea level. This means that the drowned part of the iceberg must have been at least 130 m thick in order to reach the seabed and thereby push the sediments. Any deforming iceberg must have come from SE, due to the deformation direction in Western Buvika. This indicates that the ice-front most likely would have been close to the deformation site, just to be able to produce icebergs of the needed dimensions. With the ice-front located further up-valley, the water depth would be less, and therefore also the icebergs produced would most likely be too small.

Previous deglaciation chronology studies indicate that the investigated area became ice-free during Allerød, and that the glacier re-advance in YD terminated at moraines further inland at Holem (Reite *et al.* 1982; Reite 1983b, 1995; Rise *et al.* 2006). Newer studies, this included, indicate more ice oscillations in the area during Late Allerød than earlier assumed (Olsen *et al.* 2006, 2007), possibly including thick fjord-ice (Ottesen *et al.* 1995; Feragen 1997). A Late Allerød ice-advance may have ended in a floating ice-front, possibly an ice-shelf in the fjord, and the extent of this partly floating ice-front is unknown. We consider such a Late Allerød/Early YD ice advance to be a better candidate for the deformation of the Western Buvika sediments than grounding icebergs.

Shoreline displacement and sedimentation in Buvika

Around 10000 ^{14}C- years BP the sea level reached 150 m above the present shore line, and the Buvika valley was isolated from the Gauldalen valley (Solberg *et al.* in press,b). Lake Ånøya was isolated from the sea due to a bedrock threshold north in the lake, and afterwards the lake acted as a sediment trap and major sediment input to Buvika decreased. The fast emergence continued and the river started to erode the deposits north of Lake Ånøya. No traces of raised Holocene river deltas or river terraces of coarse material are detected, probably since mostly clayey material was eroded and redeposited. Observations in and along the river show cobbles and boulders, interpreted as remnants of ice-rafted detritus (IRD) or material eroded from the ice-marginal ridge 2.5 km north of Lake Ånøya (Southern Buvika, Fig. 3). After 6500 ^{14}C- years BP there were mainly fluvial incision and sliding activity in Buvika, since the accumulation of sediments only occurred beyond the present-day shoreline (Solberg *et al.* in press,b).

Landscape development, sliding activity and quick-clay formation

Vigda incised the deposits in Buvika north of Lake Ånøya during the Holocene, and the eroded sediments were transported and redeposited further north as the sea level was lowered. The slopes along the river were exposed to clay sliding, as seen from numerous slide scars along the river valley (Solberg *et al.* in press,b). Larger slides are often initiated by small slope failures caused by river or groundwater erosion.

Geotechnical drilling profiles close to Vigda show near the surface coarse material that is interpreted as fluvial deposits. Also slide material is present in these upper parts, since some samples contained terrestrial organic material in clay. These results indicate that sliding activity has influenced the river's course and level.

The valley fill of Buvika is inhomogeneous, varies across the valley and seems to influence the erosion pattern. Groundwater erosion played an important role in the formation of the ravines due to the coarse-grained layers draining and eroding (by seepage) the slope towards Vigda. This has resulted in an extensive ravine formation along the eastern margin of the valley. Such ravine development processes are also discussed by Selby (1982) and Higgins & Coates (1990). Most of the slide scars in this area seem to be connected to the ravine development (Fig. 3). There are few large slides in this ravine terrain, but relative shallow slope failures that widen and develop the ravines are common. It can be difficult to determine if depressions in the ravine heads are slide scars or settlements of the subsurface caused by groundwater seepage. The distance between the ravines is small, which reduces the probability for large slides since slides often are restricted laterally by ravines (Lebuis *et al.* 1983; Carson & Geertsema 2002; Robitaille *et* al. 2002).

In Central Buvika the clay is more homogeneous, with fewer and thinner sand and silt layers than in the eastern margin of the study area. During Late Holocene leaching of the clay has probably been most intensive in Central Buvika, since there are numerous relatively young slide scars here.

The morphology and the size of the Saltnes slide scar (Figs. 2, 4) clearly suggest that remoulding of quick clay was involved, since it has the classical "bottle-neck" shape (e.g. Bjerrum 1955). Water from the steep rock face west and south of the scar was stored in the coarse deposit generating a local artesian pressure, which likely accelerated comprehensive leaching and increased the pore pressure in the clay deposit prior to sliding (Solberg *et al.* in press,a). Comparable situations are discussed in La Rochelle *et al.* (1970), Carson (1981) and Carson & Geertsema (2002), mainly with examples from Quebec in Canada.

The topography of the bedrock, both covered and uncovered by sediments, will influence on the formation of quick clay (e.g. Lebuis *et al.* 1983; Janbu *et al*. 1993; Rankka *et al*. 2004). Fractured bedrock will supply the valley-fill deposit with groundwater leading to a high artesian pore pressure. A large high-lying, drainage area in bedrock will probably give rise to the highest pressures. An undulating, sediment-covered bedrock topography will often lead to quick-clay development, since groundwater gradient partly is directed upward above a peak in the bedrock surface.

Road cuts in marine sediments in Central Buvika (Fig. 4) showed folded and deformed slide deposits that were not detected on drilling profiles or resistivity profiles (Solberg *et al.* subm). Another study of clay-slide deposits has also been described for a neighbouring valley (Hansen *et al.* subm). During one or more slide events represented by the deposits, probably only a thin layer of remoulded clay acted as the slip plane. Further leaching and development of thicker quick-clay layers led to new slides in these old slide deposits.

The stratigraphy of the deposits along the hillside in Southern Buvika, with coarse material interfingering clay, probably applies for several other locations as well. The coarse-grained layers have fed the clay with groundwater increasing the leaching of salt from the pore water (Fig. 5B). Especially through heavy rainfall the pore-pressure in the clay probably increased due to the presence of coarse layers pinching out in the clay. This is also discussed by Hansen *et al.* (2007) and Eilertsen *et al*. (in press) describing the relationship between clay-slide distribution and the valley-fill stratigraphy in Målselv, Northern Norway. Also Hodge & Freeze (1977) and Lafleur & Lefebvre (1980) emphasise the significance geological conditions have on groundwater regime and slope stability.

There seems to be a relation between the thickness and frequency of coarse-grained layers and the development of ravines or quick-clay slides. East in Buvika thick and frequent layers of sand and gravel in clay drain the slope, which lead to development of deeply incising ravines, generally with steep slopes. South and north in Buvika, thinner layers of coarse material in clay lead to quick-clay development and pore-pressure build-ups, resulting in numerous slide scars (Solberg *et al.* 2007). The gradient of the layers is likely also important, since steep-lying layers with surface contact will drain the slope faster than a flat-lying layer. A summary of the connection between relative thickness of coarse layers in clay and the development of quick clay is shown in Fig. 12.

Calculations of the total volume of eroded sediments in Buvika (0.3 km^3) indicate that an average sediment volume of 30 000 m^3 has been removed every year during the

Holocene (Solberg *et al.* 2006). The Saltnes slide involved ~3.5 mill m^3, which “constitute” 116 years of the average sediment removal in one event. The amount of slide scars in Buvika (Fig. 3) indicates that sliding activity has been the main erosional factor in the area, probably triggered by river erosion. Surficial slide scars in ravine walls and in the slopes along Vigda, show that erosion continues today.

Climate changes often influence the sliding activity. Only a few of the slide scars in Buvika are dated, but historical records refer to slide events from the last 300 years, mainly in Central Buvika (summarised in Solberg *et al.* (in press,b)). Many of these clay slides occurred in Buvika in the 18th century, and this period is within what is called the Little Ice Age (LIA). Recent studies by Nesje & Dahl (2003) indicate that the LIA was not only cold, but had mild and wet winters. The increased precipitation probably led to more erosion, and was by that a contributing cause to the relative high slide activity in Buvika. Most of the slides in the 18th century in Buvika were triggered by river erosion, but at least one occurred due to rock fall (Strinda og Selbu sorenskriveri 1747-1756). Enhanced rockfall during LIA in western Norway is found by McCarroll *et al.* (1998; 2001). The 18th century was generally characterised by many slides in Norway, due to large floods and heavy rainfall (Furseth 2006).

	Relative number of layers	Dominating process	Relative rate of quick-clay formation	Early phase	Possible slide type or development of other landscape elements
THIN SAND / GRAVEL LAYERS IN CLAY	Few	Leaching	Slowly	Thin layers of quick clay	Flake type slides, relative thin layer of remoulded quick clay acting as slide plane
	Many/ frequent	Leaching	Fast	Thicker layers or pockets of quick clay	Classical bottle-neck quick clay slide, with remoulding of thick layer of quick clay
THICK SAND / GRAVEL LAYERS IN CLAY	Few	Drainage/ seepage. Leaching	Moderate	Thicker layers or pockets of quick clay?	Both ravine development and sliding activity
	Many/ frequent	Drainage/ seepage	Moderate/ Slowly	Thicker layers or pockets of quick clay?	Ravine development, often small/surficial slides connected to the ravine walls. Slides may occur between ravines.

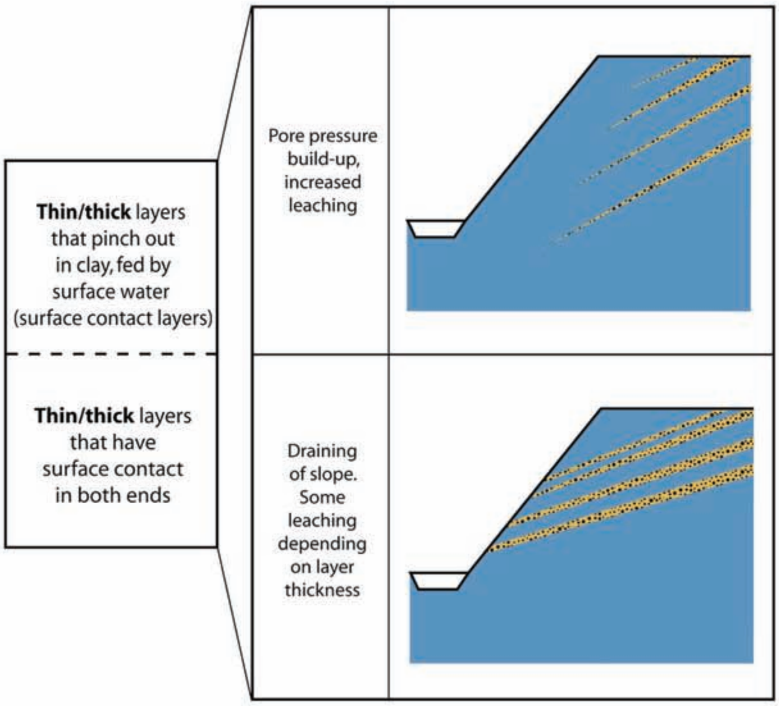

Fig. 12. Conceptual diagram of preconditions for development of quick clay, leading to different slide types. Transitional forms also exist. Note: some groundwater gradient is assumed, but not examined in detail.

Conclusions

- Seismic investigations, boomer data and geotechnical drillings show that Buvika is a hanging valley to the over-deepened Gaulosen basin, and that there are two buried bedrock thresholds in Central Buvika.
- Sedimentological and structural geological analysis of road cuts in Western Buvika, combined with sediment types and ^{14}C-dating, indicate at least one, and probably two, minor glacier oscillations in Late Allerød/Early YD prior to the Tautra sub-stage. This shows that large clay exposures can give important information on glacier fluctuations.
- Sand layers interfingering clay in Eastern Buvika were probably deposited in the distal part of a large ice-marginal glaciofluvial system at Holem in the neighbouring Gauldalen valley, during Early YD. A similar stratigraphy, but at a smaller scale, is present in the western hillside due to glaciofluvial deposition at the mouth of a small hanging valley.
- Especially in the south and the north, thinner layers of coarse material in clay have increased quick-clay development, resulting in numerous slide scars. Thick and frequent layers of sand and gravel in clay east in Buvika seem to drain the slope and facilitate ravine development, in addition to relatively shallow sliding.
- Sand layers that pinch out into the clay increase the groundwater pore-pressure during e.g. heavy rainfalls. In addition to intensify the leaching of clay, increased pore-pressures can trigger slides.
- The stratigraphy of an area, together with the isostatic rebound, strongly influences the landscape development. It determines the sizes and distribution of slides, and the ravine development.

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Paper II: Distribution of clay slides in fjord-valley deposits and their role in valley development, example from Mid Norway

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DISTRIBUTION OF CLAY SLIDES IN FJORD-VALLEY DEPOSITS AND THEIR ROLE IN VALLEY DEVELOPMENT, EXAMPLE FROM MID NORWAY

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Abstract: During and after the last ice age, several hundred meters of glaciomarine and marine deposits accumulated in Norwegian fjords. These sediments were subsequently exposed due to glacioisostatic rebound, and leaching of salts from the marine clay by groundwater resulted in the development of “quick clay” in layers or pockets. The lowered relative sea level led to incision by rivers accompanied by numerous slides involving quick clay, which completely liquefies when remoulded. The erosion pattern of a valley filled with glaciomarine and marine deposits can be quite complex, but careful analysis helps to outline the interplay between river incision, groundwater erosion and sliding. A study of a small fjord-valley in Mid Norway has resulted in the identification of slide material and numerous slide scars and ravines, relative chronology of which is established based on their position in the terrain. The valley development is divided into three stages based on knowledge of regional sea level changes, geological and geomorphological conditions, including slide morphologies and the occurrence of slide deposits. The *Early stage* lasts from the last part of the Pleistocene to 10,000 years BP, when the sea level was lowered from 175 m to 150 m above present sea level in the study area. This stage is characterised mainly by sedimentation from suspension. The *Intermediate stage* covers the next 3,500 years, when the sea level was lowered by 110 m. The accumulation continued, but to a less degree than earlier. River incision and sliding activity increased during this stage. The *Recent stage* covers the last 6,500 years and had a sea level lowering from 40 m down to present sea level. This is a solely erosion stage with several small and large slides and a continued ravine erosion. In historic time the sliding activity has been largest in the northernmost and lower-lying part of the valley. Triggering factors for clay slides are river erosion, groundwater erosion, rock fall and human influence. Increased knowledge of how sliding activity influences the terrain is important for understanding long-term erosion processes and further valley development.

Key words: Landslides, glacioisostatic rebound, marine deposits, quick clay, erosion, valley development

INTRODUCTION

During and after the last ice age, several hundred meters of glaciomarine and marine deposits accumulated in Norwegian fjords. Due to the glacioisostatic rebound the sediments are exposed on land, and the present-day rebound in the studied region is 3-4 mm per year (Reite 1994). The marine sediments mainly consist of clay and silty clay. Subsequent leaching by fresh groundwater alters the chemical composition of the pore water in the marine clay, and "quick clay" may develop (Rosenqvist 1953). When quick clay is remoulded, it completely liquefies. Slides involving quick clay can alter the landscape radically, as well as damage buildings and infrastructure. In Norway numerous clay slides have occurred, often involving quick clay (e.g. Verdal 1893 (Janbu *et al.* 1993); Ullensaker 1953 (Bjerrum 1955); Rissa 1978 (Gregersen 1981); Finneidfjord 1996 (Janbu 1996)).

Different erosional processes including surface running water (e.g. rivers, small streams) and groundwater erosion (seepage erosion) shape the landscape in areas with thick glaciomarine and marine deposits. These processes are important triggers for *sliding activity*, which is the main focus of this study.

Classification of morphologies and mapping of clay slides is important in order to understand further landscape development, but relatively few analysis have been made of clay terrains in Norway. A study in Romerike, southern Norway, differentiated erosion into three zones associated with the geomorphology of the area (Foster & Heiberg 1971). The zones reflect the way the material is brought to the stream (slide type), and the erosion intensity. In the Romerike study area future quick clay slides should occur in the *medium to upper reaches* of a tributary system because of an aggressive front of mass removal. Another study, in a valley with a large river in Mid Norway, showed that landslides most frequently occurred in the *lower* part of the river (Jørstad & Hutchinson 1961; Karlsrud *et al.* 1985). This was due to the fact that these deposits were the last to be exposed to the leaching processes, and thus the formation of quick clay presently occurred to a larger extent there than further inland. This indicates that different valley types should be classified differently in order to improve predictions for the further valley development. However, there has been relatively little focus on stratigraphic variability of the erosional pattern and how geology influences the development of the pattern, with regard to river incision, groundwater erosion and sliding activity.

The current study is from a small fjord-valley in Mid Norway (Figures 1-3). Numerous slide scars and ravines are identified. Some of the slides are known from historical records, some are dated by use of the ^{14}C-method, and others are placed chronologically based on their position in the terrain. The knowledge of regional sea level changes, geological and geomorphological conditions, including slide scar morphologies, occurrence of slide deposits and river morphology has been the foundation for the division of the valley development into the three stages *Early*, *Intermediate* and *Recent*, from last part of the Pleistocene to the present. Based on the knowledge of triggering factors of other clay slides, the likely triggers during each stage are discussed.

The purpose of this study is to show how erosion has shaped the landscape in a small valley with mainly clayey deposits, with emphasis on sliding activity. The terrain is in constant change, and the study of the geological variations and how a valley changes through stages is essential for understanding long-term erosion processes and further valley development.

Figure 1. Localisation of Buvika (modified from Henriksen 1992).

SETTING

Buvika is located in both Skaun and Melhus municipalities, in Sør-Trøndelag County, Mid Norway (Figures 1-3). The locality is about 25 km southwest of the city of Trondheim. Buvika is a small fjord-valley surrounded by 300-400 m high bedrock hills, and is characterised by its undulating terrain with numerous ravines and slide scars. The highest sea level following the last glaciation was about 175 m above present sea level (marine limit) (Reite 1983). East of Buvika lies the large Gauldal valley.

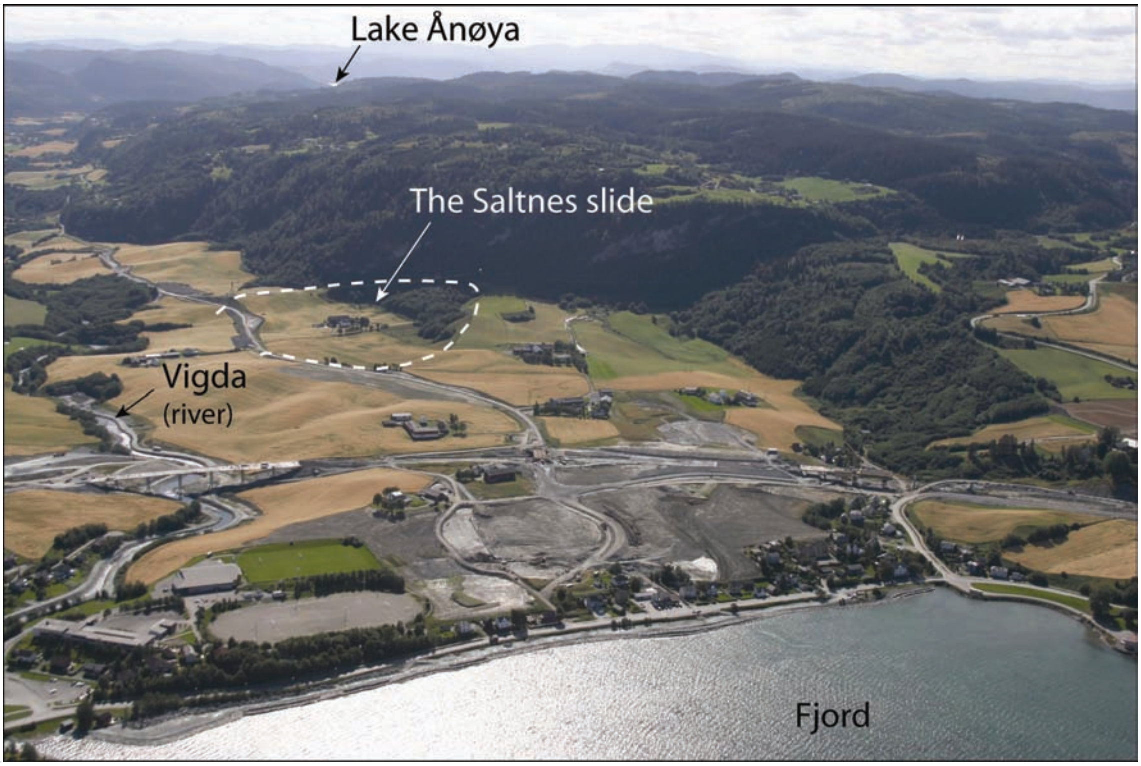

Figure 2. Buvika during construction of highway E39. Photo is taken towards south (Photo: the Norwegian Water Resources and Energy Directorate, NVE).

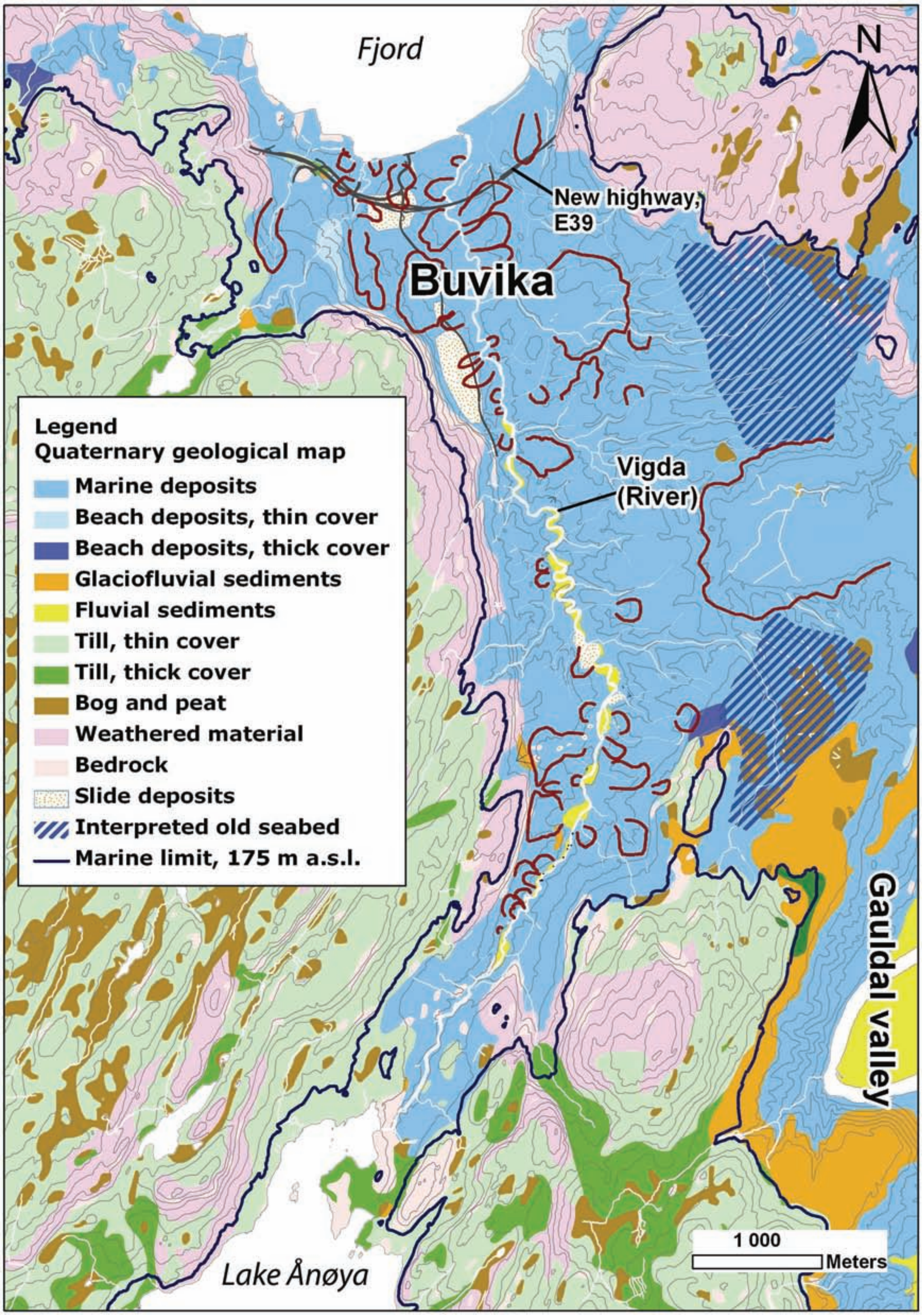

Figure 3. Quaternary geological map of the study area (modified from Reite 1983). Contour lines: 25 m.

METHODS

The data used in this study is acquired from: historical records; vertical photographs; shoreline displacement curves, topographical maps and Quaternary geological maps. Fieldwork with mapping of slide scar morphology, sedimentological/structural geological study of cuttings in slide material, observations along the river (terraces and old river courses) and observations of other morphological features in the terrain have been carried out. Sediment samples for grain size analyse and mollusc samples for ^{14}C-dating have been collected. In addition geophysical reports and numerous geotechnical drilling reports gave an extended input for understanding the sedimentological anatomy of the subsurface. The software tool ESRI's ArcGIS (version 9.1) was used in modelling the area.

VALLEY FILL DEPOSITS

Glaciomarine and marine deposits dominate the valley-fill in Buvika, and consist mainly of clay, silty clay and clayey silt deposited below marine limit (Reite 1983; Grimstvedt 2004). The sediments are deposited during the deglaciation phase of the last ice age and in Holocene, and the ages from the ^{14}C-datings of mollusc samples in sediment layers are in the range 11,285±60 to 9,510±45 years BP. Cuttings studied in the field and geotechnical drillings show that most of the clay seems to be laminated or layered with silt, sand and/or gravel. Some of the studied sediments are deformed, either as a result of glacio-tectonics or sliding activity.

Reports from numerous geotechnical investigations and geoelectrical profiling in central Buvika show large amounts of quick clay layers and pockets. Some parts of the subsurface are favourable for the development of quick clay (Janbu *et al.* 1993): e.g. near the surface; near bedrock; where groundwater gradient is large (e.g. in slopes), and where clay is interfingering silt/sand/gravel layers. These factors show that often only parts of the marine deposits are quick. Still, all the marine clay has the potential of being quick at different times.

Other valley-fill deposits in Buvika are: coarse material interpreted as till; a small glacifluvial sand and gravel ridge beneath clay about 5.5 km to the south of the fjord (Reite 1983); coarse material indicated on geophysical profiles that possible are glaciofluvial deposits or till underneath marine deposits (Dalsegg *et al.* 2006); sand and gravel fans, probably glaciofluvial and deposited from small hanging valleys on the western valley side (Figure 3).

There are a few bedrock outcrops below marine limit. Above marine limit there are mainly till, exposed bedrock and weathered material.

Slide deposits

Folded and faulted sediments were detected in large road cuttings along the new highway E39 (Figure 3). Also terrestrial organic material was present, and the deposit was interpreted as slide material (see also Table 1). Parts of the slide deposits are removed by younger slides or slope failures.

Other slide material in the valley is detected in connection with slide scars along the river Vigda. Some slide deposits are interpreted from geotechnical drilling profiles and/or geophysical profiles (Helle 2004; Lefstad 2002; Dalsegg *et al.* 2006). Also on the seabed outside Buvika slide material is detected by the use of sonar (Hansen *et al.* 2005).

MORPHOLOGY

Vigda is the main river in Buvika. It has a catchment area of 149 km^2 (Hagen 2003). Lake Ånøya (149 m a.s.l.) lies about 8 km south of the Vigda's outlet in the Trondheimsfjord. The real length of the river is 10.6 km because of meandering. Along the first km from Lake Ånøya the river has a mean gradient of about 2.9º. Further, down to the fjord, the sloping is averagely 0.6º. Vigda incised the terrain as the shoreline was displaced relatively rapidly northwards during glacioisostatic rebound, and the river course has probably not changed much during time. There has been a continuous down cutting in the sediments during the Holocene. The northernmost 2 km of the river Vigda has recently been erosion protected with boulders.

A gently inclined, dissected sediment platform along the eastern margin of the valley is interpreted as a remnant of the old seabed (Figure 3). During the deposition of an ice-margin delta in the deglaciation phase of the last ice age (displayed southeast on the map on Figure 3) (Holtedahl 1929; Nemec *et al.* 1999), coarse material interfingering with clay was probably deposited into Buvika. Several geotechnical drilling profiles support this interpretation (e.g. Lefstad & Eggereide 2002; Lefstad 2006).

The Buvika valley is divided into three sections (Figure 4). *Valley section 1* just north of Lake Ånøya is narrow and confined by bedrock hills on each side. There are two bedrock thresholds along the river Vigda, and the river course is relatively straight. The river gradient is the steepest in this part of Buvika (mean: 1.7º). Downstream of the small glaciofluvial ridge, boulders in and around the river are observed. Two large slide scars among several small ones are present. One of the large slide scars lies below a glaciofluvial fan in the western hillside.

