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Regional structural analysis of rock slope failure types, mechanisms and controlling bedrock structures in Kåfjorden, Troms.

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Abstract

Unstable areas that produce rock slope failures often come with large consequences. The understanding of why and where they might occur is necessary to mitigate damage and prevent casualties. In Troms County, Northern Norway, a total of 133 unstable rock slopes have been detected so far, evidencing that a great focus on such geohazards is important. This study has focused on seven unstable rock slope areas in Kåfjorden, Troms, with the main focus on analyzing and better explain bedrock structures and their controlling effect on the location and further development of the studied rock slopes. There has also been a focus on whether different trending regional lineaments may have controlled the rock slope failures in Kåfjorden.

This regional study includes five localities on the northeastern side of the fjord and two on the southwestern side of the Kåfjord valley. The Caledonian bedrock of the study area mainly comprises meta-psammites and mica schists with well-developed Caledonian ductile fabrics and post-Caledonian brittle structures. The main foliation varies within the study area, showing a dominant dip towards SW on the northeastern side of the fjord, and NW-dip on the southwestern side of the valley.

The controlling bedrock structures of the failure areas are (i) Caledonian ductile fabrics, (ii) a combination of Caledonian ductile fabrics and post-Caledonian brittle structures, and (iii) post-Caledonian brittle structures. Three of the studied unstable rock slopes comprise backscarps that are foliation-parallel, and are interpreted to be controlled by the foliation alone. Four localities are interpreted to fail due to a combination of fractures and foliation, and one is controlled only by brittle fractures. The failure mechanisms within the study area vary as the controlling bedrock structures of the failures vary.

Four localities are interpreted with the main failure mechanism as slide topple types of failure, while the other localities are classified with other failure mechanisms. The trend of lineaments found controlling are the NW-SE –trending ones, parallel to parts of the fjord of Kåfjorden, and the E-W –trending ones, which trend parallel to the central segment of the fjord. Thus, the SW -dipping foliation and the NW-SE –striking steeply dipping fractures are the dominant controlling structures, with brittle E-W –striking fractures as subsidiary controlling structures of the study area.

Den som gjør ingenting,
gjør ingenting galt.

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I would also like to thank the Norwegian Water Resources and Energy Directorate (NVE) in Manndalen for the transport some of the days in the field. Fieldwork is more efficient with a helicopter than when you hike up to 1200 m.a.s.l. to get good outcrops.

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Maren L. Andresen,
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1 Introduction

1.1 Background of the study

Norway is a country with high and steep mountains and numerous valleys and fjords, forming a dramatic, often over-steepened terrain. This type of immature landscape is especially prone to geohazards, such as frequent rock falls and snow avalanches, and the rarer, but just as dangerous, larger rock slope failures. Rock slope failures have caused some of the greatest natural disasters in Norway throughout the history, such as the ones in Loen (in 1905 and 1936) and Tafjord (in 1934) which resulted in 174 casualties (Harbitz et al., 2014). In total, 33 000 historic landslides are registered in Norway, resulting in 4475 fatalities (Hermanns et al., 2012). A large increase in the frequency of geohazard events is predicted in the future due to a changing and more erratic climate (Jaedicke et al., 2008). A better understanding of why and where geohazards occur, especially those with large consequences such as rock slope failures, is therefore necessary to mitigate damage and prevent casualties.

The failure modes and mechanisms of initiation of rock slope failures are poorly understood and failures can occur due to many contributing factors. Thus, an increased focus on rockslides and -avalanches is important. The Geological Survey of Norway (NGU) began systematic mapping of unstable rock slopes in Norway in 2005 to better understand the more than 300 detected localities (Hermanns et al., 2014). Most of the localities investigated so far are located in Sogn and Fjordane, Møre and Romsdal, Troms and some in Rogaland (Oppikofer et al., 2015). Traditionally, extensive fieldwork has been the most important tool for the understanding of displacement, controlling structures, triggering mechanisms and the driving mechanisms of rock slope failures. More recently, remote sensing data derived from techniques such as InSAR, LiDAR and DGPS have complimented information obtained in the field. Characterization of the hazard using numerical models to predict size, intensity and run-out distances (e.g. RockyFor3D, DAN3D, RocFall, RAMMS etc.) add meaningful detail to the risk analysis process. The traditional methods are not to be disregarded, but should perhaps be complemented with the new mentioned techniques.

Due to the steep mountain slopes in Troms and inherited bedrock structures, numerous mountain slopes susceptible to geohazards exist, with some of great rock fall potential and others especially prone to rockslides. Holmen, a part of Oksfjellet in Kåfjord valley is especially prone to rock falls, and two such events have occurred there within the last five years (2013 and 2016). Boulders up to 5 m in diameter collapsed and destroyed properties. Three other localities adjacent to the study area are considered high-risk objects, and are under permanent monitoring by the Norwegian Water Resources and Energy Directorate. These failure areas are Jettan and Indre Nordnes at Nordnesfjellet east of the Lyngenfjord, and

Gámanjunni 3 in Manndalen. Jettan and Indre Nordnes have been monitored since 2009 and Gámanjunni 3 since 2016 due to their accelerating deformation rate, and the disastrous consequences related to such. Jettan and Indre Nordnes are assumed to form displacement waves as secondary consequences in the Lyngenfjord in relation to slope failures, possibly leading to casualties in many villages along the fjord (Blikra et al., 2009, Böhme et al., 2016). A catastrophic failure at Gámanjunni 3 may also cause severe damage, as the river is expected to be dammed. Subsequently, a lake will form reaching far up the flat valley of Manndalen flooding and causing damage to settlements there. Based on new calculations, subsequent dam burst of this lake is not expected to occur (Bjerke et al., 2018).

1.2 Objectives

The overall objective of the study is to analyze unstable rock slope areas in Kåfjorden, Troms, Northern Norway, in order to better explain different slope failure types, mechanisms and controlling bedrock structures. The high number of unstable rock slopes in Kåfjorden makes this area perfect to address differences and similarities between unstable rock slope sites, and to discuss the possible controlling factors and mechanisms of failure for the chosen localities. This study also aims to get a better understanding of the relationship between regional lineaments in the bedrocks and location of unstable rock slopes in Kåfjorden. The thesis will discuss how (or if) various bedrock structures are the controlling factors for potential failure mechanisms at each locality. The bedrock geology, the internal, ductile Caledonian structures and brittle post-Caledonian (rift-margin) faults of the area are important, and provide a background for comparison with previous work on structurally controlled unstable rock slopes in Troms.

The workflow is to make detailed maps of the selected unstable areas trying to identify the controlling factors for deformation of each locality. The maps are made based on own fieldwork, study of previous published literature (e.g. Husby, 2011, Bunkholt et al., 2013a, Bunkholt et al., 2013b, Bredal, 2016), and the study of aerial photos taken from www.norgeibilder.no in combination with a detailed Digital Elevation Model (DEM). Figuring out why the collapses occur, and the different failure mechanisms, an understanding of the bedrock structures' influence and possible control is crucial.

1.3 Previous work

Records of historical rock slope failures in Troms date back to the 17th century, and as several events have occurred since then, the interest in rock slope failures has increased immensely (Furseth, 2013). Rock slope failures are not only interesting to geologists, but also to the average Norwegian as there can be disastrous damages to settlement and casualties related to it. The Geological Survey of Norway (NGU) began systematically mapping of potential unstable rock slopes in Troms in 2006, and the Norwegian Water Resources and Energy

Directorate (NVE) have been in charge of the mapping since 2009, with NGU performing the mapping. A total of 133 unstable rock slopes have been detected in Troms so far (Bunkholt et al., 2011, Bunkholt et al., 2013a, Hermanns et al., 2014, Oppikofer et al., 2015, NGU, 2018). The mapping of unstable rock slopes in Troms is a cooperation between the Geological Survey of Norway, the Norwegian Water Resources and Energy Directorate, the relevant municipalities of such localities, NORUT and the University in Tromsø – The Arctic University of Norway (UiT). Several master theses have been published as a part of the project by students from UiT on rock slope failures in Troms (e.g. Husby, 2011, Rasmussen, 2011, Eriksen, 2013, Skrede, 2013, Hernes, 2014, Bredal, 2016). The master projects done on Nomedalstind (Husby, 2011) and Oksfjellet (Bredal, 2016) are of particular interest in this master thesis, and presented in chapter 5.

Several papers and reports have been written about localities in Kåfjorden with focus on results from mapping, monitoring and risk classification of the unstable rock slopes, as there are great consequences related to such (e.g. Bunkholt et al., 2011, Devoli et al., 2011, Øydvin et al., 2011, Bunkholt et al., 2012, Bunkholt et al., 2013a). As the focus of this project includes rock slope failures' relation to the regional lineaments in Northern Norway, several papers on this topic are of interest. This includes e.g. Dehls et al. (2000) who discusses the interpreted neotectonic post-glacial Nordmannvikdalen fault and Bunkholt et al. (2013b)'s paper on some of the localities investigated in this project. The paper by Redfield and Hermanns (2016) is also interesting as they rejects the Nordmannvikdalen fault as a neotectonic feature.

1.4 Definitions

Table 1 - Table of important terms and their definitions used in this thesis.

Term	Definition
Backthrust	A thrust oriented oppositely to the direction of thrusting (Bergh et al., 1997).
Conjugated fractures	Fracture sets intersecting at an angle of approximately 60° (Fossen, 2016).
Column	Single column of intact bedrock.
Creep	Extremely slow displacement of soil material (Hungr et al., 2014).
dGPS	Differential Global Positioning System.
DSGSD	Deep-seated gravitational slope deformation. A very large slow-moving gravitational landslide (Agliardi et al., 2013).
Failure	Most significant displacement event, which develops a sliding surface, or zone (Hungr et al., 2014).
Fracture	Discontinuity with spacing perpendicular oriented to the strike (Kearey, 2001). Will use the term '*fracture*', not '*joint*' in this thesis.
Graben	Downfaulted segment between two faults or fractures (Kearey, 2001).
InSAR	Interferometric Synthetic Aperture Radar.
LIDAR	Light Detection and Ranging.
Lineament	Morphological linear feature of structural or tectonic origin.
Morphostructure	Geomorphological feature of structural or tectonic origin, e.g. scarp or graben (Agliardi et al., 2001).
Permafrost	Ground temperature below the freezing point for two or more consecutive years (Péwé, 1983).
Retrogressive displacement	Failure surface and possibly backscarp propagating backwards (Agliardi, 2012).
Thrust fault	A fault bounding thrust sheet, common in fold-and-thrust belts (Boyer and Elliott, 1982).

2 Study area

This chapter will present the location of the study area, and briefly describe it. Information on climate and weather is included, as well as a presentation of the regional geology in Troms, where the Caledonian nappes within the study area are emphasized. Post-Caledonian brittle structures are important to consider in relation to the aims of this study, and a presentation is given on the regional lineaments appearing within the study area.

2.1 Location

The study areas in this thesis are located east in Troms county in Kåfjorden, which is a sub-fjord of the greater Lyngenfjord (Fig. 1). Kåfjorden has an irregular orientation; from north to south, the fjord changes from NW-SE -trending, to E-W, and NW-SE again in the south (Fig. 1 and Fig. 2). The localities include selected unstable rock slopes with variable degree of deformation located on both the northeastern side of the fjord and southwestern side of the valley. The topography is typically alpine with steep cliffs and mountain slopes closest to the fjords exceeding 1000 m.a.s.l., deep and narrow valleys and numerous smaller side valleys and cirques. Above ca. 1000 m elevation, the mountains are rather flat and less dramatic, with the Lyngen Peninsula as an exception (chapter 2.3.3). East of the Kåfjord valley, the terrain flattens out at approximately 800-1000 m.a.s.l. and appears as a plateau towards Finland.

The selected localities in Kåfjorden are chosen based on different geological and structural factors. For example, areas within different units of the Caledonian nappes were studied and compared with each other. The chosen localities comprise both sides of the valley, and were chosen based on presumed different failure mechanisms, and some key locations identified by the NGU. The areas studied include Nordmannviktind, Gavtavárri, Nomedalstind, Rismmalčohkka, Badjánanvárri, Ruovddášvárri Oksfjellet and Langsnøen. The first five of these areas are located on the northeastern side of the Kåfjord and the valley, while Oksfjellet and Langsnøen are located on the southwestern side of Kåfjorden valley (Fig. 2).

