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Stratigraphic evaluation of a Holocene clay-slide in Northern Norway

Abstract An almost 6,000 years old slide in marine clay at Fossmoen, Northern Norway is studied to: characterize the scar, the slide deposits and the slide event; evaluate the role that stratigraphic variations played for failure; and view the slide event within long-term landscape development. A geological model for the area is based on drilling, outcrops and ground-penetrating radar with emphasis on the stratigraphic variations of fjord deposits. The slide's age implies that the deposits were sensitive already shortly after emergence above sea level, and layers are still sensitive. River incision was probably responsible for the initial slide, whereas stratigraphy and groundwater movement controlled the location and shape of the scar. Laminated, inclined and discontinuous bedding are suggested as playing different roles for ground-water flow and pore pressures, adding to existing models on the development of soft and sensitive layers prone to sliding.

Keywords Landslide · Clay · Stratigraphy · Groundwater · Norway

Introduction

Geological conditions are important for landslides as failure may be restricted to specific levels within the stratigraphy of unconsolidated deposits (e.g. Feyling-Hanssen 1954; Hutchinson 1961, 1965; Clague and Evans 2003; Bichler et al. 2004). Knowledge of stratigraphic variations may thus be important for hazard evaluations. The Quaternary fill of valleys along the Norwegian coast often includes thick accumulations of soft, stratified marine and glacimarine clay. Leaching of salt by groundwater is an important prerequisite for the development of sensitive clays, including quick-clay, as originally described by Rosenquist (1953). Clay slides, especially those involving quick clay, may be highly destructive, and improved understanding of conditions that may decrease stability and/or affect sliding processes is of general interest.

The marine deposits of Norwegian valleys have varied stratigraphic organization although main components are similar. Both historic and older slide scars are widely distributed, and their occurrence is connected to various parts of the valley fill system (Hansen et al. 2002; Eilertsen and Hansen 2004). It is the aim of the present case study (1) to describe and evaluate the geological conditions of an old, well-defined clay slide at Fossmoen in Northern Norway (Fig. 1); (2) to point to the significance of stratigraphic variations on groundwater movement, pore pressures and the development of sensitive clays; (3) to view this slide within a long-term landscape development; and (4) to show how prehistoric slide events can be reconstructed through a combination of mapping, geophysics and drilling. A reconstruction of the sea level and the level of river incision at the time of the slide is also important to constrain the time and cause of the Fossmoen slide event. The position of the sliding plane is compared to the stratigraphy and the paleo-landscape at the time of failure. The stratigraphic conditions of importance for groundwater movement and for the development of soft, sensitive layers are discussed and summarized in a model. The model is meant to serve as an inspiration and help for the reconstruction and understanding of slide events in deposits with significant stratigraphic variability.

Materials and methods

Investigations at Fossmoen (Fig. 1) included detailed morphological analysis of the slide scar, of the slopes of the Fossmoen terrace, as well as analysis of the vegetation. Positioning was carried out using GPS, and altitudes were measured electronically combined with a hand level. Detailed examination of the deposits of Fossmoen was carried out at three localities. The sediments were logged and photographed documenting lithologies, bedding characteristics and bounding surfaces at three localities, locs. 1, 2 and 3. Grain size analysis was carried out by laser diffraction (Coulter). Fossils of marine molluscs and of wood were collected for identification and for ^{14}C dating. Geotechnical drilling and ground-penetrating radar profiling were also carried out.

Geotechnical drilling

Two rotary/pressure soundings (BH001 and BH11) and one piezocone test (CPTU) at BH11 were carried out on the Fossmoen terrace (Figs. 1 and 2). NGU drilled BH001 to obtain information on lithological variations based on penetration time, applied pressure, use of hammer percussion, flushing water and some sampling. A geotechnical consultant company carried out drilling of BH11 during quick-clay mapping (Nerland and Gregersen 2004). The Norwegian Geotechnical Institute carried out interpretation of the sensitivity of deposits in this drilling. A constant, or decreasing, applied force during drilling is considered as an indication of sensitive sediments. The method has turned out to be efficient for the recognition of quick clay (Viberg 1984). The rotary/pressure soundings provided general information on the lithological variations, and CPTU gave greater detail on the upper 20 m of the stratigraphy, including information on pore-pressure conditions at the time of drilling (Fig. 2).

Ground-penetrating radar

Ground-penetrating radar (GPR) has previously proved to be a suitable tool for characterizing the internal structure of some slides involving unconsolidated sand and clay (Barnhardt and Kayen 2000). The stratigraphy of the Fossmoen terrace, as well as of the Fossmoen slide scar have been investigated using a PulseEkko IV GPR system, with a 1,000-V transmitter and an antenna frequency of 100 MHz (Figs. 1 and 3). Data were collected in step mode with