In *Valley section 2* the river meanders, and the meander belt is today about 300 m wide at the most. The lateral migration has been limited over time, shown by the steep slopes on each side of the river. The average river gradient in this section is 0.5º. Relatively short ravines incise the slope between the river and the back scarp of a huge slide scar in the neighbouring Gauldal valley (ca 1.4 km^2). There are few slide scars in section 2, but one of them is historical (1864, see Table 1). Depth to bedrock beneath the valley-fill is unknown in this part of the valley. Geotechnical drillings indicate relatively frequently occurring layers of coarse material in the clay (Lefstad & Eggereide 2002; Lefstad 2006). Also observations in and along the river show cobbles and boulders, partly interpreted as ice-rafted detritus (IRD).

The valley widens into *Valley section 3*. There are a lot of relatively young slide scars in the area, and large areas with slide deposits were discovered in road cuttings. The river Vigda meanders less than in section 2 and has a slightly lower gradient than upstream (0.4º). Numerous deep ravines incise the terrain east of the river. The bedrock surface falls steeply into the Trondheimsfjord basin and the sediment thickness below Vigda in central Buvika is at least 120 m (Pedersen 2003).

Clay Slides

Different slide types are observed in Buvika, from small slumps to large slides. Figure 4 shows slide scars of sizes from 450 m^2 to 400,000 m^2 in the three valley sections. In addition to this, surficial slides and slope failures occur every year, especially in the ravines.

Soil creep or surficial slides occur when the soil is saturated, e.g. after heavy rainfall or during snow melt. Traces of surficial sliding in several ravines and along the river Vigda are detected, especially east in Valley section 2. Surficial scars are discovered in different levels of the ravine slopes, probably due to groundwater erosion. The surface erosion results in overturned trees, which makes the ravine impassable. Due to the lack of vegetation cover in the scars the slopes are vulnerable to further erosion.

Slope failure penetrates deeper into the slope than soil creep and surficial sliding. They may look like slide scars, but are mostly less than 1 m deep. These shallow failures are detected in all the valley sections, and are often caused by erosion in the outer curve of the river or a small stream in the ravine, or by groundwater erosion.

The *slide* scars are of different sizes, but it is not always easy to determine whether quick clay was involved. It is also possible that only a thin layer of quick clay was remoulded, and acted as a slip plane. The shape of the slide scar can give indications of slide type. The classical quick clay slide has a "bottle-neck" shape, where the gate of the slide scar is narrower than the largest width of the slide scar (Karlsrud *et al.* 1985; Janbu *et al.* 1993). The slide scar is often relatively deep with steep back-slopes, but this depends on the level of the slip plane. The Saltnes slide in central Buvika (Valley section 3) (Figures 2 and 4) has a "bottle-neck" shape, and was most likely a quick clay slide. The slide scar seems to have been more or less emptied during the slide, which is common when large amounts of quick clay are remoulded. Parts of the slide material can also be left behind in the scar, often as deformed blocks. The central section of a sediment block cutting in the Saltnes slide scar shows intact layering, while the outer edges are deformed.

Both relative fresh and older *submarine slides* and channels on the seabed outside Buvika are detected by the use of sonar (Hansen *et al.* 2005). Numerous pockmarks in the area indicate upward pore water transportation (or gas seepage). Some of the submarine slides scars are located near the steep slope along the fjord margin, and may have created tsunamis reaching land. Geotechnical reports show that there is quick clay below the seabed surface some distance from the shore. This may have been involved in the slides, as concluded by Gregersen (2006).

Table 1. Clay slides in Buvika referred to in historical records (some of the slides are commented in various records) and selected slides from this study.

Reference	Location	Exact year of event	Estimated year of event	Estimated area/ volume	Short description from the reference or from this study
Høyem 1894	Lihaug		1702	49,000 m^2 480,000 m^3	The farm “Saltnes” was taken in the slide.
Helland 1896	Lihaug		1702	49,000 m^2 480,000 m^3	The farm “Saltnes” was taken in the slide.
Snøfugl 1977	Lihaug		1702	49,000 m^2 480,000 m^3	Comments that the year is probably wrong.
Høyem 1894	Husby		1702	65,000 m^2 740,000 m^3	The church was taken in the slide.
Helland 1896	Husby		1702	65,000 m^2 740,000 m^3	The church was almost taken in the slide.
Snøfugl 1977	Husby Presthus	June 29 1728			The church was almost taken by the slide. The area was before 1700 called “Fallet” which indicates previous sliding activity. An area of about 80,000 m^2 was removed in the slide.
Strinda og Selbu soren-skriveri 1747-1756	Negard area		Before 1751	Probably influenced even larger areas.	At least seven slides on Nedre Saltnes cropland. Five slides into the river Vigda, one into the fjord and one triggered by rock fall. (Inspections on the farm were carried out August 5, 1751. Snøfugl (1977) says that the slides occurred in 1729.) From 370 m^2 to 17,000 m^2.
Helland 1896	Leránden	June 24 1864		22,000 m^2 440,000 m^3	The size of the slide was about 20,000 m^2. Four people were killed. The river Vigda was dammed up for a while.
Adresse-avisen 1973	Piene	Dec 30 1973			A small slide (1,500-2,000 m^3) blocked the highway 65 (E 39). A similar slide occurred at the same location about ten years earlier.
Lerfaldet 1975	Buvika school	June 5 1975			The slide was about 20,000 m^3, and occurred in connection to construction work and filling in the school area.
This study	Slide material in road cuttings north and south of the Saltnes slide		North cut: AD 435-600 (1550 ± 55 yr BP) South cut: BC ~1530 (~3270 yr BP) Maximum ages		Large blocks with slightly deformed otherwise intact laminated clay and minor amounts of unsorted or sorted coarser grained debris. Undiscovered slide scars, but deformation structures gave indications about the slide direction. In the north cutting, a thin basal slip surface was detected. Probably only partly remoulded clay, possible that not all the clay was leached at the time of the event. Geotechnical drillings from the same area show quick clay. Possible resedimented organic material.
This study	Saltnes, road cutting		BC 1270-1150 (2990±35 yr BP)	200,000 m^2 3.5 mill m^3	Organic material from a deformed soil surface. The bottom of the slide scar is 25 m a.s.l., and the sea level was about 11 m above present sea level at estimated time of the event.

Slide scar distribution

Table 1 summarises the few slides that are referred to in literature. Some of the slides are mentioned in more than one source, and sometimes there are disagreements between the sources. A selected slide scar and slide deposits from this study are also included in the table.

Most of the slide events in Buvika are of unknown age, but maximum ages for the undated slides that occurred into the river valley of Vigda are suggested on Figure 4. Assumptions for the simplified classification are:

- The river gradient has been approximately the same during the last 6,500 years BP
- Erosion by the river Vigda has triggered the slides
- The level of the slide scar outlets are the same as or higher than the river level at the time of the event

The historical slide scars are all included. Slide scars in ravines or outside the Vigda catchment area are not included in the classification. Most of the slides were probably triggered by river erosion, but groundwater erosion also played a role. 60 % of the slide events are assumed to be younger than 1,000 years BP. Most of these slides lie in Valley section 3. For the slide event groups <2,000 years BP and <3,000 years BP, most slides occurred in Valley section 1 (Figure 4).

TRIGGERING FACTORS FOR LARGE SLIDES

There are several basic factors for the natural occurrence of large clay slides (Figure 5). Even though triggering factors are known for only a few of the slides in Buvika, probably all the factors are relevant.

River erosion often lead to slope failure, which can act as an initial slide and expose quick clay. When the support of the slope is gone, larger parts of the slope fail and remoulds the quick clay. The slide develops retrogressively as new smaller or larger blocks are remoulded. Records on several slides in Buvika in the 18th century point out that some of the slides were “taken by the river” (Strinda og Selbu sorenskriveri 1747-1756). Increased river/ravine erosion capacity is often connected to rapid snowmelt or heavy precipitation

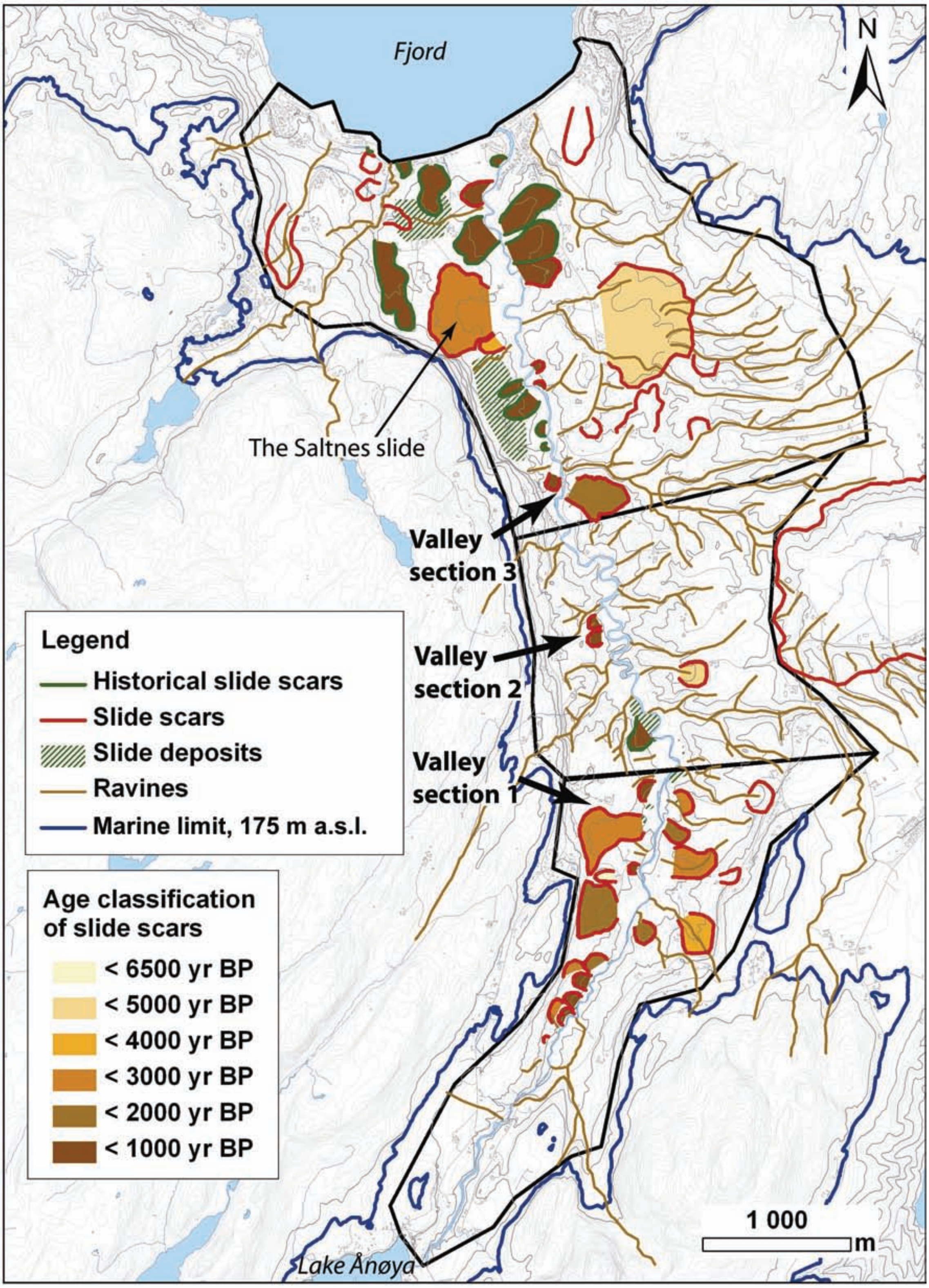

Figure 4. Slide scars; slide deposits and ravines in Buvika. The valley is divided into three sections. A simplified age classification of the slide scars is also given.

Groundwater erosion indirectly leads to the development of quick clay by leaching, but a more direct influence is by seepage and pore pressure build-ups. This was likely the case for the Saltnes slide (Valley section 3), where water from the steep rock face west and south of the slide scar was possibly stored in a coarse deposit, interpreted from.geophysical investigations (Dalsegg *et al.* 2006). Impermeable clay above the coarse deposit in connection with strong hydraulic gradients made an artesian pressure. This accelerated the leaching and might have affected mass-movement directly through increased pore pressure in the clay. This was also the conclusion from a similar study in Quebec (Canada) by Carson (1981). Today there is an artesian spring in the bottom of the Saltnes slide scar. Also for the large slide that occurred below the glaciofluvial fan in Valley section 1 (Figures 3 and 4), groundwater erosion may have been important. Coarse sediments from the fan pinching out in the clay probably resulted in pore pressure build-up and increased leaching.

Clay slides can be initiated by *rock fall*, and this was probably the triggering factor for at least two slides in Buvika. Southwest of central Buvika the bedrock wall is steep, and rock fall initiated a clay slide towards the fjord in the 18th century (Strinda og Selbu sorenskriveri 1747-1756). A cut in the slide deposits just south of the Saltnes slide scar discovered a 15 m^3 large boulder with a 16º dip towards west, surrounded by deformed clay. This boulder indicates rock fall as the triggering factor for the clay slide. Rock fall can be connected to seismic events, but earthquakes can also trigger clay slides directly. Large earthquakes are not common in Norway, but cannot be excluded as a triggering factor for older slides (Bøe *et al.* 2003).

In addition to these natural factors, *human influence* is also a common triggering factor in areas vulnerable to clay slides. In Buvika a recent slide occurred in connection to construction work in the school area (see Table 1)

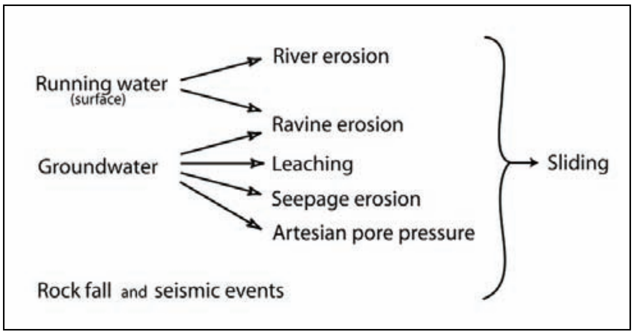

Figure 5. Basic factors for natural sliding activity.

SYNTHESIS OF VALLEY DEVELOPMENT

The valley development from last part of the Pleistocene to the present is divided into three stages: *Early*, *Intermediate* and *Recent*. The main events during each stage are presented on Figure 6.

Early stage: Deposition

The Early stage is from last part of the Pleistocene to 10,000 years BP. During this period the sea level was lowered from 175 m (marine limit) to 150 m above present sea level. The Buvika basin was connected to other fjord basins. Sedimentation from suspension was the dominating process, and the main input direction was from southeast (Gauldal area) and south of Lake Ånøya. Coarser sediments interfingering with clay were deposited during this stage; e.g. from an ice-margin delta in southeast and glaciofluvial fans in west.

If slides occurred in marine deposits during this stage, they were submarine. Groundwater migration in coastal areas, gas seepage or gravitational processes may have triggered such slides as observed in the present-day fjord (Hansen *et al.* 2005).

Intermediate stage: Deposition and erosion

The Intermediate stage is from 10,000 years BP to 6,500 years BP and the sea level was lowered by 110 m down to 40 m above present sea level. The transition between stage 1 and 2 is when the Buvika basin was isolated. Lake Ånøya was isolated from the sea due to a bedrock threshold north in the lake, and afterwards the lake acted as a sediment trap. In addition there was no longer sedimentation from southeast, so major sediment input to the Buvika basin decreased. Sea level lowering was about ten times faster than today (Reite 1983).

During this stage, a river started to erode the deposit in Buvika north of Lake Ånøya. The sediments were transported and redeposited further north. No traces of river deltas or river terraces of coarse material are detected in Buvika. The small glaciofluvial deposit 5.5 km south of the fjord was a source for coarse material as the river incised it, but this gave a relatively small coarse contribution.

The large ravines that characterise the landscape east in Buvika probably started to develop during this period. Coarse-grained sediments interfingering with clay caused groundwater erosion/seepage that developed into ravines, a process also discussed by Selby (1982) and Higgins & Coates (1990). Almost all the present-day ravines terminate in the Vigda river valley, and the erosion base for the ravines through this Intermediate stage was controlled by Vigda's level of incision.

Assuming a river gradient similar to the present, the river level at the end of the Intermediate stage was higher than virtually all the bottom levels of the observed slide scars. However, traces of slides from this stage have probably been erased by river erosion or newer slides. Since the sea level lowering was fast, large slides probably occurred due to the removal of seawater that acted as a counterweight stabilising land. Fast river incision also makes unstable slopes and initiates sliding activity. Quick clay slides may occurred during this stage, since the development of quick clay can be relatively rapid in the parts of the subsurface where groundwater flow is efficient.

Recent stage: Erosion

The Recent stage is from 6,500 years BP to the present, and the sea level was lowered the last 40 m during this period. Erosion was the main process and the accumulation of sediments occurred only beyond the present-day coastline.

All the slide scars on Figure 4 were probably formed in this period. Some of the slides are known to have been quick clay slides, based on records or the shape of the slide scar. Most slides were probably directly triggered by river erosion and initial slides, but indirectly factors like leaching, seepage erosion and pore pressure build-up were important preconditions. In addition, rock fall along the western side of the valley and human influence is known to have triggered slides.

With a few exceptions the Valley section 3 has been the most slide active area in the last thousand years. Awareness of erosion processes and other slide triggers is therefore important since quick clay is still present in the area. Valley section 2 has few slides compared to the other sections, but the relief is very steep, and the ravine surficial sliding and slope failures show active groundwater erosion. One of the youngest

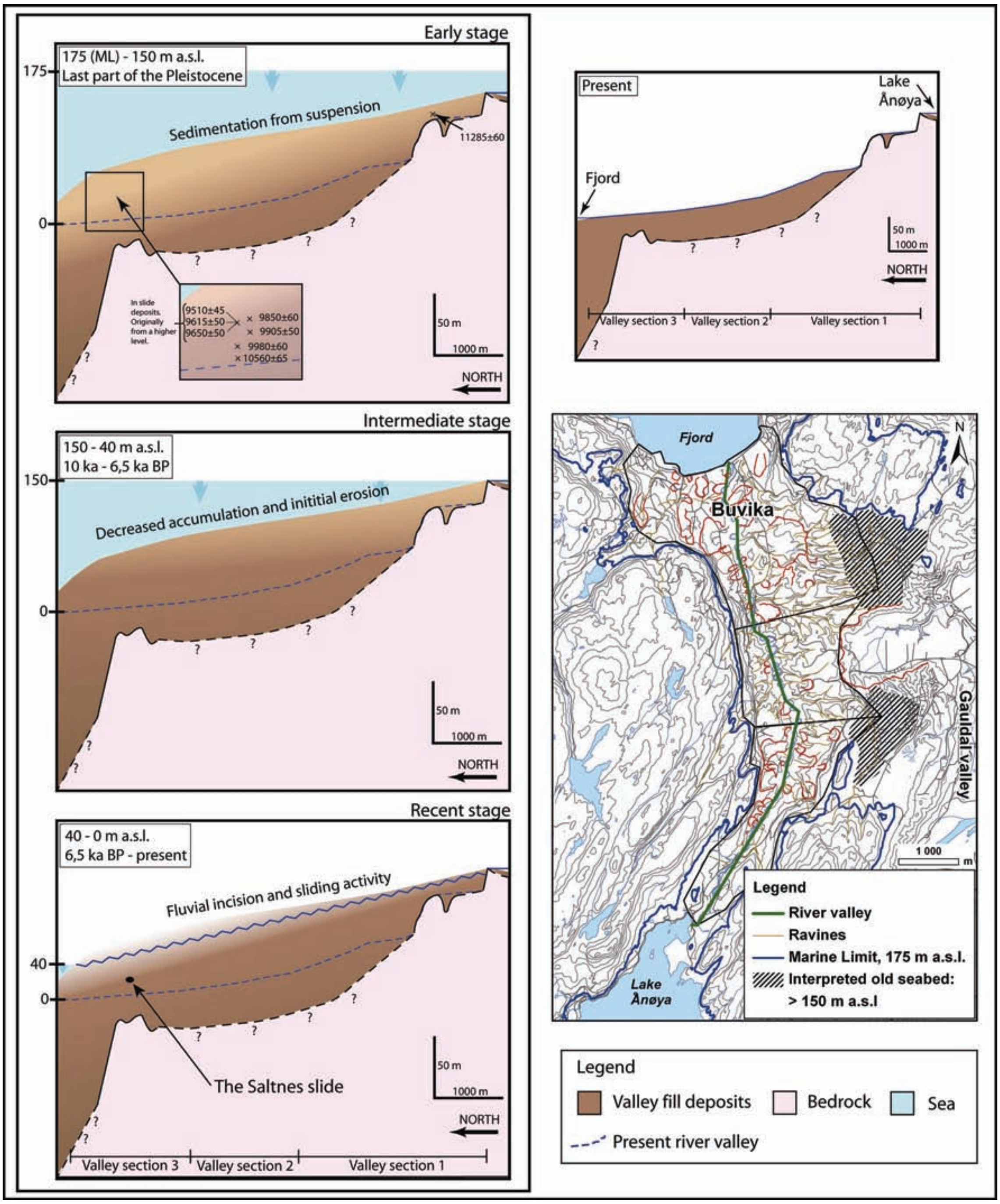

Figure 6. Valley development in three stages from last part of the Pleistocene to present. The map shows the location of the profile (river valley).

relatively large slides lies in this section, which gives the area focus for its further development.

In contrast to the Romerike study (Foster & Heiberg 1971), most of the youngest slides in Buvika occurred in the northernmost, lower part of the valley. The main river incision is limited due to the bedrock threshold just north of Lake Ånøya and the erosion protection in the river near the fjord. Also cobbles and boulders in and along the river in Valley sections 1 and 2 locally decrease erosion. In Romerike, the river still incises the terrain upstream, which makes it more rational to talk about a front of aggression. In Buvika, the incision of sediments seems to be most intense in the ravines, and not in the main river. Still, erosion scars is frequently detected in the outer-curve bank of the river despite a limited lateral migration.

The slide deposits in Valley section 3 show a flake type sliding activity where the clay seems to have been only partly remoulded. A thin layer of quick clay possible acted as the slip plane for the slide, which deformed the deposit. Later the same sediments were subjected to further leaching, and several slide scars reach into the deposit.

The valley-fill of Buvika is inhomogeneous, and gives the different parts of the valley certain characteristics. The coarse input from southeast as the basis for extensive ravine formation has probably drained the slope towards Vigda. There are few large slides in this ravine terrain, but relative shallow slope failures that widen and develop the ravines are common. The distance between the ravines is small, which reduces the probability for large slides since slides often are restricted laterally by ravines (Lebuis *et al.* 1983; Robitaille 2002). In the northern part of Valley section 3 the clay is more homogeneous, with only thin sand and silt layers in the clay. The leaching of the clay has probably been most intensive here in the last thousand years.

The road cuttings in Buvika revealed deposits from slide events that would not be detected otherwise. There are no obvious slide scars after these events, because little of the slide material was removed during the slide in addition to modification by farming and younger slides. The deposits suggest that some earlier slides were characterised by limited displacement and deformation of marine deposits over a thin remoulded quick-clay layer. This is in contrast to more recent slides that seem to involve remoulding of thicker layers of quick clay, with disintegration and evacuation of most of the slide masses.

CONCLUSION

The valley development is divided into three stages: Early, Intermediate and Recent. While the Early stage was dominated by sedimentation from suspension, the processes in the Intermediate stage were accumulation, river incision and sliding activity. The Recent stage is characterised by further sliding activity, river and ravine incision, shaping the present landscape.

Virtually all the slide scars observed in the valley are from the Recent stage and therefore younger than 6,500 years BP, and the northernmost area has the majority of observed slide scars. This area also has the youngest slide events, described in historical records. The most common clay slide triggers are river erosion and groundwater erosion, but also rock fall has triggered slides along the western margin. It is possible that some earlier slides were characterised by movement and deformation of coherent blocks of marine deposits implying displacement on a thin layer of remoulded quick clay. This is in contrast to younger slides that seem to include remoulding of thicker quick-clay layers leaving marked scars in the terrain.

Location of the bedrock and the sedimentological stratigraphy is important for the further erosion development of the Buvika valley. The Buvika example may be a help for better understanding of and prediction for the erosion development of other valleys with similar geology.

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Paper III: Large, prehistoric clay slides revealed in road excavations in Buvika, Mid Norway

Solberg, I.L., Hansen, L. & Rokoengen, K. (subm): Large, prehistoric clay slides revealed in road excavations in Buvika, Mid Norway. Submitted to Landslides May 2007

Large, prehistoric clay slides revealed in road excavations in Buvika, Mid Norway

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Abstract

Several excavated sections along new roads in Buvika, Mid-Norway, display records of large, prehistoric clay slides. Slightly undulating but otherwise intact laminated clay, with minor amounts of unsorted or sorted coarser-grained debris, appears in the sections. Folding, shearing and internal sliding planes have also been recorded, and the deposits are interpreted as slide debris. Slide-scar morphologies are diffuse or absent for most of these deposits, and the inferred slide mechanism is translation and rotation of blocks on a thin layer of quick clay. The slide blocks probably did not move far from their original position. One section cuts through a slide block inside a classic, morphologically well-defined quick-clay slide scar. Varying results from ^{14}C-datings of organic material in the deposits give only maximum ages of the slide events. The style of sliding reflected in several sections differs from slides in the area known from historical records. These younger slide events seem to be characterised by collapse and remoulding of thicker quick-clay layers. The study of the slide deposits gives information on processes and deformation history of the slides. It is suggested that the gradual formation of quick clay has an important impact on long-term landscape degradation and on the character of the present day landscape. There may be far more signs of slide activity in Norwegian valleys than solely indicated by slide scars; also in the relatively high-lying parts of the valley fill, such as interfluve areas.

Key words: landslide, quick clay, deformation structures, Norway

Introduction

Large landslides in unconsolidated deposits are known from various settings. Slides in marine and lacustrine basins are described using high-resolution geophysical surveys combined with drilling (e.g. Longva et al. 2003; Haflidason et al. 2004; Schnellmann et al. 2005). These datasets allow for examination of internal structures in three dimensions. Land-based slides, including clay slides, are often described from their morphologies combined with drilling and/or geophysics (e.g. Bjerrum 1955; Hutchinson 1961, 1965; Mollard 1977; Løfaldli et al. 1981; Calvert and Hyde 2002; Bichler et al. 2004; Hansen et al. 2007). Deposits are occasionally exposed along the back scarp or inside slide scars, or in local exposures (e.g. Bjerrum 1971; Gregersen 1981; Janbu et al. 1993; Geertsema et al. 2006; Eilertsen et al. in press; Hansen et al. subm). Such exposures give the possibility of investigating internal structures of clay slides. However, studies of long, excavated cross sections through slide deposits are relatively rare (Bjerrum 1971; Hansen et al. subm).

Large exposures due to the construction of a new highway (E39) and the upgrading of a county road in Mid Norway have given the opportunity to study the sedimentology and internal structures of large clay-slides that occurred in the fjord-valley Buvika (Figs. 1-3). Clay-slide deposits are not always easily recognised in the landscape, which is often affected by erosion processes and by agricultural activity. In Buvika, clay-slide deposits appear on hillsides and on interfluves as undulating terrain and the slides are therefore represented by their deposits more than by well-defined slide-scars, which can only be outlined approximately if at all. An exception is one section that cuts through a slide block in a “bottle-neck” scar from a classical quick-clay slide (Figs. 2, 3).

The purpose of the present paper is to study the internal characteristics of slide deposits to better understand processes and deformation history of clay slides. Aspects of the development of quick clay are also considered. In addition we focus on the role played by clay slides in the long-term processes of landscape degradation of fjord valleys. Problems related to ^{14}C-dating of slide events are also discussed.

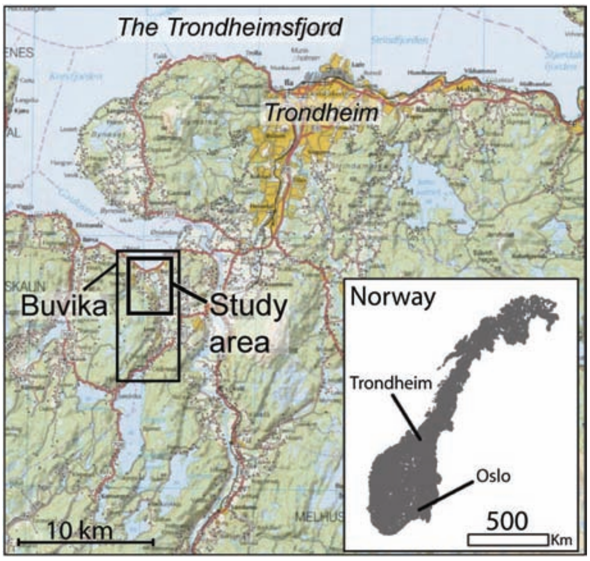

Fig. 1 Buvika is located 25 km southwest of the city of Trondheim in Mid Norway (modified from Henriksen 1992).