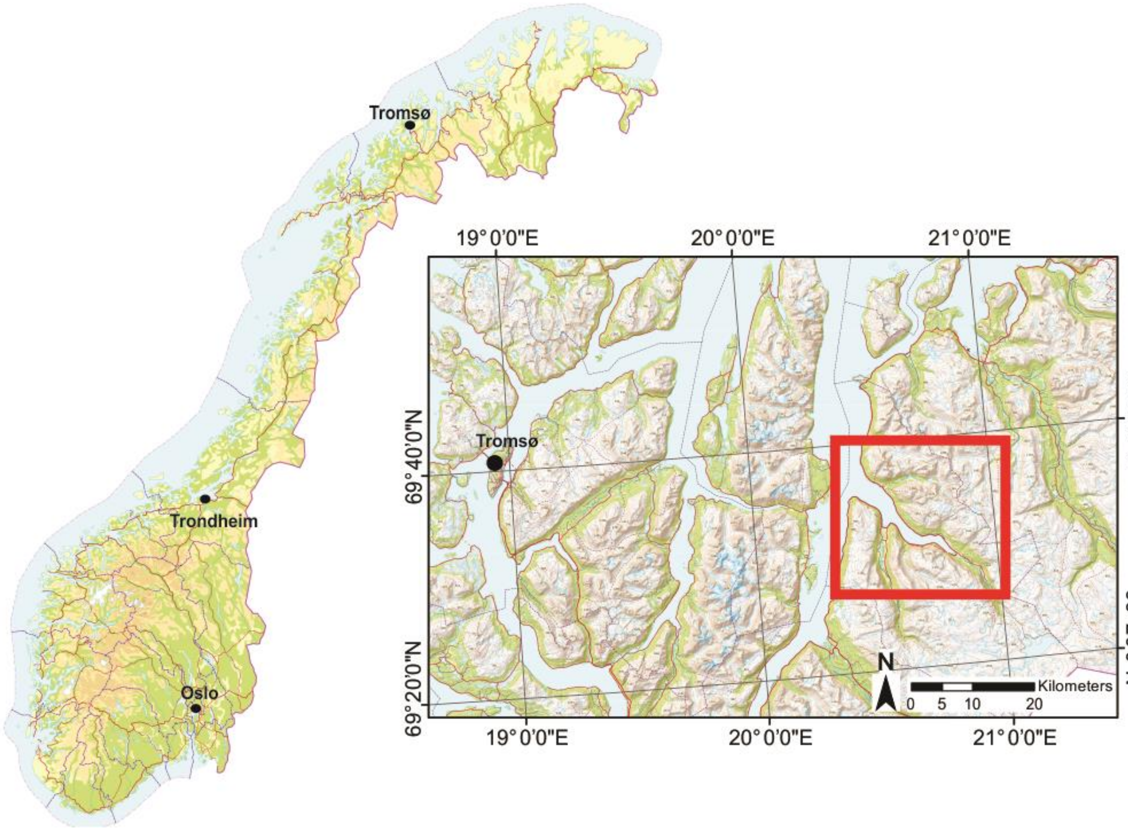

Fig. 1 - Map of Norway and central Troms. Tromsø is located to the left in the zoomed in figure, while the study area, Kåfjorden, is located within the red box to the right.

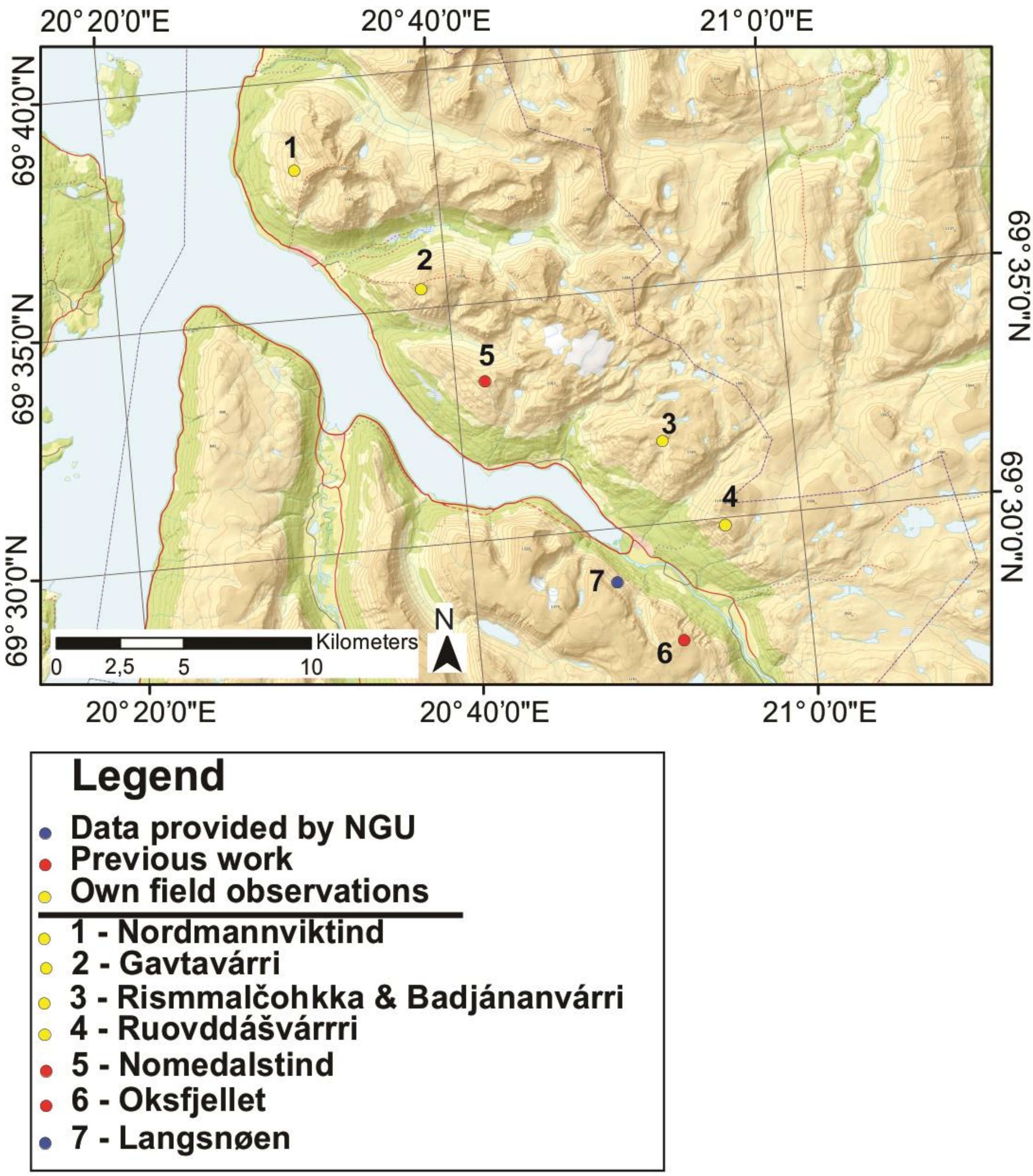

Fig. 2 - Map indicating the location of the studied areas. Yellow dots represent localities investigated during fieldwork, while red dots are localities presented based on previous work. Blue dot (Langsnøen) represents the locality where data provided by the NGU is presented.

2.2 Climate and weather

Troms County has a highly variable topography (Fig. 1 and Fig. 2). Among other factors, this varying topography gives great climatic differences between the inland and the coastal areas. Thus, amounts of precipitation vary, with an average of 300-600 mm in the sheltered areas inland, and an average of up to 1000-1500 mm annually along the most vulnerable areas along the coast. The temperatures in Troms are moderate, with July as the warmest month with an average of approximately 12°C both inland and along the coast. The winter months, December, January and February, are the coldest and the greatest differences between inland and coastal areas in average temperatures are observed, approximately -12°C vs -3°C, respectively (Dannevig, 2009).

Kåfjorden is located in the inner parts of Troms County, thus experiencing a low amount of precipitation relative to other places in Norway. The temperatures are relatively low, and investigations have established presence of permafrost in the area. The permafrost limit is located at approximately 990 m.a.s.l. in the coastal areas, while it is detected as low as 550 m.a.s.l. in the inland. In the study area of Kåfjorden permafrost may be sporadic and/or discontinuous, as it locally has been found at 600-700 m.a.s.l. in Troms (Blikra and Christiansen, 2014, Gisnås et al., 2017).

The effects water and permafrost may have on unstable rock slopes is further discussed in chapter 6.3.

2.3 Regional geology

In the coastal areas of Troms, Precambrian basement rocks outcrop as part of the Western Troms Basement Complex (WTBC), which is mainly comprised of tonalities, gneisses and intrusive rocks (Zwaan, 1995, Bergh et al., 2010). The central parts of Troms are dominated by Caledonian thrust nappes which are presumed to have been thrusted over the WTBC (Zwaan, 1995, Corfu et al., 2014). The contact between the Precambrian basement rocks and the Caledonides is considered a Permian rift-related normal fault system, the Vestfjord-Vanna Fault Complex (Doré et al., 1997). Rift-related brittle structures, such as faults and fractures, formed in relation to the collapse of the Caledonian mountains and subsequent extensional phase(s) of the opening of the Atlantic Ocean in the Cenozoic. In addition to these tectonic events, the landscape within the study areas of Kåfjorden and the rest of Northern Norway is highly affected by the many glacial erosional events and processes that occurred in Pleistocene. Typical glacial geomorphological features within the alpine landscape such as cirques, U-shaped valleys, and narrow and deep fjords are all common in Northern Norway and dominate in the study area (Ramberg, 2008).

2.3.1 Caledonian ductile structures

The Caledonian thrust nappes in Scandinavia comprise four different tectonic units, also called allochthons; Lower, Middle, Upper and the Uppermost allochthon. Generally, metamorphic grade and transport distance increase upward and westward in the allochthons (Ramberg, 2008). The nappes were thrusted east- and southeastward onto the Baltic shield during the Caledonian orogeny in Early Palaeozoic along ductile thrust faults. The orogeny was initiated by subduction of oceanic crust, leading to the final closure of the ancient Iapetus Ocean by the end of Silurian (McKerrow et al., 2000, Gee et al., 2008).

The Lower and the Middle allochthon in Troms consist of, successively bottom to top, Gaissa Nappe (Lower allochthon) and the Kalak- and Målselv Nappes (Middle allochthon) (Fig. 3). The rocks are mainly sedimentary, later low-grade metamorphosed, with the Kalak Nappe Complex of a higher metamorphic grade than the Gaissa Nappe (Lower allochthon), and show greater internal deformation (Andresen, 1988). The Upper allochthon consists of two nappe complexes, tectonostratigraphically bottom to top, Reisa Nappe Complex and the Lyngen Nappe Complex. The Reisa Nappe Complex comprise the Vaddas-, Kåfjord- and the Nordmannvik Nappes (further described below). The Lyngen Nappe Complex is made up by, bottom to top, the Lyngen gabbro/ophiolite and the Balsfjord group (Fig. 3). The Lyngen gabbro is considered old oceanic crust, as it includes parts of an ophiolite sequence, overlain by the sedimentary rocks of the Balsfjord group. The Lyngen Nappe Complex is located west of the study area (Andresen, 1988, Ramberg, 2008, Corfu et al., 2014). The Uppermost allochthon consists of the Tromsø Nappe that mainly comprises metasediments, as well as mafic and ultramafic rocks. This nappe is of high-grade metamorphic character with presence of garnet amphibolites and eclogites, (see e.g. Ravna et al., 2006).

The Lower and the Middle Allochthon are considered Baltica-derived, while the Upper Allochthon is derived from the Iapetus Ocean, as evidenced by the Lyngen Ophiolite, and is considered a 'suspect terrane' (Andresen, 1988). The Uppermost Allochthon is inferred to be of exotic terrane derived from the Laurentian Margin, as evidenced by the eclogite on the top of Tromsdalstind in Tromsø county (Fig. 3) (Andresen, 1988, Ramberg, 2008).

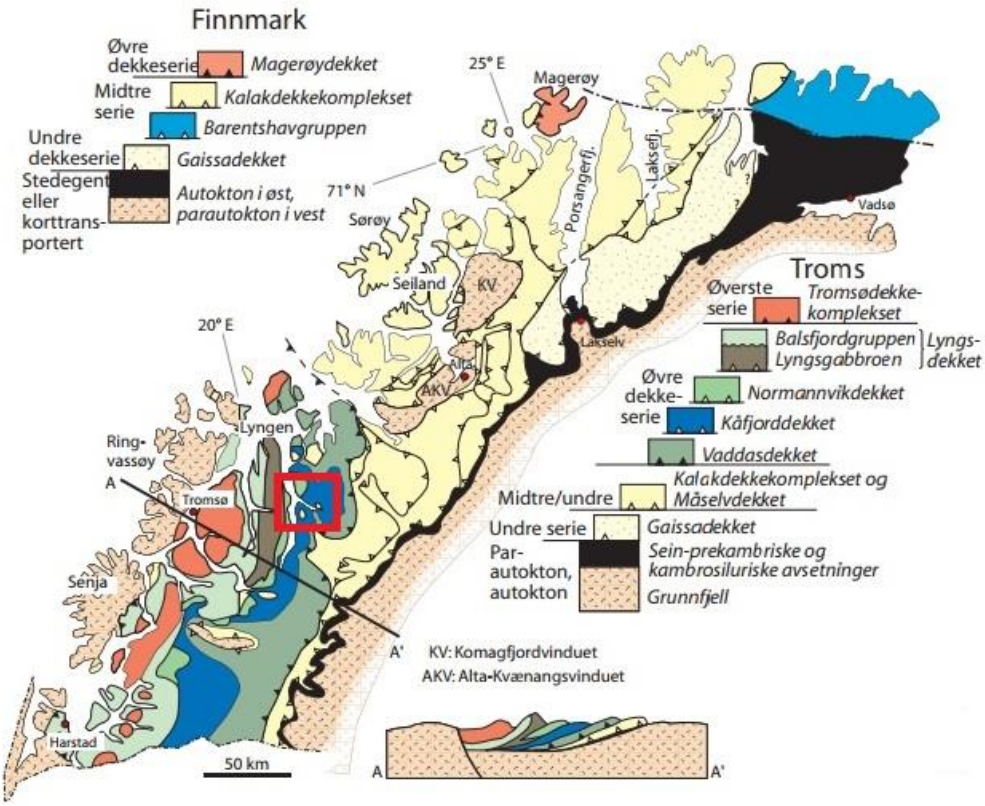

Fig. 3 - Map showing the Caledonian nappes in Troms and Finnmark, where the legend describes to which allochthon the nappes belong. The study area, marked with a red square, is in the Upper Allochthon. Modified after (Ramberg, 2008).