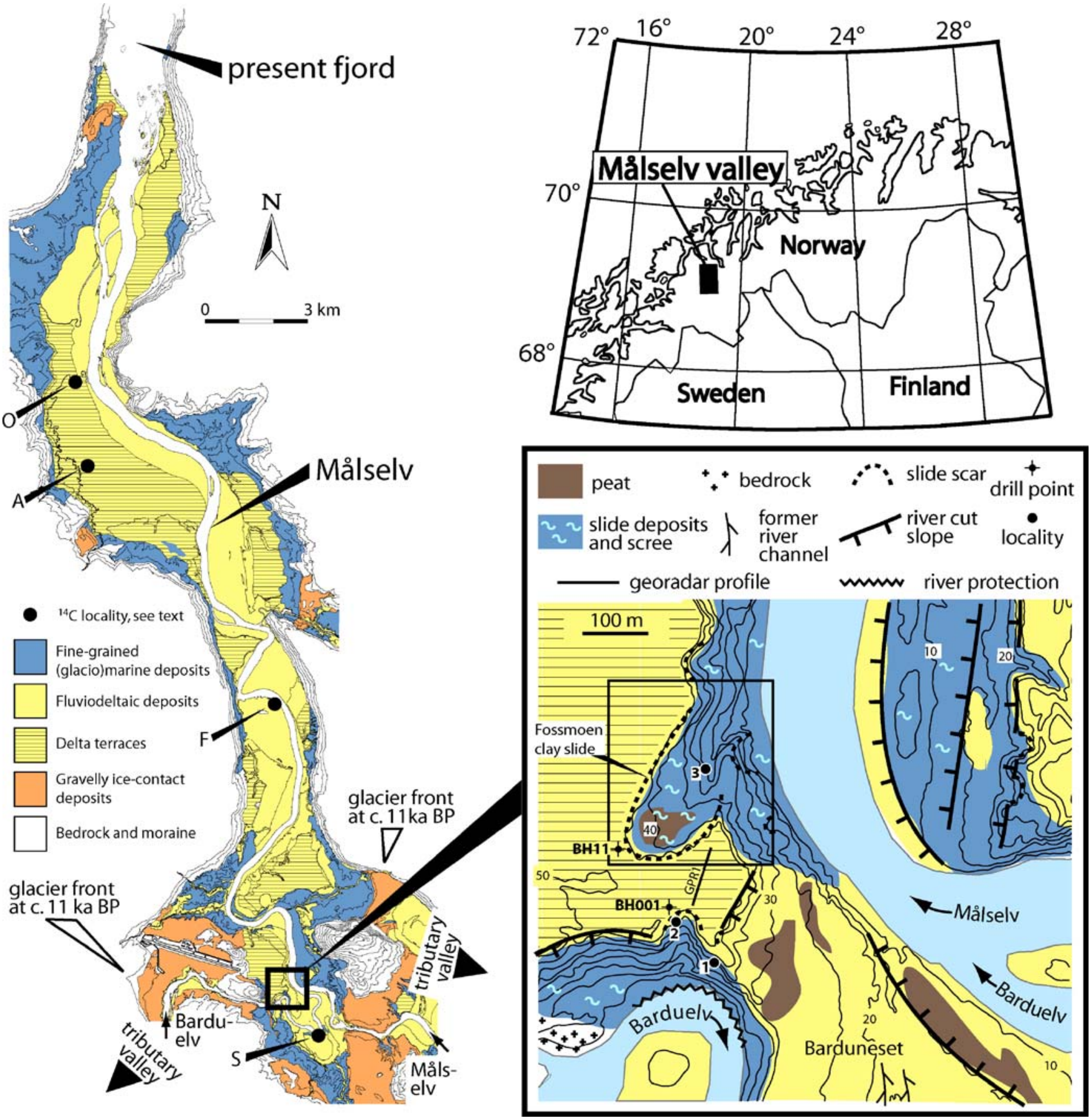

Fig. 1 Quaternary map of the Målselv valley, Northern Norway and enlarged map of the investigated area at the Fossmoen slide scar. *O* Olderneset, *A* Andreashola, *F* Fleskanesan, *S* Storleirfallet. Contour intervals are 20 and 5 m on the *overview map* and the *inserted map*, respectively

steps of 25 cm to favour high-resolution data. Raw data were processed and plotted using PulseEKKO IV software (version 4.2). Processing included the use of a 'dewow' filter to remove low-frequency induction effects, in addition to 'trace to trace averaging' (spatial filter set to 2) and 'down the trace averaging' (time filter set to 3). SEC (spreading and exponential) gain was used to highlight the major reflections and to preserve the relative amplitude variations (van Overmeeren 1998). The profiles have also been corrected for topography. A velocity of 0.06 m/ns was estimated by direct comparison of the reflection pattern and the exposure at loc. 3 and common mid point measurements. The time-to-depth conversion was considered most reliable within the slide scar because of saturated conditions, whereas the water table was found at some depth in the sandy terrace. The consequence was an underestimated depth conversion near the top of the terrace. Results were generally good, but some reflections in the terraces had been identified as noise because the reflections followed the break at the escarpment of the scar (Fig. 4). Apparent reflections in clay sections were also identified as artefacts by Barnhardt and Kayen (2000).

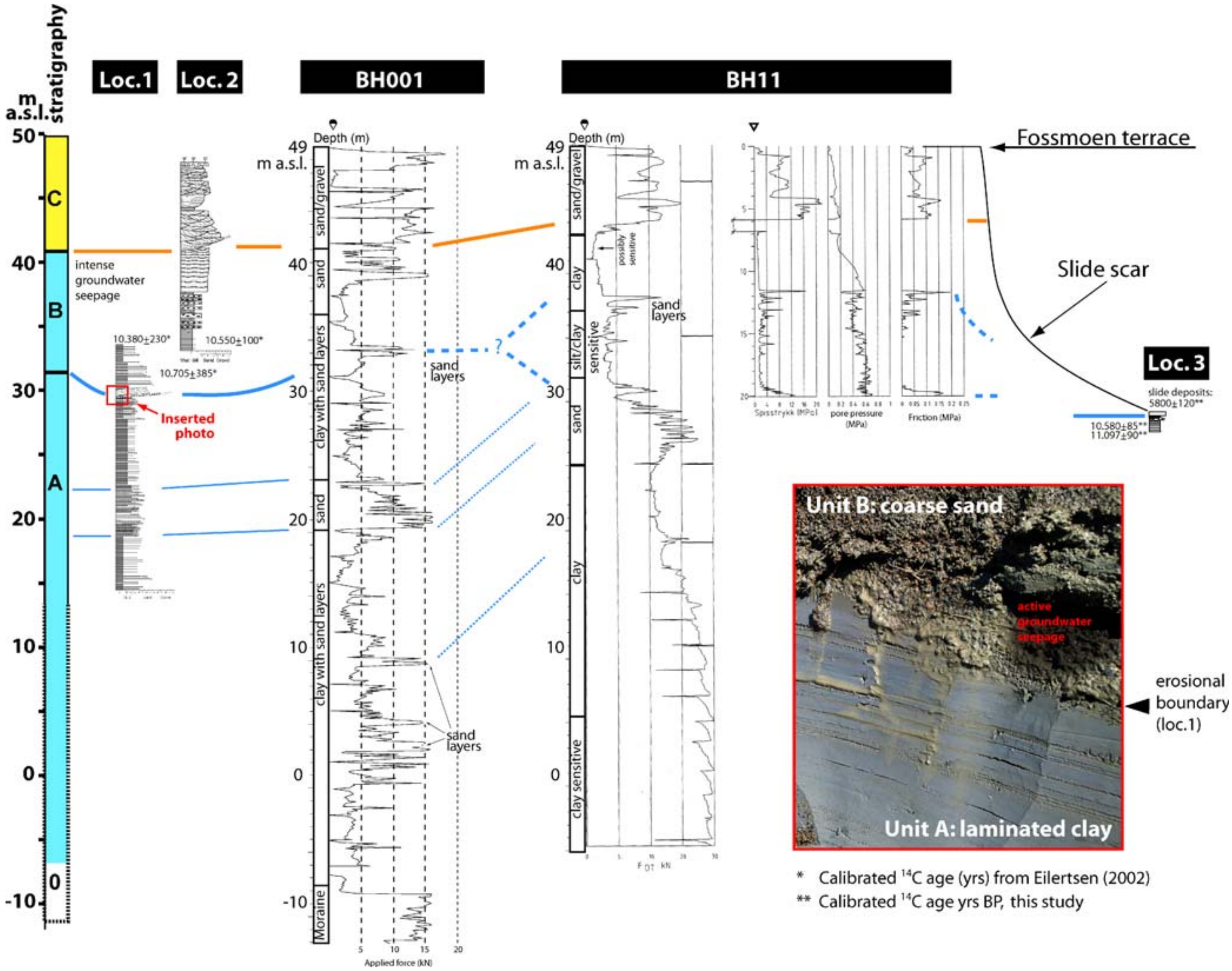

Fig. 2 Stratigraphy of Fossmoen derived from exposures and drillings together with a simplified cross section showing the position of the Fossmoen slide scar. The *inserted photo* shows active groundwater seepage from a layer of coarse-grained sand at the boundary between units A and B at loc. 1. See Fig. 1 for location

Setting

Thick sediment successions of glacial, (glacio-)marine, deltaic and fluvial origin accumulated during, and after, the last major deglaciation of the Målselv valley (Fig. 1). Glacial deposits are preserved among bedrock exposures along the valley sides. Large, gravely, ice-contact deposits at bedrock sills at the mouth of two large tributary valleys were formed around 11,000 calendar years BP during a period of overall glacier retreat towards the south (Fig. 1). Deposition of ice-contact deposits and widely distributed glaciomarine sediments took place as fjord- and valley-glaciers retreated. Fjord sediments continued to accumulate after deglaciation during the fall of relative sea level caused by glacio-isostatic rebound. Målselv and Barduelv rivers and minor streams eroded the emerging deposits creating widely distributed fluvial and deltaic terraces (Fig. 1). Present-day erosion is associated with large landslides and exposure of coarsening-upward successions of glaciomarine, marine, deltaic and fluvial sediments along the rivers.