Setting

Buvika is located in Skaun municipality, Sør-Trøndelag County, Mid Norway. The study area is about 25 km southwest of the city of Trondheim (Fig. 1). Buvika is a small bedrock-confined fjord-valley surrounded by 300-400 m high hills of bedrock, and is characterised by its undulating terrain with numerous ravines and slide scars. Vigda is the main river in Buvika.

During the last glaciation Norway was glacio-isostatically depressed, and the sea inundated coastal areas as glaciers retreated. In Buvika the highest sea level after the last glaciation (marine limit, Fig. 3) was about 175 m above the present sea level (Reite 1983). The fjord arm received an enormous amount of sediment from melt-water, which resulted in the accumulation of very thick fine-grained deposits. The valley-fill is dominated by glaciomarine and marine clays with local occurrences of coarser-grained deposits like glacial outwash sediments (Reite 1983; Solberg et al. subm).

During and after the deglaciation, the deposits emerged as relative sea level fell due to glacioisostatic rebound. The emergence was followed by fluvial incision and erosion, which were occasionally accompanied by large clay slides. Groundwater leaching of salt from the pore water of the clayey deposits resulted in formation of quick clay in pockets or layers (e.g. Rosenqvist 1953; Janbu et al. 1993). When quick clay is remoulded, it completely liquefies. A lot of destructive quick-clay slides have occurred along the coastal parts of Norway, and some of them are described in historical records (e.g. Jørstad 1968; Gregersen 1981; Janbu et al. 1993). A map showing the slide-scar distribution in Buvika is given in Solberg et al. (in press, b). The slide scars mapped in the study area (central Buvika) are shown in Figure 3. The thick quick-clay deposits have been a major challenge for the highway construction in Buvika.

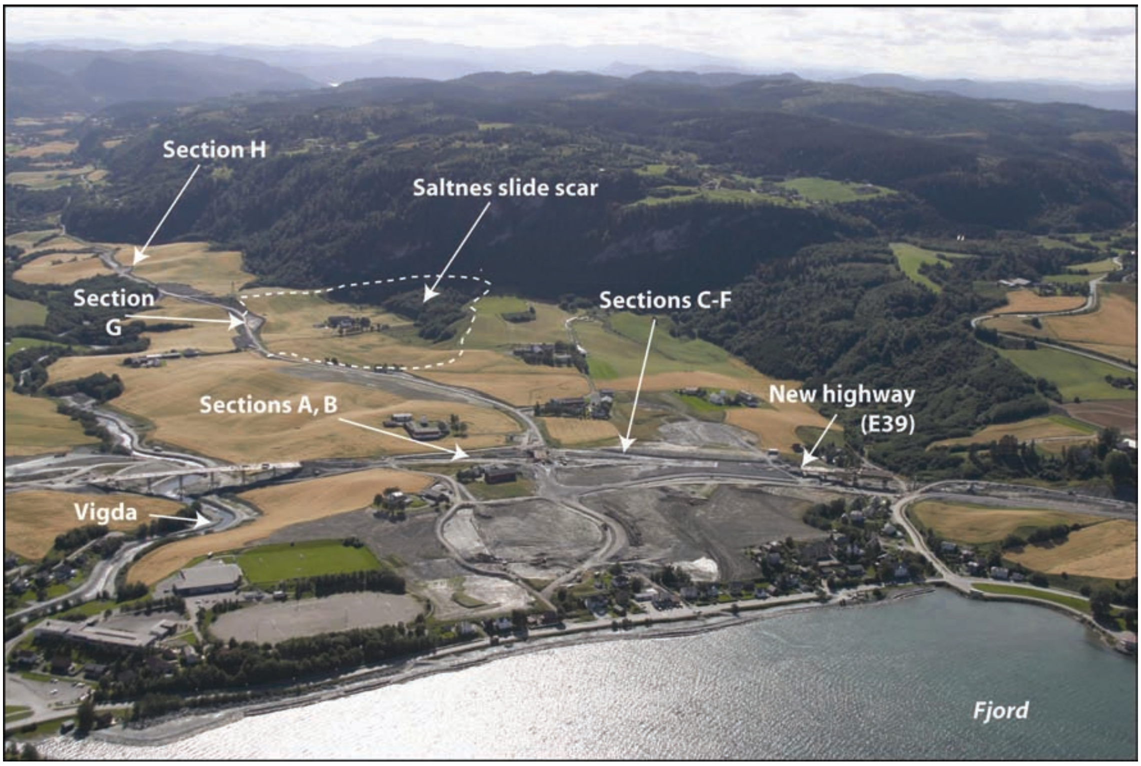

Fig. 2 Buvika with location of the road excavations (Sections A-H) and the Saltnes slide scar (Photo taken towards south: the Norwegian Water Resources and Energy Directorate (NVE)).

Methods

The investigation of slide deposits in clay is preconditioned by the existence of large machine-excavated exposures. The exposed section walls were inclined 20-30 degrees, and were investigated after a few weeks of weathering by which sedimentological structures appeared more clearly in the sections. The sections were available for study for a relatively short time before they were covered. The structures in the sections were photographed, mosaics were created and the main structures were drawn into profiles. Lithology was determined in the field. Mollusc shells and shell fragments, in addition to terrestrial organic material, were collected and species determined by Svend Funder,

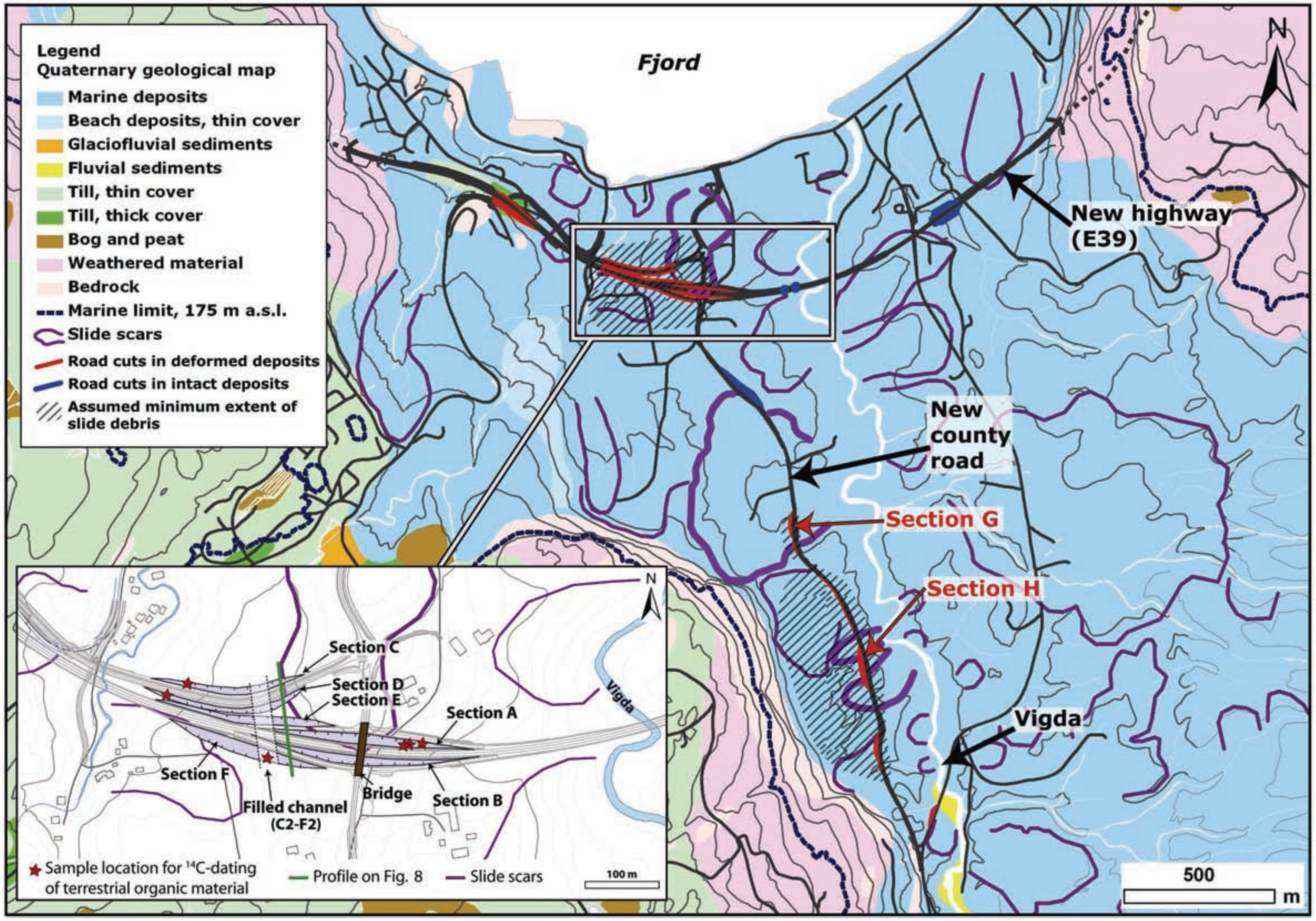

Fig. 3 Quaternary geological map of central Buvika with location of road sections. Contour lines: 25 m.

Paula Utigard Sandvik and Helge Irgens Høeg. Some of the samples were used for ^{14}C-dating (Bowman 1990), carried out by Radiological Dating Laboratory, NTNU, Trondheim (conventional), and Uppsala University (AMS). Dates are in the text given as uncalibrated ^{14}C-years before present (BP, A.D. 1950).

Geotechnical drilling reports with data from the section areas have been used, produced by different companies: Statens Vegvesen (the Norwegian Public Roads Administration), Rambøll Norge AS, and NGI (the Norwegian Geotechnical Institute).

Results

Most parts of the road sections in Buvika display deformation structures in clay. The selected sections for this study (A-H) are from eighty to more than one hundred meters long. The eight sections are located in different parts of the landscape: Sections A-F cut through an interfluve, where signs of slide scars are diffuse or absent. Section G displays the internal structures of a solitary block of clay within a well-defined slide scar. Section H is located just east of a steep ~250 m high rock face of greenschist, a large boulder of which was detected in the deposits.

In the following the term *section* is used for road excavations that represent a continuous wall. Each section is divided into *units.* One unit consists of one or several *deposit types*.

Slide deposit types

The slide deposits are divided into six main types, but transitional types have also been detected. Figure 4 shows examples of some of the deposit types in Sections A and F.

Type I: Horizontally laminated to slightly deformed clay deposits (occur in all sections)

These deposits dominate the investigated sections, and consist of laminated to structureless clay (Figs. 4a, 4d), with a few mollusc shells or shell fragments. A few, some millimetres up to 20 cm thick, sand layers and lenses are present. In addition, poorly sorted, up to 10 cm thick beds occur, with grain-sizes up to pebble size. Well-preserved mollusc shells and shell fragments are common in these coarse-grained beds.

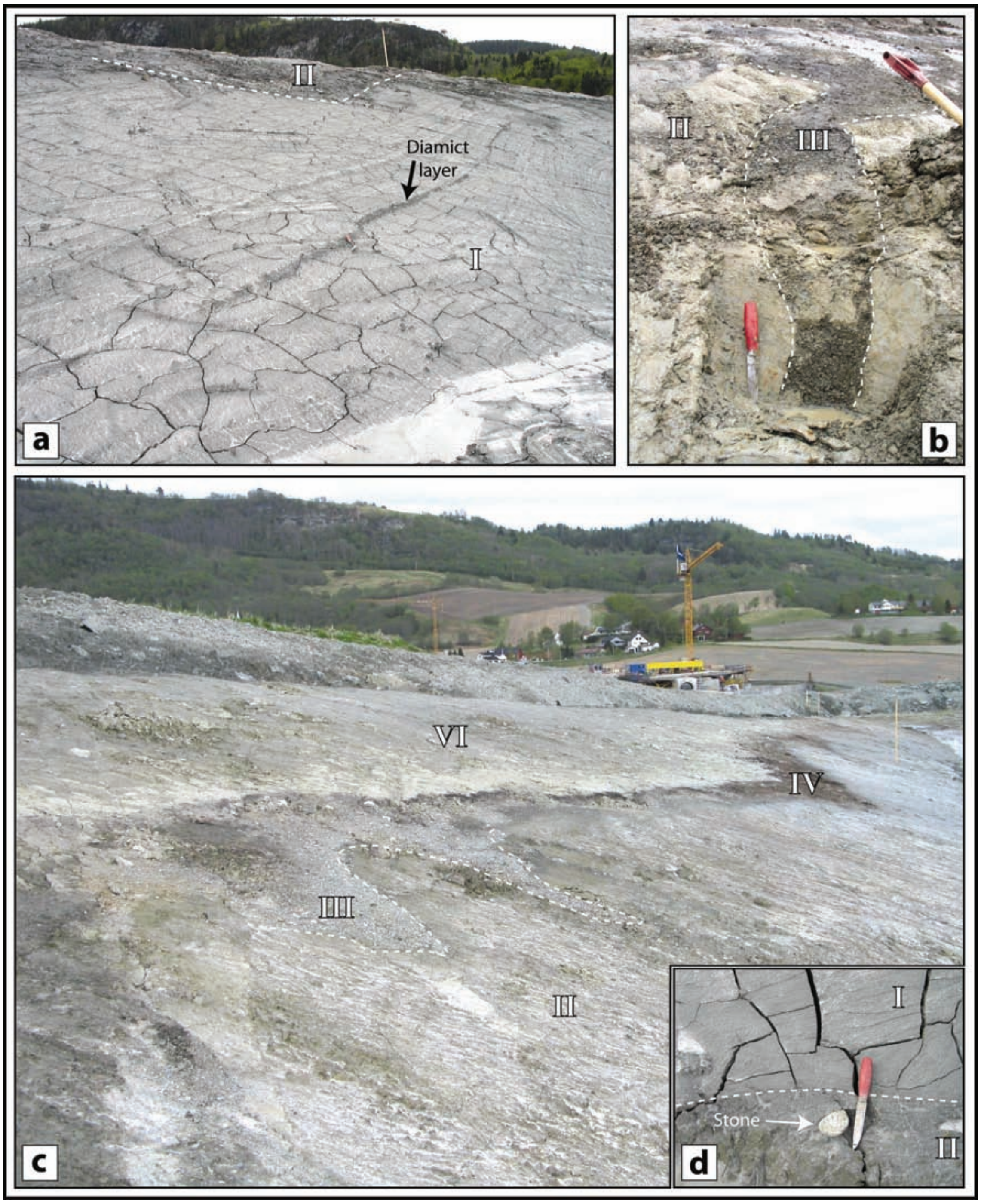

Fig. 4 Various deposit types in slide material. **a** *Deposit type I:* laminated to structureless clay, *Deposit type II:* clay, sand and gravel with scattered stones and sometimes organic remains (Section D). **b** Deposit type II, *Deposit type III:* poorly sorted gravel (Section A). **c** Deposit type II, III, *Deposit type IV:* Organic material, *Deposit type VI:* compact, structureless and poorly sorted sediments (Section A). **d** Deposit type I and II (Section A, boundary between Unit A1 and A2). Location for figure parts b, c and d is shown on Fig. 6.

Some bedding intervals display smaller deformation structures such as folds (Fig. 5). A few bioturbated horizons were observed.

The fine-grained laminated sediments were deposited from suspension in a fjord-marine environment in Preboreal time shortly after the last deglaciation (Table 1). Several thousand years after emergence above sea level, the deposits were involved in large landslides. During sliding, thick sediment accumulations were kept almost intact and deformation is only reflected in gentle undulation, folding and faulting. Parts of the material may be more structureless. Distinction between slide-blocks and undisturbed lamination can be difficult and large exposures are necessary to detect their internal structures.

Type II: Highly deformed and/or unsorted deposits (occur in all sections)

These relatively compact deposits are common and consist of poorly sorted sediments of clay, sand and gravel with scattered stones, pieces of wood and other organic remains (Fig. 4). Some parts are more gravel-dominated than others, and clasts consisting of greenschist fragments are common. Mollusc shell fragments occur locally. Folded and deformed slabs of laminated clay and/or sand are present.

The deposit accumulated from mixtures of mud and gravel that were subjected to intense deformation and shearing. Remains of original bedding in clay deposits may be partly preserved although displaced and deformed during sliding. This deposit type can, in some cases, be mistaken for fill material from cropland levelling (Type VI).

Type III: Poorly sorted gravel (occurs in Sections A and H)

A few beds of poorly sorted gravel are present. Gravel clasts consist mainly of local greenschist. The beds may occur as some decimetres thick near-vertical veins or dykes of gravel. The veins are irregular and the contact with the surrounding deposits is sharp (Section A, Fig. 4b). One of the veins can be followed upwards into a subhorizontal and highly irregular gravel bed. The gravel may also occur as a larger pocket inside deposit type II, including large amounts of mollusc shell fragments (Section H).

The gravel in veins was probably transported during water escape in deformed clay during sliding. Some gravel was also extruded to the surface.

The shell fragments in the gravelly pockets indicate a marine environment, and the gravel was likely deposited by debris flows during deglaciation. The deposit was subsequently deformed during sliding.

Type IV: Organic deposits (occur in Sections A, H and just south of Section G)

Organic material occurs as a few decimetres-thick layers, which may, in some cases, be followed horizontally over 30 m, draping underlying, deformed deposits (Figs. 4c, 6). It also occurs as vertical or near vertical layers. The deposit partly consists of *in situ* peat with numerous fragments of wood or seeds. Other organic material has been transported by water (H. Høeg, pers. comm.). Remains of leaves, birch, alder and raspberry seeds have been ^{14}C-dated (Table 2).

Other deposit types

Type V: Sandy deposits (occur in Section H)

This deposit type consists of a structureless, silty, sandy layer with small fragments of coal and wood. The deposit was detected in one layer, which varies in thickness from ~20 cm up to 1 m. The lower boundary is gradual. The layer is interpreted as an old soil/cultivation layer.

Type VI: Compact, structureless and unsorted deposits (occur in Sections A, C, D, E and H)

These relatively compact, structureless deposits consist of poorly sorted sediments of clay, sand and gravel with scattered stones, pieces of wood and other organic remains (Fig. 4c). The material may look like deposit type II, but is interpreted as fill material from cropland levelling.

Table 1 ^{14}C-dated mollusc shell or shell fragments in resedimented material. Dating type is AMS, and 440 years correction for reservoir effect is used. Determination of species made by S. Funder. All samples are detected in slide deposits in Section A, and show ages of Preboreal time.

Lab. Ref.	Location	Metres a.s.l.	Mollusc type	Sediment	^{14}C-age
TUa-5166	Section A, Unit A1	27	*Mytilus edulis*	Clay, rich in clasts	9510±45
TUa-5167	Section A, Unit A2	27	*Arctica islandica*	Clay, rich in clasts	9615±50
TUa-5169	Section A, Unit A1	27	*Mytilus edulis*	Clay, rich in clasts	9650±50

Table 2 ^{14}C-dated terrestrial organic material in central Buvika (AMS: TUa; conventional: T). Determination of species was made by P.U. Sandvik and H.I. Høeg. All samples are detected in clay-slide deposits, in road cuts.

Lab. Ref.	Location	Metres a.s.l.	Material type	^{14}C-age	Calibrated age	$\delta^{13}C$ %	Time
T-17255	Section A, Unit A3	28	Wood, *birch (Betula)*	1550±55	AD 435-600	-26,1*	Sub-atlantic
TUa-4884	Section A, Unit A2	27	Wood, *birch (Betula)*	1855±60	AD 85-240	-29,3	Sub-atlantic
TUa-4882	Section A, Unit A2	27	Wood, *birch (Betula)*	8330±65	BC 7480-7295	-29,6	Boreal
TUa-4883	Section C, Unit C1	16	Wood, *pine (Pinus)*	2370±40	BC 410-395	-24,0	Sub-atlantic
T-17256	Section D, Unit D4	16	Wood, *birch? (Betula?)*	5515±100	BC 4460-4255	-26,1*	Atlantic
T-17257	Section F, Unit F2 (Old channel)	30	Wood, *aspen (Populus)*	4500±90	BC 3355-3035	-26,1*	Sub-boreal
TUa-5289	Saltnes slide, near section G	35	Leaves	2990±35	BC 1270-1150	-26,4	Sub-boreal
TUa-5290	Section H, Unit H1	40	Seed, *raspberry*	3320±35	BC 1640-1535	-29,3	Sub-boreal
TUa-5288	Section H, Unit H1	40	Wood, *alder*	3225±35	BC 1520-1435	-31,5	Sub-boreal

* Value assumed, not measured

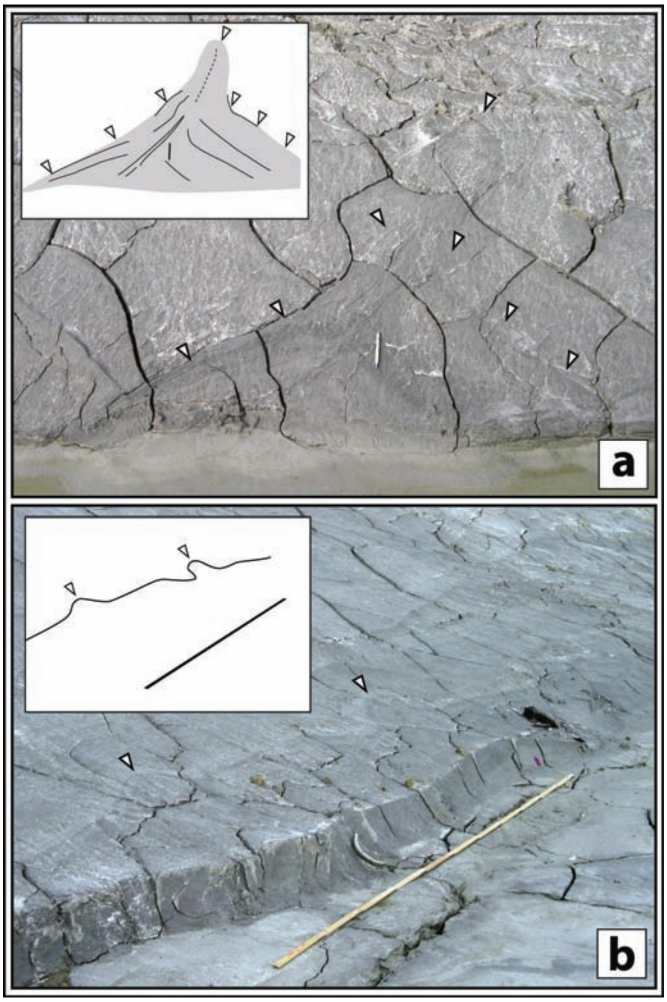

Fig. 5 Internal, small-scale deformations in laminated clay (deposit type I) in Section A, Unit A1 (Location shown on Fig. 6).

Description of sections

Section A: Compressional features (fold, shear, extruded gravel)

The description covers mainly the 110 m long part of Section A east of a bridge (Fig. 3). Section A is divided into five units distinguished by deposit types and internal structures (Fig. 6).

Unit A1 makes up the westernmost part of the exposure and displays deposit type I of horizontally laminated clay with small, internal deformation structures at the base of the section (Figs. 5, 6). One deformation type appears as a small westerly dipping tight fold in clay (Fig. 5a), while the other deformation type consists of small, open folds (Fig. 5b). Both deformation types only affect a specific stratigraphic interval and the laminated clay above appears unaffected. The eastern part of the laminated clay deposits appears homogenous and desiccation cracks of the exposure's surface display a semi-radial pattern (Fig. 6).

Unit A2, the eastern two-thirds of Section A, displays westerly dipping beds of clay and unsorted sediments with signs of folding and thrusting (deposit type I and II). A few irregular, steeply dipping dykes of gravel dissect the inclined clay beds. The contact with the surrounding deposits is sharp, and the veins cut through laminated clay (Fig. 4b). One of the veins can be followed upwards into a subhorizontal, deformed and highly irregular gravel bed overlying the clay (deposit types II and III) (Figs. 4b, 6). Inclusions of mud are present in the dyke (Fig. 4b). The inclined boundary between the clay of Unit A1 and the unsorted deposits of Unit A2 is relatively sharp (Fig. 4d).

Unit A3 consists of a horizon of organic deposits (deposit type IV) that overlies the inclined and folded beds described above. Some of the organic material is folded into the underlying Unit A2 (Fig. 6). Unit A4 consists of westerly inclined laminated clay (deposit type I) that grade eastwards into unsorted deposits of Unit A5 (deposit type VI).

Field observations suggest that the lamination of Unit A1 continues west of the bridge. However, the middle part of the section was removed or covered due to construction work (Fig. 3).

Three ^{14}C-datings of terrestrial organic material (*Betula*) have been carried out from Section A. Some organic material was flushed out during the slide, and did not grow on the locality (H. Høeg, pers. comm.). The sample in Unit A3 gave the age 1550±55 years BP, and the two samples from A2 gave the ages 1855±60 and 8330±65 years BP (Fig. 6; Table 2).

Also three samples of marine mollusc shell fragments from the Units A1 and A2 have been ^{14}C-dated (Fig. 6; Table 1). The mollusc shells from Unit A1, *Mytilus edulis* (blue mussel) (9510±45 years BP; 9650±50 years BP), generally live in shallow water (0-10 m). However, the clay-dominated facies indicates deposition at some depth and not near shore, so the molluscs are likely transported, possibly by seaweed or gravity flow. *Arctica islandica* from Unit A2 (9615±50 years BP) is common on a seabed of mud and clay (Christensen et al. 1978).

Section A represents a cross section through the front of a large clay slide that moved towards E-SE. The internal structures at the slide's margin are complex but the

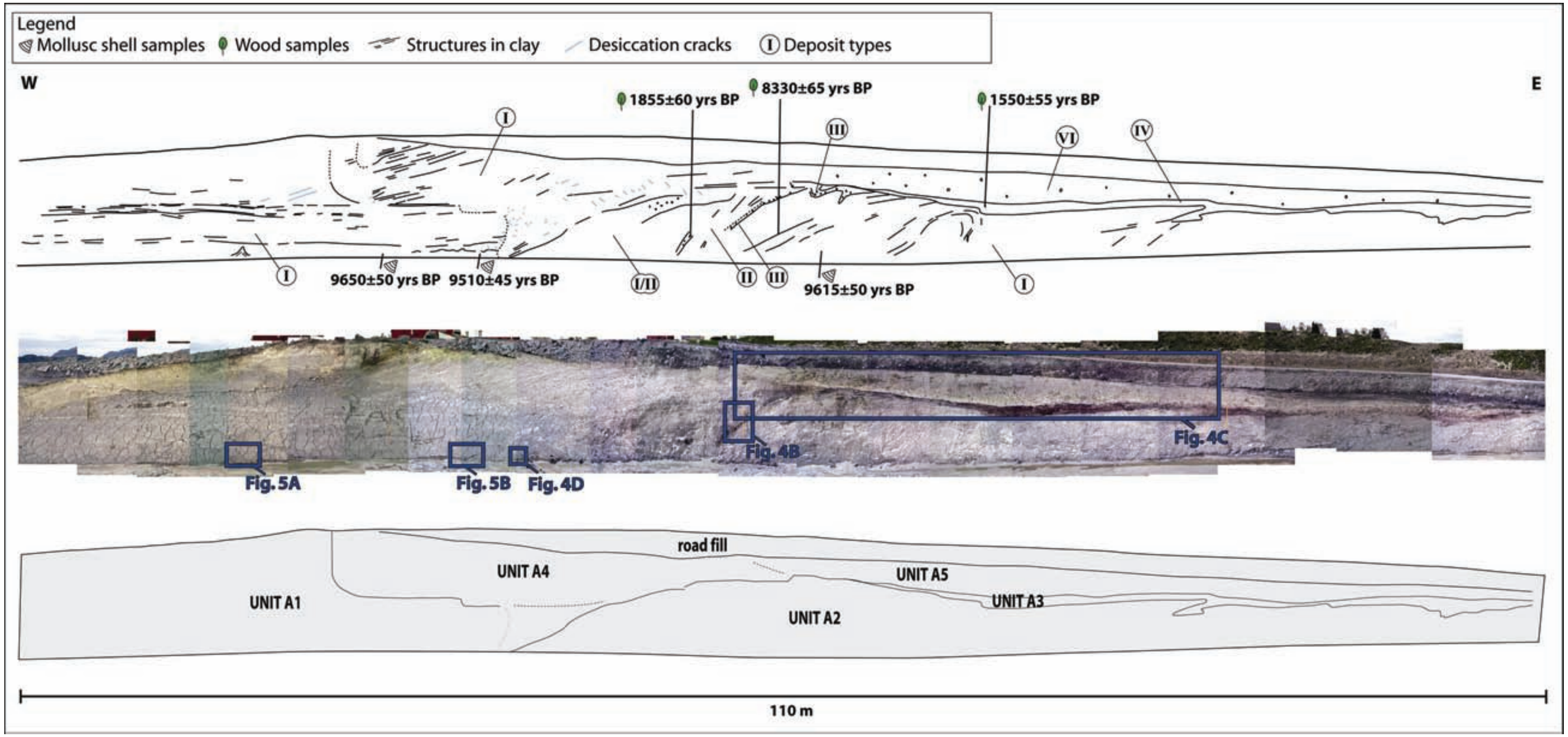

Fig. 6 Section A, east of the bridge (See Fig. 3 for location). **Top:** Deformation structures and deposit types. Structures in the blank areas were difficult/impossible to outline. See Table 1 and Table 2 for ^{14}C-dating specifications. **Middle:** Photo-mosaic. Figs. 4 and 5 show details from the section. **Bottom:** The units.

main features clearly display a compressional regime with stacking and folding of clay slabs. Desiccation cracks on the slightly weathered exposures may reflect stress fields during the final stage of the slide. The small-scale fold structures in Unit A1 were probably formed just above the sliding plane (see Section B), due to increased friction here. The tight fold representing an injected clay feature in the surrounding clay (Fig. 5a) was probably made through a higher stress level than the more open folds (Fig. 5b). The tight fold may represent the start of dyke formation and separation of two blocks of laminated clay. The feature did not develop further due to weakened stress level towards the end of the sliding.