In the study area, only rocks of the Upper Allochthon are present, named the Reisa Nappe Complex, which shows a change from low-grade metamorphic schists and meta-psammites in the lower parts to higher grade gneisses and amphibolites upwards (Fig. 3) (Corfu et al., 2014). The Vaddas Nappe consists of meta-volcanic and sedimentary rocks of late Ordovician to early Silurian age, metamorphosed in greenschist to lower amphibolite facies. Main rock types include amphibolites, amphibolitic schists, marbles and quartz-feldspathic schists (Andresen, 1988, Lindahl et al., 2005). The Kåfjord- and Nordmannvik Nappes further west and stratigraphically overlying the Vaddas nappe are of higher metamorphic grade. Sedimentary rocks, such as marbles, mica-rich schists and gneisses, dominate in both of these nappes. The Kåfjord Nappe rocks are mainly metamorphosed in middle to upper amphibolite facies, locally up to granulite facies as evidenced by migmatites. As for the Nordmannvik nappe, middle to upper amphibolite facies metamorphic rocks dominate with traces of higher-grade rocks

(Andresen, 1988, Faber, 2018). The study area comprise rocks from the Kåfjord- and Nordmannvik Nappes.

During the Caledonian orogeny, the four allochthons were thrusted along ductile thrust faults making it an imbricated foreland fold- and –thrust belt (Northrup, 1996, Gee et al., 2008). The Upper and Uppermost allochthons were thrusted onto Baltica, while the Lower and Middle are Baltica-derived. The ductile thrust faults separate each nappe, and a high degree of deformation along the contacts is commonly displayed as shear zones with various mylonitic rocks (Northrup, 1996, Faber, 2018). Due to the Caledonian orogenic formation, structures likely to find in the remnants of it are mylonites, isoclinal to open asymmetric folds, thrusts and back-thrusts, boudines, lenses and sigma clasts, where some of these elements can be interpreted and used as kinematic indicators (Zwaan, 1988). Due to the east- and southeastward thrusting, units often show large-scale isoclinal and open asymmetric folds and a well-developed foliation. It is particularly in the schistose units the foliation is well developed and –preserved, which is one of the most common rocks in the study area (Gee et al., 2008, Corfu et al., 2014). The ductile Caledonian foliation is especially important regarding unstable rock slopes, and is therefore explained further in chapter 3.1.2.

2.3.2 Post-Caledonian brittle structures

Post-Caledonian brittle structures in Troms are frequent, such as the many fjords and basins following major faults, as well as structures down to millimetre scale, e.g. fractures. The structures originate from the collapse of the Caledonian orogeny, multiple rifting- and extensional episodes later in the Palaeozoic and from the opening of the Atlantic Ocean during the Mesozoic and Cenozoic. The brittle lineaments onshore and offshore mainly trend NE-SW and ENE-WSW, with NW-SE as subordinate orientations, and are traceable from Finnmark southwards to the Lofoten-Vesterålen margin (e.g. Gabrielsen et al., 2002, Bergh et al., 2007, Faleide et al., 2008, Indrevær et al., 2013).

The Lofoten-Vesterålen margin is characterized by a series of steeply dipping NNE-SSW and NE-SW -striking lineaments with horsts mainly onshore and grabens offshore exposed as fjords, i.e. the Vestfjorden basin. Three extensional events are suggested by Bergh et al. (2007). The oldest event is of Permian-Jurassic age, forming NNE-SSW –striking normal faults dipping ESE and WNW offshore due to WNW-ESE –oriented extension followed by NNW-directed oblique-extension. The next event is of Early to late Cretaceous age, forming the NE-SW to ENE-WSW-striking oblique normal faults. The latter is of Late Cretaceous to Palaeogene age producing NE-SW –striking faults offshore with conjugate WNW-striking shear fractures onshore, as a result of the opening of the Atlantic Ocean (Norwegian-Greenland Sea). A regional zigzag pattern (Fig. 4) of the faults is formed onshore and offshore in the narrow

Lofoten-Vesterålen margin with asymmetric half-graben structures (Bergh et al., 2007, Faleide et al., 2008).

The West Troms margin comprises the planar Vestfjorden-Vanna Fault Complex and the listric Troms-Finnmark Fault Complex which both strike NE-SW, dipping SE-ward. Whereas the onshore faults mainly comprise normal faults trending NNE-SSW and ENE-WSW, similar to those of the Lofoten-Vesterålen margin (Fig. 4). These fault complexes form a major horst that comprises several islands on the margin, e.g. Senja, Kvaløya and Ringvassøya, named the West Troms Basement Complex, which is an uplifted exhumed basement horst (Fig. 4). Onshore brittle faults in the Western Troms margin mainly appear as NNE-SSW and ENE-WSW trending normal faults, similar to the Lofoten-Vesterålen margin (Fig. 4) (Indrevær et al., 2013).

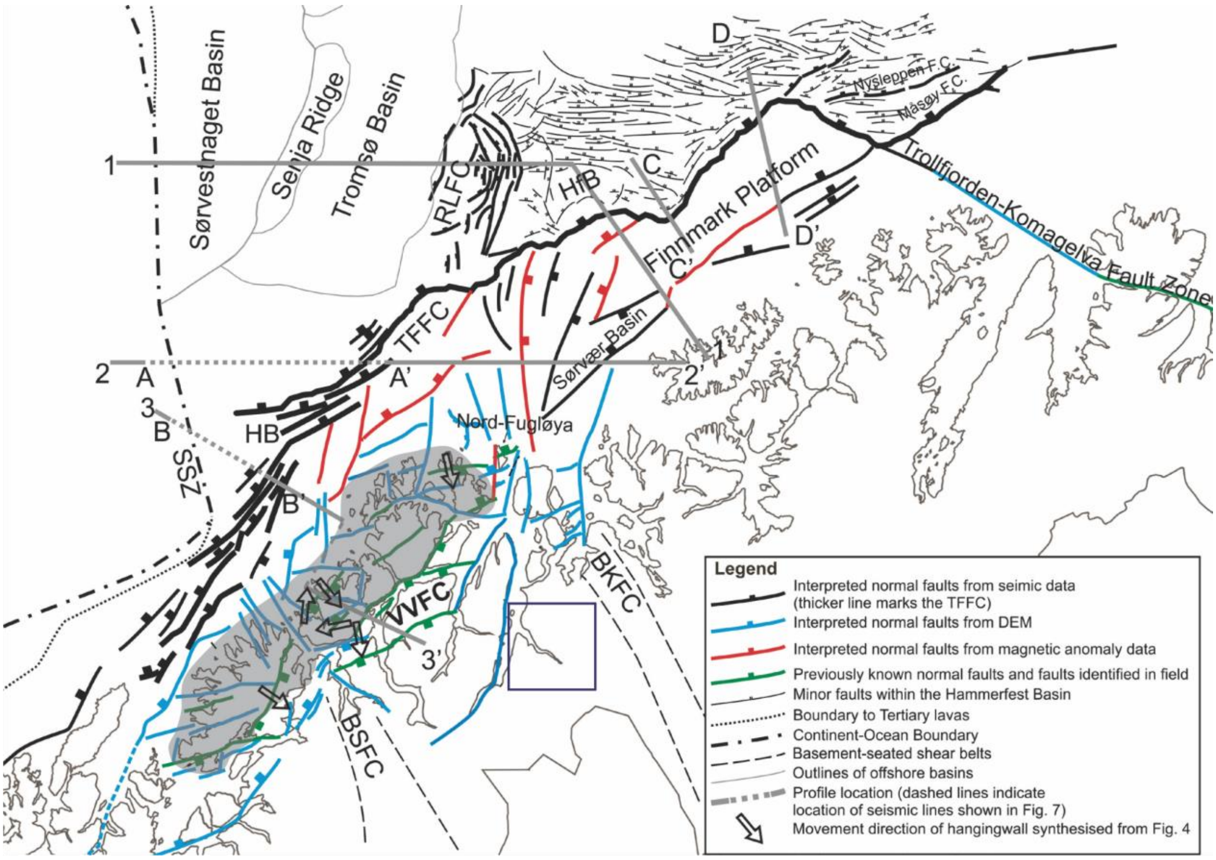

Fig. 4 - Regional map of the main faults on the SW Barents Sea margin. The grey, transparent area comprises the WTBC, while the blue box indicates the location of the study areas. BKFC - Bothnian-Kvænangen Fault Complex, BSFC - Bothnian-Senja Fault Complex, RLFC - Ringvassøy-Loppa Fault Complex, SSZ - Senja Shear Zone, TFFC - Troms-Finnmark Fault Complex, VVFC – Vestfjorden-Vanna Fault Complex. Modified after Bergh et al. (2010) and Indrevær et al. (2013).

2.3.2.1 Post-Caledonian lineaments in the study area

The study areas in Kåfjorden are located east of the N-S –trending Lyngenfjorden (Fig. 1 and Fig. 2). Kåfjorden trends NW-SE, locally altering to E-W –trending in the central part, with the Kåfjorden valley to the south trending NW-SE (Fig. 1). In central Troms, the larger structural lineaments dominantly trend NNE-SSW to N-S, e.g. Lyngenfjorden and Ullsfjorden, NE-SW, e.g. Breivikeidet and Straumsfjorden, E-W to ENE-WSW, e.g. across Reisadalen and westward toward Kåfjorden, and from Lyngenfjorden to Manndalen, and NW-SE e.g. in Rotsunddalen, and the Nordmannvikdalen fault/feature (Fig. 5) (Zwaan, 1988).

The Nordmannvikdalen fault/feature is a topic of debate, where Dehls et al. (2000) describes the fault/feature as a normal fault exposed for approximately 2 km parallel to the Nordmannvik valley with an offset up to 2 m of neotectonic origin. Redfield and Hermanns (2016), on the other hand, describes the Nordmannvikdalen fault/feature as a scarp that certainly is *not* of neotectonic origin, but either a surface expression of a deep-seated gravitational slope deformation, DSGSD, or a creep of topsoil, as the scarp entirely consists of intact soil. The other post-glacial fault in Northern Norway, the Stuoragurra fault, strikes NE-SW- to NNE-SSW, and can be traced for 80 km in discontinuous sections (Dehls and Olesen, 1999). This fault strikes parallel to other post-glacial faults in Fennoscandia, e.g. the Pärvie fault in Northern Sweden. The Stuoragurra fault and the other NE-SW- to NNE-SSW –striking post-glacial faults are considered reverse faults (Wu et al., 1999).

The Lyngen peninsula is along the northeastern side characterized by steep slopes of "… aligned, triangular faceted spurs that dip straight into the fjord and that resemble those commonly observed along active normal faults" (Osmundsen et al., 2010). Based on InSAR data, Osmundsen et al. (2010) concluded that the Lyngen peninsula is bound by brittle faults, and that the peninsula itself comprises the footwall of a normal fault. The areas east of the Lyngen peninsula and the Lyngenfjord, the hanging wall of the proposed fault, is subsiding by a few millimetres per year relative to the horst the peninsula represents (Osmundsen et al., 2010).

The study by Osmundsen et al. (2010) on the relationship between alpine topography and tectonics in Norway suggests faulting onshore has led to the formation of densely spaced pre-glacial fluvial patterns. The glaciers later followed these pre-glacial V-shaped fluvial patterns, forming U-shaped valleys and cirques. Regarding the study area, several sub-valleys join the large Kåfjord valley and fjord, possibly following traces of post-Caledonian faults.

The post-Caledonian lineaments mapped out within the study area are presented in Fig. 46 in chapter 5.8. Those interpretations are based on literature, own field observations and studies of detailed DEM's and aerial photos.