The surficial deposits in the area are described by Nålsund and Hamborg (1985). For detailed description of the valley deposits and of the geological evolution of the Målselv valley, see Eilertsen (2002) and Eilertsen et al. (2005, 2006). The area has also been subject to mapping of recent and old slide scars and active erosion (Hansen et al. 2002), and the distribution of slide scars is compared to the overall valley fill (Eilertsen and Hansen 2004). The investigated area at Fossmoen is located near the confluence of Målselv and Barduelv rivers between two major gravelly ice-contact deposits (Fig. 1). Sensitive clay is registered in the area, and the Fossmoen area is included on a quick-clay hazard map produced by the Norwegian Geotechnical Institute (Nerland and Gregersen 2004).

Morphology of the study area

This study is concentrating on a single, well-defined slide-scar at Fossmoen in a sandy to gravelly, fluvio-deltaic terrace at 47–49 m a.s.l. (Figs. 1 and 3). The Fossmoen terrace, which is covered by a

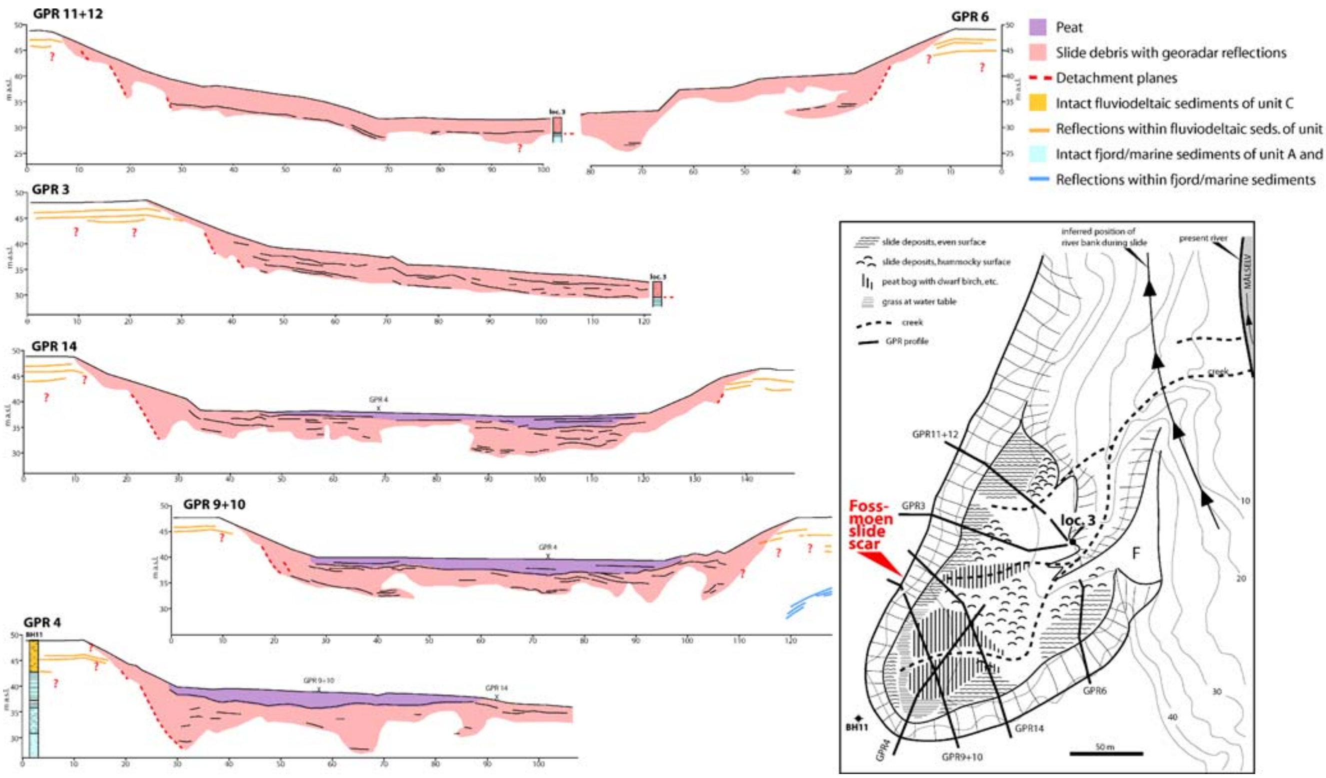

Fig. 3 Detailed map of the Fossmoen slide scar with position of georadar lines

forest of pines and birch, is bordered towards south and east by steep slopes eroded by outer river bends of the Målselv and Barduelv rivers. Finer-grained deposits, including fine sand, silt and clay are exposed in the slopes. Low-lying sets of terraces are found on the eastern side of the Målselv river, with traces of fluvial erosion at levels beneath 20 m a.s.l. The elevation of the surface of the present-day river is about 6 m a.s.l. at Fossmoen, and the river is over 100 m wide. The depth of the river channel at Fossmoen is estimated to be more than 3 m. The gradient of the Målselv river, from Fossmoen to the present day delta about 25 km to the north, is on average 0.01°. River discharge reaches its maximum during snowmelt in June/July where discharge north of the confluence of Målselv and Barduelv rivers on occasions exceeds 1,500 m^3/s (Sværd 2001).

Active erosion of the slopes of the Fossmoen terrace

The slopes along the Målselv and Barduelv rivers are densely vegetated. Slopes are irregular with numerous ravines and vary from being almost vertical to being gently inclined over small distances. The slopes are eroded by small ravines and show several signs of gravitational processes, such as slide scars, slide blocks, scattered active mud flows, tilted tree trunks, as well as seepage and piping of groundwater. The fact that ground-water piping is an important erosional agent is especially clear along the Barduelv riverbank, which is presently secured along the entire outer bend (Fig. 1). Still, the slope is actively retreating because of slides and mudflows. The processes are sufficiently active to expose the in situ sediment stratigraphy. The outer riverbank along the Målselv river is presently eroded by the river.

Stratigraphic data

Correlations

The geotechnical drillings give some stratigraphic information but at a low resolution. Control on lithological interpretation of the drilling is obtained by comparing BH001 with exposures nearby, primarily at loc. 2. Correlations of exposures and drill holes are presented in Fig. 2. The profiles in BH001 and BH11 display comparable drill patterns, and the main trends are correlated to the stratigraphy observed in sections. Marked spikes in BH001 and BH11 possibly represent thinner, coarse-grained beds in the clay-rich deposits as exposed at 30 m a.s.l. at loc. 1 (Fig. 2). However, correlation is made in a rather general way, as detailed stratigraphic data are not available from the drilling and as discontinuous beds characterize this stratigraphic level (see below). The geotechnical drilling display marked intervals with sensitive clay/silt (Fig. 2). Correlations of stratigraphic sections are supported by biological content and ^{14}C datings.

Stratigraphic model for the Fossmoen area

The construction of the geological model is based on the stratigraphic records of locs. 1, 2 and 3 combined with information from drillings on the main stratigraphic trends (Fig. 2). GPR data give information on geometry, position of detachment planes and internal bedding but primarily of the uppermost part of the deposit (Figs. 3 and 4). This is mainly because of the reduced penetration of the GPR signal in marine clay-rich deposits (Jol and Bristow 2003). Bedrock is exposed along Barduelv (Fig. 1), and the bedrock surface lies deeper in the area of Fossmoen below the level of drilling.