The steeply dipping dykes of gravel in Unit A2 imply separation of blocks of laminated clay. High pore pressure due to compression of sediments during sliding may have led to water escape that was able to transport and deposit coarse material in the escape dyke and on the front of the slide. Water accumulations are common in deposit depressions that are formed during a clay slide, due to the impermeable material. The organic material in Unit A3 has been flushed out into a water pond and later turned into a peat bog. Organic accumulation occurred partially during sliding as inferred from the fact that parts of Unit A3 are folded into the underlying Unit A2.

Unit A4 probably rotated during sliding, displaying tilted layers and an almost vertically boundary with Unit A1. It is uncertain if this occurred contemporaneously with the other slide described above.

All or part of Unit A5, is probably fill material due to cropland levelling. This interpretation is based on the presence of drainpipes, in addition to local information about an old peat bog in the area.

Section B: Internal deformations and basal slide plane

Section B is located parallel to Section A along the road alignment (Fig. 3), and it displays three units (Fig. 7c). Unit B1 consists of soft, horizontally laminated clay (deposit type I). The western part of the unit contains some deformation features comparable to those described above for the lower parts of Unit A1, such as small, open folds and local, tight fold-like structures. Small-scale open folds are also present in the eastern part of Unit B1, below Unit B2 (Fig. 7e).

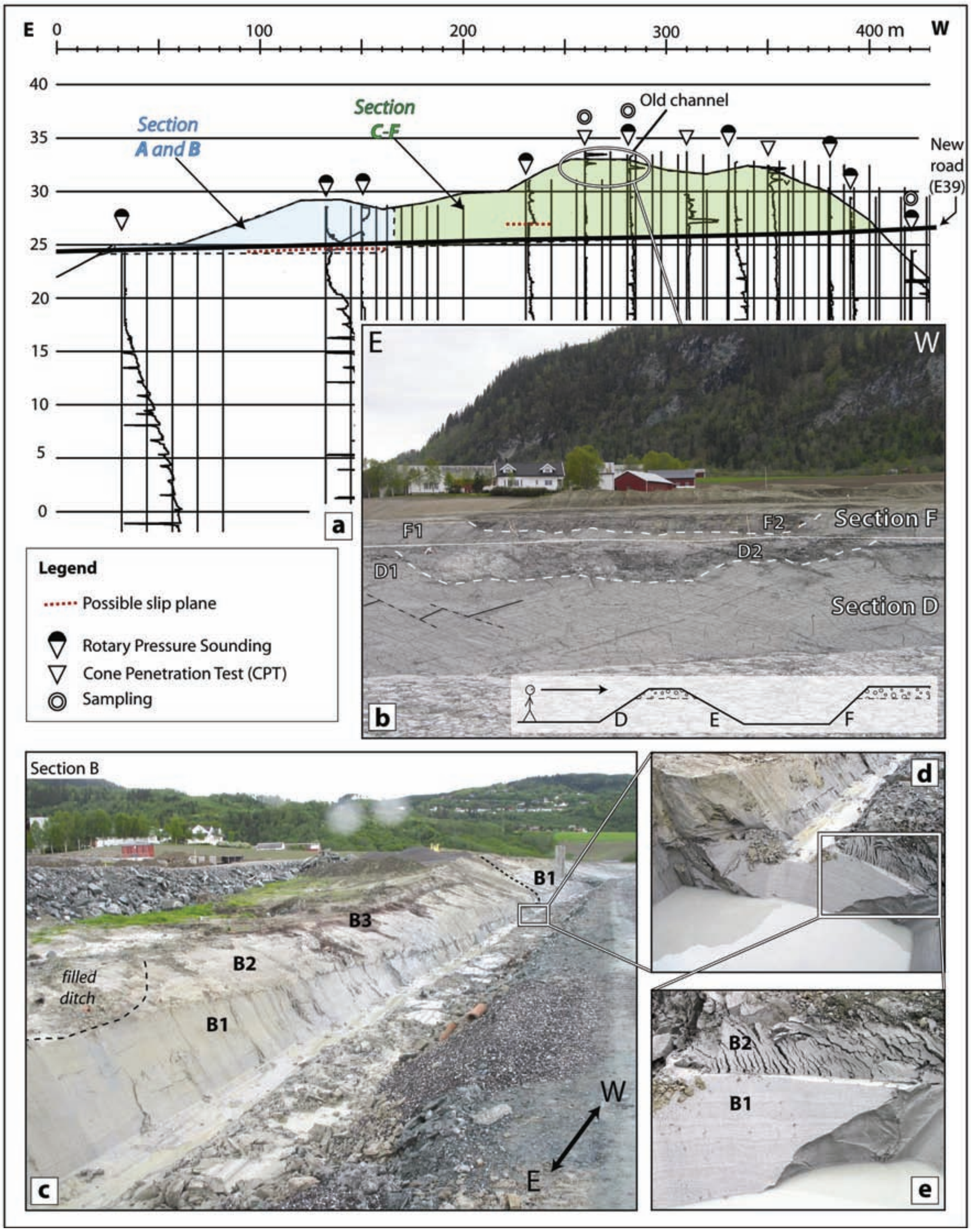

Fig. 7 a Drilling profiles near Sections A-F (Geotechnical drilling data from Berg and Hove (2001); Engen and Jensen (2003)) (See Fig. 3 for location of sections). **b** Channel feature (Units D2, F2) filled with deposit type II cutting into laminated clay (deposit type I) (Units D1, D2). Notice the inclined bedding with faults in laminated clay below the channel. **c-e** Section B, notice the basal deformations in Unit B2.

Unit B2 consists of unsorted and deformed sediments of clay, silt and fine sand (deposit type II). The base of Unit B2 is concave and erosionally, overlying Unit B1. A compact, relatively dry layer of clay with seams of fine sand represents the lowermost contact between Unit B2 and Unit B1. The layer is a few decimetres thick and displays a characteristic pattern of steeply inclined cracks (Figs. 7d, 7e). Unit B3 is horizontally-lying organic material (deposit type IV) (Fig. 7c).

The deposits of Section B are interpreted as slide material. The boundary between Unit B1 with more or less undisturbed soft clay and the dry and compact clay with vertical cracks in the basal parts of Unit B2 represents a slide plane (Figs. 7c-7e). The slide plane is also recognised in a geotechnical drilling profile (Fig. 7a).

Unit B1 correlates to Unit A1, and Unit B3 to Unit A3, in Section A. Unit B2 is more disturbed than Unit A2, and cannot be correlated directly, which shows that structures may vary over short distances. The slide plane in Section B is not recognisable in Section A.

Sections C, D, E and F: Compressional and extensional features inside slide material

Sections C, D, E and F are located west of Section A and B, and lie north of a steep bedrock hill and some small undulating clay terraces (Figs. 2, 3). There are four units displayed in all or some of the Sections C-F (Fig. 8). Unit C1-F1 consists of thick, laminated, undulating clay deposits with sets of normal faults and large open folds (deposit type I, Fig. 4a). A few layers of gravel or diamict material occur in this unit (Fig. 4a). A pocket of organic-rich clay was detected in the lower part of a more deformed part of Unit C1, containing a tooth from a deer (O. Wiig; pers. comm.). A wood piece (*Pinus*) was also sampled here, giving the ^{14}C-age 2370±40 years BP (Fig. 8; Table 2).

Unit C2-F2 constitutes a channel structure filled with an unsorted mixture of clay, sand, gravel, scattered stones and wood fragments (deposit type II). The south-north trending channel-structure in the upper part of Unit C2-F2 is a couple of meters deep and may be traced over several excavated sections (Figs. 3, 4a, 7a, 7b, 8, 9). Cross-sections through the channel reveal an asymmetric trough-shape with a thin layer of pebbles and sand over a slightly irregular base. The boundary between the channel and the surrounding clay is relatively diffuse. The deposits below the channel are normally faulted in some of the sections. In Section F (Unit F1) wood fragments (*Populus*), collected in the filled channel, were dated and have an age of 4500±90 years BP (Table 2).

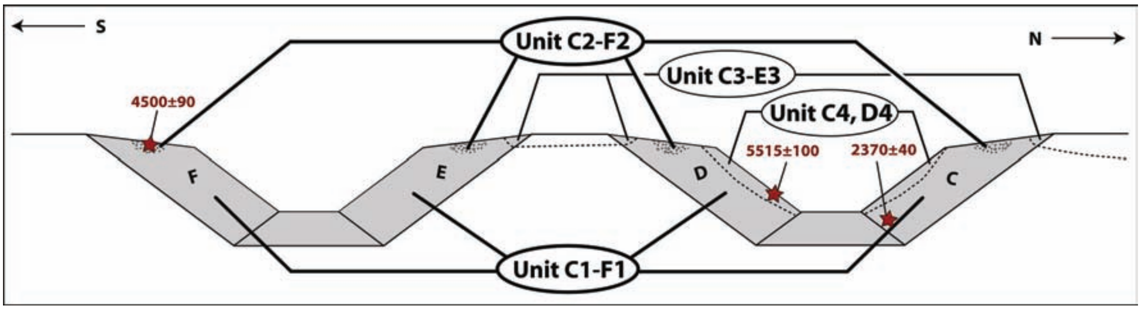

Fig. 8 Principle drawing of part of the Sections C-F. For location of profile, see Fig. 3.

A third unit is displayed in Section C, D and E: Unit C3-E3, which consists of structureless clay (deposit type VI) (Figs. 8, 9). It overlies Units C1-E1, and the boundary between Unit C1-E1 and Unit C3-E3 is trough-shaped.

The last unit, Unit C4 and D4, is located in the westernmost part of Sections C and D and consists of compact and highly deformed clay (deposit type II). Unit D4 truncates subhorizontal lamina in Unit D1. A relatively large wood piece (probably *Betula*) was collected in the compact disturbed material of Unit D4, and gave the ^{14}C-age of 5515±100 years BP.

The deposits in Sections C, D, E and F are interpreted as deformed during one or more slide events. Strike and dip measurements in folds indicate a general direction of movement towards E-NE. The normal fault in the laminated clayey sediments below the channel indicates that the channel was shaped due to extension during a slide event. Mixed material was possibly flushed into a depression between slide blocks.

Unit C3-E3 is interpreted to be clayey material filled into a historical slide scar just north of Section A-F, during cropland levelling. The boundary between Unit C3-E3 and Unit C1-E1 represents the slide plane in the rear part of the slide scar (Figs. 3, 8, 9).

Unit C4 and D4, located at the section edges in the slope of a brook (west of Sections C-F, Figs. 3, 8), is probably a further reworked part of the clay-slide deposits. This is possibly due to much younger and smaller slides than what the rest of the sections represents.

Fig. 9 Large fold and a fault in laminated clay (Unit E1), filled channel (Unit E2) and traces of a slide scar filled with clay from cropland levelling (Unit E3) in Section E. Weathering of the exposures allows for the identification of the structures.

Section G: Structures of a solitary slide block

Section G is located in the southern part of a large slide scar (200 000 m^2), called the Saltnes slide (Figs. 2, 3, 10) (Solberg et al. in press, b). The Saltnes slide event was a classical quick-clay slide having a “bottle-neck” shape that formed due to remoulding of large amounts of quick clay. Only a few slide blocks with more or less intact layering were left behind in the scar, exemplified by the deposits of Section G.

The section is 80 m long and consists mainly of deposit type I. Large parts of the section show clay with subhorizontal silt and sand laminas and layers. Most of the structures are intact, except for a part that has indistinct or no structures (Fig. 10b). The edges on each side of the section are compact and structureless (deposit type II) (Figs. 10a, 10b).

Just south of Section G the road cuts through the slide-scar wall, and here a buried old soil surface was detected (deposit type IV). Leaves and other surface material were sampled and ^{14}C-dated and gave the age 2990±35 years BP (Table 2; Figs. 10e, 10f).

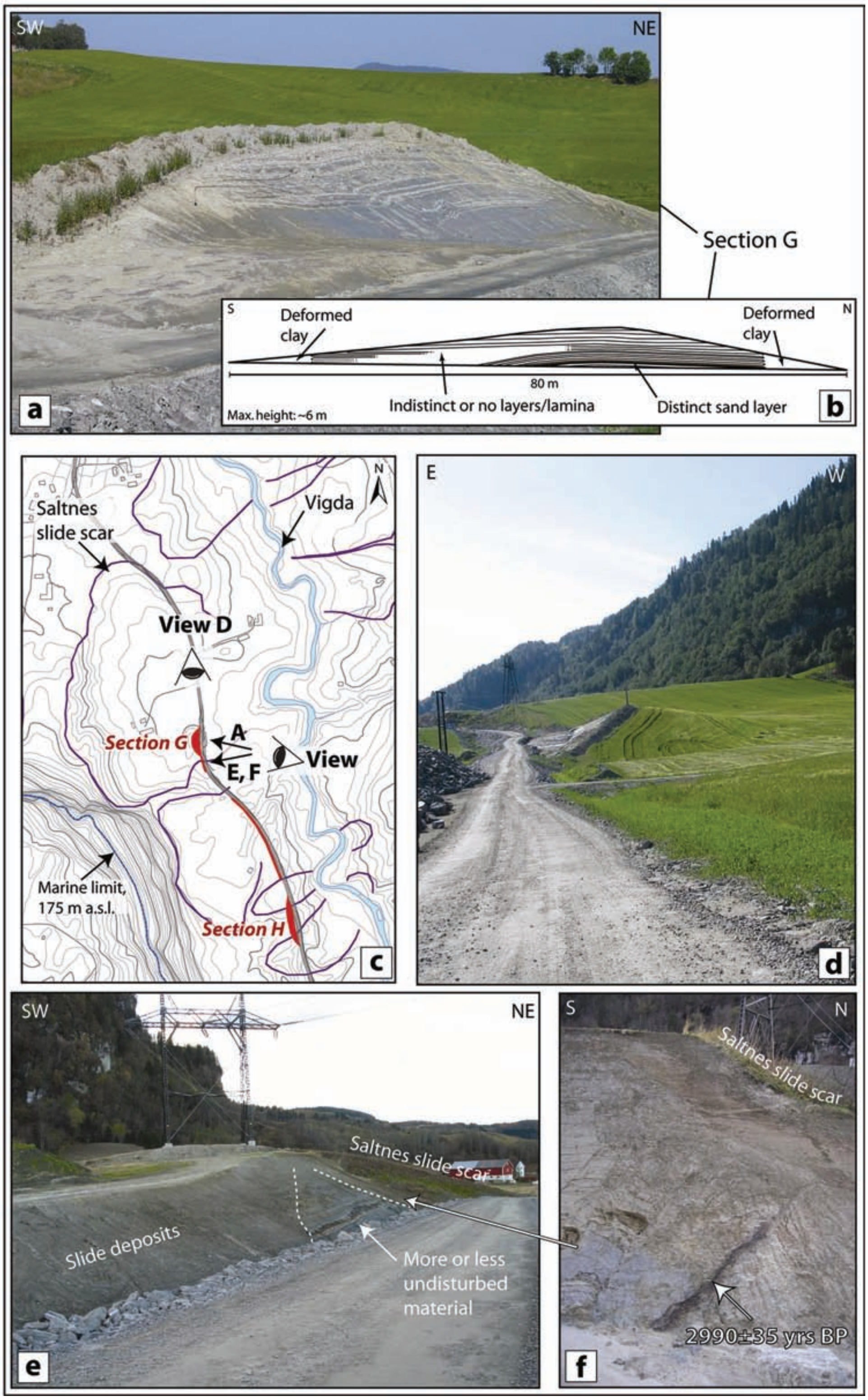

Fig. 10 a Section G located in Saltnes slide scar. **b** Structures in Section G. **c** Site map. **d** The slide block in Saltnes slide scar. **e** Road cut showing slide material on both sides of undisturbed material. **f** Buried soil surface due to the Saltnes slide event. For ^{14}C-dating details, see Table 2.

The buried organic material probably represents surface material on a block rotated during the Saltnes slide event. On the southern side of these slide deposits there are laminated clay and sand layers that seem to be undisturbed (Figs. 10e, 10f).

Below the Saltnes slide scar there are indications of a thick deposit of coarse material like sand and/or gravel overlying bedrock, and the deposit thins out towards east and north (Dalsegg et al. 2006, Solberg et al. in press, a). This coarse deposit is covered by clay that partly contains sand layers, as shown in Section G.

Section H: Faults, rotation and highly deformed material

Section H is the southernmost of the studied sections (Figs. 2, 3). It is 100 m long, shows disturbed clayey material, and is divided into seven units (Fig. 11). Unit H1 is located in the middle of the section and consists of deformed laminated clay, partly with tilted sand layers (deposit type I). Small faults are detected in the tilted sand layers (Fig. 11). A few boulders are present in the clay, mainly consisting of crushed greenschist. In the lower part of the unit there is gravel underlying unsorted clasts-rich deposits (deposit type III and II, respectively), and no sedimentary structures are recognised. Large amounts of mollusc shell fragments were detected in the gravel. Unit H1 has a vertical organic layer in the northern part. The boundary between the organic material and the clay is relatively sharp to the north, while there is a more gradual transition to the south. There is also well-preserved material, like roots, near the northern boundary (to Unit H2). Two samples of raspberry seeds and fragments of alder from this vertical layer have been dated (Fig. 11; Table 2). The two samples have nearly identical ages, of 3320±35 and 3225±35 years BP.

Unit H2 consists of compact, laminated clay (deposit type I). Parts of the unit are relatively undisturbed with horizontal laminas. Other parts show faulting and tilted layers, and an approximately one-metre thick deformation zone (Fig. 11). A relatively flat 15 m^3 boulder that dips 16° towards the west is located in the upper part of the unit. Inside Unit H2 is the highly deformed Unit H3. A lot of disturbed structures such as tilted layers and small folds are recognisable in this clayey material (deposit type I).

Unit H4 consists of structureless clay (deposit type I) that lies below the organic deposit of Unit H5. Unit H5 is a 35 m long horizontal layer of peat-like material, mixed

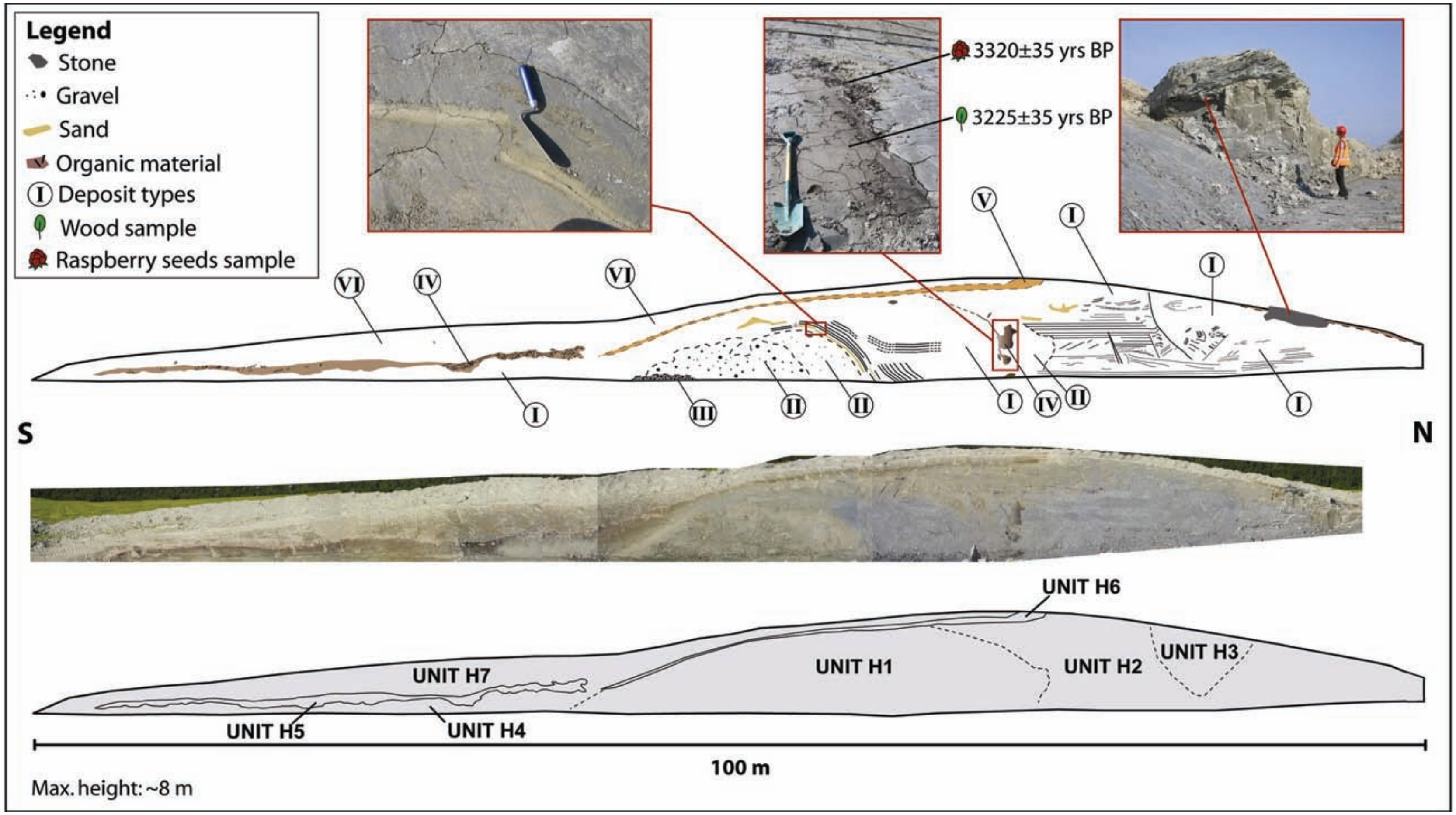

Fig. 11 Section H (See Fig. 3 for location). **Top:** Deformation structures and deposit types. Structures in the blank areas were difficult/impossible to outline. Details from ^{14}C-datings in Table 2. **Middle:** Photo-mosaic of the section. **Bottom:** The units.

with a lot of wooden sticks and roots (deposit type IV). The material has not been dated, but appears relatively young. The boundary between Unit H4 and H5 is gradual.

Unit H6 consists of structureless silty and sandy material with small fragments of wood and coal (deposit type V). There is a gradual boundary with the underlying clay. The uppermost Unit H7 is structureless clay with scattered highly angular pebbles and stones (deposit type VI).

The degree of deformation varies in the section, but Units H1-H3 may all have been involved in one or more flake-type slide(s), where blocks rotated relative to each other, and only a thin layer of quick clay was remoulded and acted as a slide plane. Internal deformation may have occurred during sliding, as shown by the deformation zone in Unit H2. However, it cannot be excluded that these deformations were made by an older submarine slide during fjord sedimentation.

The dated material may be resedimented, but at least the results give a maximum age of a slide event (~3.3 ka years BP). The types of organic material in the deposit indicate that the slide event occurred above sea level. In addition the section lies 30-40 m a.s.l., well above the sea level at that time, which was 12-13 m above present sea level in this area (Reite 1983).

Later, more recent slides removed parts of the slide deposits, leaving behind slide scars on each side of the section (Figs. 3, 10c). Unit H4 may be slide deposits from the southernmost of these slides. Unit H5 probably grew as a peat bog in the slide scar, together with coppice. Parts of the slide-scar walls were subsequently cultivated, shown by Unit H6. Unit H7 is most likely fill material from newer cropland levelling.

Information on slide deposits from geotechnical sound drillings

Geotechnical drillings in the study area do not give any direct indications of slide deposits. Still, in the area of Section A and B, there is a small increase in drilling resistance and a subsequent decrease in the contact between Unit B2 and Unit B1 in one drilling (Fig. 7a). Without the road excavations, this would have been interpreted as dry crust clay, and not as a possible slide plane for an old slide event. Only one of the rotary pressure soundings from Sections C-F has a signature similar to the one from the drilling in Section B (Fig. 7a). There were no slide planes detected in the excavations at this level that were comparable to the one in Section B. The cone penetration test (CPT) is suitable for detection of coarse-grained layers, and the channel structure in Sections C-F is recognisable on two CPT profiles. Also a diamict layer west of the channel is detected in a CPT profile in Sections C-F (Fig. 7a).

Along the county road, several drillings were carried out before Sections F and G were excavated. No clear slide planes are recognisable, and the profiles do not indicate that parts of the sediments are slide deposits (unpublished drilling data from Rambøll Norge AS).

Discussion

Deformation structures in clay-slide deposits

The slides discussed in this paper are all interpreted to have occurred above sea level, due to the presence of terrestrial organic material, the maximum age of the slides from ^{14}C-dating and the height of the slide deposits compared to the shoreline displacement curve (Reite 1983).

Sections A-F and H give information on the internal processes and movements of large clay slides, including thrust planes, normal faults and folds. Folds indicate a local direction of compression and movement in some of the sections. This does not necessarily show the location of the source area, since a rotation of large clay blocks may occur during sliding. At least some of the slide blocks were originally from almost the same stratigraphical level, since the ^{14}C-dated mollusc shell fragments from Unit A1 and Unit A2 gave relatively consistent and almost overlapping ages from Preboreal time (9.6-9.5 ka years BP, Table 1; Fig. 6).

Different types of slide deformations seem to appear at the front, at the slide plane and internally in the slides documented in this study. *In the front* of slide blocks, folding and thrusting occur, due to compression of the sediments and separation of the material into blocks moving relative to each other. Where the *slide plane* is exposed at the slide front there are small-scale, near-vertical cracks and compact, disturbed material just above it (Unit B2, Fig. 7d). In contrast, slide planes at some distance to the slide's front seem to be characterised by soft clay with small open to tight folds (Unit A1 and western part of Unit B1). Below the slide plane, small-scale open folds are formed in the otherwise undisturbed laminated clay (Unit B1 below Unit B2). *Internally* in slide blocks the deformation has been relatively small for Section G and moderate for Sections A-F, as shown by more or less intact layering. In Section H, there are also internal deformation layers between more intact layers (Unit H2). However, it cannot be excluded that some of these deformations are formed by a submarine slide during fjord sedimentation. All the sections have parts that are heavily deformed, observed as compact material with very few or no structures, both internally and at the slides margins.