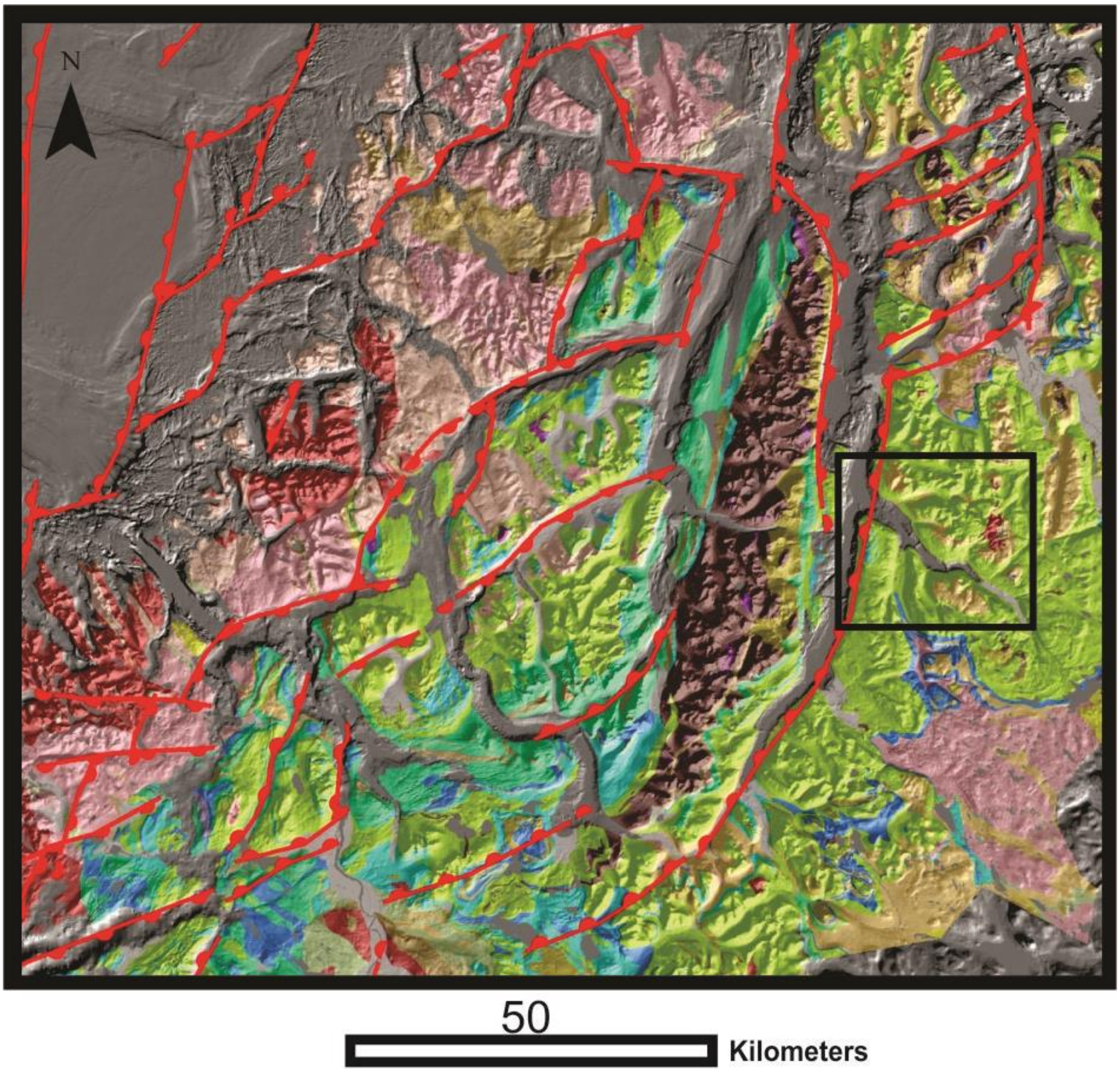

Fig. 5 – Map of the regional lineaments in Troms. The black box indicated the location of the study area of Kåfjorden. Modified after (Hansen et al., 2011).

2.3.3 Quaternary geology

Over the Quaternary period, glaciations and interglaciations have affected the topography of Norway by means of erosion, carving and sedimentation (Olsen et al., 2013). An alpine landscape with all its common elements is descriptive of the topography in Norway, and particularly for Troms and within the study area of Kåfjorden.

The last glacial maximum (LGM) dates to approximately 25 000 – 18 000 years before present (B.P.) in Troms (Olsen et al., 2013). The land is currently still rising to obtain isostatic equilibrium due to glacial retreat. After the LGM, several re-advances and retreats of the ice occurred, as evidenced by moraines. In Troms, some of these events are the Yngre Dryas event (11 000 – 10 000 B.P.), Ørnes event (9 800 – 9 900 B.P.) and Skibotn event (9 500 – 9 600 B.P.) (Corner, 1980, Dehls et al., 2000, Ramberg, 2008).

During glaciations, mountain slopes and valleys experience high degree of erosion, leading to oversteepening and deepening, respectively. Pre-existing bedrock structures may enhance the erosion if orientations are favourable, and as a result of the erosion, the internal stress within the rocks will increase. After a glacier retreats, the steep slopes remain, and the increased stress may exceed the rock strength, destabilizing the oversteepened slopes. The retreat of the ice also removes the support and the pressure previously exerted on the bedrock, leading to a release of energy commonly along the pre-existing bedrock structures of favourable orientations. This is known as debuttressing, and may destabilize the rock slopes by development of a tensile stress in the pre-existing structures. Isostatic rebound after large ice sheets retreat may further destabilize the eroded oversteepened slopes by increasing the relief of the rebounding area. All of these processes destabilize the rock slopes, and may lead to different types of failures such as rock avalanches, rockslides or rock falls (Ballantyne, 2002, McColl, 2012, Böhme, 2014).

The possible control deglaciation may have on rock slope failures is further discussed in chapter 6.3.

3 Theory

Several different types of failures in rock may occur depending on different controlling factors present, such as bedrock structure, rock strength and water content. In this chapter, there will be an overview on the controlling bedrock structures of rock slope failures types. Further, a brief section on common geomorphological features will follow, and the main characteristics of different rock slope failure types from literature are presented.

3.1 Structures controlling rock slope failures

Geological structures, such as ductile foliation and folds, and brittle faults and fractures, are known to decrease or increase the stability of rock slopes depending on orientation in space relative to the unstable slope, and deformation history (Saintot et al., 2011, Stead and Wolter, 2015). The bedrock in the study area of Kåfjorden dominantly comprises metamorphosed Caledonian rocks, with a commonly well-developed Caledonian foliation and post-Caledonian brittle fractures.

3.1.1 Lithology

Different lithologies within an unstable rock slope may decrease or increase the stability of an unstable area. A lithological contact is a discontinuity that can act as a plane of weakness, and may enhance failure, especially if this contact daylights in the slope (Stead and Wolter, 2015). Tectonic activity influencing the rocks may further decrease the stability as this often forms new bedrock structures, e.g. faults, foliation, folds, etc. Based on mineral content within the lithologies, formation of a sliding surface will be more probable in layers enriched in anisotropic minerals, such as micas, which are common within the study area (Zwaan, 1988, Henderson et al., 2006, Stead and Wolter, 2015). Schistose rocks with a high mica content are found to have friction angles varying between 20-27° (Wyllie and Mah, 2004). Mineral banding and gneiss foliation, for instance, cause a lower shear strength within the bedrock, and are found to be especially susceptible to the formation of sliding surface (Henderson et al., 2006).

3.1.2 Foliation

Foliation, a metamorphic planar fabric, is often closely related to unstable rock slopes in metamorphic rocks due to its anisotropy. The rocks within the study area generally have a well-exposed SW-ward dipping (ca 30-35°) foliation, and the foliation-parallel shear zones/thrust faults of Caledonian origin, and therefore is nearly slope-parallel in five of the seven localities (Zwaan, 1988). Foliation may dip parallel, obliquely or perpendicularly to a sliding surface, thus accommodating different failure mechanisms, e.g. planar sliding with slope-parallel foliation, or toppling with oppositely dipping foliation (Stead and Wolter, 2015).

A study from Møre and Romsdal shows rock slope failures with foliation dipping towards the valley or the fjord commonly comprise sliding surfaces parallel to the foliation (Henderson et al., 2006).

3.1.3 Folds

Large-scale folds have been mapped within the Caledonian bedrock of the study area of Kåfjorden (Zwaan, 1988). As folding occurs, discontinuity sets may form parallel to and radially out from the fold axis as tensile fractures, and as bedding-parallel fractures that may enhance sliding (Badger, 2002). The folding of the Caledonian rocks occurred at depth, thus apparent fold-related fractures are not likely to have formed during the folding of the rocks, nor are they expected to be found within the study area (Zwaan, 1988). Failures within the study area that are related to folds are therefore considered related to sliding along near slope-parallel foliation of a limb and/or along the axial surface of folds (Hermanns and Longva, 2012). Isoclinal, recumbent and asymmetric overturned, variably plunging folds are related to the main thrusting (shortening) event, while upright folds are more gentle and open, and have undergone less deformation. Several phases of folding in different directions cause even more complex bedrock deformations (Stead and Wolter, 2015).

3.1.4 Faults and fractures

As described in chapter 0, not many major brittle faults exist within the area of focus, but the presence of certain types of faults may steepen the slopes, thus inducing instability of the slopes (Stead and Wolter, 2015). The Lyngenfjorden normal fault along the eastern side of the Lyngen peninsula exposes the fault surface dipping straight into the fjord, confirming its effect on landscape/mountain slopes (Osmundsen et al., 2010). It has been suggested that the alpine topography of Norway is highly influenced by faults, e.g. valleys and fjords following trend of faults. If the valleys and fjord within the study area are, in fact controlled by faults, reactivation of these faults may lead to an oversteepening, destabilization and formation of (more) unstable rock slopes in Kåfjorden (Henderson et al., 2006, Osmundsen et al., 2010). Faults may behave as structural controlling features of unstable rock slopes, either alone or in combination with other structures such as foliation or fractures. Faults intersecting with these structures may form different types of failure mechanisms, e.g. wedge failure, which was concluded for one of the areas studied at Middagstinden in Møre and Romsdal by Krieger et al. (2013).

Brittle fault zones often comprise fault gouge or –cataclasite, which have lower rock mass strength than intact bedrock (Stead and Wolter, 2015). If orientation of the fault is favourable relative to a slope, a possible sliding along the fault may occur, due to presence of the weaker, crushed rocks.

Fractures are alone able to control rock slope failures, as well as in combination with other structures such as lithological contacts or foliation (Wyllie and Mah, 2004). The backscarps of unstable rock slopes do often follow pre-existing fractures inherited in the bedrock formed during e.g. extensional events, and opening of the backscarps may occur due to later tension exerted on the slopes (chapter 2.3.2) (Henderson et al., 2006). Some failures can be controlled by fractures, e.g. a wedge failure with two intersecting fracture surfaces. Fractures may delimit and control local collapses internally within an unstable area where orientation and frequency of the fractures are favourable (Goodman and Bray, 1976, Wyllie and Mah, 2004, Saintot et al., 2011, Hungr et al., 2014).

3.2 Geomorphological features

This chapter will briefly introduce common geomorphological features observed on unstable rock slopes, and their possible and relevant relation to structural features inherited in the bedrock. Geomorphological features can be surface expressions of the underlying tectonic structures and their geometries, and are called *morphostructures* (Agliardi et al., 2001).

The *backscarp* is the uppermost back-bounding delineation of an unstable rock slope. A backscarp may follow pre-existing structures in the bedrock, e.g. a foliation surface, along strike of one orientation of fractures, or a combination of several fracture sets oriented differently. The backscarp may expose the sliding surface of a failure, or be covered by talus material, where the latter is common for the lower parts of a backscarp (Saintot et al., 2011).

Scarps are morphostructures dipping downslope that may form due to local collapses within an unstable area along pre-existing bedrock structures, e.g. sliding along a fracture surface. Scarps may delimit further collapse within an unstable area, and lateral scarps delimiting collapses may be considered *sidescarps*. A scarp dipping oppositely to the direction of failure and the backscarp is considered a *counterscarp* (Agliardi et al., 2001, Crosta et al., 2013).

Terraces are horizontal to sub-horizontal areas within unstable rock slopes that often show little deformation and comprise (partly) intact bedrock. Terraces may form due to down-faulting or sliding along structural surfaces, and are commonly delimited by scarps (Kearey, 2001).

Ridges and depressions: A ridge is an elongated body slightly elevated relative to the surroundings commonly composed of (partly) loose material. They may form due to collapse or opening of fractures as material is compressed in front. *Depressions* are features slightly lowered relative to the surroundings, often linear in shape and may be considered morphostructures as they often are surface expressions of fractures. Ridges and depressions are often located in vicinity to one another where the depression has formed due to e.g. opening of a fracture, and material downslope has been compressed resulting in a ridge (Henderson et al., 2006, Sigmond et al., 2013).

Talus is considered as all loose, disintegrated bedrock material deposited downslope of the unstable area, often concentrated in lobate shapes. The material varies in size from e.g. 10 cm up to several meters (boulders). The largest particles are often deposited in the lower parts or below the lobes, as they have higher potential energy (Saintot et al., 2011).

Rock glacier is a slow-moving lobate talus deposit that is fed with material from upslope of the glacier. It may or may not contain ice, and as for the study area, the rock glaciers are considered of non-glacial origin, where the ice is considered present due to permafrost (Tolgensbakk et al., 1988, Berthling, 2011).

3.3 Classification of rock slope failure types

This subchapter will form the basis for the classification of the failure types of each locality based on the results (chapter 0). The different rock slope failure types are presented with their individual key information. Rock slope failures, in general, may be classified and described differently based on focus, e.g. by volume, displacement mechanism or velocity. In this thesis, the focus is on the internal bedrock structures and morphological structures.

Glastonbury and Fell (2010) present schematic cross-sections of eight different types of rock slope failures based on case studies of 51 historical events of large rapid rockslides. Hermanns and Longva (2012) adapted this classification to the geological conditions in Norway, mainly igneous and metamorphic rocks, to further add two more mechanisms first introduced by Braathen et al. (2004). An amalgamation of categories from these three papers and their presented theory on structurally controlled rock slope failures is the basis for the discussion in this thesis (Fig. 6). The only category excluded in this review is the ‘collapse slump compound slide’, as it has not been observed in Troms.

3.3.1 Translational landslides

A translational slide usually has a structurally controlled sliding surface. This is a planar structure, e.g. bedding or foliation, that is a pre-existing structure within the failure area formed due to deformation. Glastonbury and Fell (2010) found rainfall to be a common trigger for such rock slope failures, and there is a low degree of internal disruption and fracturing prior to collapse. There are four main types of translational slides: large rock glide, rough translational slide, planar translational slide and toe-buckling translational slide.

A *large rock glide* usually consists of a large rock mass with high normal stress on a low-angled sliding surface with inclination equal to the angle of friction of the sliding masses (Fig. 6a).

A *rough translational slide* will have the sliding surface following fractures dipping outward the slope or near parallel to it, with internal bedrock structures, e.g. foliation, dipping inward the mountain slope (Fig. 6b).

A *planar translational slide* has planar bedding or major structures dipping outward at approximately 20-30° as the sliding surface, and does often comprise less rock masses than a large rock glide (Fig. 6c).

Toe-buckling translational slides have local buckling at the toe of the failures as the sliding surface has a lower angle at the toe than in the rear parts of initiation. The sliding surface does not daylight (Fig. 6d).