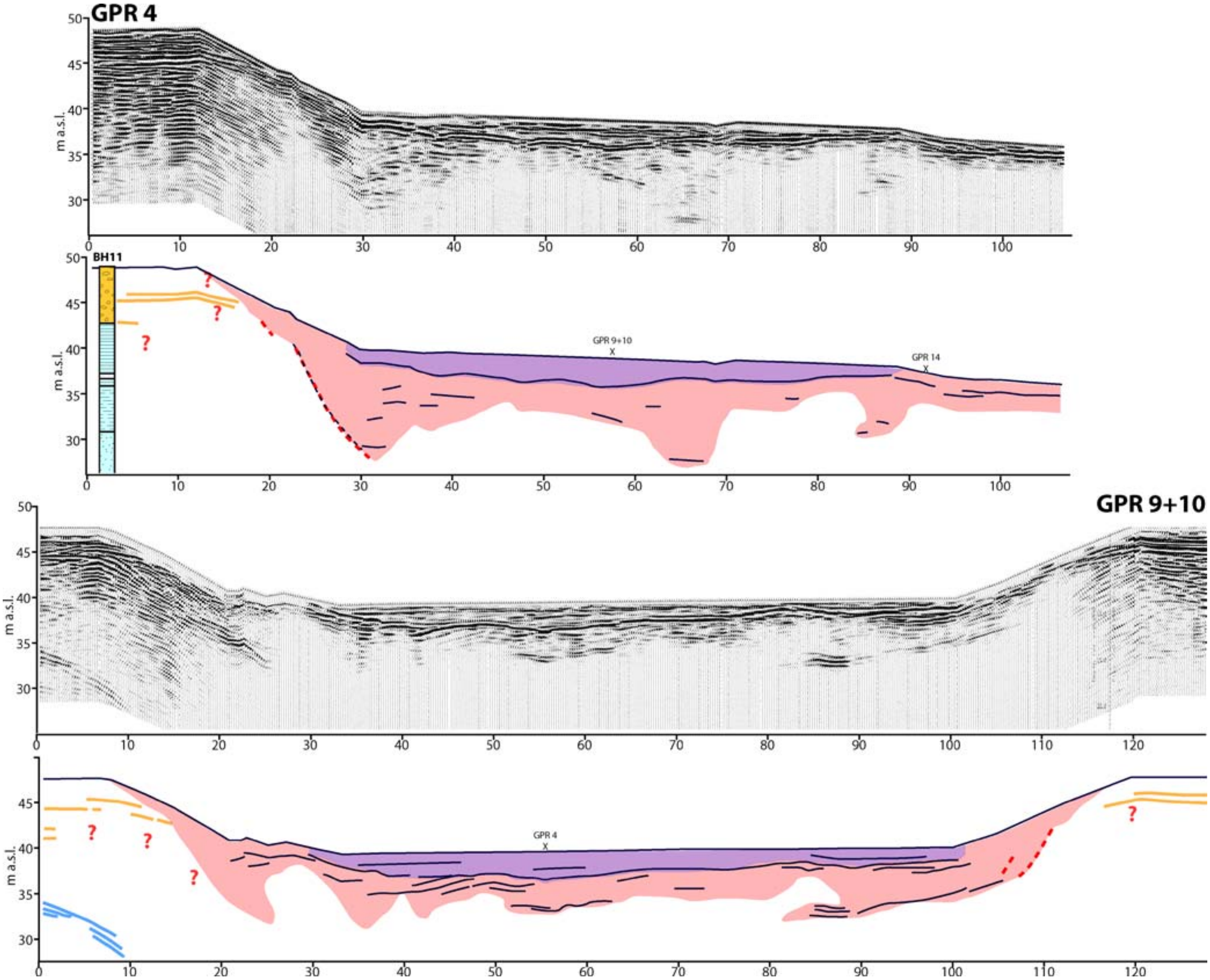

Fig. 4 GPR profiles from the Fossmoen slide scar. The area marked with an *F* on the map is interpreted as formed by fluvial processes during, or shortly after, the slide. The depth scale is based on a velocity of the radar signal of 0.06 m/ns. For legend see Fig. 3

The uppermost 35 m of the Fossmoen stratigraphy consists of four units (Figs. 2 and 5). A sketch of the model is presented in Fig. 6. The lowermost unit 0 consists of coarser-grained sediments, possibly glacial deposits overlaid by clay. Unit A consists of rhythmically and parallel-laminated clay, silt and very fine sand deposited in a glaciomarine environment. Coarse-grained layers are more frequent south of the slide scar than at the back scarp (BH001 and BH11; Fig 2). Unit B has a varied composition with discontinuous bedding. It comprises a fining upward succession (B1), overlain by a coarsening upward succession (B2). Unit B is deposited in a marine environment. Clay deposits of unit B occur at a higher elevation near the back scarp (BH11). The presence of thick clay layers northwest of the slide scar is supported by low penetration of the GPR signal. Data show that the base of unit B and some internal beds are inclined towards northwest in the area south of the Fossmoen slide scar. Unit C consists of interbedded gravelly sand and silt and is fluviodeltaic (Figs. 2 and 3).

Results

The Fossmoen slide

The Fossmoen slide-scar is about 120 m wide, 250 m long and 10 m deep. (Figs. 1 and 3). When including the estimated volume of deposits in the slide-scar based on GPR, the total volume of slide debris is about 400,000 m^3. The outlet of the slide scar is oriented toward the NNE, which is clearly oblique to the present-day course of the Målselv river. Profiles show that the edge of the slide escarpment is well defined, and the slopes are inclined up to about 35°. The centre of the slide is flat and gently sloping northeastwards near the back scarp.

The vegetated escarpment of the slide scar is relatively smooth but is locally interrupted by minor steps on the slope and scattered sediment accumulations along the base of the escarpment. Thicker accumulations are found near the slide's outlet. The central part of the slide scar is characterized by (1) poorly drained areas with the