The large blocks of deformed material in Sections A-F and H indicate that not all the clay was remoulded during sliding. Possibly only a relatively thin layer of quick clay was remoulded, resulting in a transfer of the blocks over a relatively short distance. Although the basal sliding plane is not visible in Section A, structures suggest that it is located just below the exposure in accordance with observations in Section B. Liquefied quick clay probably lubricated the slide plane, allowing the formation of only small-scale fold structures during settlement near the front of the slide block (Figs. 5, 6). Increased stress and compaction associated with water escape during final movement deformed the clay of Unit B2. Small vertical cracks formed due to compaction. Escape of liquefied quick clay resulted in increased friction, and movement ceased. The post-sliding dry-out of the clay has also been faster due to the cracks in the slide material. Unremoulded slide deposits may have the same properties as *in situ* sediments, while remoulded quick clay is stable when excess pore-water has dissipated. The slide events in Vibestad and Furre (Mid-Norway) in 1959 are recent examples of slides where large blocks slid on a thin layer of remoulded quick clay (Hutchinson 1961, 1965). The slide at Furre was a flake-type slide, while the Vibestad slide was more complex and retrogressive. The clayey part of the sediments was not totally remoulded, and blocks of slide deposits formed an undulating and partly terraced surface as also observed in Buvika. In Furre the slide plane consisted of a quick-clay layer with a thickness of only 10 cm or less. Even though only one certain slide plane is detected in Sections A-F in Buvika (in Section B), more slide planes cannot be excluded, regardless of the number of events that the sections may represent. A study of a modern slide in Canada shows that flake-type slides may have several slide planes (Geertsema et al. 2006).

Water escape in dykes, shown in Unit A2 (Figs. 4b, 4c, 6), indicates how energy dissipates during sliding. According to Hutchinson (1961), fresh sliding surfaces in normally consolidated clay often show considerably higher pore pressure than the hydrostatic pressure. This is due to the breakdown of the clay structure and transference of part of the overburden load to the pore water. This high water pressure may exceed the tensile strength of clay deposits, leading to the formation of a hydrofracture, as presented in a glacio-tectonic study (Rijsdijk et al. 1999). The crack is subsequently filled with gravel, due to a forceful upward flow of water. The gravel may have originated from a coarse-grained layer or pocket in the clay, or from sorting of diamict layers, which are present locally in other sections (Fig. 4a). The gravel accumulated in the almost vertical dyke as the water flow ceased, during the end of sliding. Organic material have been flushed out by the water and deposited on the land surface. Both the gravel and the organic material have been partly folded into the slide material. This shows that the extrusion of gravel and organic material occurred during final slide movement. According to Rijsdijk et al. (1999), such gravel-filled hydrofractures cannot develop in unconsolidated muds as a product of gravitational movement, since they would liquefy as soon as the hydraulic pressure increases significantly. This is in contrast to the present study that shows that the gravel-filled dyke probably was created due to hydrofracturing during clay sliding. However, hydrofracturing will not occur in quick clay due to liquefaction. This indicates that the entire slide block did not contain quick clay and that only a thin layer of quick clay was present at the sliding plane in Section A.

Exposures northwest in Buvika showed highly folded clayey silt in the lower part, and subhorizontal clayey silt in the upper part (Solberg et al. subm). The lower layer was interpreted to be glacio-tectonised deposits, due to its position, the fold axis direction and the structure interpretation. Still, it can be difficult to determine what caused deformations in a clayey deposit. If modern terrestrial organic material is present, it is most likely slide deposits.

Stability considerations and sliding in old slide deposits

Further leaching of the clay in the slide deposit after settlement led to formation of quick clay, confirmed by scars from later quick-clay slides cutting into the older slide deposits (Fig. 3). The slide scar just north of Sections A-F (Fig. 3), whose slide plane is indicated in Sections C-E (Unit C3-E3, Figs. 8, 9), is from the 18th century (Høyem

1894, Snøfugl 1977). Such slide scars, together with river/brook erosion, may also have erased traces of older slide scars and slide material. The original slide deposit may have been thicker and been subsequently eroded. A reconstruction of the entire seabed for Buvika has been made based on interpretations of morphology with remnants of the old seabed and the local sea level curve (Solberg et al. 2006; Solberg et al. in press, b). The reconstruction suggests that the valley fill in the area of Sections A-F have been 15-20 m higher than it is today. The landscape degradation possibly occurred during several early flake-type slide events. This indicates that there may be more slide deposits in areas interpreted as *in situ* sediments, both in Buvika and in other valleys with elevated marine deposits.

Aspects on chronology of events for Sections A-F and dating

The structures in the Sections A-F may suggest one very large slide event, since continuous lamination occurs over considerable distances. However, evidence of more slides may have been removed by erosion, exemplified by slide scars that cut into the sections (Fig. 3).

All the Sections A-F may reflect one large slide event (*Scenario I*). Large folds, as shown in Section A, may represent the front of slide blocks. The slightly different direction of movement measured in the folds indicates that slide blocks moved separately. The dated material in Unit A3 gives the maximum age of *Scenario I* (1550±55 ^{14}C years BP), implying that all the other dated samples from Sections A-F are resedimented.

Another possibility is that parts of Section A and B are disconnected from the other sections, since limited exposures could not verify that they are connected to Sections C-F. A two-event scenario (*Scenario II*) may be divided into *Event 1* (reflected in Sections C-F) and *Event 2* (interpreted from parts of Sections A-B). The dated wood piece from Unit C1 gives a maximum age of *Event 1* (2370±40). For Sections A-B, the dating of *mollusc shell samples* gave consistent indications of that Units A1 and A2 is from almost the same stratigraphical level. The *terrestrial organic material*, on the other hand, gave very different ages, suggesting that mixed organic material was involved in the slide. The youngest age is from the sample in the peat bog (Unit A3), which was flushed out, and did not grow on the location. It therefore gives a maximum age of *Event 2* (1550±55 ^{14}C years BP). The older samples are assumed to be resedimented.

Even though samples of terrestrial organic material can be useful in order to date a slide event, the type of material and location of the sample is crucial to the usefulness of the results. Numerous dated wood pieces scattered in a clay-slide deposit are resedimented, and datings only give maximum ages. The best material for dating is obtained from short-lived plants on an old growth surface, buried by slide deposits. This is also concluded in Hansen et al. (subm), where wood fragments in a slide deposits gave a much older age than the buried vegetated surface just below the slide deposits. The closest to an optimal dating situation in Buvika, is the dating of the Saltnes slide event. The dated organic material is from an assumed buried soil surface just south of Section G (Fig. 10f; Table 2).

Source areas for the slide deposits and slide triggers

There are no obvious slide scars connected to the slide debris detected in the road excavations in Buvika, except for Section G in the Saltnes slide scar. The extents of the slide debris indicate that large areas have been relocated, but probably not far due to the moderate degree of deformation. Indications of direction of movement are given in some of the sections. Even though some rotation of blocks during sliding may have occurred, the slide deposits in Sections A-F seem to come from south, southwest or west for both scenarios described above. The terrain nearby also gives indications of the source area for the slide(s). Undulating terraces located just south of Sections C-F may be slide deposits, connected to the slide event(s) represented by the sections.

A clay slide in the 18th century, just west of the Saltnes slide scar, was triggered by a rock fall (Strinda og Selbu sorenskriveri 1747-1756). A rock fall might have been the trigger for the slide event(s) represented by the Sections A-F. The presence of clasts of greenschist (e.g. in the dyke of Unit A2) indirectly indicates that a rock fall was involved. In addition, river erosion may have initiated sliding.

Further south, in Section H, Unit H1-H3, the slide was most likely triggered by a rock fall originating in the exposed steep bedrock face to the west. Movement of the boulder probably resulted in the westward dip (Figs. 10c, 11).

The extent of the slide deposits can be difficult to determine, especially when younger slide scars cut into both older slide deposits and *in situ* sediments. In Buvika other road sections showed undisturbed layered deposits (Fig. 3), which may be *in situ* sediments (Solberg et al. subm). Such information can help to outline the limit of slide deposits.

Water from the steep rock face west and south of the Saltnes slide scar may have been stored in the coarse deposit below the clay creating an artesian pressure. This accelerated the quick-clay development and might have affected mass-movement directly through increased pore pressure in the clay (Solberg et al. in press, a, b). River erosion was possibly the trigger of the slide. Section G is a slide block left behind in the scar from this event.

Conclusions

Deposits of large clay slides in Buvika display different types of slide deformations at the front, at the slide plane and internally. Folds, thrusts and water-escape dykes occur in front due to compression and separation of slide blocks. At the slide plane near the front of the slides there may be steeply inclined cracks in compact material. Slide planes at some distance from the front of the slides are characterised by deformations in soft clay such as small open to tight folds. Internally in slide blocks the deformations are relatively small to moderate. Heavily deformed material occurs locally in all sections, both internally and at the slides margins. Terrestrial organic material in buried layers or mixed with clay occurs both in front of and internally in slide blocks. For most of the studied sections (A-F and H) the deposits suggest that sliding took place on a thin layer of quick clay (translated and rotated slide blocks).

Slide events that include collapse and remoulding of thick quick-clay layers are dependent on massive quick-clay development, and in Buvika they mostly seem to represent relatively young slide events. Still, *old* slide scars with the clearly defined classic shape of quick-clay slides, like the Saltnes slide scar, are present. The conditions here must then have been favourable for relatively fast quick-clay development. The source area for old flake-type slides may be difficult to outline exactly, due to later erosion.

In the area of Sections A-F there is laminated clay with only a few coarse-grained layers. The quick-clay development has therefore been slower, possibly starting with thin clay layers. This is reflected in the slide deposits of Sections A-F, where the quick-clay development continued after sliding. These deposits would probably have been interpreted as *in situ* sediments without the road excavations, indicating that other areas in elevated marine sediments may also be slide deposits. Old slide deposits, however, are not necessarily stable since continued quick-clay development may result in new slides, as shown by the slide scars that cut into Sections A-F and H.

The long-term development of quick clay has an important impact on landscape degradation and on the character of the present day landscape. The study of large road excavations has given a valuable contribution to this knowledge, including slide processes and deformations.

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Solberg IL, Rønning JS, Dalsegg E, Hansen L, Rokoengen K, Sandven R (in press)a Resistivity measurements as a tool for outlining quick-clay extents and valley fill stratigraphy: feasability study from Buvika, Central Norway. Canadian Geotechnical Journal

Solberg, IL, Hansen L, Rokoengen K (in press)b Distribution of clay slides in fjord-valley deposits and their role in valley development, example from Mid Norway. Accepted for The 1st North American Landslide Conference, June 3-8 2007, Vail, Colorado

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Paper IV: Resistivity measurements as a tool for outlining quick-clay extents and valley-fill stratigraphy: feasability study from Buvika, Central Norway

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Resistivity measurements as a tool for outlining quick-clay extents and valley-fill stratigraphy: feasability study from Buvika, Central Norway

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Abstract: Thick, marine clay deposits in valleys along the Norwegian coast are occasionally subjected to large landslides involving quick clay. Detailed mapping of the extent of quick clay is of great interest for planning and protection purposes, as the position of quick clay within slopes has a major impact on the landslide risk.

Ground conditions in the small valley Buvika, Mid Norway, are characterised by thick occurrences of quick clay, documented in numerous geotechnical investigations. The resistivity method is potentially well suited for outlining pockets of quick clay since quick clay has a slightly higher electric resistivity (10-80 Ωm) than intact unleached clay (1-10 Ωm). This is due to a higher salt content in the latter. These relations are supported in this study by pore-water salt content measurements. The acquired resistivity profiles are compared with the geotechnical drilling data and other geophysical data. Results are promising, and acquired resistivity profiles are interpreted in terms of quick-clay extents, stratigraphy, bedrock influence, and groundwater drainage patterns. Mismatch between intersecting resistivity profiles may be an indication of local geological variations.

Key words: 2D resistivity, marine sediments, stability, quick clay, groundwater

Introduction

Certain areas in Norway like Trøndelag and parts of Eastern and Northern Norway are prone to large landslides in sensitive marine clays, including quick clays. Slope failures in the marine deposits occur every year, with varying sizes and extents. Large damaging slides involving remoulding of the quick-clay deposits are relatively infrequent. Small initial slides do not necessarily involve quick clay, but can trigger much larger slides if quick clay is present (Gregersen 1981; Karlsrud et al. 1985). Slides can be triggered naturally, but human activity is often an important factor.

Any improvements to existing methods for risk mapping and site investigations in areas with marine clay would be of great interest. Usually quick-clay pockets or layers in the subsurface are detected by geotechnical drilling. Laboratory testing on core samples is the most reliable method of confirming the existence of quick clay. Still, this method is expensive and time-consuming, and it only gives information at individual points within the investigated area. Electrical resistivity imaging is a relatively cost-effective geophysical method; it is non-destructive, and gives a continuous image of the subsurface.

Electrical resistivity imaging is widely used in applications such as groundwater delineation, mineral exploration and location of fracture zones in bedrock. However, it has rarely been used for detecting quick clay in Norway. Early comparison of one-dimentional vertical electrical sounding with results from geotechnical soundings and sampling concluded that the resistivity method was useful to detect quick-clay layers (Løken 1968; Berger 1983; Mørk 1983). Later, continuous vertical electrical sounding revealed a much more heterogeneous nature of the sensitive clay than concluded from the geotechnical investigations (Roth 2002; Larsen 2002). In both Canada and Sweden, 2D resistivity measurements have been carried out in connection with marine deposits and slide hazards (Dahlin et al. 2001; Calvert and Hyde 2002; Leroux and Dahlin 2003; Bichler et al. 2004; Rankka et al. 2004; Dahlin et al. 2005). The Swedish and Canadian investigations show that resistivity profiling gives an overview of the ground conditions, but they also conclude that it is essential to supplement the results with other surveys. Development of both measuring equipment (Dahlin 1993) and data processing involving the inversion method (Loke 2004) has made the investigations easier, faster and more reliable. Results from the resistivity measurements thus provide an excellent basis for selecting representative locations for more detailed investigations.

The classification of sediments from the resistivity values in the present study is based on the experience of several similar investigations (Berger 1980, 1983; Calvert and Hyde 2002; Rankka et al. 2004). The limits between the different classes are gradational:

- Unleached/intact marine clay: 1-10 Ωm
- Leached, possible quick, clay: 10-80 Ωm
- Dry crust clay, slide deposits or coarser material: above 80 Ωm

The study area is Buvika, Central Norway (Fig. 1), which has thick marine deposits. Previously, numerous geotechnical investigations were carried out in this area, due to the construction of a new highway (E39). The investigations show that there are large deposits of quick clay in the area, and a landslide hazard map has been produced on the basis of some of these investigations (Gregersen 1988; www.skrednett.no).

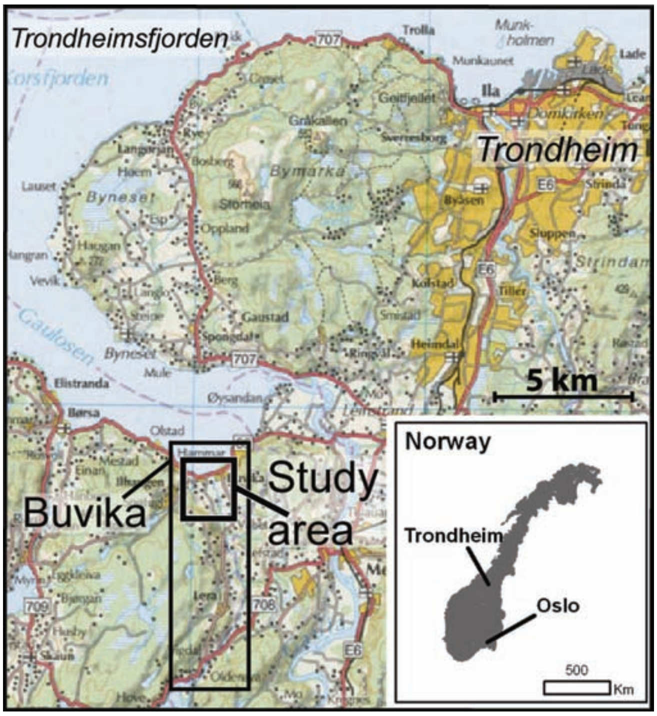

Fig. 1. Location of Buvika (modified from Henriksen 1992).

The main purpose of this article is to evaluate the resistivity method and its ability to outline the extent of quick clay in Norwegian marine deposits. This is done by comparing resistivity results with the large amount of existing geological and geotechnical data. The role played by the salt content in pore water is considered, as well as the influence of bedrock on the measurements. The conformity between intersecting profiles will also be discussed. In addition, the results of the study will be used in order to interpret groundwater drainage patterns and the general geological and stratigraphical distribution of sediments in the study area, which is important for formation of quick clay and for the interpretation of quick-clay extents.

Setting

Buvika is located in Skaun municipality, in Sør-Trøndelag County, Central Norway (Figs. 1, 2), about 25 km southwest of the city of Trondheim. Buvika is a small fjord-valley system surrounded by 300 to 400 m high bedrock hills, and is characterised by its undulating terrain with numerous ravines and slide scars.

During the last glaciation Norway was glacio-isostatically depressed, and when the glaciers melted, the sea flooded coastal areas. In Buvika the highest sea level after the last glaciation (marine limit) was about 175 m above the present sea level (Reite 1983) (Figs. 3, 4). The valley fill is dominated by glaciomarine and marine deposits. Locally, coarse-grained deposits such as glaciofluvial sediments are detected (Reite 1983; Solberg et al. in prep). During and after the deglaciation, the area was glacio-isostatically uplifted and such exposing the marine deposits. Erosion by rivers, groundwater and landslides controlled the development of the present landscape.

Fig. 2. Buvika during construction of highway E39. The photo is taken towards southwest (Photo: the Norwegian Water Resources and Energy Directorate, NVE).

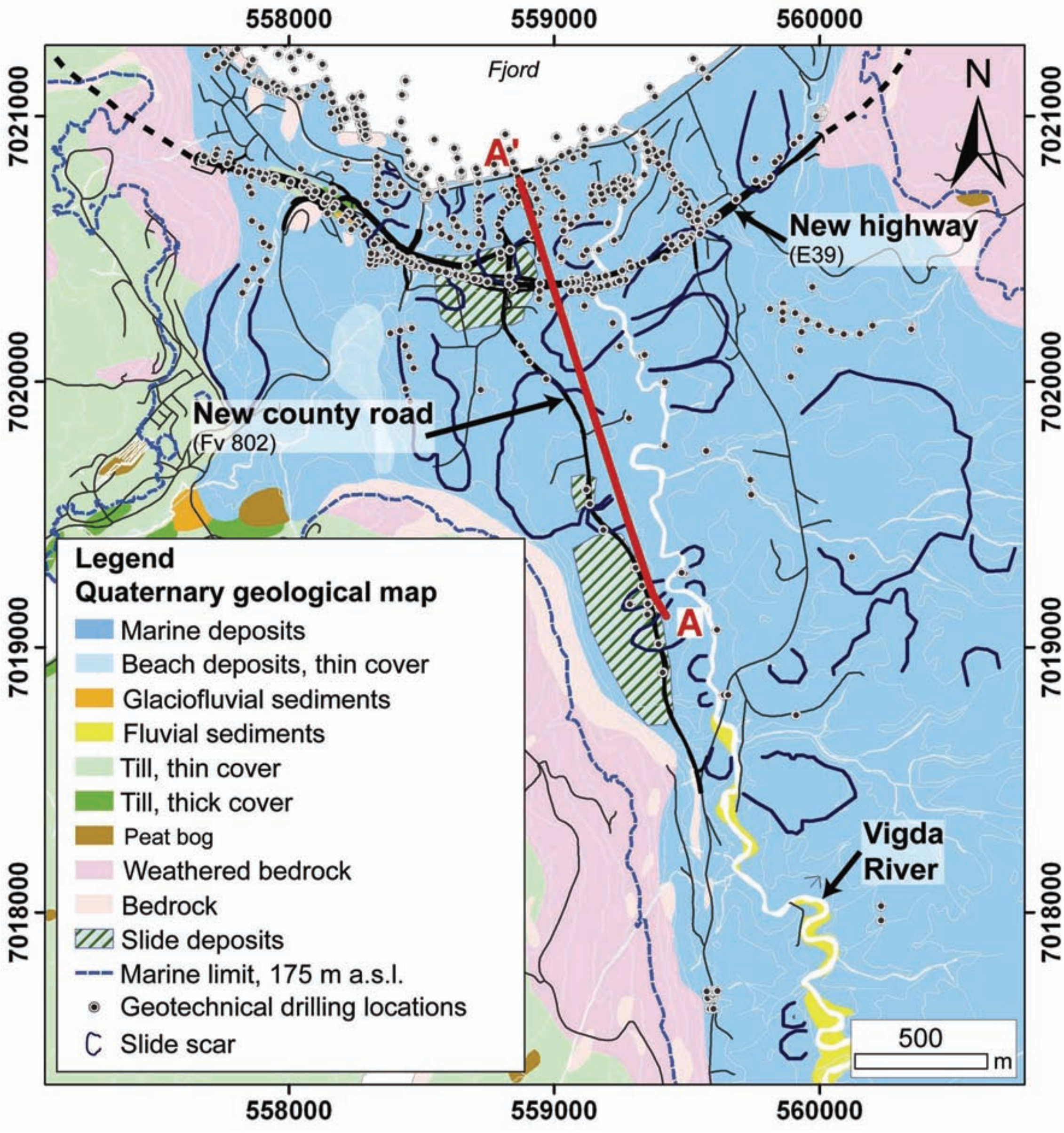

Fig. 3. Quaternary geology of Buvika (modified from Reite 1983). Profile A-A' is shown on Fig. 9. Geotechnical drilling locations in central Buvika are shown (based on geotechnical reports from Statens Vegvesen (the Norwegian Public Roads Administration), Rambøll Norge AS, NGI (the Norwegian Geotechnical Institute) and NTNU (the Norwegian University of Science and Technology)).

Methods

Geophysical investigations

Resistivity and induced polarisation (IP) measurements

In this study, two-dimensional (2D) resistivity measurements were carried out, based on the Lund-system developed by Dahlin (1993). Four active cables were used with the Wenner electrode array (Reynolds 1997). The measuring equipment was an ABEM Terrameter SAS 4000 (ABEM 1999), using a current of 200 mA. The steel electrode separations were 2, 5 and 10 m (Dalsegg et al. 2006). It should be noted that there is always a trade-off between depth penetration and resolution. With 10 m electrode spacing it is possible to get information from the surface and down to ~130 m depth, however, with relatively poor resolution. To get better resolution, 2 m electrode spacing was used for some profiles, which limits the penetration to ~25 m. A compromise was used for some of the last measured profiles, with 5 m between the electrodes. Here the resolution is moderate and the penetration is ~60 m. Thirteen resistivity profiles were measured in Buvika, with the profiles 2-9 constituting a fence diagram (Fig. 4, Table 1). Profile lines with multiple labels indicate repeat profiles with different electrode spacings.

Table 1. Resistivity profiles measured in Buvika with Wenner electrode configuration (based on Dalsegg et al. 2006).

Profile No.	Profile length (m)	Electrode spacing (m)	Approximately penetration depth (m)	Relative resolution	Induced Polarisation (IP) measured
1a	400	2	25	High	x
1b	400	10	130	Low	x
2a	1000	10	130	Low	x
2b	1000	2	25	High	x
3	440	2	25	High	-
4	1000	10	130	Low	x
5	1080	5	60	Moderate	-
6	900	5	60	Moderate	-
7	700	5	60	Moderate	-
8	1100	5	60	Moderate	-
9	1500	5	60	Moderate	-
10	600	5	60	Moderate	-
11	500	5	60	Moderate	-

The Wenner electrode array (Wenner-α) was chosen for this project because it is well suited for a layered subsurface (Reynolds 1997). The method gives a poorer resolution than some other arrays, but it has a higher signal-to-noise ratio. Other electrode arrays like Dipole-Dipole and Schlumberger will possibly give better lateral resolution, but these methods are more time consuming and can produce more noise in the results (Dahlin and Zhou 2004).

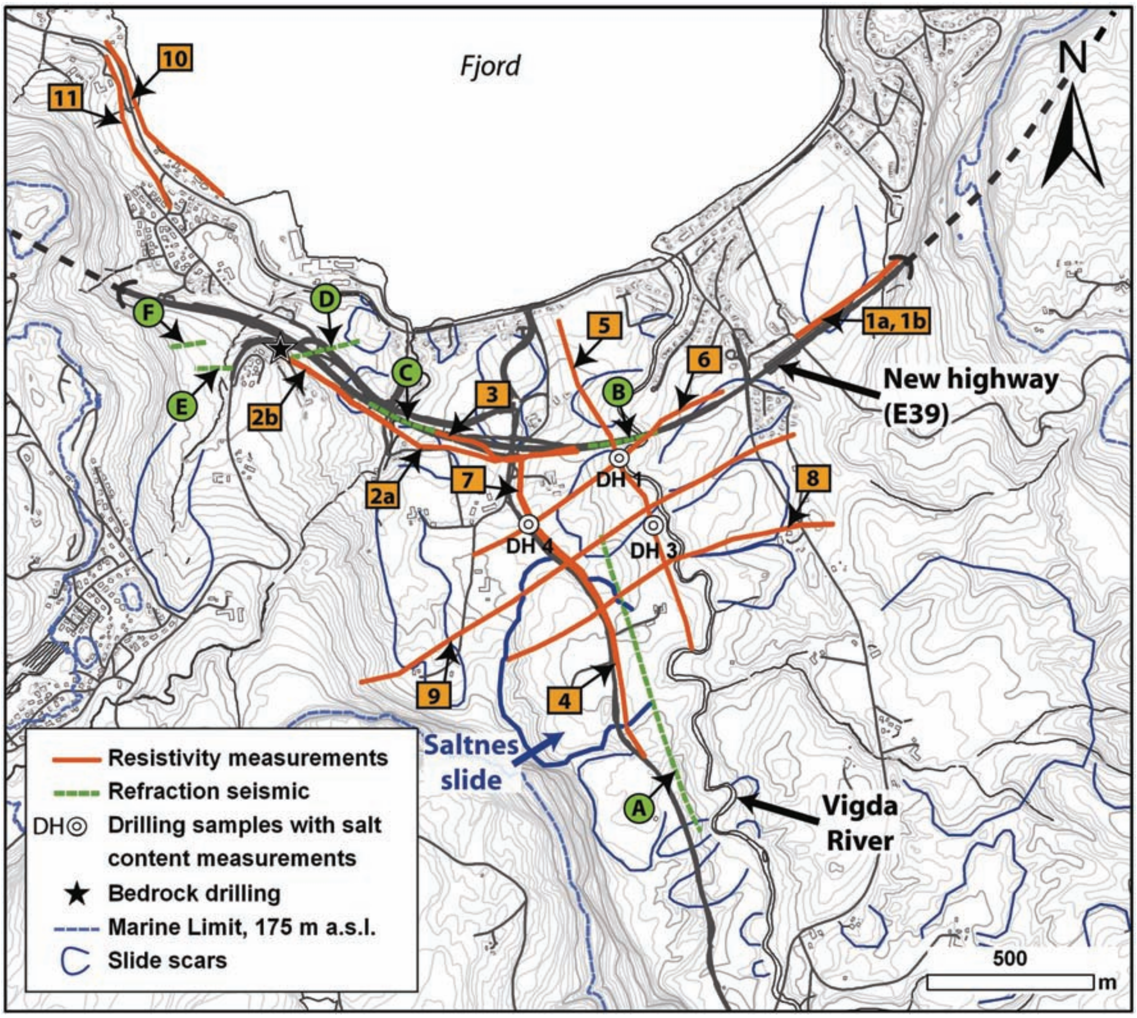

Fig. 4. Geophysical measurements in Buvika. The locations of three geotechnical sample locations connected to salt content measurements, and one bedrock-drilling location are also shown (contour lines: 5 m).

Raw data from the resistivity measurements gives the apparent resistivity of the subsurface. This represents a weighed mean of all the resistivity values that fall within the influenced soil volume. To get the specific resistivity in Ωm from different parts of the subsurface forming a physical model, the data are inverted. The purpose is to produce an apparent resistivity pseudosection that matches the measured data. Recorded resistivity and induced polarisation (IP) in this project were inverted by the computer program Res2DInv, using the least-square method (Loke 2004). The inversion was executed with a vertical to horizontal flatness filter ratio 0.5, which emphasises horizontal structures in the subsurface (Dalsegg et al. 2006). The profiles are inverted separately, and the fence diagram shows a quasi-3D characterisation of the subsurface in the central part of the valley (Profiles 2-9) (Figs. 4, 5). The profiles are displayed in ArcScene for comparison, and the scaling of the different profiles is equally set. Profile 1 (a and b) lies east in Buvika, along the alignment for the new highway E39. Profiles 10 and 11 are located in the western part of the valley, close to the shoreline. The main focus in this study will be on the profiles 2-9.

Existing research suggests the following classification of resistivity values for sediment types encountered in this study (Berger 1980, 1983; Calvert and Hyde 2002; and Rankka et al. 2004). The classification is tested in this study by comparison of resistivity values and geotechnical properties.