3.3.2 Internally sheared compound landslides

Internally sheared compound landslides do typically have a sliding surface with defects or irregularities downslope, such as faults or fracture sets. Earthquakes may provide the most common triggering effect, although not limited to compound slides. The rock mass of the failures often appears with a high degree of internal disruption and fracturing prior to collapse. Four types of internally sheared compound slides were classified; bi-planar compound slide, curved compound slide, toe buttress compound slide and irregular compound slide (Glastonbury and Fell, 2010).

A *bi-planar compound slide* has two dominant structures dipping differently. The structures intersect outwards which may form a wedge collapsing along a steeper dipping discontinuity in the upper part, and a shallow-dipping discontinuity in the lower parts (Fig. 6e).

A *curved compound slide* consists of a folded sliding surface where the dip of the upper part is larger than the angle of friction and the dip of the lower part is smaller than the friction angle, similar to bi-planar compound slide (Fig. 6f).

A *toe buttress compound slide's* sliding surface is at least 10° steeper in the rear parts than at the toe where buttressing of the rock masses occur (Fig. 6g).

An *irregular compound slide* has an irregular sliding surface, i.e. along folded bedding, with large variations of inclination (e.g. from 5° to >50°) (Fig. 6h).

3.3.3 Rock fall slides

A rock fall slide occurs where the slopes are steep, and internal structures, such as fractures, dip steeply outwards sub-parallel to the slope gradient. As the fractures may daylight in the slope, the friction between the block and the intact bedrock is the only force keeping the block in place. A collapse will occur when the driving forces overcome the frictional forces along the fracture surface, allowing columns/blocks to slide along the fracture surface (Braathen et al., 2004) (Fig. 6i).

Wedge failures are in this project considered a subordinate type of translational slide, but are similar to rock fall slides, and therefore described here. As a rock fall slide is controlled by *one* discontinuity daylighting in the slope, a wedge failure is controlled by *two* intersecting discontinuities. These discontinuities, e.g. fractures, intersect at a line with a dip greater than the angle of friction, 50-55° vs 35-40°, respectively, and the intersecting line dips gentler than the slope it surfaces in (Wyllie and Mah, 2004, Hungr et al., 2014).

3.3.4 Slide topple

A slide topple is a failure mechanism in a steep slope with steeply dipping to sub-vertical fractures, and a pre-existing outward dipping bedrock structure, e.g. foliation. The steeply dipping to sub-vertical fractures separate several blocks, leading to an outward rotation of the outermost blocks that eventually may collapse, referred to as toppling. A slide topple is complimented by a plane dipping outward, e.g. foliation, that detaches the blocks from the intact bedrock, and enhances sliding along such a plane, which is the key feature separating rock fall slides and slide topples (Fig. 6j) (Goodman and Bray, 1976, Braathen et al., 2004). This failure mechanism is what Braathen et al. (2004) classifies as a “complex field with planar fault geometry resulting in domino-styled block configuration” (Braathen et al., 2004).

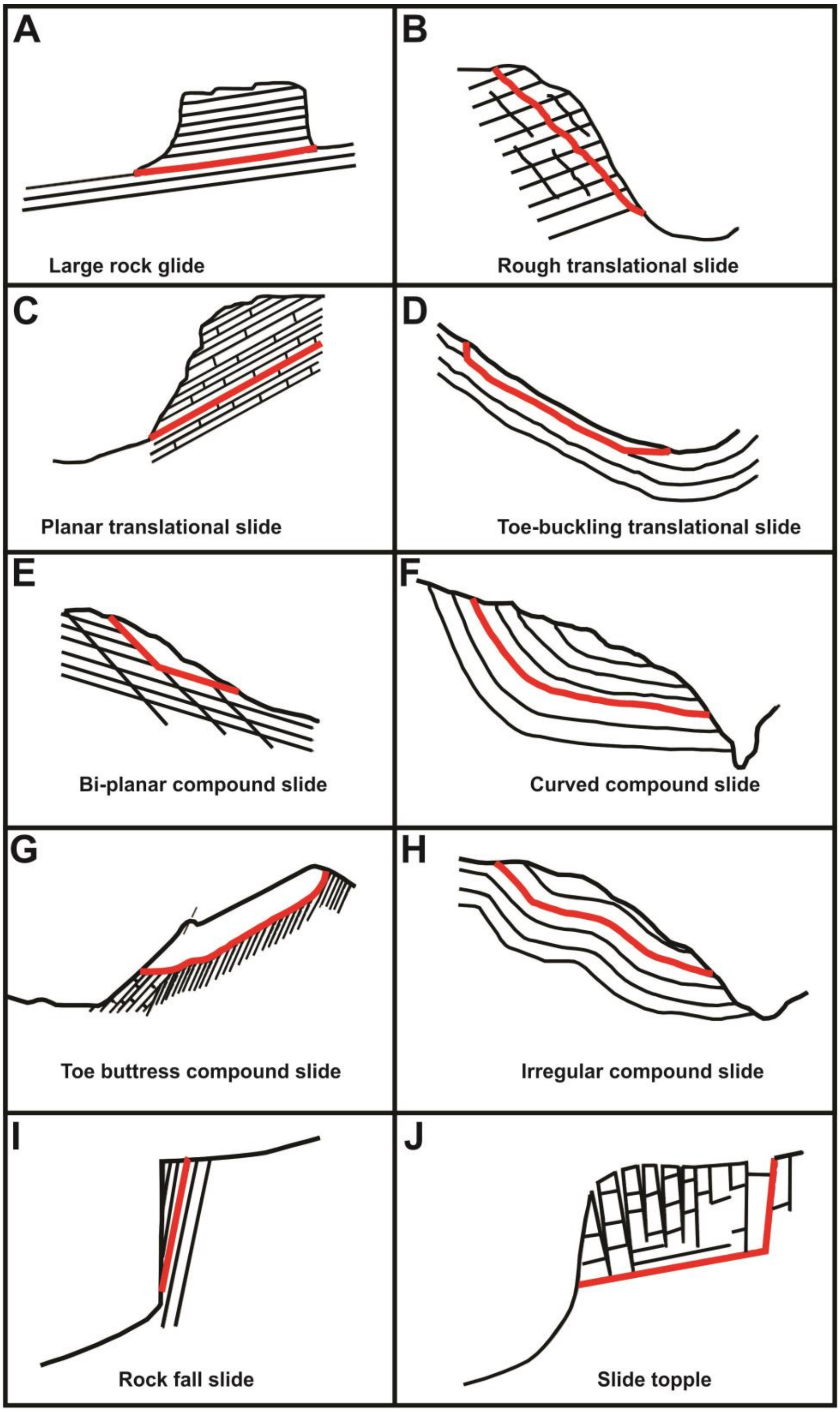

Fig. 6 - Schematic cross-sections of different rock slope failure mechanisms. The red lines/curvatures in the figures are the considered sliding surface. Modified after (Braathen et al., 2004, Glastonbury and Fell, 2010, Hermanns and Longva, 2012).

4 Methods

This chapter presents the methods and software used in this thesis. To reach the previous mentioned goals of the study, fieldwork has been essential for the understanding of the different localities. This together with studying aerial photos, Digital Elevation Models (DEM), detailed maps and structural data collected by NGU, have been the most important work aspects utilized to get the complete overview of the relation between bedrock structures and regional trends.

4.1 Regional mapping and base data

The study area is investigated using the topographic map 10153 Storfjorden 1:50 000 in 'Norge-serien' from the Norwegian Map Authority (NMA). The topographic map from www.geonorge.no is used in ArcGIS as a WMS-server. Aerial photos are from NorgeiBilder (www.norgeibilder.no) from 2011 (0.4 m) and 2016 (0.25 m). The NGU has available bedrock maps at a scale of 1:50 000 and 1:250 000, both of which have been referenced.

All structural and geomorphological data, as well as retrieved maps are projected using ESRI ArcMAP 10.5. The coordinate system used in ArcMAP is WGS 1984 UTM Zone 33. The DEM used is the 1 m resolution retrieved from www.hoydedata.no. All structural features measured, as well as those made available by the NGU, are stereographically projected using Orient 3.6.3. To complete figures and illustrations, CorelDRAW Graphics X8 and Corel PHOTO-PAINT X8 have been applied.

4.2 Fieldwork

Fieldwork was conducted in August and September 2017. In order to reach the goals of the thesis (chapter 1.2), fieldwork enabled to map and categorize each of the failure areas in Kåfjorden. Mapping of local bedrocks, internal bedrock fabrics and structures, brittle fractures as well as geomorphologic features were the focus during the fieldwork, with a predominant focus on the structural elements. The most important task was to examine bedrock fabric and structure, and possible variations in orientation within each locality to conclude on a specific rock slope failure type.

Oksfjellet, Nomedalstind and Langsnøen were not visited in the field, as data of these localities were made available. The localities visited in the field were Nordmannviktind, Gavtavárri, Rismmalčohkka, Badjánanvárri and Ruovddášvárri, all located on the northeastern side of the fjord. Structural data were obtained as strike/dip using the right-hand rule (360/90) with a compass with an inclinometer.

5 Results

In this chapter, a description of each locality will be given. This includes bedrock maps with interpreted structural elements, such as fractures and average orientation of foliation, and geomorphological features, e.g. scarps, talus etc. Structural orientation data (stereographic projections), and interpreted profiles of the unstable areas are also included to easier classify and interpret the failure mechanisms. Further, a brief preliminary interpretation based on fieldwork, observations and data of each locality follows. The results presented on Nomedalstinden (Husby, 2011) and Oksfjellet (Bredal, 2016) are mostly based on the previous work/theses, on data provided by the Geological Survey of Norway and on own studies of aerial photos and DEM's. As for the Langsnøen locality, the Geological Survey of Norway have provided all the data presented in this thesis. New bedrock maps with structural data and geomorphological features are made for these three localities, while the interpreted profiles on Nomedalstind and Oksfjellet are retrieved and modified from their projects.

Even though Rismmalčohkka and Badjánanvárri are interpreted as two different unstable rock slope failures, they are presented in the same chapter, as there are many similarities between the two localities (chapter 5.3). Table 2 summarizes the key features of each locality, with failure mechanisms and controlling bedrock structures inferred, based on the descriptions and later discussion (chapter 6).

Table 2 - Overview of the localities with key information about bedrock and structures, and interpreted failure mechanisms and controlling factors. Locality 1-5 are studied in the field (Fig. 2). The lithologies are the dominant ones for each locality. Valley aspect is the average inclination and direction the slopes face. The attitudes of foliation is the average and/or the most common for the localities.

Nr.	Locality	Height m.a.s.l.	Lithology	Average valley aspect	Foliation (strike and dip)	Failure mechanism	Controlling structures
1	Nordmannviktind	1355	Feldspathic quartzite and schists	35-40° to SW	NW-SE to E-W, dipping 30° to W and SW	Slide topple	Foliation and fractures
2	Gavtavárri	1281	Mica schists and gneisses	40-45° to SW (east and west)	N-S to NW-SE, dipping 20-40° to W-WSW. Up to 50° in east	- Irregular compound slide (east) - Rock fall slide (west)	- Foliation (east) - Fractures (west)
3	Rismmalčohkka	1013	Meta-arkose to feldspathic quartzite and mica schist	35-40° to SSW	WNW-ESE and NW-SE, dipping 30° to S and SW	Planar translational slide	Foliation
3	Badjánanvárri	1169	Meta-arkose to feldspathic quartzite and mica schist	25-35° to S	NW-SE, dipping 30-60° to SW	Bi-planar compound slide	Foliation and fractures
4	Ruovddášvárri	1096	Meta-arkose and calcareous and dolomitic marbles	50-70° to S	NNE-SSW to NE-SW, dipping 10-30° to E and SE	Slide topple	Foliation and fractures
5	Nomedalstind	1051	Meta-arkose, gabbro and amphibolite lenses and mica schist	30-35° to SSW	NW-SE, dipping 35-40° to SW	Toe buckling translational slide	Foliation
6	Oksfjellet	1051	Mica schist of various biotite and muscovite content	70-75° to NE	NW-SE to NNE-SSW, 15-40° to WNW-NNW	Slide topple w/ wedge failure and rock fall slide	Foliation and fractures
7	Langsnøen	1358	Mica schist with various content of biotite and muscovite	70-80° to NE	NW-SE and NE-SW, 10-30° to SW and NW	Slide topple	Foliation and fractures

5.1 Nordmannviktind

Nordmannviktind is the northernmost locality in the study area (Fig. 2 and Fig. 7), located where Kåfjorden meets Lyngenfjorden. It is one of the highest mountains in the area with its peak at 1355 m.a.s.l. The work has focused on the slope facing southwest, along the ridge oriented NW-SE from approximately 1197 m.a.s.l. The ridge and the slope mainly consist of crushed and weathered material with few outcrops of intact bedrock. The outcrops are mainly isolated columns of intact bedrock along the NW-SE –trending ridge. This bedrock is also well exposed along the southern NE-SW –trending scarp of the mountain (Fig. 7 and Fig. 8).

The peak itself (1355 m.a.sl.) is located east of the studied ridge and comprises steep cliffs on the northwestern and southeastern side. The bedrock comprises rocks of the Nordmannvik Nappe, generally massive in appearance and talus is chiefly angular and concentrated in lobes.