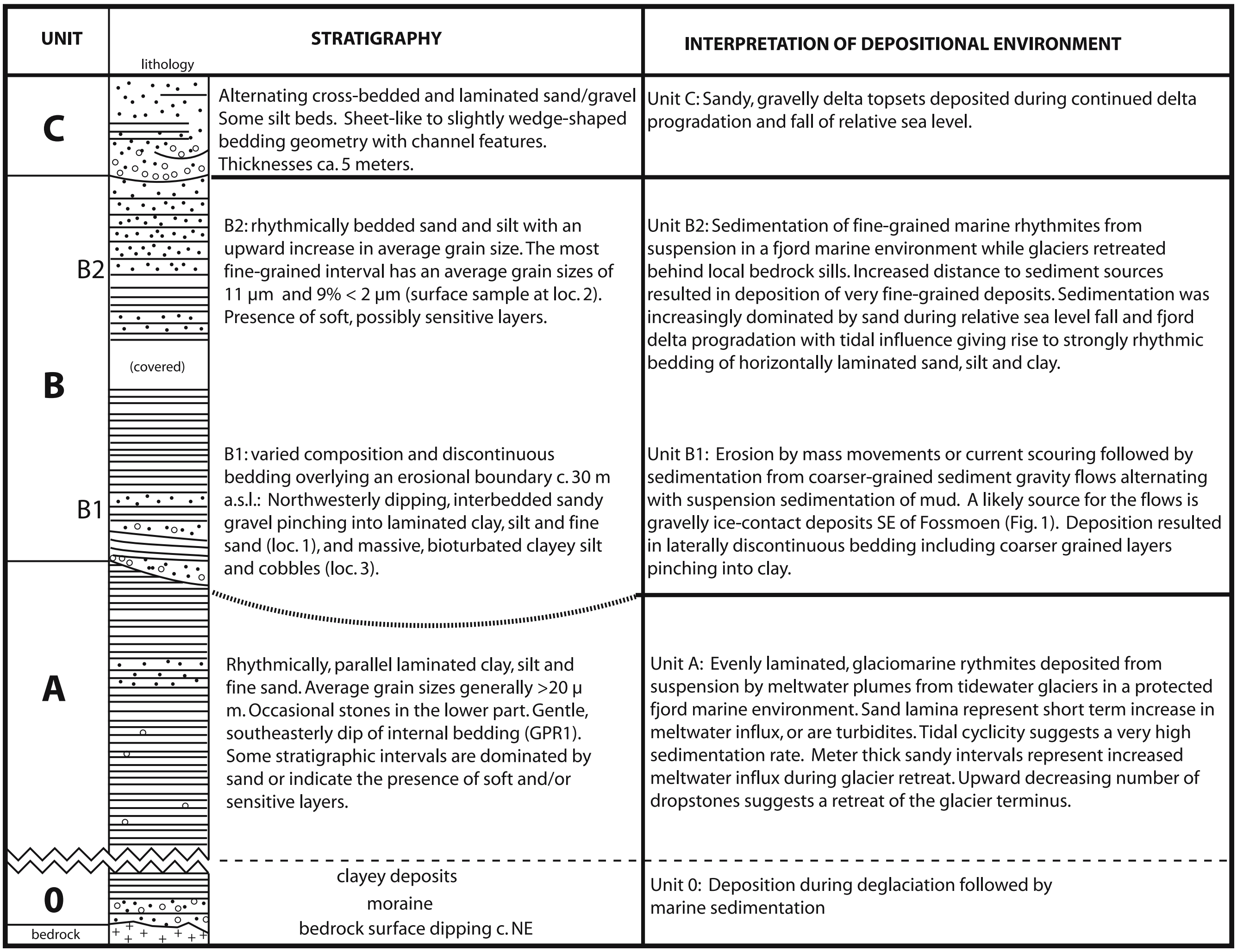

Fig. 5 Stratigraphic model of Fossmoen with interpretations

groundwater table near the surface, covered by peat bog, grass, mosses, dwarf birch and scattered trees; and (2) dry areas with rugged topography and trees dominated by birch (Fig. 3). Minor creeks drain across the slide scar through peat bog and merge in a major ravine that cuts into the slide-scar's mouth. Small sediment exposures and muddy water in the stream in the ravine testify to ongoing, active erosion. The water in the stream originates from groundwater seeping out at the base of the slide-scar and ravines.

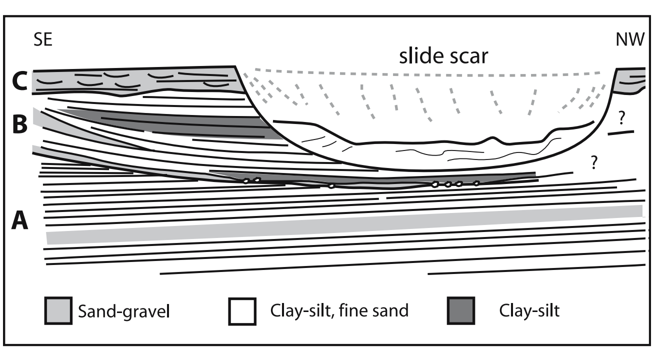

Fig. 6 Schematic presentation of the stratigraphy at the Fossmoen slide scar in a cross section

The morphology and proportions of the elongate Fossmoen slide scar are typical of that of a quick clay slide or an earth flow involving fluid mud. A major part of the sediments disintegrated and escaped the scar during free retrogression (Mitchell and Markell 1974; Porshmann et al. 1983; Karlsrud et al. 1985).

Slide deposits

Slide deposits in the slide scar are represented by hummocks or are covered by peat (Fig. 3). Accumulations along the escarpment represent more coherent slabs of sediment that moved from the scar during the final stage of the slide. Thick slide masses along the sides of the scar mouth are most likely collapsed 'shoulders' of the slide.

Slide deposits are exposed near the outlet of the slide scar at loc. 3 (Fig. 7), where they overlie undisturbed clay-rich deposits. The slide deposits consist of a mixture of sand and gravel with veins or slabs of clay (mean grain size, 12 µm; 8%<2 µm) overlain by troughs filled by normally graded coarse sand. The altitude of the exposed slide plane between slide deposits and undisturbed clay is at about 28 m a.s.l. and is characterized by a soft layer of remoulded clay with a mean grain size of 9 µm (11% < 2 µm). The small grain size suggests that the source of remoulded and deformed clay is from a fine-grained part of the local stratigraphy. Groundwater is percolating through the coarse-grained sediments. The base of one sandy trough contains remains of wood and bleached quartz sand with humus, which originate from a former, vegetated, well-developed soil profile on the Fossmoen terrace. The wood fragments found at loc. 3 were radiocarbon dated, yielding an age of 5,800±120 calendar years BP. This is interpreted as corresponding to the age of the slide event (Fig. 7, Table 1).

The radar structure of deposits in the slide scar is divided in three (Figs. 3 and 4): (1) nearly continuous and slightly wavy reflections near the surface represent peat deposits (purple). Marked reflections represent the boundary to the underlying slide deposits; (2) almost 'transparent' parts, representing clayey deposits (no colour). Vague reflections in the latter may, however, represent bedding in fine-grained deposits that were not remoulded during sliding. Coherent 'transparent' material is present in the centre of the slide, and near the outlet, and (3) slide deposits represented by discontinuous to undulating or