- *Resistivity 1-10 Ωm – unleached marine clay:* The clay has been exposed to little leaching since deposition. The pores in the clay still contain salt water, in which ions continue to maintain the electrical forces between the clay particles. Because of the large concentration of ions in the pore water, the conductivity of the clay is good, and thus the resistivity values are low. Blue-toned colours on the resistivity profile mark the unleached marine clay.
- *Resistivity 10-80 Ωm – possible quick clay:* Sensitive clay develops as groundwater leaches ions from the marine clay. When the total electrolyte content is less than 5 g/l, the content of K (potassium) and polyvalent cations are low, and with a high amount of Na (sodium), the repulsive forces increase (Rosenqvist 1953; Hilmo 1989; Andersson-Sköld et al. 2005). The structure is then labile, and very sensitive to mechanical influence. This is the quick clay stage in the marine clay. The electrical conductivity of the deposit is still good, but not as good as for the unleached marine clay. The resistivity values should therefore be a bit higher for quick clay than for unleached clay. Still, other sediment features can give resistivity values similar to those of quick clay: With further leaching of the quick clay, more stabilising ions (Mg, Ca) will dominate

the pore water. This strengthens the bindings between the clay particles, but the concentration of ions is still low (Hilmo 1989). In that case, the resistivity values may be the same as for quick clay, although the deposit is not sensitive anymore. In addition, silt and fine-grained till can have resistivity values in the same range as quick clay (Berger 1980). This means that between 10 and 80 Ωm the material is not *necessarily*, but *possibly* quick clay. The possible quick clay is marked by greenish to yellowish colours on the resistivity profile.

- *Resistivity above 80 Ωm – coarser material and bedrock:* Dry crust clay, deposits from clay slides, and coarser materials like sand and gravel will have higher resistivity values than marine clay (Berger 1980, 1983). However, compared to most bedrock types, the values are low. Resistivity values for bedrock can be several thousands Ωm (Telford et al. 1990). The transition into bedrock resistivity values appears gradual, and it is sometimes difficult to separate sand and gravel from bedrock. On the resistivity profile yellow to orange marks dry crust clay; orange, red and sometimes purple characterise sand and gravel. Purple colour may also represent high-resistivity bedrock on the profile.

Induced polarisation (IP) is the capacitance effect, or chargeability, exhibited by electrically conductive materials. A current is applied to the ground and switched off a few seconds later. If polarisable materials are present, there will be a residual voltage (an overvoltage) that decays with time. The decay rate of the discharge is registered and given in milliseconds (Reynolds 1997). It has been reported that a moderate salt content in interaction with clay minerals can give maximum IP effect (Dahlin et al. 2001). IP is also a well-known method for identifying disseminated sulphides in prospecting of ore. Since IP is measured with the same electrode spreads as the resistivity measurements, the method was tested in five profiles in Buvika (Table 1) (Dalsegg et al. 2006).

Refraction seismic

The seismic refraction method records the travel time of refracted seismic waves in the subsurface. Velocities of materials vary from 200 m/s (loose sand) to more than 7000 m/s (crystalline rock) (Telford et al. 1990). Clay generally has higher velocity than sand.

Different layers in the subsurface can only be distinguished when the velocity of the layers increases with depth. Even if this condition is met, a layer can be hidden if it is too thin (blind zone) (Reynolds 1997).

Refraction seismic profiles were carried out in the planning phase of the new highway E39 as well as for other construction work in Buvika (Fig. 4) (Hillestad 1963; Rye and Lefstad 1987; Pedersen 2003). In addition, the Geological Survey of Norway (NGU) carried out a 1 km long seismic line in connection with this study (Profile A on Fig. 4) (Dalsegg et al. 2006). The 24 channel digital seismograph ABEM Terraloc MK6 was used, and three arrays along the profile were measured. Dynamite was used as energising source. For further description of the measurement, see Dalsegg et al. (2006). In this study, the seismic profiles were mainly used to outline the location of the bedrock surface covered by sediments.

Geotechnical investigations

Field tests

Geotechnical investigations were carried out during the planning phase of the new highway through Buvika, especially in the central part of the valley. There are more than 700 drilling locations in the area (Fig. 3).

The geotechnical information was collected from numerous reports, produced by different companies: Statens Vegvesen (the Norwegian Public Roads Administration), Rambøll Norge, NGI (the Norwegian Geotechnical Institute) and NTNU (the Norwegian University of Science and Technology). The main types of investigation are listed and briefly described in Table 2. The drilling profiles can give information about soil type, layering and sensitivity of the materials. The sensitivity, indicating presence of quick clay, can be evaluated from the slope of the penetration resistance curve, where the resistance remains constant over a distance or even drops with a negative slope by depth. This is explained by the collapsible nature of the quick clay, along with an almost negligible component of added rod friction in the quick-clay zone.

Table 2. The main geotechnical investigation types used in Buvika, with short method description and information type (based on Sandven 2002).

Investigation type	Description	Information type
Cone Penetration Test Undrained (CPTU)	The rod system with a probe is continuously pushed into the subsurface, and values of cone resistance, friction and pore pressure are registered continuously.	Sediment stratification, soil type indication, mechanical soil parameters.
Rotary Pressure Sounding	The rod system with a purpose-made tip is forced into the subsurface with both rotation and static downward pressure. The rotation and penetration rate is constant.	Indicated sediment stratification, occasionally soil type and depth to bedrock (not verified).
Total Sounding	Sediment stratification, shear strength, deformation properties, index properties, permeability.	Indicated sediment stratification, occasionally soil type and verified depth to bedrock.
Core sampling	Generally a ϕ54 mm piston sampler is used to give undisturbed samples in clays for subsequent laboratory testing.	Sediment stratification, shear strength, deformation properties, index properties, permeability.

Laboratory tests

The most reliable information on sensitive material is obtained when clay from geotechnical core samples is tested in a laboratory. When the remoulded shear strength (s_r) is less than 0.5 kN/m^2 the clay is characterised as quick, and for classification of sensitive clay, the following definitions are used (NGF 1975):

$$S_t = \frac{s_u}{s_r} = \frac{undrained \quad undisturbed \quad shear \quad strength}{remoulded \quad shear \quad strength}$$

Low sensitivity: $S_t < 8$
Medium high sensitivity: $8 < S_t < 30$
High sensitivity: $S_t > 30$

The natural salt content in seawater is generally 35 g/l. When clay with salt pore water is leached by fresh groundwater due to isostatic rebound with the former seabed becoming dry land, the salt content in the pore water is reduced. Marine clay with the salt content in the pore water reduced below 5 g/l, can become sensitive and show quick-clay behaviour (Bjerrum 1954). It is not common to measure pore-water salt content in geotechnical index tests on clay samples. However, in the Buvika clay the salt content was measured on samples from three drilling locations (Fig. 4) (Helle 2004). The pore water in the samples was first squeezed out by the use of air pressure. Thereafter, a *Radiometer Copenhagen CMD 2e* instrument was used to determine the electrical conductivity of the pore water, from which the salt content was found from calibration charts. The calibration charts are established from conductivity measurements on samples with exactly known salt content. For further description of the method, see Sandven and Svaan (1993).

Results and discussion

Quick clay extent

There are some general factors of the subsurface that are known as favourable conditions for formation of quick clay: near the bedrock, near the surface, in areas with large groundwater flux (e.g. in slopes, excess or artesian pore pressure conditions), and in deposits where the clay is interfingered with silt, sand and gravel layers (Janbu et al. 1993). All these conditions give good influx of water to the generally impermeable clay. The study of the intersecting resistivity profiles in a fence diagram (Fig. 5), along with geotechnical drilling profiles, supports these general statements, as shown later.

Occasionally the resistivity profiles indicate quick clay, while geotechnical results show low sensitivity. As mentioned in the introduction, clay with resistivity values between 10 and 80 Ωm, which has been exposed to further leaching, still has low electrolyte content, but it is not necessarily quick anymore. The resistivity method can hence only indicate quick clay and not verify it.

Central area

The interpretation of resistivity profile 3 (Fig. 6) is relatively clear: a 2-3 m thick surface layer of dry crust clay (orange) and a pocket of unleached clay (blue) in quick clay (green) underneath. The high-resistive material in the surface layer (red/purple) is a road fill of stones and boulders. The interpretation of the geotechnical drillings is

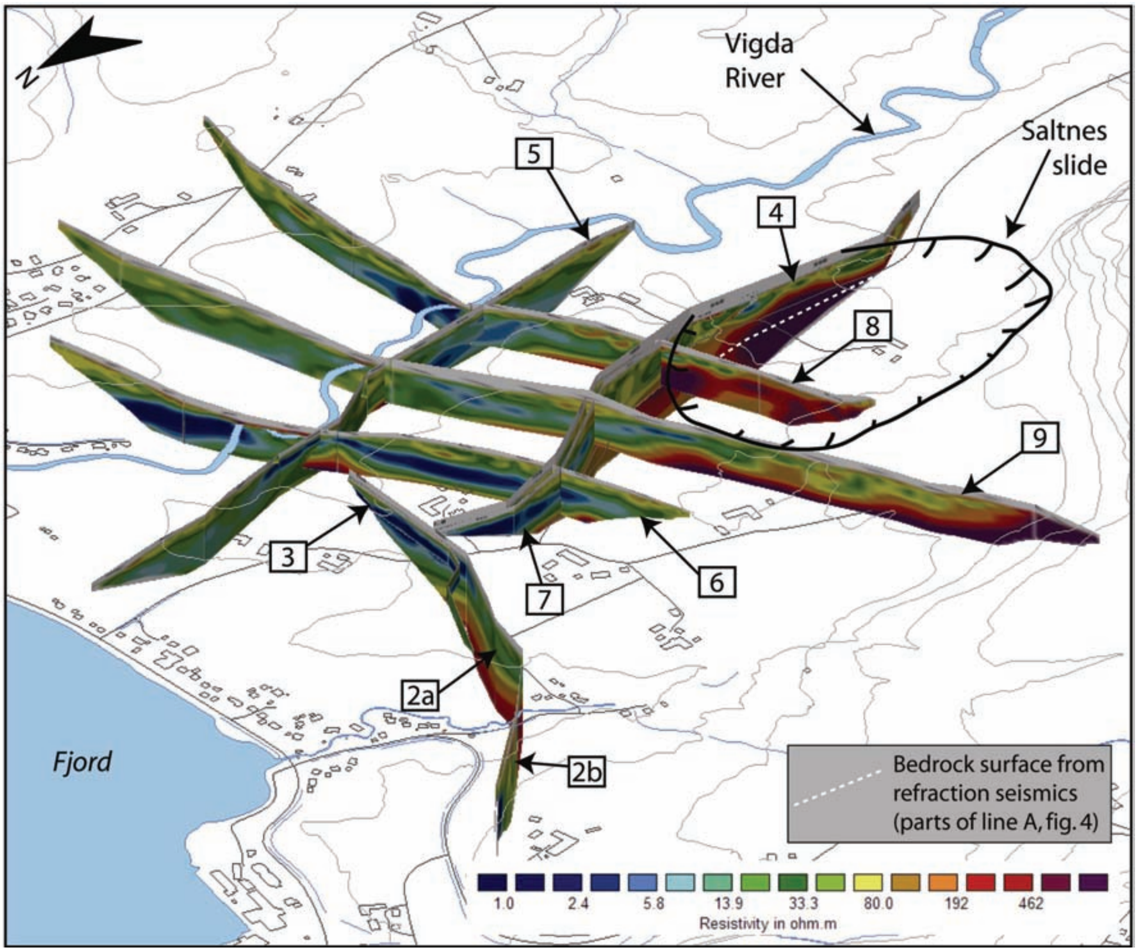

Fig. 5. Fence diagram of resistivity profiles 2-9. The white dashed line indicates bedrock interpreted from refraction seismic measurements (contour lines: 25 m) (data from Dalsegg et al. 2006).

similar (Fig. 6B). In the eastern part of the profile, the increased penetration resistance in the drilling profiles corresponds to the pocket of unleached (non-quick clay) in the resistivity profile. In the western part, where the resistivity values indicate quick clay (10-80 Ωm), the drilling resistance is generally low or decreasing by depth, which indicates sensitive material as previously stated. Similar comparisons have been made for all the resistivity profiles, even though the amount of geotechnical drillings near the resistivity profile lines varies.

Together with the geotechnical data, resistivity profile 3 seems to give a good picture of the material properties of the subsurface. In order to verify the interpretation, only 3-4 geotechnical drillings/samplings would have been necessary along the profile, suggesting that a significant amount of drilling could have been avoided in this case.

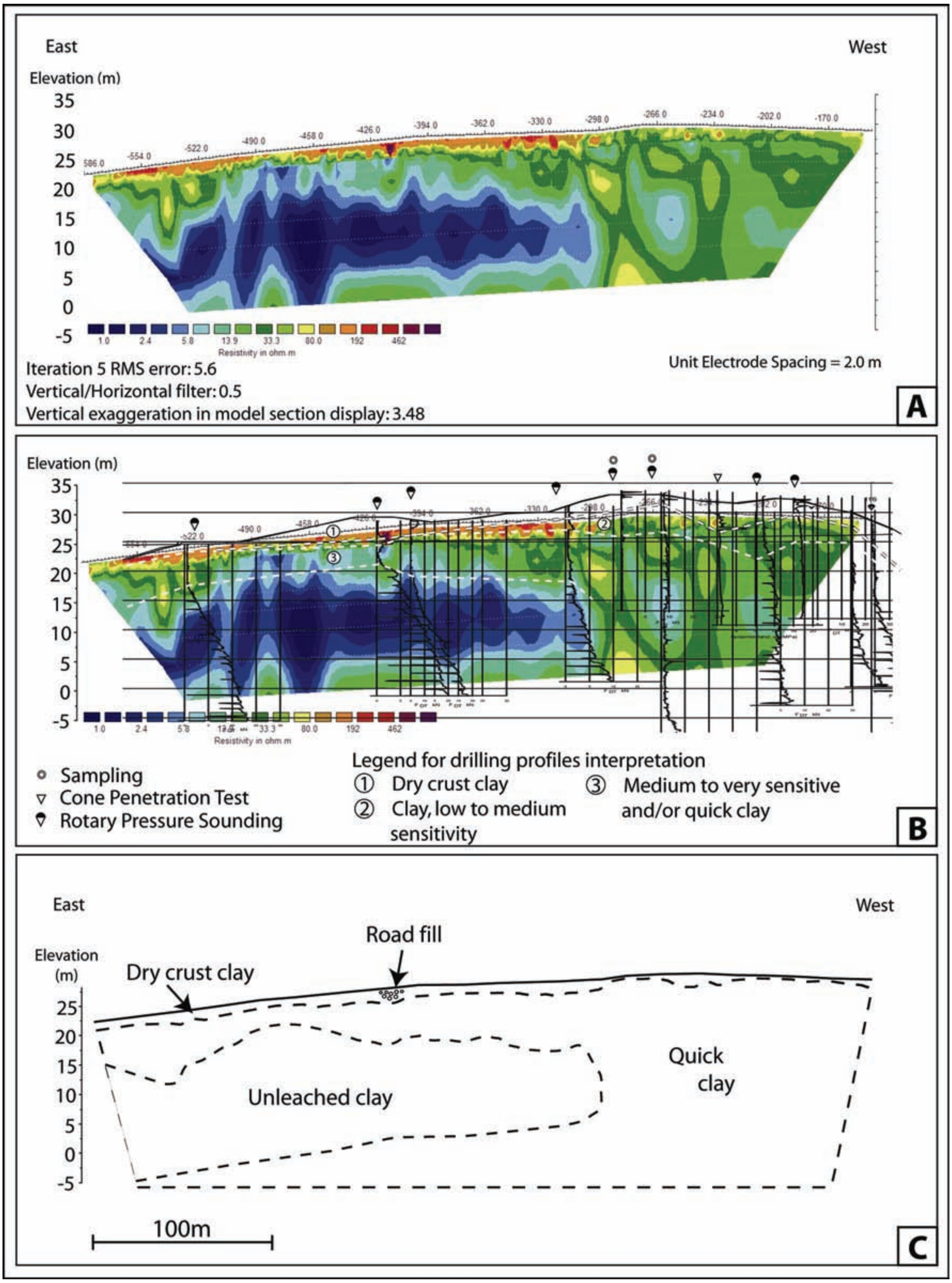

Fig. 6. Resistivity profile 3 (see Fig. 4 for location) **(A)**, with geotechnical drilling profiles (drillings were carried out before surface sediment removal) **(B)**, and interpretation **(C)**. (Data from Berg and Hove 2001*a*; Engen and Jensen 2003; Dalsegg et al. 2006).

This also applies for the other resistivity profiles, in spite of their varying quality. However, the amount of ground investigations required will vary between different types of projects and soil conditions.

East of Vigda River

East of Vigda River, the resistivity profiles show mainly leached clay (10-80 Ωm) in slopes above the river level (Figs. 5, 7). The geotechnical drillings in the vicinity of the profiles show mostly alternating zones of non-sensitive clay or quick clay, partly interbedded with silt, sand and gravel, particularly in the southern part (Berg and Hove 2000; Lefstad 2002; Lefstad and Eggereide 2002a, 2002b; Helle 2004). Such layers may have accelerated the formation of quick-clay zones, since they increase the freshwater supply to the deposit. However, the resolution in the resistivity profiles is lower than the thickness of the coarse layers, which makes these impossible to identify. In this respect, some of the geotechnical test methods such as the CPTU, give a more comprehensive and detailed overview of the stratigraphy and the soil conditions.

Western area

In the western part of central Buvika, the resistivity values are above 80 Ωm in the deeper sections of the profiles (4, 8 and 9, Fig. 5). According to the classification of resistivity values, this is possibly coarse material such as sand and/or gravel overlying the bedrock. This can also be confirmed by using an extended resistivity scale to visualise the inverted data, e.g. that the scale is 1-5000 instead of 1-500. A refraction seismic profile in this area shows that the depth to bedrock is 50-70 m (Fig. 5) (Dalsegg et al. 2006). No coarse material has been detected between the clay and the bedrock on the seismic profile, but this layer may be hidden due to velocity inversion or a blind zone. The western part of resistivity profile 8 crosses the large slide scar from the Saltnes slide, involving a clay area of almost 200 000 m^2 (Solberg et al. in press) (Figs. 2, 4, 5, 7). The morphology and the size of the scar clearly suggest that quick clay was involved in the slide, since it has the characteristically “bottle-neck” shape of a slide scar in quick clay (e.g. Bjerrum 1955). The morphology further suggests that a lot of sensitive material was removed during sliding. The resistivity values in the back of the

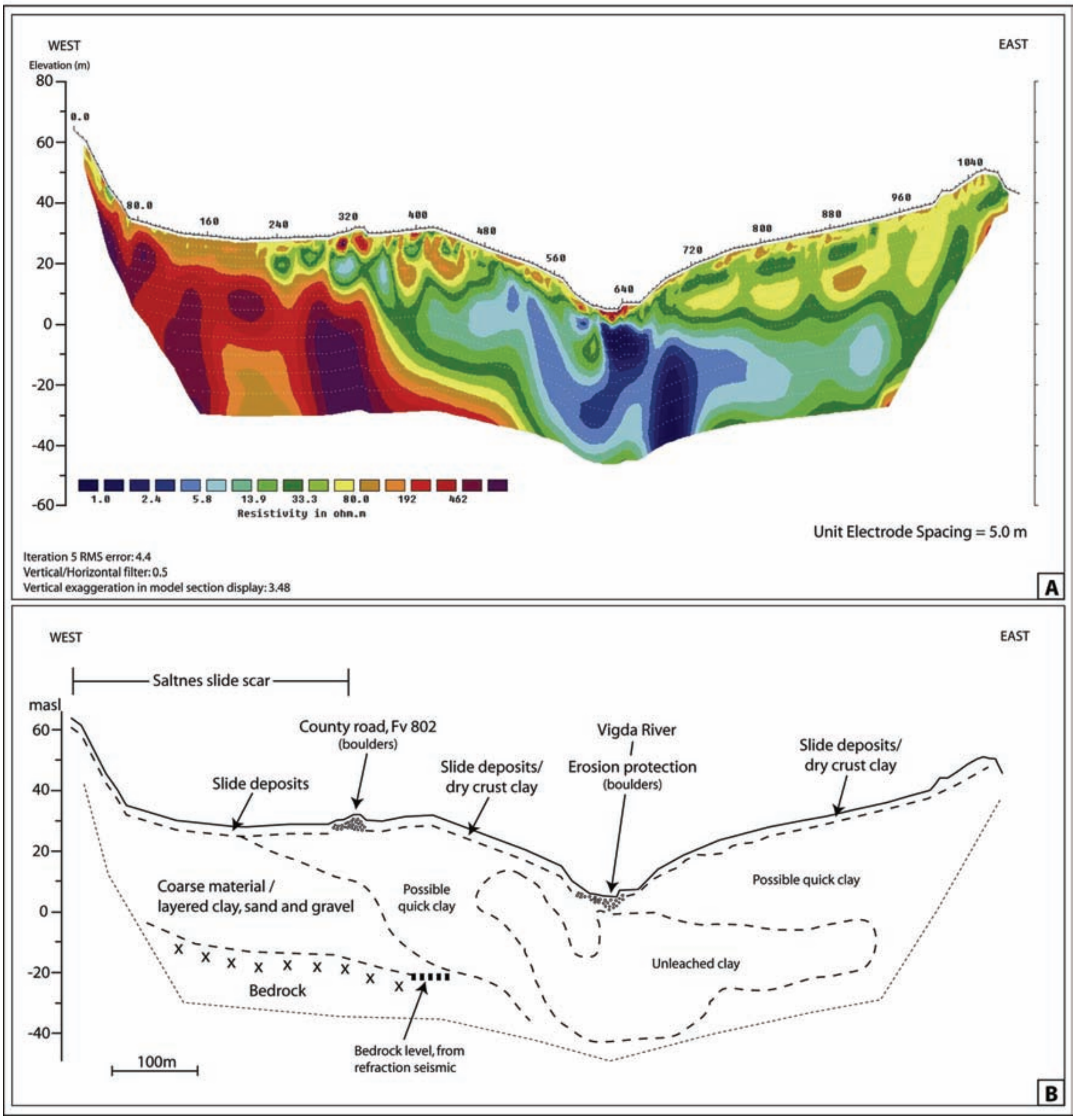

Fig. 7. (A) Resistivity profile 8 (see Fig. 4 for location). **(B)** Interpretation with regard to sediment types and sensitivity based on resistivity measurements and refraction seismic investigations (data from Dalsegg et al. 2006).

present slide scar are relatively high, showing the presence of more stable material like crusted clay (Figs. 5, 7A). Water from the steep rock face west and south of the scar was possibly stored in the coarse deposit (Fig. 7B), generating a local artesian pressure, which likely accelerated the leaching and increased the pore pressure in the clay deposit prior to sliding. Today, an artesian spring still exists in the bottom of the slide scar. Carson (1981) discussed a similar situation in Quebec in Canada. Strong hydraulic gradients associated with high pore pressure accelerate leaching of salt, and might directly trigger mass movement.

Early attempts in Norway to measure resistivity in drilling holes showed that the leaching rate was highest close to the bedrock (Løken 1968). The presence of coarse material between fractured bedrock and clay often gives artesian conditions. From investigations in Sweden, conditions related to artesian water, undulating bedrock surface, underlying coarse material or high permeability layers in the clay are shown as preferable for the development of quick clay (Rankka et al. 2004; Andersson-Sköld et al. 2005).

Salt content and resistivity values

In most soil and rock types mineral grains insulate against electrical currents. The resistivity is controlled by the water content in pores or fissures, i.e. the amount of water, and the distribution and amount of dissolved ions. Since clay minerals to a certain degree are conductive, ions will bind to clay particles and reduce the resistivity value of the deposit (Dahlin 1993; Dahlin et al. 2001).

The three drilling locations where the salt content in the pore water was measured are located close to four of the resistivity profiles (Fig. 4). Figure 8 shows resistivity values in parts of profiles 5 and 6, compared to pore-water salt content, shear strength and sensitivity of laboratory samples and the in situ drilling resistance. There is generally good correlation between all the different methods with respect to the location and extent of quick-clay zones. Since resistivity values are connected to the electric conductivity and the material properties in the deposit, it is particularly interesting to observe that the salt content measured in the pore water from samples agrees well with the resistivity classification. In the potential quick-clay zones on the resistivity profiles (10-80 Ωm), the pore water salt content is below 5 g/l and the sensitivity is high, mainly due to the drop in remoulded shear strength s_r. Previous research (e.g. Rosenqvist 1953) shows that the undrained shear strength is only slightly influenced by the variations in salt content, whereas the remoulded shear strength is significantly influenced. The quick clay in its undisturbed state may not differ much in geotechnical properties compared to non-leached, intact clay.

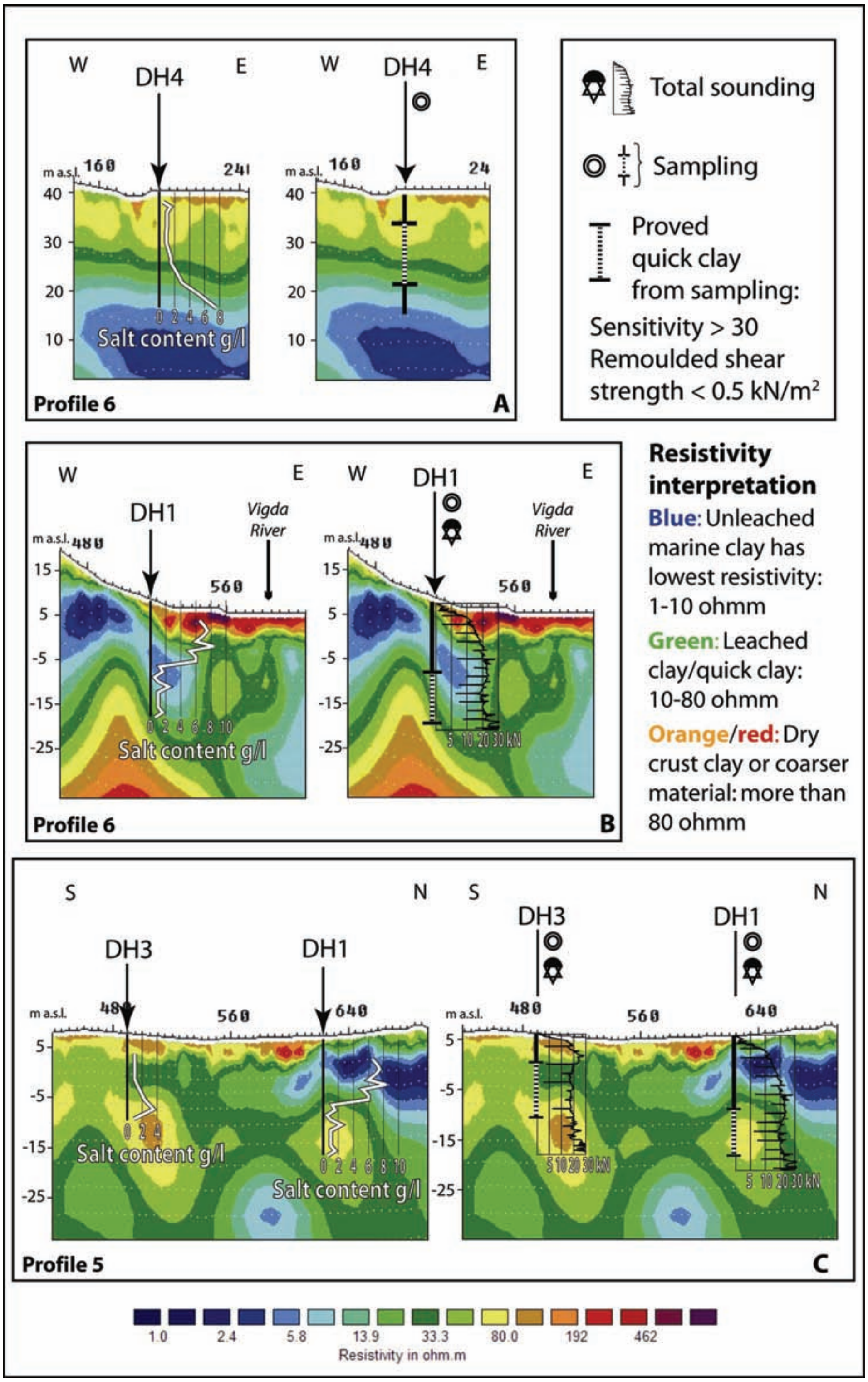

Fig. 8. Details on the resistivity profiles 5 and 6, total sounding, tested samples and pore water salt content (white curve) in drill holes DH1, DH3 and DH4. For drilling locations, see Fig. 4 (data from Helle 2004; Dalsegg et al. 2006).