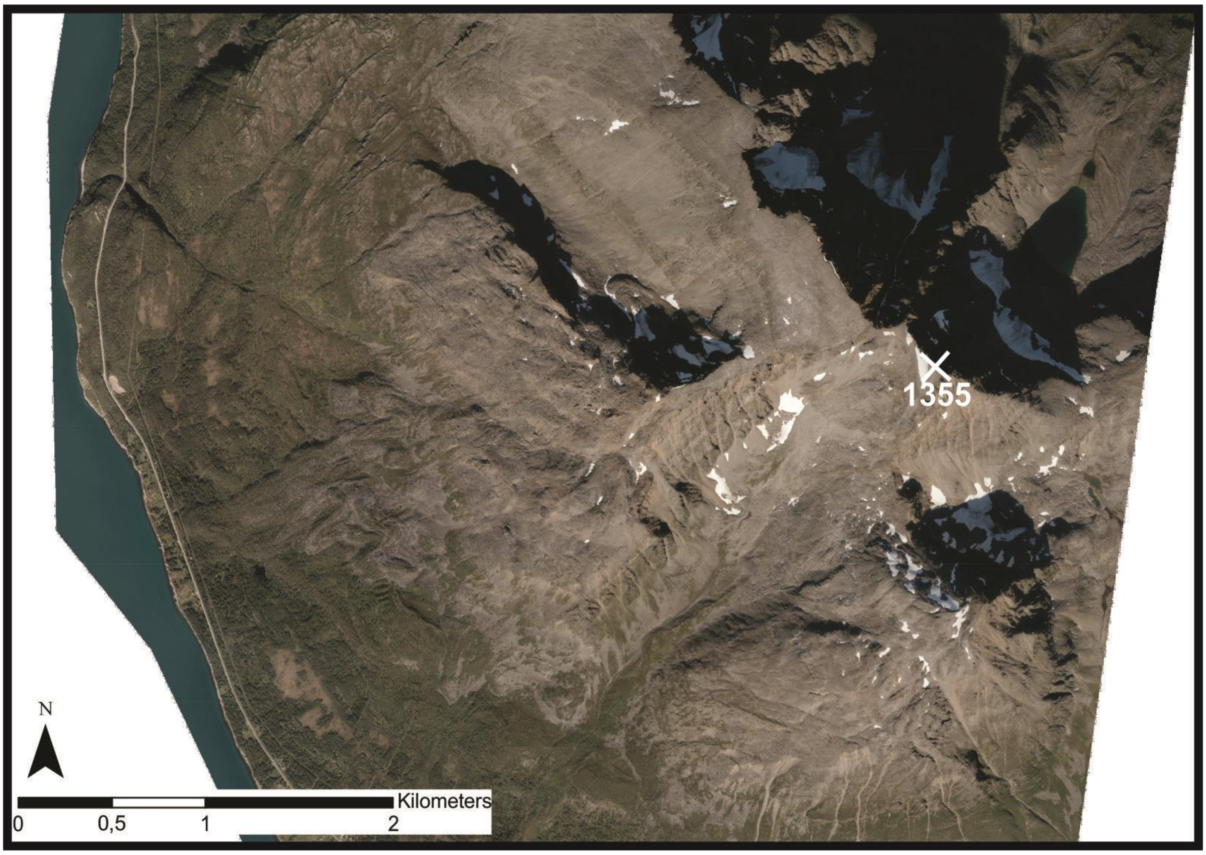

Fig. 7 - Aerial photo of Nordmannviktind with the southwest facing slope of interest. The cross indicates the highest point of the mountain at 1355 m.a.s.l. Retrieved and modified from www.norgeibilder.no.

5.1.1 Bedrocks and structural architecture

Nordmannviktind comprises bedrocks of the Nordmannvik Nappe, and the bedrock mainly consists of foliated feldspathic quartzite. Garnet- and quartz-rich mica schists are located tectono-stratigraphically below (Fig. 8). Locally, blue elongated crystals of kyanite are observed in the feldspathic quartzite (Fig. 11C).

The Caledonian ductile foliation of the bedrock strikes N-S and NW-SE to E-W with a uniform gentle dip (30^{o}) to the west and southwest (Fig. 9A,Fig. 11A and Fig. 11B). The E-W- striking foliation dip in both directions, N- and S-ward. The most common dip direction is; however, to the W and SW (Fig. 9A). The foliation is not as pronounced in the feldspathic quartzites as it is in the schists of the locality.

Brittle fractures observed in the intact bedrock along the columns are linear in map view, often appearing in an orthogonal pattern where different striking fracture sets intersect. The most common fracture sets strike N-S, NW-SE and E-W (Fig. 9B). The N-S –striking fractures define two opposing sets, one low-angle set dipping ca 15° W and a second set dipping steeply to sub-vertically (60-85°) eastward (Fig. 9 and Fig. 11B). Similarly, fractures striking E-W dip steeply (75-85°) both north- and southwards (Fig. 9B). The NW-SE- striking fractures do in general dip steeply (40-60°) southwestward. The gentler-dipping of these fractures are sub-parallel to both the slope and the foliation (Fig. 10).

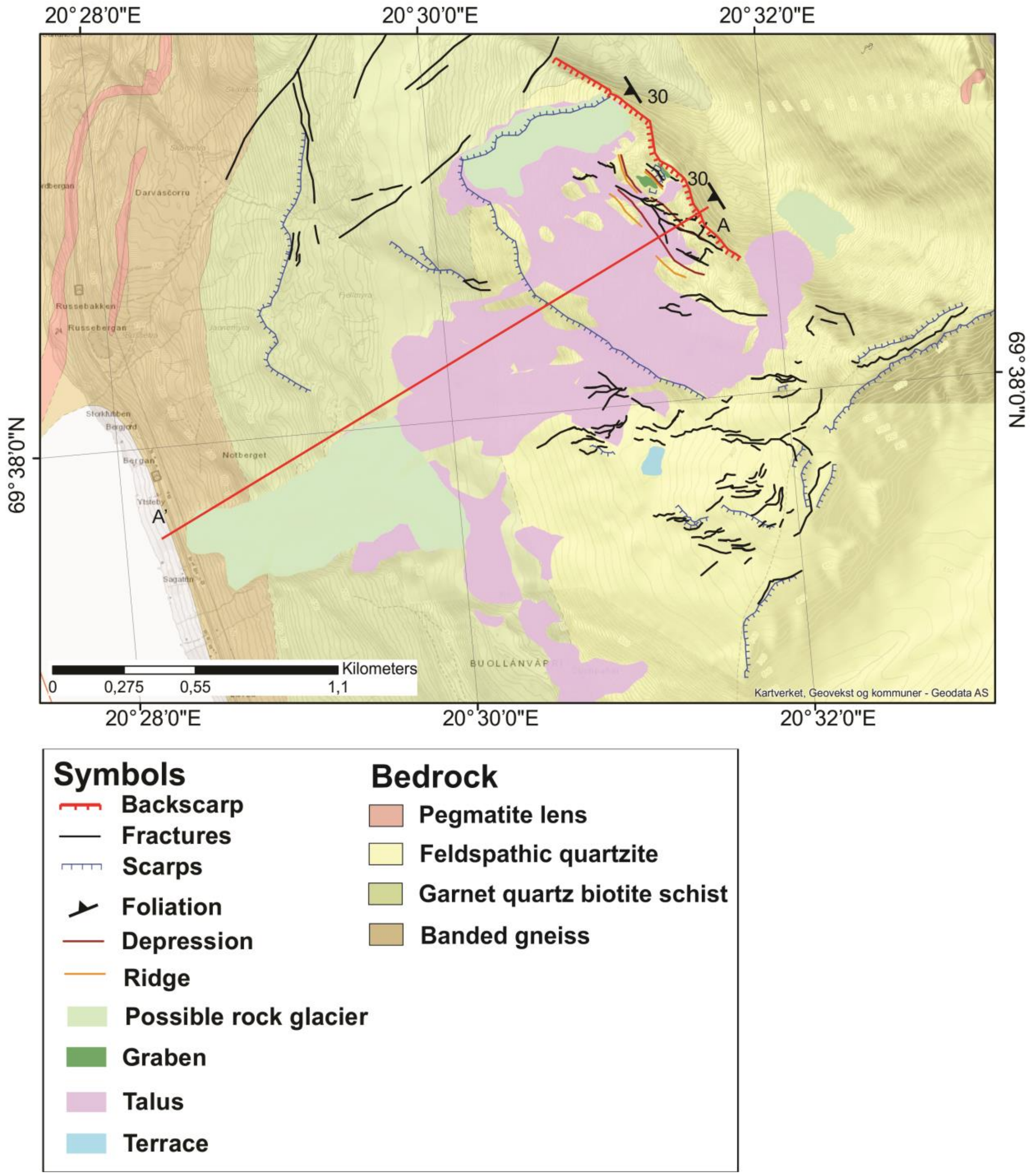

Fig. 8 - Bedrock map of Nordmannviktind with structural and geomorphological features. Profile line A – A' is indicated from the NW-SE –trending ridge with the columns forming the backscarp. Bedrock map made available by the NGU.

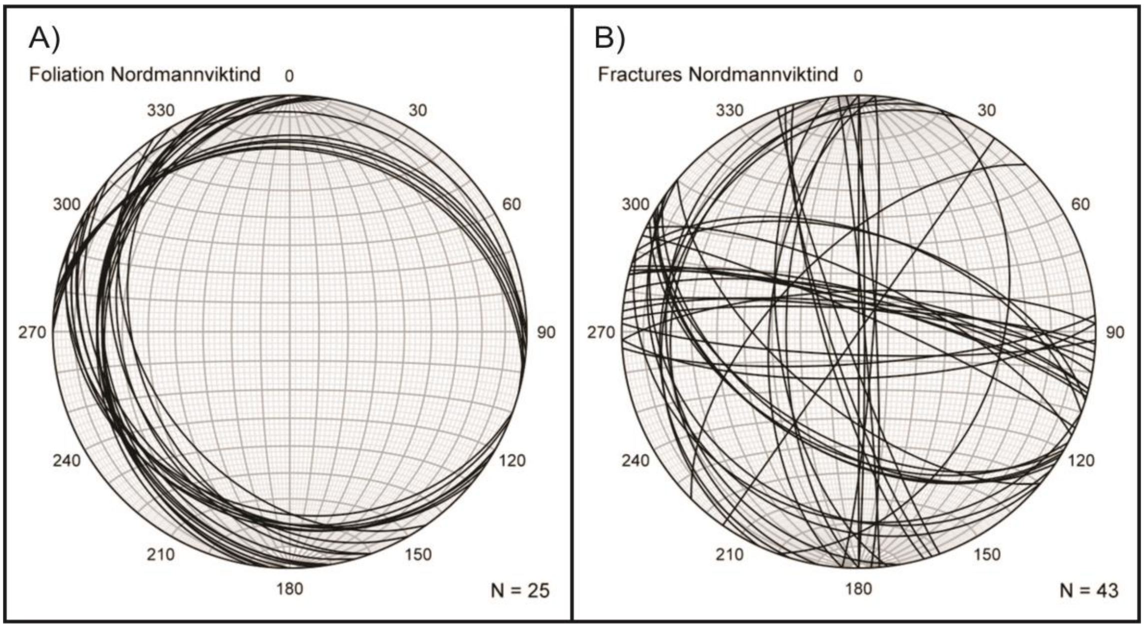

Fig. 9 – Stereographic projections of the bedrock structures at Nordmannviktind, where A) presents the Caledonian ductile foliation and B) presents the brittle post-Caledonian fractures.

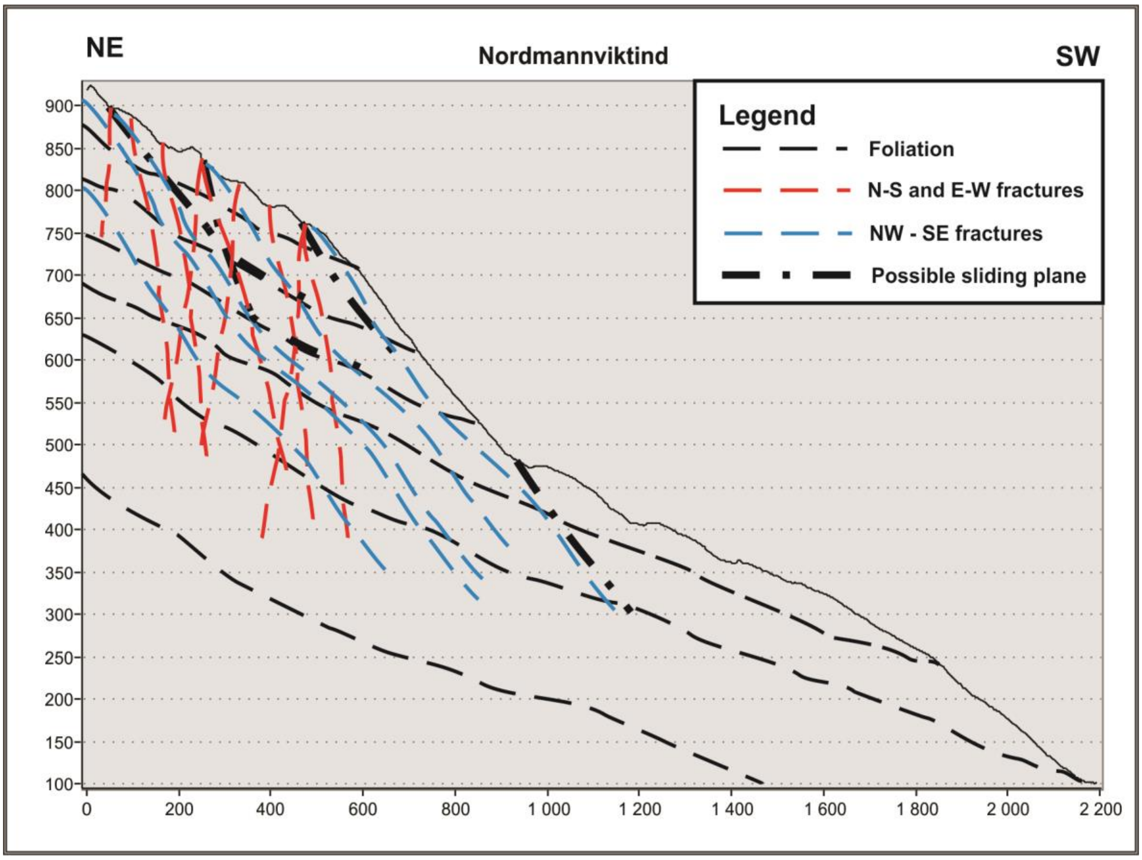

Fig. 10 – Interpreted profile along line A - A' in Fig. 8 of the structural features at Nordmannviktind. The foliation and fractures are only measured along the backscarp, thus this cross-section illustrates an interpretation of the structures' behavior internally and downslope.