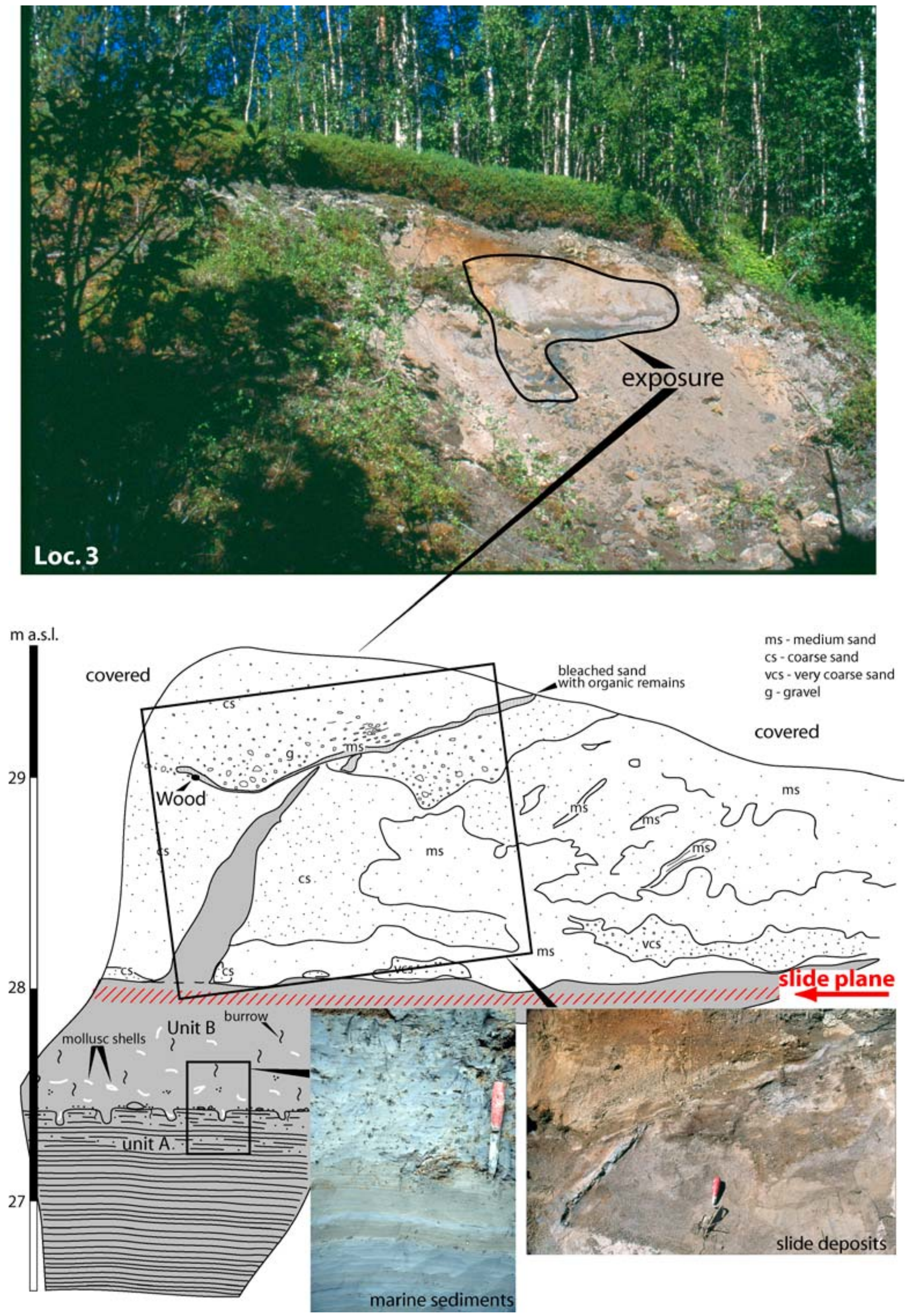

Fig. 7 Slide deposits with irregularly bedded sand and gravel and veins of clay overlying in situ stratigraphy at loc. 3. The slide plane is characterized by soft remoulded clay. The trough-shaped feature at the *top* was formed by short-lived channels in a late stage of the slide. See Fig. 1 for location

Table 1 ^{14}C datings from material collected at loc. 3 at Fossmoen

Lab. no.	Dated material	δ^{13} C (‰)	^{14}C age years BP	Calibrated age (before 1950) (Stuiver and Reimer 1986; Stuiver et al. 1998)
T-15882	Wood (pine)	−26.1	5.055±85 conventional	5.800±120 years BP
Tua-4646	Skjell[a]	1.0[b]	9.700±70[c] AMS	11.097±90 years BP
Tua-4647	Skjell[a]	1.0[b]	9.340±70[c] AMS	10.580±85 years BP

Dating was carried out by NTNU, Trondheim (conventional), and Uppsala University (AMS).

[a] *Balanus crenatus*

[b] Assumed value

[c] Corrected for a marine reservoir effect of 440 years

irregular reflections that are possibly reflecting the structures in relatively coarse-grained deposits including gravel, sand and silt (pink). These sediments occur as pockets in 'transparent' clayey deposits and are especially large and deep near the back scarp. Pockets at the escarpment pinch into more fine-grained deposits towards the centre. Continuous reflections within slide deposits possibly represent the groundwater table. Clear boundaries between 'transparent' and 'reflective' radar signatures along the escarpment are interpreted as detachment planes. These are either located between faulted blocks of sediment or represent the boundaries of sediment-filled cracks in marine deposits (Figs. 3 and 4). The contact between undeformed sediments in the terrace and slide deposits on the slopes is blurred by noise problems in the terrace as described above. However, some continuous reflections are interpreted as stratification within unit B and C (Fig. 2).

Detachment planes

A major detachment plane has been detected in an outcrop at about 28 m a.s.l. as the boundary between intact laminated clay and disturbed sediments (loc. 3, Fig. 7). This exposure provides an important control on the interpretation of the slide plane in the nearby GPR profile. The boundary between 'transparent' clayey sediments and sandy deposits with internal reflections also coincides with the level of seepage. It is noteworthy that slide deposits are apparently found at a lower level in GPR6 than the slide plane recorded at loc. 3 (Fig. 4). This may be explained by erosion caused by the liquefied flow during sliding as recorded by Kenney (1968). Alternatively, there is a locally improved penetration of the georadar signal in the marine sediments. On the GPR profiles, detachment planes are recognized along the escarpment as described above. The basal slide plane is not apparent on the

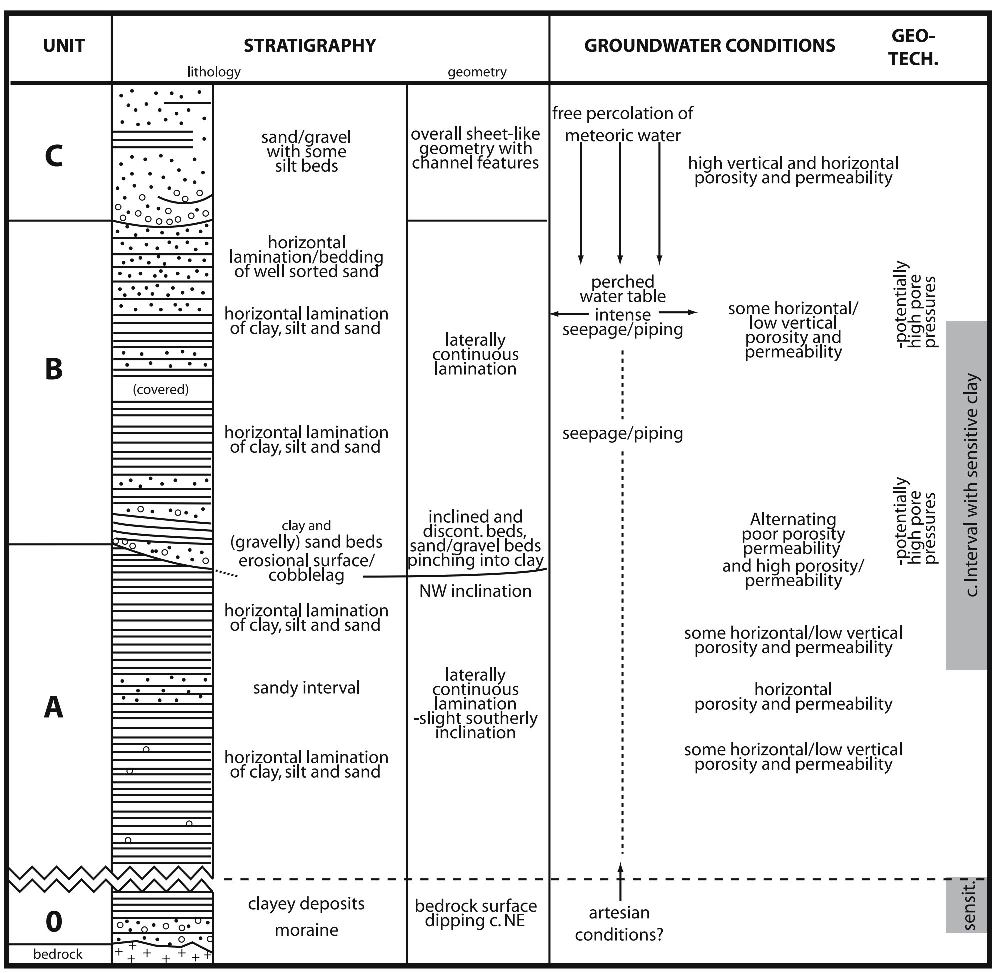

Fig. 8 Summary of geology and groundwater conditions of the Fossmoen terrace in the area of the slide

GPR profiles when it occurs entirely within clayey deposits. However, the irregular, undulating reflection pattern within the slide scar gives an indication of the thickness of slide deposits. A general interpretation suggests that the basal slide plane lies between 25 and 35 m a.s.l.