A Swedish case study on chemical aspects of quick clay showed that the electrical conductivity increases with the summation of the cation concentrations, which is also related to the sensitivity (Andersson-Sköld et al. 2005). When the electrical conductivity is converted to resistivity values, there is hence agreement between the Swedish results and the results observed in Buvika.

Indications of a buried coarse-grained ridge

Indications of a "ridge" of coarser material, or frequent layers of coarse material are given in the lower section of resistivity profile 6 (Figs. 5, 8). None of the geotechnical drilling profiles nearby reach this depth (ca. 30 m below sea level), but significantly layered material (clay, silt, sand) is recorded right above the suggested coarse-grained deposit. In addition to layered material the drilling profiles show quick clay (Berg and Hove 2001*a*; Engen and Gregersen 2001; Engen and Tuft 2002; Engen and Jensen 2003; Helle 2004). This is in accordance with the resistivity values on profile 6. Refraction seismic investigations in this particular area show deep bedrock (down to 120 m below sea level) (Rye and Lefstad 1987; Pedersen 2003; Dalsegg et al. 2006). The seismic profiles indicate clay above bedrock, but coarse material may be hidden due to a lower seismic velocity. It is noteworthy that an intersecting resistivity profile does not indicate the presence of coarse-grained material (profile 5, Fig. 5). This is explained by the possible geometry of the deposit, as discussed later. An interpretation of the sediment distribution in central Buvika, based on drilling, seismic data and resistivity profiles is shown in Fig. 9 (profile A-A' on Fig. 3).

Barriers for quick-clay slides

In Buvika, the quick-clay zones are widespread, but unleached, non-sensitive clay also occurs as pockets and/or layers within the quick clay. The presence of thick strata of sand, gravel or non-sensitive clay may act as local subsurface barriers, and may limit the extent of a potential quick-clay slide. A barrier should however be large enough to remain stable, even if the support disappears during a hypothetical slide. Indications of thick coarse-grained deposits on bedrock, or the bedrock alone, will help to classify areas as relatively stable. Resistivity measurements may potentially be used as a tool for

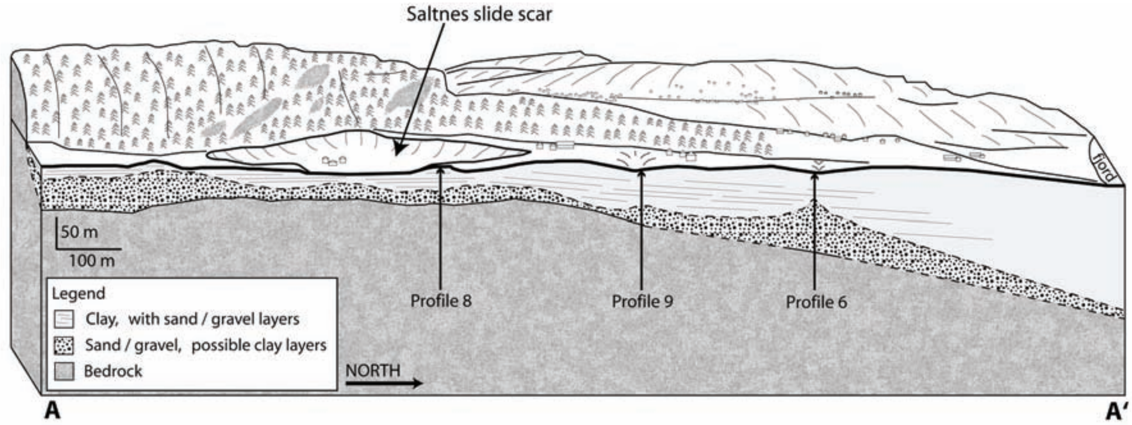

Fig. 9. Indication of sediment distribution upon bedrock. Based on data from refraction seismic profiles, geotechnical drilling profiles and resistivity profiles (see location of profile A-A' on Fig. 3). Most of the clay is leached, and therefore possibly quick.

evaluation of such barriers. Solbrække (2005) evaluated the presence of such barriers in Buvika, mainly based on geotechnical drillings. He concluded that more subsurface surveys should be carried out to discover and evaluate possible barriers for slides in the studied area.

In this study, barriers are exemplified by the coarse deposit indicated below the Saltnes slide scar in resistivity profile 8, suggesting that a large quick-clay slide will probably not occur in this particular area in the future (Figs. 5, 9).

Groundwater drainage pattern

The groundwater drainage pattern is controlled by the bedrock surface, the topography and the distribution of different sediment types. Resistivity profiles perpendicular to Vigda River (6, 8 and 9, Fig. 5) generally show leached clay in the slopes and down to the river level. Beneath this level, the resistivity values vary in the different profiles. East of the river, stratified material increases groundwater drainage towards the river and the sea. The coarse material interfingering the clay most likely correlate with an ice-margin delta in the neighbouring valley to the southeast (Holtedahl 1929; Nemec et al. 1999; Solberg et al. in prep). Some of these layers probably pinch into the clay in a north-westerly direction, which may have caused increased pore pressure in the area. A lot of slide scars and ravines in this part of Buvika are likely connected to this stratigraphy (Solberg et al. 2007; Solberg et al. in prep).

West of the river, drilling data indicate layered material in the vicinity of the coarse deposit interpreted from the resistivity profiles 4, 8 and 9 (Fig. 5). Water from the steep rock face to the west is transported on the terrain surface and through the sediments towards the river and the sea. Increased leaching of clay is shown by higher resistivity values in a vertical pocket right under the river level (profile 6, Fig. 8B). This is explained by upward-directed merging flow of groundwater near the river (Price 1996). Several of the geotechnical reports state that an artesian excess pressure exists in the bottom of the valley (e.g. Berg and Hove 2001*a*, 2001*b*). Increased resistivity in clay below the river is also apparent in profile 5 and 9 (Fig. 5). Profile 8, on the other hand, shows a relatively large unleached clay pocket beneath the river level, and only a small pocket with slightly higher resistivity (Fig. 7A). One possible reason is that depth to buried coarse material below clay is larger, or that such material is even absent at this location.

Together these examples suggest that varying groundwater conditions may exist along a river, and that groundwater drainage may preferentially take place along certain pathways. These examples also show that the resistivity method may be helpful in pointing out areas with increased upward flow of groundwater, e.g. at locations with a buried aquifer or several sand layers.

Differentiation between conductive bedrock and unleached clay

Usually the seismic data and the geotechnical investigations agree with the resistivity data with regard to depth to bedrock, although the bedrock surface is often displayed as a gradual transition in the latter. However, an exception to agreement between resistivity values and other surveys is seen on profile 2 (a and b) (Figs. 5, 10). Both drillings and seismic profiles show a sediment cover of 10-20 m (Rye and Lefstad 1987; Berg and Hove 2001*a*; Pedersen 2003). The resistivity profile, on the other hand, show very conductive material below this depth, with the same resistivity values as for unleached marine sediments (Fig. 10). Induced polarisation (IP) was measured here, and shows chargeable material in parts of the subsurface. A 20 m deep bedrock core drilling was carried out in order to verify this (location shown by an asterisk in Fig. 4) (Dalsegg et al. 2006). Numerous graphitic layers were encountered in a metamorphic phyllite rock, where graphite is a very conducive and chargeable mineral. Even though IP is only occasionally measured in sediment investigations, it can be useful to carry it out more frequently to separate between conductive rock and salty, unleached clay.

The exact position of a buried bedrock surface is sometimes difficult to outline from resistivity profiles parallel to steeply dipping geological contacts, such as buried bedrock along steep valley sides. Profiles perpendicular to these structures will potentially give more accurate information but a combination of intersecting profiles is optimal as discussed in the following section. Interference from irregular bedrock surfaces is often avoided in the central part of a valley where the depth to bedrock may be very large.

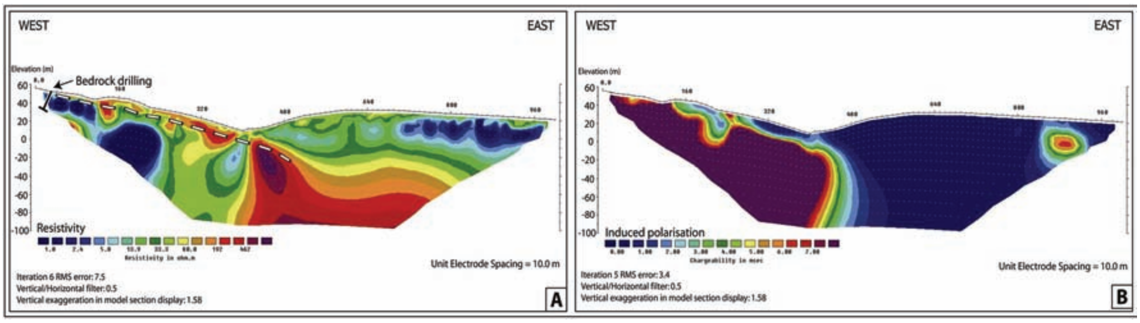

Fig. 10. Resistivity **(A)** and induced polarisation **(B)** in profile 2a. Dashed line indicates bedrock interpreted from other investigations. Bedrock drilling location is marked by an asterisk on Fig. 4 (modified from Dalsegg et al. 2006).

It is difficult to visualise both detailed and contrasting clay properties at the same time as showing true values of bedrock in one resistivity profile. The reason is that a large difference in resistivity values usually exists between sediments and bedrock. The resistivity scale chosen to visualise inverted data should therefore be adjusted to the purpose of the project.

Variations in intersecting resistivity profiles – degree of conformity

The conformity in the intersection of the different profiles in the fence diagram is generally good (Figs. 5, 11A), with some exceptions.

One type of disagreement is that geophysical layers with similar resistivity values have different thickness in the profiles, even though the number of geophysical layers is the same (Fig. 11B). This type of disagreement most often occurs in the deepest part of the profiles. The profiles may contain the same resistivity values, but at varying depth intervals. A possible reason is that the resolution varies in different profiles due to dissimilar electrode spacing (Table 1). When data are inverted, the subsurface is separated into blocks, and the thickness of the first layer of blocks is set at 0.5 times the electrode spacing. The thickness of each subsequent layer is normally increased by 10%. This means that the resolution in the profile is better if the electrode spacing is small, and in the upper part of the profiles. In addition, the lower part of the profiles undergoes a more unrestrained inversion due to lack of data. In order to retrieve valuable information from a certain depth, it is therefore important to measure deeper.

Another type of disagreement is when the crossing profiles show completely different resistivity values at the same depth (Fig. 11C). One explanation for the deviation is likely that the profiles are perpendicular to each other, and describe a subsurface phenomenon whose extent or shape varies in different directions. Measured potential values are influenced from a width of the subsurface as the current spreads out laterally. This means that the resulting resistivity values describe an average from a relatively large volume. The extent of a good or poor conductor may therefore seem to vary on profiles in different directions, depending on its geometry.

An example of this is a possible ridge of coarse-grained material (or layered sediments) in profile 6, as discussed earlier (Figs. 5, 8B). A buried ridge parallel to profile 6 is possibly large enough to influence the measurements, giving rise to the increased values on this profile. In profile 5, which is perpendicular to both profile 6 and the suggested ridge, this feature has however not affected the resistivity values. In profile 5 the resistivity values remains low, and the highly conductive clay probably predominate over the influence of the coarse material. A similar situation seems to occur in the intersection of profiles 9 and 5.

These examples suggest that crossing resistivity profiles may give valuable information about the subsurface even when resistivity values do not match.

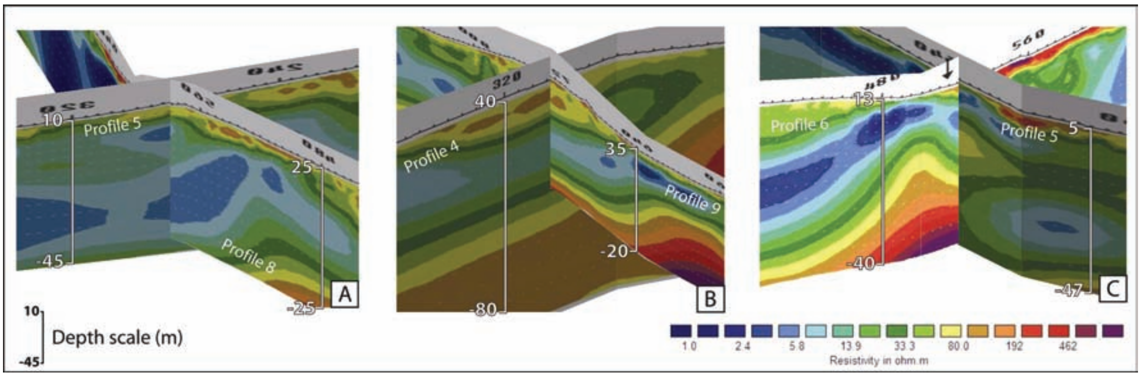

Fig. 11. Intersecting resistivity profiles with good conformity **(A)** and with disagreements **(B** and **C)**.

Conclusions

The study shows that the resistivity method is useful for detecting sections of possible quick clay in the subsurface. A classification of possible quick clay corresponds to a range of resistivity values between approximately 10 and 80 Ωm, which complies with results from Canadian and Swedish investigations (e.g. Calvert and Hyde 2002; Leroux and Dahlin 2003). The classification given in the introduction is demonstrated to be applicable to the data from Buvika. The use of resistivity measurements as a tool for outlining geotechnical properties of clay thus is strengthened by this study. Focus is also set on other areas for application of the resistivity method, related to formation of quick-clay deposits. However, the method cannot verify presence of quick clay since both leached, non-quick clay and silty, non-sensitive material can give resistivity values of the same range (10-80 Ωm). Still, the indications are important in selecting areas for further investigations and for refining the interpretation of the subsurface.

The resistivity results give an outline of a large area within a relatively short time compared to geotechnical investigations. In an area without previous investigations the resistivity method will give an overview that constitutes a basis for further exploration and determine optimal locations for geotechnical drillings and ground truthing. The present study indicates that as much as one half of the drilling points along the new road could have been avoided if resistivity measurements had been carried out prior to the geotechnical drillings. Further studies are however necessary for a more exact estimate of the possible cost savings related to the combination of resistivity measurements and geotechnical investigations. The resistivity measurements give a continuous and relatively detailed picture of the subsurface, but are a supplement, and not a substitute for other surveys, such as geotechnical investigations.

Groundwater drainage patterns may be interpreted from the resistivity profiles since increased groundwater drainage can be associated with leaching and subsequent formation of quick clay. Increased groundwater drainage may be explained by steep surface gradients and/or the presence of coarser-grained layers or bedrock. Pore-water salinity measurements reflecting the degree of leaching showed a generally good agreement with the resistivity values.

Because of the large difference between resistivity values, the boundary between sediments and bedrock appears gradual. It can hence be difficult to estimate the exact depth to bedrock. In addition, conductive mineral types like graphite can give the same resistivity values as marine clay. Induced polarisation measurements can in such cases be used to differentiate between bedrock and sediments.

Large disagreements between intersection profiles occasionally occur. This is mainly related to different electrode spacing in the profiles, or it reflects geological variations in 3D.

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ENCLOSURES

ENCLOSURE 1: ASTRACTS PUBLISHED DURING THE PHD STUDY

1. Solberg, I.L., Dalsegg, E., Hansen, L., Rønning, J.S. & Rokoengen, K. 2004: Resistivity profiling as a tool for outlining the extent of quick-clay pockets near Trondheim, Norway. The 32nd International Geological Congress (32IGC) 2004, in Florence, Italy.

2. Solberg, I.L., Hansen, L. & Derron, M.H. 2006: Long-term erosion of a Norwegian fjord-valley dominated by marine deposits. The 4th ESF SEDIFLUX Science Meeting, 29.10-2.11.2006, in Trondheim, Norway. NGF Abstracts and Proceedings 4, 64.

3. Solberg, I.L., Rokoengen, K. & Hansen, L. 2007: Dalinnfyllingshistorie, landskapsutvikling og stabilitet til marine avsetninger; eksempel fra Midt-Norge. (Valley in-fill history, landscape development and stability of fjord-valley sediments; example from Mid Norway). The 20th Winter Meeting January 8-10 2007, in Stavanger, Norway. NGF Abstracts and Proceedings 1, 93.

4. Solberg, I.L., Rønning, J.S., Dalsegg, E., Hansen, L., Rokoengen, K. & Sandven, R. 2007: Bruk av resistivitetsmålinger i kvikkleirekartlegging, eksempel fra Buvika, Midt-Norge (Resistivity profiling as a tool for outlining the extent of quick-clay, example from Buvika, Mid Norway). The 20th Winter Meeting January 8-10 2007, in Stavanger, Norway. NGF Abstracts and Proceedings 1, 92.

1. Poster presentation at The 32nd International Geological Congress (32IGC) 2004, Florence, Italy

Resistivity profiling as a tool for outlining the extent of quick-clay pockets near Trondheim, Norway

Solberg, I.L.[1], Dalsegg, E.[2], Hansen, L.[2], Rønning, J.S.[2] & Rokoengen, K.[1]

1) Institutt for geologi og bergteknikk, NTNU, Sem Sælands veg 1, 7491 Trondheim

2) Norges Geologiske Undersøkelse, 7491 Trondheim

Thick, marine clay deposits in valleys along the Norwegian coast are occasionally subjected to large landslides involving quick-clay. The clay was deposited in fjords following the last deglaciation and has been exposed above sea level due to glacioisostatic rebound. Subsequent leaching of salts from the clay by groundwater has resulted in the development of quick-clay. Detailed mapping of the extent of quick-clay is of general interest for planning and protection purposes, as the position of quick-clay within slopes has a major impact on the landslide risk. Ground conditions along a new section of a highway across a valley in Buvika, mid Norway, are characterized by thick occurrences of quick-clay, as shown from numerous geotechnical investigations. The stability of the area during and after road construction is, therefore, of major concern. Resistivity measurements have been carried out, in addition to geotechnical drilling, to help outline the form and extent of quick-clay pockets. The resistivity method is potentially well suited for this purpose since quick-clay has a slightly higher electric resistivity (15-80 ohmm) than unleached clay (1-10 ohmm) due to a higher salt content in the latter. The acquired resistivity profiles have been compared with drilling data and the resistivity method evaluated. Results show that the correlation is good between the drilling profiles and the resistivity profiles in the central part of the valley whereas data are more ambiguous near the valley sides. A reason for this is probably the influence of a steeply dipping bedrock surface at shallow depth along the sides of the valley.

Resistivity profiling as a tool for outlining the extent of quick-clay pockets near Trondheim, Norway

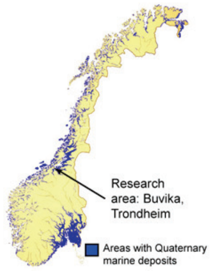
Solberg, I.L.[1], Dalsegg, E.[2], Hansen, L.[2], Rønning, J.S.[2] & Rokoengen, K[1]
1: Norwegian University of Science and Technology, 2: Geological Survey of Norway

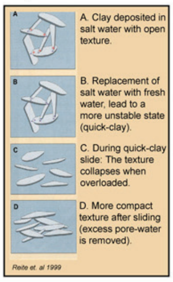
Thick, marine clay deposits in valleys along the Norwegian coast are occasionally subjected to large landslides involving quick-clay. Detailed mapping of the quick-clay extent is of general interest for planning and protection purposes, as the position of quick-clay within slopes has a major impact on the landslide risk. Resistivity measurements have been carried out, in addition to geotechnical drilling, to help outline the form and extent of quick-clay pockets. The resistivity method is potentially well suited for this purpose since quick-clay has a slightly higher electric resistivity (10-80 Ωm) than unleached clay (1-10 Ωm) due to a higher salt content in the latter.

Background

Clay that accumulated in fjords following the last deglaciation was later exposed above sea level during glacioisostatic rebound. Subsequent leaching of salt from the clay by groundwater has resulted in local development of quick-clay. When quick-clay is remoulded, it can lead to large landslides.

Ground conditions along a new section of a highway across the small valley Buvika, near Trondheim, are characterized by thick occurrences of quick-clay. This is shown from numerous geotechnical investigations. The stability of the area during and after road construction is, therefore, of major concern.

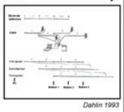




Methods

Resistivity measurements

Two-dimensional (2D) measurements were carried out, using the Wenner electrode array. Electrode seperations were 2, 5 and 10 m. The resistivity measurements were inverted by the computer program RES2DINV (Loke 2001).



Geotechnical drilling

Skanska Norway AS is constructing the new road. Numerous geotechnical investigations have been carried out, and the main drilling types are:

- Cone Penetration Test Undrained (CPTU)
- Rotary Pressure Sounding
- Total Sounding
- Sampling

The results are compared to the results from the resistivity measurements.

Interpretations of the resistivity profiles

Marine clay contains ions that will conduct electricity, while quick-clay contains less ions, leading to higher resistivity. The classification of resistivity values into unleached and quick clay is arbitrary and based upon experience. The threshold used may vary from site to site and can only be used as a guideline.

The resistivity profiles only outline the general distribution of the sediment in the ground. The data quality is poorer in the outer parts of the profile.

A possible classification:

Blue (1-10 Ωm): Unleached clay

Green (10-80 Ωm): Quick clay

Orange / red: Dry crust clay or coarser material (e.g. till, gravel)

Preliminary conclusions

The geotechnical drilling profiles and the resistivity profile fit best together in the middle of the valley, where the depth to bedrock is 60-110 m.

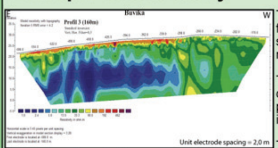
In the eastern part of the valley there is less conformity between the geotechnical drilling profiles and the resistivity profile. One reason for this may be the effect of quick-clay altering processes (strengthening of binding forces, see ex. 2).

The resistivity profiles seem to be usable for detection of sensitive clay, but there are some challenges in the method, e.g. the exact salt content compared to the resistivity values.

What next?

- Acquire extra resistivity profiles e.g. perpendicular to the existing profiles to get a better control on 3D.
- Carry out extra geotechnical drilling for comparison.
- Study of salt content and resistivity values.

Example 1: Mid-valley

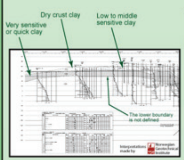


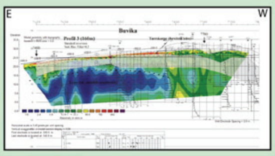
The depth to bedrock varies from 60 m to 110 m (from seismics). The sediments are mainly clay and silt.

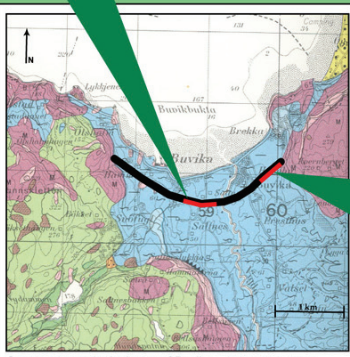
There is relatively good correlation between the drilling profile and the resistivity profile in this part of the valley.

The resistivity profile shows that the surface layer is dry crust clay. The green colour suggests the presence of quick-clay, under the crust. The layer is thicker in the western part of the profile. In the eastern part there is probably a pocket of unleached clay (blue).

The acquired resistivity profiles have been compared with geotechnical data (Skanska Norway AS), which correlates very well with the resistivity results. The drilling profiles show that there is a quick-clay layer above less sensitive clay in the eastern part. In the western part the layer of sensitive / quick clay is thicker.



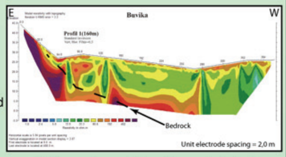




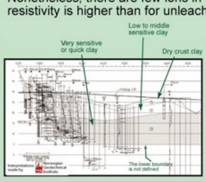
Quaternary geological map of Buvika
Black line: New E 39
Red lines: Resistivity measurements
Blue: marine deposits
Green: till (above marine limit)
Pink: bedrock

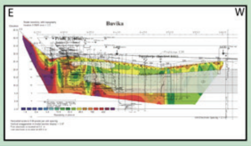
Example 2: Valley side

The depth to bedrock in the eastern side of the valley varies from 5 m to 40 m (drilling). The sediments are mainly clay and silt.



The resistivity in the eastern part of the profile is high, and represents till or bedrock. Resistivity values of 10 - 80 Ωm (green) suggest the presence of quick-clay beneath the dry crust clay (orange). This partly conflicts with geotechnical data showing that the upper 5-10 m of the clay has low sensitivity. Beneath there is quick-clay. A possible reason for this conflict, is that clay may pass the quick-clay stage. In that case the clay regains low sensitivity due to introduction of other ions, which strengthen the bonds between the grains. Nonetheless, there are few ions in the clay, which is the reason why the resistivity is higher than for unleached clay.





Presented at The 32nd International Geological Congress (32IGC), Italy, 2004

NTNU Norwegian University of Science and Technology · NGU Geological Survey of Norway · ICG International Centre for Geohazards · The Norwegian Water Resources and Energy Directorate

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2. Poster presentation at The 4th ESF SEDIFLUX Science Meeting, 29.10-2.11.2006, Trondheim, Norway

Long-term erosion of a Norwegian fjord-valley dominated by marine deposits

Inger-Lise Solberg[1], Louise Hansen[2] & Marc-Henri Derron[2]

[1]Department of Geology and Mineral Resources Engineering, NTNU, Norway

[2]Geological Survey of Norway

Several hundred metres thick glaciomarine and marine deposits accumulated in Norwegian fjords during and after the last major deglaciation. Some of these deposits were later exposed on land due to glacio-isostatically uplift during the Holocene period. Buvika, as an example, is a small fjord-valley in Mid Norway surrounded by 300 to 400 m high bedrock hills, today characterized by undulating terrain with numerous ravines and slide scars. In Buvika the highest sea level (marine limit) following the last glaciation was about 175 m above present sea level. This is reflected by high occurrences of glaciomarine and marine deposits, which dominate the valley fill. Some coarser-grained deposits like glaciofluvial sediments are also present. During early uplift, sediment input from glaciers decreased, and the fjord-valley was increasingly subjected to erosional processes.

This study describes various erosion processes like river erosion, groundwater-seepage erosion, and sliding activity that have taken place within Buvika, as part of an attempt better to understand the long-term erosional pattern and landscape development of areas with thick marine deposits. Calculations are made on the volume of sediments that have been removed by erosion from the valley following isolation from an upstream lake shortly after deglaciation. Part of the present landscape in Buvika is interpreted as a remnant of the old seabed. This interpretation is the basis for reconstruction of the entire seabed as illustrated by a number of profiles in different sections across the valley. Another source of information for the seabed reconstruction is the local sea level curve. The total amount of eroded sediment is calculated by summarizing the volumes of each valley section. Methods used will be presented, including a discussion of their uncertainties.

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1: Department of Geology and Mineral Resources Engineering, NTNU, Norway, 2: Geological Survey of Norway

Introduction

In order to better understand long-term erosion and landscape development of a valley with thick marine deposits, calculations have been made of the total volume of eroded sediments during the Holocene.

Parts of the present landscape in the valley are interpreted as remnants of the old seabed. This interpretation, in addition to the local sea-level curve, is used to reconstruct the entire, former seabed.

Setting

Glaciomarine and marine deposits up to several hundred metres in thickness accumulated in Norwegian fjords during and after the last deglaciation. Some of these deposits were later exposed on land due to glacio-isostatic uplift during the Holocene period. Subsequent leaching of marine clay by groundwater resulted in the formation of ***quick clay*** in pockets and layers in the subsurface.

Buvika is a small fjord-valley in Mid Norway surrounded by 300-400 m high hills of bedrock, today characterised by an undulating terrain with numerous ravines and slide scars.

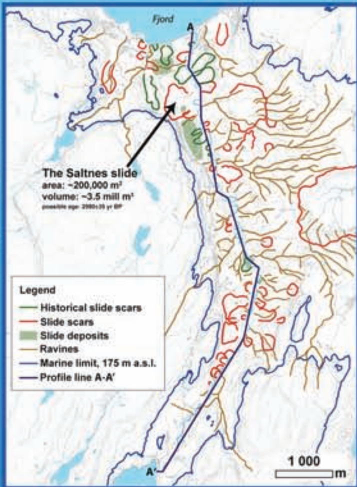
In Buvika, the highest sea level (marine limit) following the last glaciation was about 175 m above the present-day sea level. The valley fill is dominated by glaciomarine and marine deposits. Some coarser-grained deposits such as glaciofluvial sediments are also present. During early uplift, sediment input from glaciers decreased, and the fjord-valley was increasingly subjected to erosional processes.