5.1.2 Geomorphological elements

The backscarp that delimits the unstable area at Nordmannviktind is a ridge trending NW-SE with a few columns of intact bedrock of feldspathic quartzite (Fig. 8). A steep hillside from the ridge is filled by talus of the same host rock, faces northeastward, and ends in Helvetesdalen. The study area faces southwest, and is also covered with talus blocks of the host rock. This suggests that the talus blocks on the slopes were derived from the ridge.

There are some scarps within the study area. The most prominent and longest one appears to separate the talus-covered parts of the failure area with the vegetation-covered parts northwest of the failure area (Fig. 7 and Fig. 8). There are few scarps within the failure area, some south of the backscarp, and a few downslope of the long, prominent scarp.
Different sized and shaped talus material cover most of the SW-facing slope of Nordmannviktind (Fig. 8). The dominant block shape is angular and the size vary from 10 cm up to several 10's of meters (Fig. 11C and D). The talus material is in particular concentrated in linear depressions and in lobes (Fig. 8). The deposited talus material appears massive with defined edges (Fig. 11D).

The depressions are frequent along the slope, and have an extent from a couple of meters up to several hundred meters. Dominant trend of the depressions are NE-SW and NW-SE, the NW-SE –trending are parallel to the ridge and the strike of the SW-dipping foliation (Fig. 11E). Some of the depressions show irregular geometries and varying orientation along, from NE-SW –trending, alternating to E-W- and NW-SE along, and some depressions merge with each other (Fig. 8). Many of the depressions are located adjacent to and are parallel to talus ridges, which display same extent, geometry and orientation as the depressions. These talus ridges are often located on the lower side of the depressions (Fig. 8). Some ridges are steeper on the side closest to the depression, and thus may be interpreted as counterscarps (Fig. 11E) (Agliardi et al., 2001).

Several talus lobes occur in the lower part of the studied slope, mainly below 600 m.a.s.l. The size of the lobes vary, and many of the lobes truncate other lobes. Some lobate shapes are considered rock glaciers of non-glacial origin (Fig. 8) (Tolgensbakk et al., 1988). Most of the talus above the long, prominent scarp is considered a continuous to discontinuous cover of talus material, rarely concentrated in lobes but locally along the depressions and as a thin cover (Fig. 8 and Fig. 11F). The delimitation of the failure area is the NW-SE –trending ridge with columns, cut off by NE-SW striking fractures in the northwestern part of the failure area parallel to trend of the long prominent scarp (Fig. 8). The lower limit is considered the scarp in the central parts of the study area, and the southeastern delimitation is the NE-SW –trending cliff, interpreted as a scarp (Fig. 8).

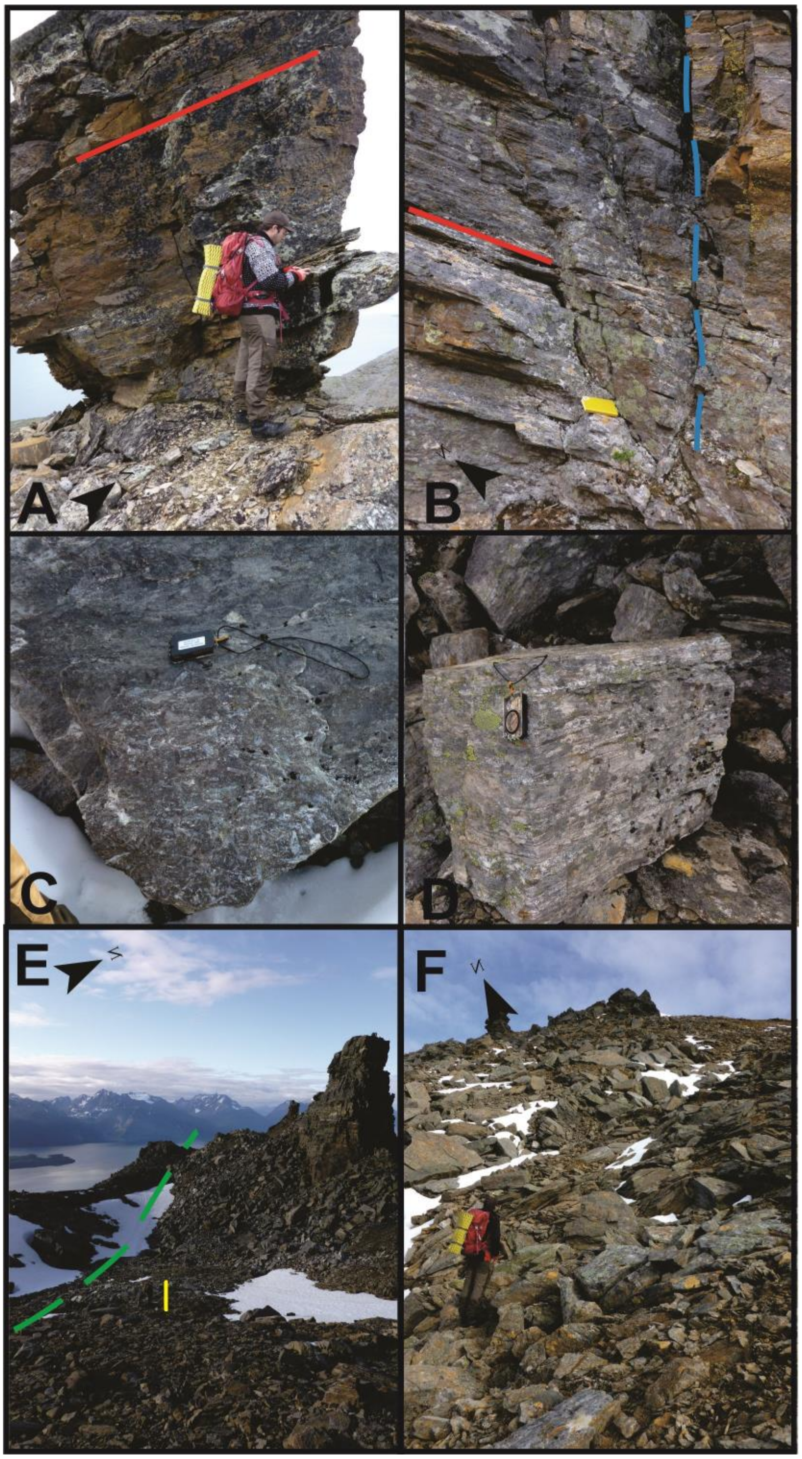

Fig. 11 – Outcrop photos of bedrock structures and geomorphological elements at Nordmannviktind. A) A column along the backscarp, where the red line follows the foliation and the steep faces are exposed fracture surfaces. B) Column along the backscarp with the red line following the foliation, and the blue line follows trace of a sub-vertical fracture. C) Representative shaped and sized block of talus with elongated crystals of kyanite. D) Representative shaped and sized block of talus material, angular with defined edges, possible delimited and collapsed along orthogonally intersecting fractures, as the sides intersect at ca 90°. E) A column with talus material (to the right), with a marked NW-SE –trending depression (green line) adjacent to a ridge in the left part of the photo. The yellow line indicates the size of the scale (person). F) Shows a representative photo of the talus covered slopes above 600 m.a.s.l. of the locality.

5.1.3 Preliminary interpretation

At Nordmannviktind, the foliation in the feldspathic quartzite and in the schists dips ca 30° SW, downslope (Fig. 9A), more prominent in the schists than in the quartzite. A cover of talus material of varying thickness overlies the bedrock. Above 600 m.a.s.l., the material represents a thin cover, and is often concentrated in parallel, linear NW-SE –trending depressions. Below 600 m.a.s.l. and below the long scarp, it concentrates in lobes (Fig. 8). These observations may suggest that the bedrock has partly disintegrated and been displaced as a rockslide, or possibly with a creep –movement downslope. The SW-dipping foliation may represent the sliding surface depositing talus material in lobes.

Linear NW-SE –trending depressions, NW-SE –striking fractures parallel to the foliation and the NW-SE –trending backscarp further suggest a failure southwestward. The steeply-dipping fractures indicated in the profile (Fig. 10) are found to delimit the columns along the backscarp, in particular those dipping south- and westward. In combination, this may indicate that talus blocks have disintegrated due to rock falls controlled by the steeply-dipping fractures intersecting forming the orthogonal geometries (Fig. 11D).

The columns at the backscarp show sub-vertical to vertical fractures, as well as the near 30° -dipping foliation, which may suggest toppling along the steep fractures and sliding along the foliation as possible (Fig. 11A and Fig. 11B). As the depressions trend parallel to the steeply SW-dipping fractures (Fig. 11E), the depressions may be surface expressions of opened brittle fractures. Some of the lobes of various sized talus material are considered rock glaciers (Tolgensbakk et al., 1988). In combination, the structural data indicate an overall *slide topple* type of mechanism of the rock-slope failure at the SW-facing slope of Nordmannviktind with sliding along foliation, and toppling along the fractures (Hermanns and Longva, 2012). The gentler-dipping NW-SE –striking fractures may, in combination with the foliation, have controlled the failure, cf. profile in fig. 10. Thus, the failure can be interpreted as both a *slide topple* type, and a *bi-planar compound slide* (Fig. 6J and Fig. 6E, respectively) (Glastonbury and Fell, 2010).

5.2 Gavtavárri

Gavtavárri is located between Nordmannviktind and Nomedalstind, south of Olderdalen, and has its highest peak at 1282 m.a.s.l (Fig. 2). The work has focused on the west- to southwest facing slope consisting of mica-schists and meta-psammites with a well-developed foliation (Fig. 12, Fig. 13 and Fig. 14A). The western part of the area comprises definite terraces, bounding scarps, and talus material. The backscarp in this area follows steeply-dipping NW-SE- and NE-SW –striking fractures intersecting (Fig. 12 and Fig. 13). The eastern part has a fully foliation-parallel backscarp with steep slopes covered by some material, and scarps trending perpendicular to the foliation (Fig. 13). In order to describe structural and geomorphological features and variations in orientation of the elements, the failure area is subdivided into an eastern area (profile A-A') and a western area (profile B-B') (Fig. 12 for line of division, and Fig. 13).

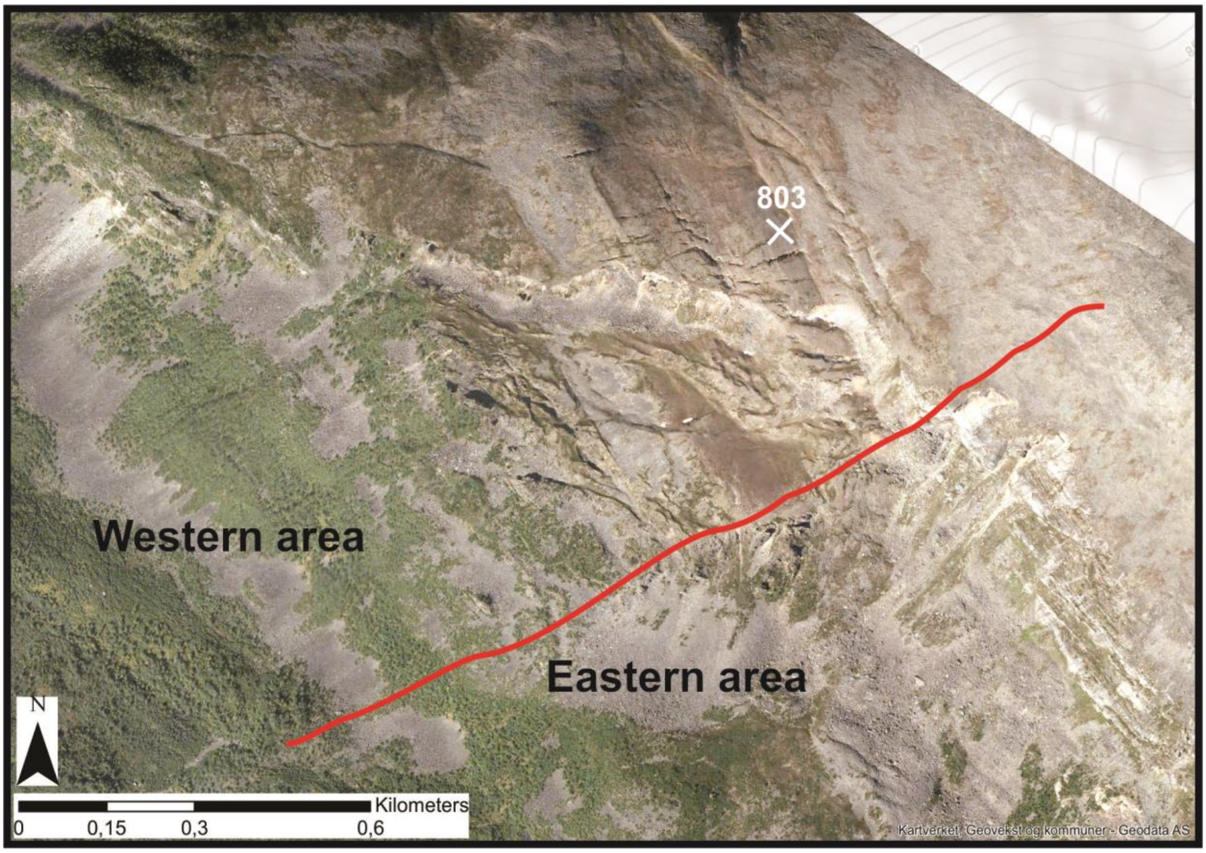

Fig. 12 - Aerial photo of Gavtavárri with scale. The red line in the middle separates the two areas, eastern part below the red line, and the western part above the red line. The point 803 m.a.s.l. is not the peak of the mountain, but a sub-peak. Aerial photo from www.norgeibilder.no.