Groundwater

Groundwater conditions in Fossmoen are only known from surface features such as ground-water seepage and have not been studied in wells. However, observations are clearly linked to the slide scar and to the stratigraphy and are therefore considered as being of importance for the slide. Field evidence shows that the water table is fluctuating near the surface of the peat bog inside the slide scar (Fig. 3). Seepage seems to be particularly active along the northwestern side of the escarpment. The main direction of groundwater flow is assumed to be towards southeast. Water merges in a creek parallel to the southeastern escarpment (Fig. 3). Seepage of groundwater is also observed in the slopes of Fossmoen along the Barduelv and Målselv rivers (Fig. 1). Pore pressures were measured during drilling of BH11 displaying an increase at the transition to marine deposits.

Groundwater movement in Fossmoen is controlled by topography, bedrock and distribution of permeable and impermeable layers in the deposits (Figs. 6 and 8). Meteoric water is able to percolate almost freely through unit C because of the coarse-grained nature of the sediments. This is reflected in relatively low pore pressures during drilling of BH11 (Fig. 2). A few thin silt layers delay infiltration locally.

The top of unit B at loc. 2 consists of well-sorted laminated sandy sediments with high porosity and permeability. Internal, multiple, thin and horizontal silt layers reduce vertical percolation. This favours water saturated conditions, a perched water table and horizontal ground water movement. The downward increase in the thickness and number of mud layers most likely increase this effect. This is supported by the observation of intense groundwater seepage from the laminated fine-grained part of unit B at loc. 2 at about 35 m a.s.l. and increased pore pressures during drilling of BH11 (Fig. 2).

The presence of thicker sand beds at the base of and within the lower part of unit B that erosionally cut through finely laminated clay, silt and fine sand locally assists in more effective groundwater drainage through these fine sediments. This, in turn, may enhance leaching of the surrounding clay deposits. The presence of sand layers in clay may also increase local pore pressure conditions (Demers et al. 2002). It is suggested that the presence of coarser-grained layers pinching into clay, as well as discontinuous sand layers, will increase this effect. In the case of Fossmoen, bedding is dipping and pinching out towards the assumed main direction of groundwater flow (towards southeast). However, the northwestward inclination of interbedded fine-grained beds in unit B south of the slide scar may delay groundwater flow towards the southeast. This creates a 'pool' of groundwater, whereas groundwater flow is possibly enhanced along the strike of bedding parallel to the slide scar towards northeast. These conditions had possibly a controlling effect on the oblique orientation of the slide scar.

Protuberances of fractured bedrock covered by Quaternary deposits may be the source of groundwater flow, with high hydraulic gradients and artesian conditions enhancing quick-clay development (e.g. Bjerrum et al. 1971; Karlsrud et al. 1985). The Fossmoen terrace is located about 500 m east of a bedrock protuberance in the valley (Fig. 1).

Reconstruction of the slide event

Reconstruction of the slide event almost 6,000 years ago includes establishment of the former landscape, sea level and level of river incision as summarized below. A sea level curve for Fossmoen has been reconstructed from dated terrace levels in the Målselv valley (Figs. 1 and 9). This suggests a sea level at Fossmoen of about 19–21 m above the present level during the time of the slide. The river level of Målselv at Fossmoen is presently at about 6 m a.s.l., and the

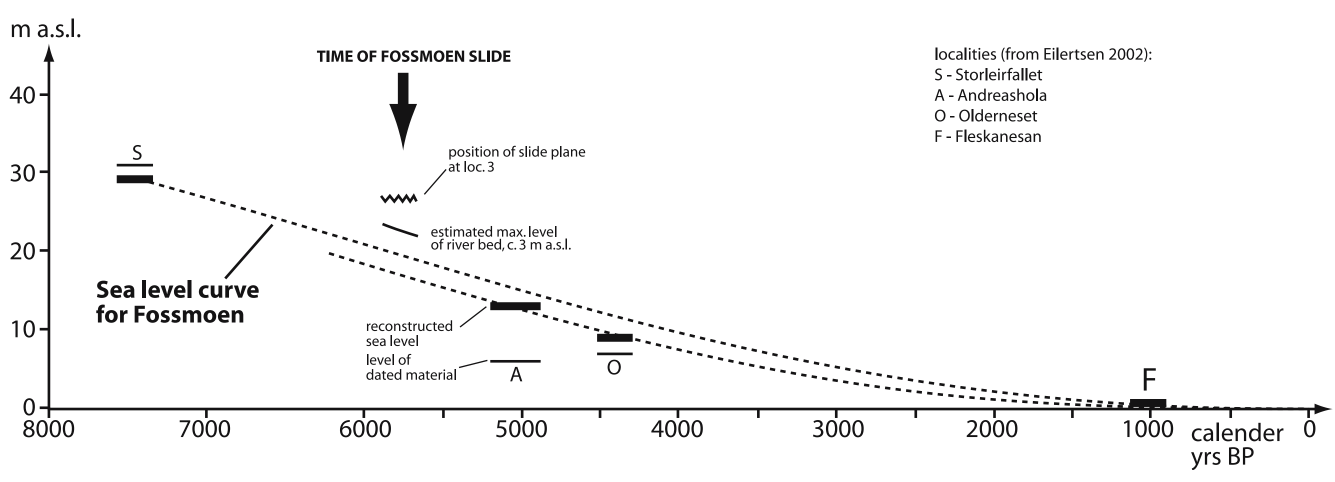

Fig. 9 Reconstruction of sea level at Fossmoen. Calibrated ^{14}C ages and corresponding terrace levels and sea levels are from Eilertsen (2002). Figure 1 displays the location of the mentioned localities. The southernmost terrace at Storleirfallet (*S*) is located a few kilometres from Fossmoen, and the two areas are considered as having the same sea level history. The sea level history at Andreashola (*A*) and Olderneset (*O*) more than 10 km to the north of Fossmoen is slightly different because of a smaller glacioisostatic rebound in the northern part of the Målselv valley in accordance with regional uplift patterns. However, the general sea level trends of areas of *A* and *O* are expected to be similar. Data from Fleksanesan (*F*) help constraining the sea level curve. The sea level curve for the *A*–*O* area is drawn through four data points, including the present sea level, giving a simple, curved line. The *S*–*F* curve follows the trend of the *A*–*O* curve that intersects three data points

channel depth is estimated to be a minimum of 3 m. A similar minimum channel depth is considered as realistic for the time of sliding. It follows that the level of the riverbed during sliding was most likely around 22–24 m above present sea level. The lateral position of the river channel was also slightly different from the present position. A likely position of the former river channel during sliding is outlined in Fig. 3 (black arrows). The channel was not located further to the west than indicated in Fig. 3 because the existing slope along Fossmoen limited the river's course. A few traces of former river channels are present on terraces south of the confluence of Målselv and Barduelv rivers at about 20 m a.s.l. (Fig. 1).

The clay slide took place about 2,000 years after the emergence of Fossmoen above sea level as a result of glacioisostatic rebound. Pore-water salinities in the younger part of the marine deposits may have been somewhat lowered already during sedimentation in relatively shallow, brackish water. Groundwater leaching of units C and B favoured the development of soft, sensitive layers in parts of unit B. Carbon-14 dating shows that sensitive layers developed at the latest two millennia after the emergence of the delta terrace, 6,000 years ago. Although sensitivity and thicknesses of sensitive layers may change over time, some layers are apparently still soft/ sensitive (BH11; Fig. 2).

Climate records for the inland areas of Northern Norway suggest that the period of 8,500–5,700 years BP was characterized by high precipitation (Vorren et al. 1999). The high precipitation possibly enhanced leaching. A raise of the water table would also increase the overall loading of the terrace, and raised pore pressures were possibly enhanced by the presence of inclined, laterally pinching and discontinuous beds primarily within unit B.