Important erosion processes in the area

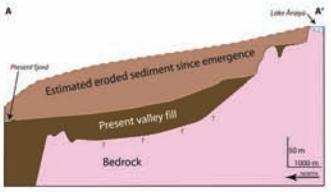
1. *Sliding activity* includes all sizes of slide, from surficial slides to large quick-clay slides.

2. *River erosion* often lead to slope failure, which can act as an initial slide and expose quick clay. When the support of the slope is removed, larger, retrogressive quick-clay slides can be triggered.

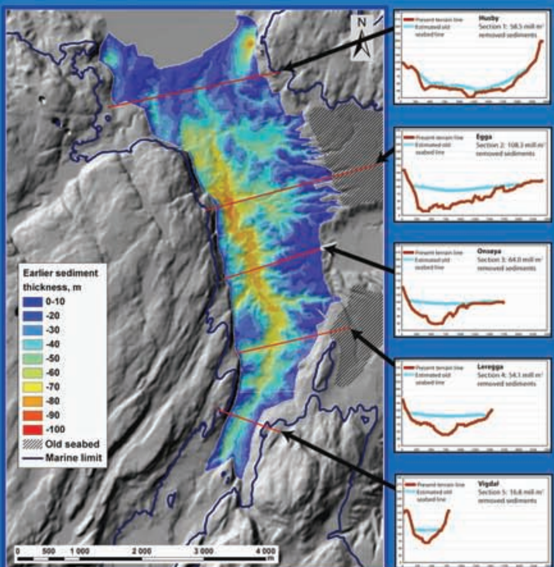
3. *Groundwater erosion* such as seepage and piping may trigger slides. Groundwater drainage also leads to local pore-pressure build-ups and the long-term development of quick clay by leaching.



Sediment infill and erosion



The valley development is divided into three stages. In the ***Early stage*** (the last part of the Pleistocene - 10,000 years BP) the sea level was lowered from 175 m to 150 m above present-day sea level. The stage was characterised mainly by sedimentation from suspension. During the ***Intermediate stage*** (10,000-6,500 years BP) the sea level was lowered by 110 m. The accumulation continued, but to a lesser degree than earlier. River incision and sliding activity increased. In the ***Recent stage*** (6,500 years BP - present) the sea level was lowered by the last 40 m. This is a solely erosional stage with several small and large slides and continued ravine erosion.



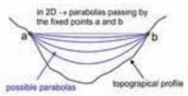
Conclusions

1. Total volume of removed sediment: 0.3 km³.
Mean sediment removal rate (last 10,000 years): 30,000 m³/y.

2. The main element of uncertainty in the calculation is the estimation of the old seabed surface in the eroded valley.

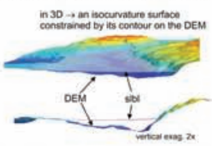
3. Further approaches in this study could be estimations of amount of sediment removed by slides and river transport, respectively, during the Holocene.

Volume estimation - Method



In order to estimate the volume of eroded sediment, the initial surface has been extrapolated using the *sloping local base level* (SLBL) method (Jaboyedoff & Derron 2005).

The SLBL method is an iterative excavation or filling of the DEM until a curvature is reached. In 2D, along a topographical profile, it provides a way to draw quadratic curves forced to pass through points on the profile (Fig. above).



In 3D, the SLBL surface is defined by its contour on the DEM and its concavity. Volume estimations can be made for different curvatures of the initial surface. When no other data are available, this geometrical extrapolation provides a rough estimation of the eroded volume.

Literature

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Solberg, I.L., Hansen, L. & Rokoengen, K. (subm.): Distribution of clay slides in fjord-valley deposits and their role in valley development, example from Mid Norway. Submitted to the 1st North American Landslide Conference 2007, Vail, Colorado.

NTNU Norwegian University of Science and Technology — NGU — ICG — The Norwegian Water Resources and Energy Directorate

Presented at 4th ESF SEDIFLUX Science Meeting, Trondheim, Norway 2006

3. Poster presentation at The 20th Winter Meeting January 8-10 2007, Stavanger, Norway

Dalinnfyllingshistorie, landskapsutvikling og stabilitet til marine avsetninger; eksempel fra Midt-Norge

Solberg, I.L.[1], Rokoengen, K.[1] & Hansen, L.[2]

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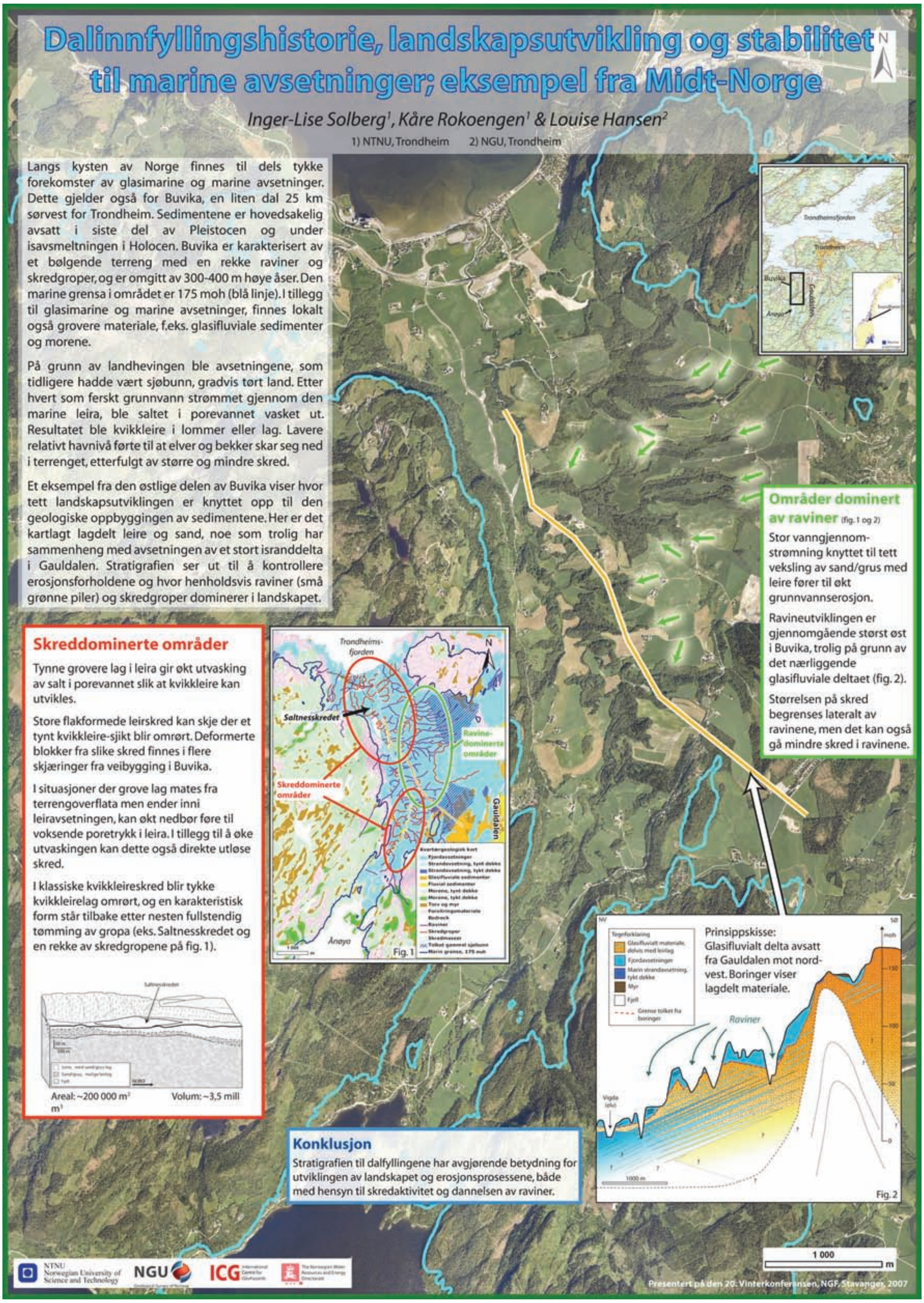
Langs kysten av Norge finnes til dels tykke forekomster av glasimarine og marine avsetninger. Stratigrafien til dalfyllingene ser ut til å være viktig for utviklingen av landskapet og erosjonsprosessene, spesielt med hensyn til skredaktivitet og dannelsen av raviner. Disse forholdene er hovedfokuset i et studie om landskapet og stratigrafien til sedimentene i Buvika, en liten dal i Midt-Norge.

Buvika er karakterisert av et bølgende terreng med en rekke raviner og skredgroper, og er omgitt av 300-400 m høye åser. Den marine grensa i området er 175 moh. Dalsedimentene er dominert av glasimarine og marine avsetninger, hovedsakelig avsatt i siste del av Pleistocen og under isavsmeltningen i Holocen. Lokalt finnes også grovere materiale, for eksempel glasifluviale sedimenter og morene. På grunn av landhevingen ble avsetningene, som tidligere hadde vært sjøbunn, gradvis tørt land. Etter hvert som ferskt grunnvann strømmet gjennom den marine leira, ble saltet i porevannet vasket ut. Resultatet ble kvikkleire i lommer eller lag. Lavere relativt havnivå førte til at elver og bekker skar seg ned i terrenget, etterfulgt av større og mindre skred. Når strukturen i utvasket, marin leire kollapser blir leirmassene flytende og det skjer et kvikkleire-skred.

Et eksempel fra den østlige delen av Buvika viser hvor tett landskapsutviklingen er knyttet opp til den geologiske oppbyggingen av sedimentene. Her er det kartlagt lagdelt leire og sand, noe som trolig har sammenheng med avsetningen av en stor israndavsetning i nabodalen. Stratigrafien ser ut til å kontrollere erosjonsforholdene og hvor henholdsvis raviner og skredgroper dominerer i landskapet.


Dalinnfyllingshistorie, landskapsutvikling og stabilitet til marine avsetninger; eksempel fra Midt-Norge
Inger-Lise Solberg[1], Kåre Rokoengen[1] & Louise Hansen[2]
1) NTNU, Trondheim 2) NGU, Trondheim
Langs kysten av Norge finnes til dels tykke forekomster av glasimarine og marine avsetninger. Dette gjelder også for Buvika, en liten dal 25 km sørvest for Trondheim. Sedimentene er hovedsakelig avsatt i siste del av Pleistocen og under isavsmeltningen i Holocen. Buvika er karakterisert av et bølgende terreng med en rekke raviner og skredgroper, og er omgitt av 300-400 m høye åser. Den marine grensa i området er 175 moh (blå linje). I tillegg til glasimarine og marine avsetninger, finnes lokalt også grovere materiale, f.eks. glasifluviale sedimenter og morene.
På grunn av landhevingen ble avsetningene, som tidligere hadde vært sjøbunn, gradvis tørt land. Etter hvert som ferskt grunnvann strømmet gjennom den marine leira, ble saltet i porevannet vasket ut. Resultatet ble kvikkleire i lommer eller lag. Lavere relativt havnivå førte til at elver og bekker skar seg ned i terrenget, etterfulgt av større og mindre skred.
Et eksempel fra den østlige delen av Buvika viser hvor tett landskapsutviklingen er knyttet opp til den geologiske oppbyggingen av sedimentene. Her er det kartlagt lagdelt leire og sand, noe som trolig har sammenheng med avsetningen av et stort israndelta i Gauldalen. Stratigrafien ser ut til å kontrollere erosjonsforholdene og hvor henholdsvis raviner (små grønne piler) og skredgroper dominerer i landskapet.
Skreddominerte områder
Tynne grovere lag i leira gir økt utvasking av salt i porevannet slik at kvikkleire kan utvikles.
Store flakformede leirskred kan skje der et tynt kvikkleire-sjikt blir omrørt. Deformerte blokker fra slike skred finnes i flere skjæringer fra veibygging i Buvika.
I situasjoner der grove lag mates fra terrengoverflata men ender inni leiravsetningen, kan økt nedbør føre til voksende poretrykk i leira. I tillegg til å øke utvaskingen kan dette også direkte utløse skred.
I klassiske kvikkleireskred blir tykke kvikkleirelag omrørt, og en karakteristisk form står tilbake etter nesten fullstendig tømming av gropa (eks. Saltnesskredet og en rekke av skredgropene på fig. 1).
Saltnesskredet
Areal: ~200 000 m²
Volum: ~3,5 mill m³
Trondheims-fjorden
Saltnesskredet
Ravine-dominerte områder
Skreddominerte områder
Gauldalen
Ånøya
Fig. 1
Områder dominert av raviner (fig. 1 og 2)
Stor vanngjennom-strømning knyttet til tett veksling av sand/grus med leire fører til økt grunnvannserosjon.
Ravineutviklingen er gjennomgående størst øst i Buvika, trolig på grunn av det nærliggende glasifluviale deltaet (fig. 2).
Størrelsen på skred begrenses lateralt av ravinene, men det kan også gå mindre skred i ravinene.
Trondheimsfjorden
Trondheim
Buvika
Gauldalen
NV
SØ
Prinsippskisse:
Glasifluvialt delta avsatt fra Gauldalen mot nord-vest. Boringer viser lagdelt materiale.
Tegnforklaring
Glasifluvialt materiale, delvis med leirlag
Fjordavsetninger
Marin strandavsetning, tykt dekke
Myr
Fjell
Grense tolket fra boringer
Raviner
Vigda (elv)
moh
150
100
50
0
1000 m
Fig. 2
Konklusjon
Stratigrafien til dalfyllingene har avgjørende betydning for utviklingen av landskapet og erosjonsprosessene, både med hensyn til skredaktivitet og dannelsen av raviner.
1 000 m
NTNU Norwegian University of Science and Technology
NGU
ICG
Presentert på den 20. Vinterkonferansen, NGF, Stavanger, 2007

4. Oral presentation at The 20th Winter Meeting January 8-10 2007, Stavanger, Norway

Bruk av resistivitetsmålinger i kvikkleirekartlegging, eksempel fra Buvika, Midt-Norge

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Skred i marine avsetninger er nokså vanlig i dalene langs kysten av Norge. Siden disse skredene ofte involverer kvikkleire, er det nødvendig å foreta detaljert kartlegging av løsmassene i forbindelse med arealplanlegging og sikring av utsatte områder. Spesielt i skråninger vil forekomsten av kvikkleire ha stor innflytelse på faren for skred.

Glasimarine og marine sedimenter ble avsatt på havbunnen under og etter siste istid. Disse sedimentene ble etter landhevingen utsatt for grunnvannsgjennomstrømning, og langsomt har det salte porevannet blitt erstattet med ferskvann i deler av avsetningen. Kvikkleire kan utvikles når saltinnholdet er under et visst nivå (5 g/l), og kvikkleira blir flytende ved omrøring fordi strukturen kollapser.

Grunnforholdene i en liten dal i Midt-Norge er karakterisert av store forekomster av kvikkleire, dokumentert gjennom omfattende geotekniske undersøkelser. Muligheten for å sammenligne med foreliggende felt- og laboratoriedata gjorde derfor området til et egnet teststed for kartlegging av kvikkleire med resistivitetsmetoden. Metoden har et stort potensiale siden mulig kvikkleire har noe høyere resistivitetsverdier (10-80 Ωm) enn leire med saltholdig porevann (1-10 Ωm). Resistivitetsmålinger har blitt utført i tretten profiler og sammenlignet med både geotekniske data og til dels andre geofysiske data (Dalsegg *et al.* 2006; Solberg *et al.* (subm)). Resistivitetsverdiene er også sammenholdt med målinger av saltinnhold i porevannet til leirprøver.

Resistivitetsmålinger i områder med marine avsetninger ser ut til å kunne skille mellom kvikk og ikke-kvikk leire, og vil være nyttig i initialfasen til et prosjekt for å kartlegge mulige kvikkleireforekomster. Siden metoden ikke definitivt kan påvise kvikkleire på grunn av en viss overlapp med resistivitetsverdier for andre jordarter, må den kombineres med andre metoder. Den vil likevel kunne gi svært nyttig informasjon om grunnforholdene, og indikere gunstige lokaliteter for videre undersøkelser.

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ENCLOSURE 2: TOTAL LIST OF PUBLICATIONS DURING THE PHD STUDY

Papers

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ENCLOSURE 4: LARGER VERSION OF SELECTED FIGURES

Paper I

Landscape development and deglaciation history of fjord-valley deposits in Buvika, Mid Norway.

- Figure 8

Paper III

Large, prehistoric clay slides revealed in road excavations in Buvika, Mid Norway.

- Figure 6
- Figure 11

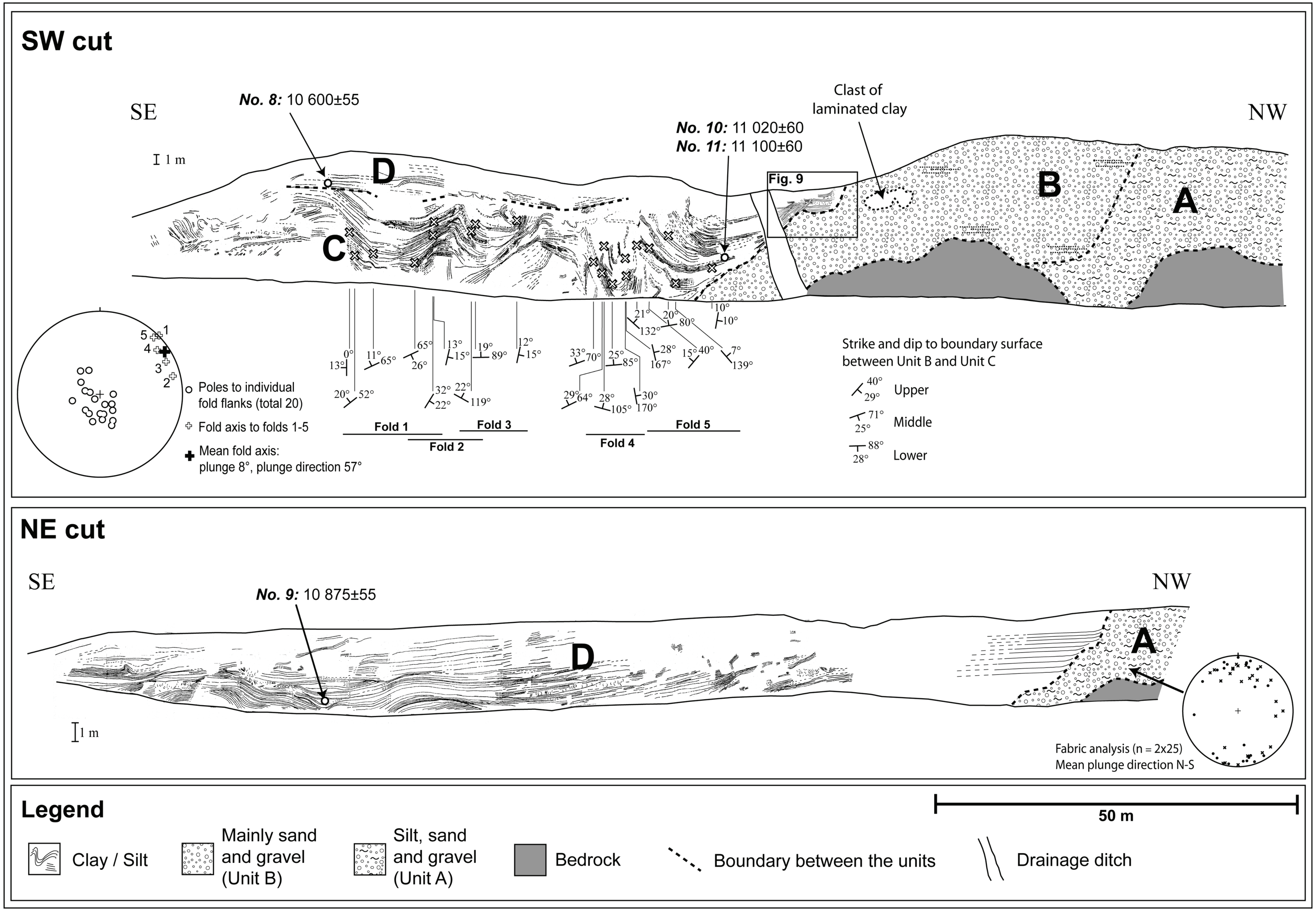

Fig. 8. from Paper I. The two cuts in Western Buvika, shown in Fig. 7. Units A and B: mainly coarse-grained material with indicative layering in Unit B, Units C and D: mainly fine-grained material. Structures in the blank areas in Unit C and Unit D were difficult/impossible to outline. Sample locations and results from ^{14}C-datings of mollusc fragments, in years BP (Table 1) are shown. For location, see Figs. 2-4.

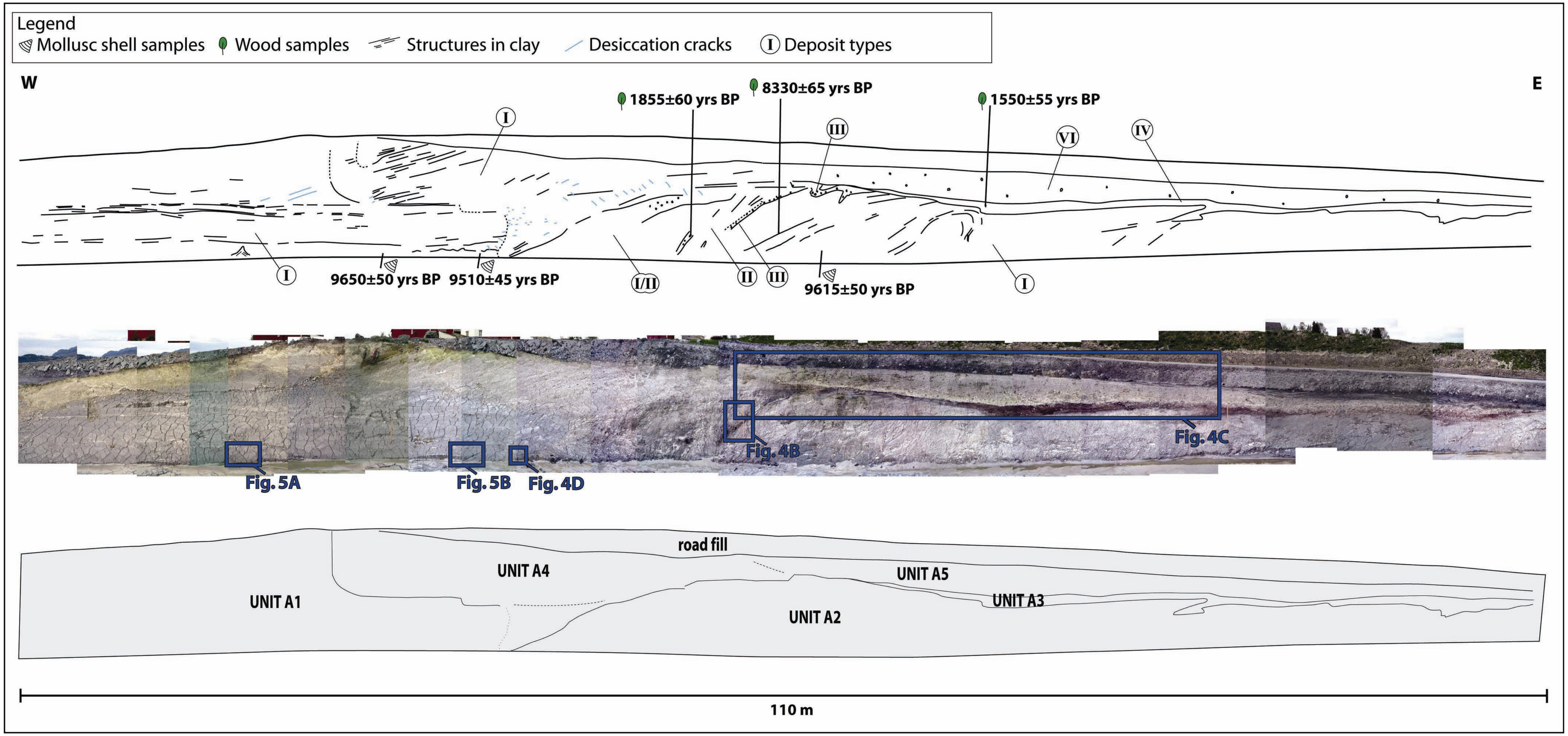

Fig. 6. from Paper III. Section A, east of the bridge (See Fig. 3 for location). **Top:** Deformation structures and deposit types. Structures in the blank areas were difficult/impossible to outline. See Table 1 and Table 2 for ^{14}C-dating specifications. **Middle:** Photo-mosaic. Figs. 4 and 5 show details from the section. **Bottom:** The units.

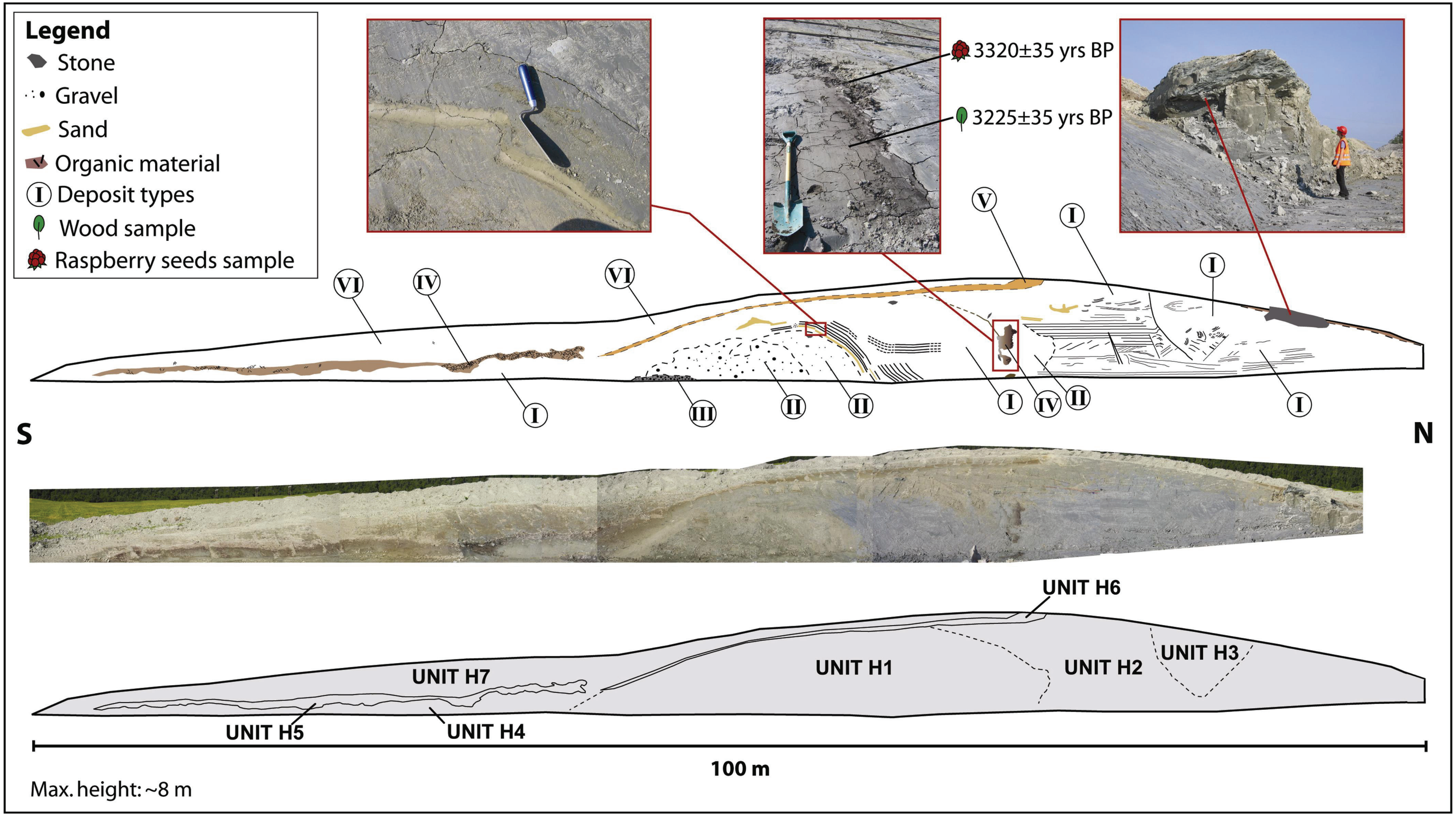

Fig. 11. from Paper III. Section H (See Fig. 3 for location). **Top:** Deformation structures and deposit types. Structures in the blank areas were difficult/impossible to outline. Details from ^{14}C-datings in Table 2. **Middle:** Photo-mosaic of the section. **Bottom:** The units.