The trigger of the Fossmoen slide was most likely river erosion, but the position of the slide plane and the oblique orientation of the scar are suggested as being controlled by the stratigraphic configuration and the direction of groundwater flow. The slide developed in a retrogressive manner, whereas soft and sensitive layers were remoulded. Grain size analysis suggests an origin of the remoulded clay within the finer-grained parts of the stratigraphy in unit B. A major position of the slide material escaped the scar during sliding. However, GPR profiles suggested that about one third of slide debris still remains in the slide scar. The liquefied slide masses possibly eroded a depression in the slide plane during their escape from the scar as suggested from GPR profiles at the slide mouth.

The slide deposits blocked the river that was forced eastwards. This is most likely reflected in the river-cut slope along terraces east of the Fosssmoen slide at about 20 m a.s.l. (Fig. 1, inserted map). The river's continued westward migration is reflected in the lower levels of river cut slopes on the eastern bank of Målselv (Fig. 1, inserted map). Sediments that escaped the slide mouth were removed through river erosion. River erosion has now resumed at the foot of the terrace/section/slope along Fossmoen.

Discussion

Groundwater flow is important for leaching and softening of clay, and sensitive (quick) clay formations are concentrated at locations where groundwater flow is increased (Løken 1983; Viberg 1984). Sand layers promote groundwater flow (e.g. Rankka et al. 2004). However, it is suggested that different types of sand layers in clay and various stratigraphic relationships play different roles for groundwater conditions. Thin, conform, horizontal lamina of sand, silt and clay increase (horizontal) groundwater flow and enhance a perched water table (inserted photo, Fig. 2). Such laminated sediments dominate the stratigraphy at Fossmoen (Fig. 7). These horizontally laminated sediments were deposited as rhythmites in front of a fjord delta with high but varying sedimentation rates and tidal influence. Some rhythmites are dominated by fines and others are generally sandy, depending on the distance to the sediment source.

Clayey deposits immediately underlying permeable deposits at the land surface may be particularly affected by high rates of groundwater flow. The permeable deposits are usually of shallow marine or fluviodeltaic origin. Deposition under lowered salinities during emergence would result in initially lowered pore-water salinities. In the Ottawa valley in Canada, a layer of leached clay with low-pore water salinities below a sandy terrace is considered to be formed by groundwater movement in the overlying sand package (Calvert and Hyde 2002; Calvert 2003). Similar conditions may prevail in unit B, right under the relatively coarse-grained unit C at the top of the Fossmoen terrace. The decreasing penetration resistance in BH11 below unit C may be explained by a present-day high sensitivity of the clay (Fig. 2). Supporting evidence suggests that a very fine-grained layer in the upper part of unit B was remoulded during sliding (Fig. 7). However, successively lowered drilling resistance right under coarse-grained sediments may also result from change in resistance against drilling within the overlying coarse layer (Odd Gregersen, personal communication).

Thicker sand beds, associated with erosional surface(s) within the stratigraphy, promote groundwater flow through the finely laminated sediments in contact (inserted photo, Fig. 2). Sand layers in clay, particularly if connected to permeable deposits at the land surface or bedrock, may be particularly important for groundwater flow and leaching processes (Rankka et al. 2004). The presence of sand layers in clay-rich deposits may also play an important role for pore pressure conditions (Demers et al. 2002), although thick, well-drained beds may have a stabilizing effect (Lebuis et al. 1983). However, wedge-shaped and discontinuous, permeable beds, and other structures leading to a confluent groundwater flow patterns may be of particular importance for pore-pressure conditions. Such bedding geometries are present at Fossmoen, especially in the lower part of unit B that contains dipping, wedge-shaped coarse-grained layers and lens-shaped features interbedded with fine-grained beds (Figs. 5 and 6). These features represent particular erosional/depositional events in the former fjord basin (Fig. 5). Influx of coarse-grained material may have happened because of increased melt-water production during the final glacier retreat in the fjord, combined with lowered sea level. A possible source for the flows is the coarse-grained ice-contact deposits to the southwest (Fig. 1).

The northwestward inclination of bedding south of the slide scar in unit B possibly delayed groundwater flow towards the southeast before sliding, thus creating a local groundwater 'pool'. However, groundwater flow was possibly enhanced along the strike of these features parallel to the slide scar. This flow pattern is reflected in the present-day drainage pattern of the Fossmoen slide scar (Fig. 3). Here, most active groundwater seepage occurs along the northwestern side of the scar originating from the area northwest of the slide scar (Fig. 1). Creeks in the slide scar merge in a larger creek that presently drains northeast out of the slide scar. It follows from the above that bedding geometries controlling groundwater flow may have had some influence on the oblique orientation of the slide scar relative to river flow. Upward flow of groundwater from the bedrock could add to this effect.

In the lower part of the stratigraphy near the present river level, BH11 displays a relatively thick layer of sensitive clay in the lower part of unit A (Fig. 2). BH001 contains coarser-grained layers at this level, and unit 0 may represent glacial deposits (Fig. 2). The coarser-grained layers possibly enhance groundwater flow, increasing sensitivity of the surrounding clay as commonly described for clay deposits associated with glacial deposits and other coarse-grained sediments over bedrock (e.g. Rankka et al. 2004).

The present study demonstrates that small to meso-scale stratigraphic variations may be important for ground conditions in areas prone to clay slides. Different types of sand layers seem to play different roles for ground water flow. The stratigraphic variations of the deposits are intimately linked to the geological history of the area (Fig. 5). The model for the geological conditions of the Fossmoen slide presented in this paper adds to a general model of quick clay formation. It emphasizes the role played by topography, bedrock and underlying glacial deposits for groundwater movement. The model presented in this paper underlines the importance of the distribution of permeable layers in, and above, stratigraphic successions of clay. The presented model for preferential development of soft, sensitive layers in stratified, fjord-marine, clay-rich deposits is considered applicable to the entire Målselv valley and to other comparable depositional settings.

Conclusions

Investigations of a Holocene clay slide at Fossmoen in Northern Norway give an insight into the long-term landscape history including the development of soft, sensitive layers and groundwater conditions in a sandy terrace prone to sliding.

A geological model for the area explains the distribution of permeable and impermeable layers in clay that are linked to groundwater movement, the development of soft sensitive layers and the clay slide. The model also explains the prerequisites and origin of stratification types and of bedding geometries. The study adds to a general model for the development of sensitive layers in clay. It highlights the role played by topography, bedrock and glacial deposit beds for groundwater movement.

The presented model underlines the importance of the distribution of permeable layers in and above successions of marine clay. It may be summarized in the following points:

- Thin, conformable sand laminae promote a perched water table and horizontal groundwater flow through clay deposits.
- Permeable, coarse-grained layers cutting the laminated deposits promote groundwater flow through the latter. The coarse-grained beds are especially efficient for groundwater flow when in contact with the permeable layers at the land surface.
- Permeable deposits at the land surface promote groundwater flow and leaching of underlying clay deposits.
- Discontinuous beds may locally promote high pore-pressure conditions, especially when inclined sand beds are pinching into clay in a down-dip direction. The oblique orientation of the slide scar is controlled by stratigraphy and the strike of inclined bedding.

The study also presents the internal ground-penetrating radar structure of a scar generated by a flow slide. The slide deposits consist of pockets of relatively coarse-grained deposits in clay being deep near the backscarp. Detachment planes are recorded in the escarpment. The GPR method was not able to detect with confidence the basal sliding plane, but the structures allow an estimation of the volume of the slide. About one third of the slide scar is still occupied by slide debris.

Finally, the study outlines a methodology for reconstructing pre-historic clay-slide conditions. This includes a reconstruction of local sea level history, valley fill history as well as long term landscape degradation by rivers and slides. These parameters are useful when analysing the natural distribution of slides in fjord marine deposits in Målselv valley as well as other comparable depositional settings.

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