5.2.1 Bedrocks and structural architecture

The eastern part of Gavtavárri consists of a hornblende biotite-rich mica schist with a well-developed and –preserved foliation. The western part comprises banded gneisses and garnet-rich micaceous schists, with presence of smaller veins and irregular bodies of pegmatite. Outside the circular body of the gneiss, the western part also comprise the same mica schist as the eastern part (Fig. 13). The banded gneiss, pegmatites and the garnet quartz biotite schists are considered rocks of the Nordmannvik Nappe, while the other rocks of the locality are from the Kåfjord Nappe (Zwaan, 1988).

The Caledonian ductile foliation at Gavtavárri mainly strikes N-S and NW-SE with a mostly uniform, gentle (20° to 40°) dip towards W-WSW, downslope towards the fjord (Fig. 14A, Fig. 15 and Fig. 16). In the eastern part of Gavtavárri, the foliation is locally folded and steeper than in the western part, dipping up to 50° (Fig. 15, Fig. 19A and Fig. 19B). The folds are partly overturned with fold amplitudes from 50 cm up to several meters. The fold axis trends towards SE, and backlimbs dipping towards SW, sub-parallel to the slope and foliation (Fig. 19 C and Fig. 19D). Folded intact bedrock and talus material of the hinge and forelimbs were observed. Locally, material had broken off along the axial surface of smaller folds, now a part of the talus assemblage below the foliation-parallel backscarp in the eastern part. Folds were also observed along exposed fracture surfaces in the western part behind the backscarp. These are smaller in amplitude than in the eastern part with backlimbs dipping towards SW as well (Fig. 19D).

Brittle post-Caledonian fractures observed in the intact bedrock of the study area at Gavtavárri have three dominant strikes, NE-SW, NW-SE and E-W. Most of the observed fractures dip steeply, between 60-90° (Fig. 14B and Fig. 16). The fractures crosscut each other and the gently dipping foliation on several locations causing failures, e.g. along the backscarp in the western area. The crosscutting fractures also form open spaces where they intersect (Fig. 17). The fractures in the eastern part crosscut the foliation at a high angle, locally exposing sub-vertical to vertical scarps (Fig. 13, Fig. 19A and Fig. 19B). Several open fractures are located on the plateau behind the backscarp in the western part, appearing in a zigzag manner in map view (Fig. 13, Fig. 17 and Fig. 19D).

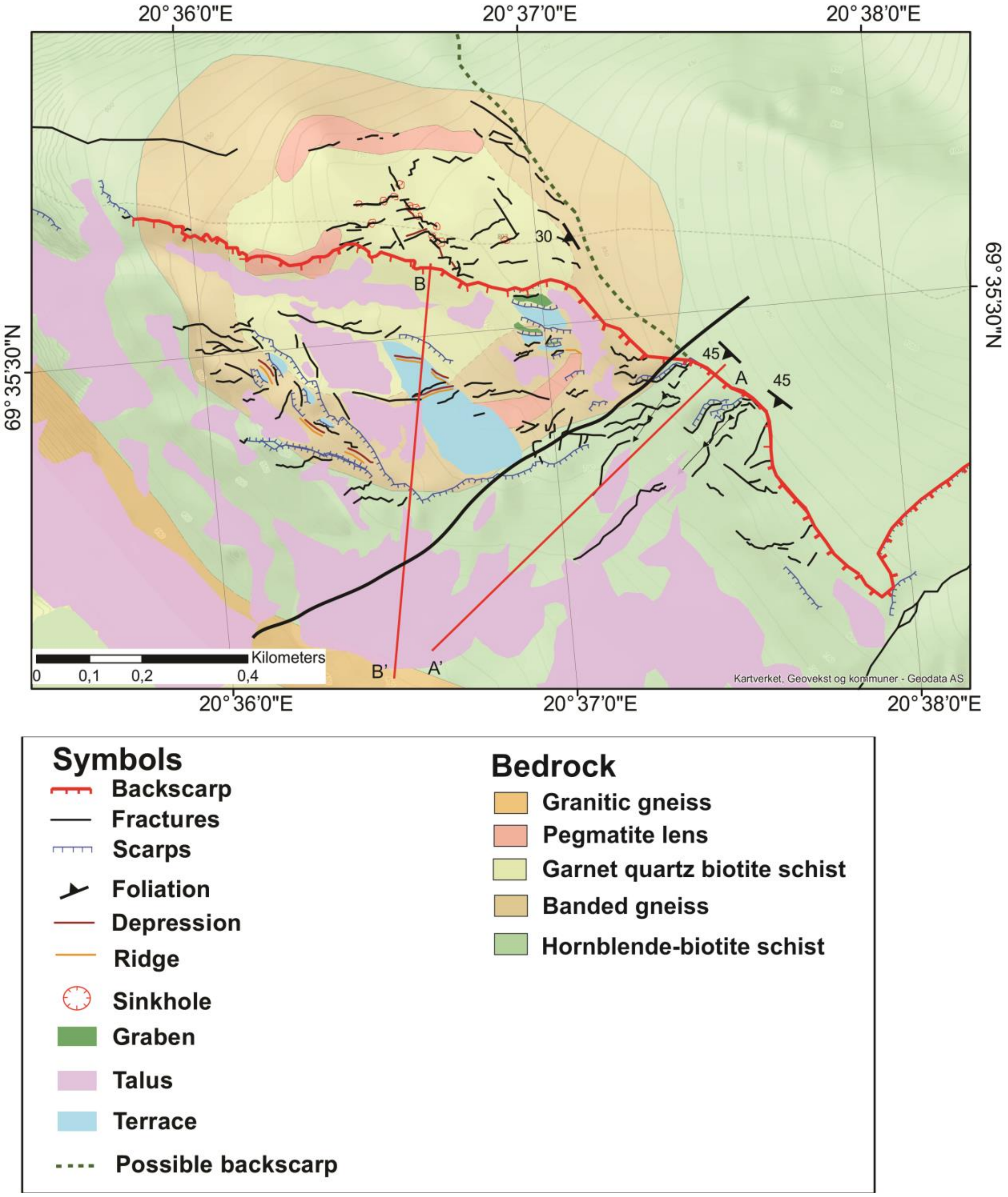

Fig. 13 - Bedrock map of Gavtavárri with structural and geomorphological features. Profile line A – A' is located in the eastern area, and profile line B – B' is located from the backscarp in the western area downslope towards the eastern area across the main terrace. The main terrace is the largest, blue-colored area below the backscarp. The long black line is the line of division for sub-area A and B. Bedrock map made available by the NGU

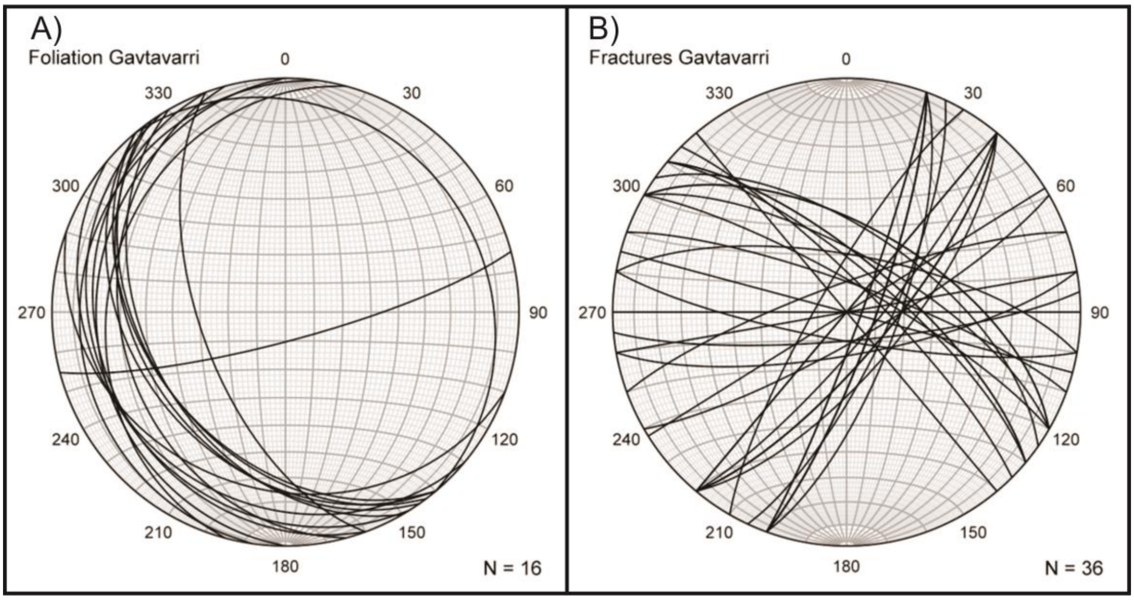

Fig. 14 – Stereo plots of the measured bedrock structures at Gavtavárri. A) Represents the observed ductile foliation, and B) presents the brittle fractures.

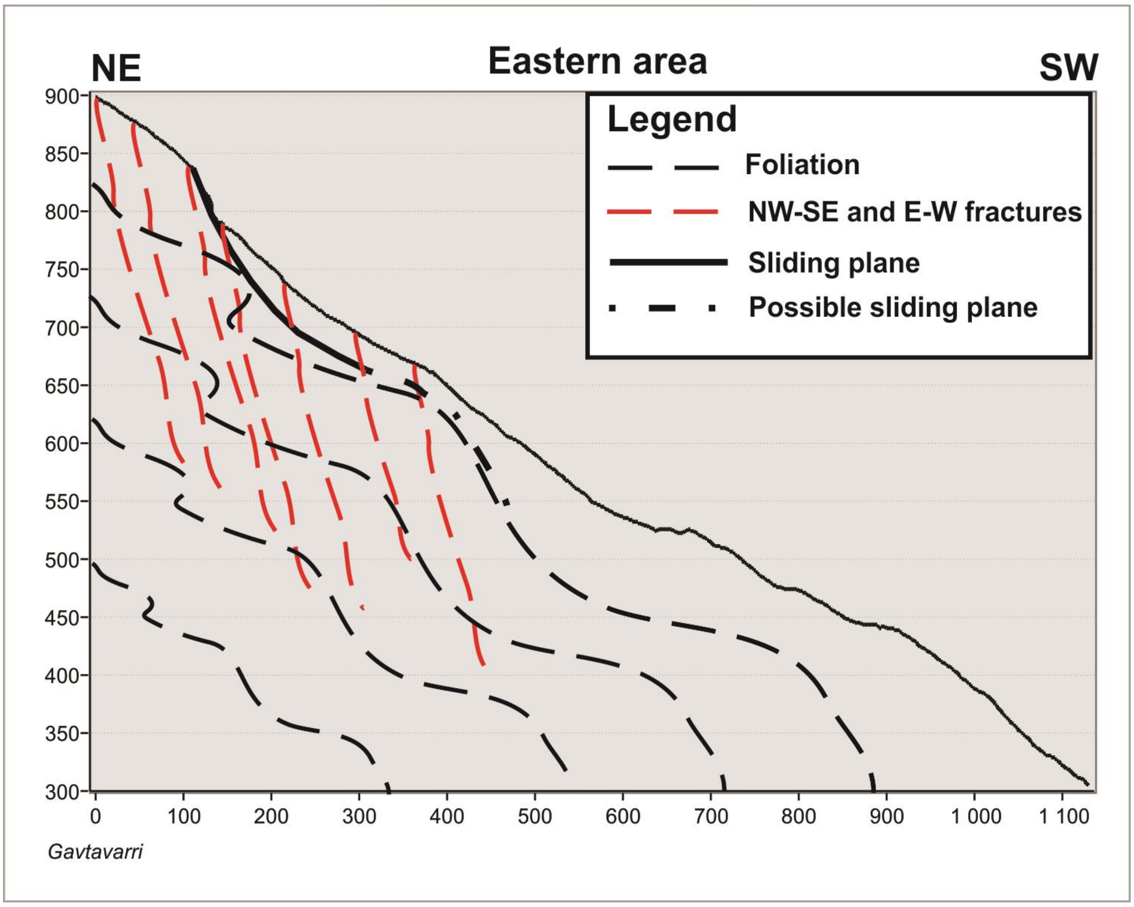

Fig. 15 – Profile A-A' in Fig. 13 of Gavtavárri. Features parallel to the profile are not included. Folding of the foliation is observed in the upper part along the backscarp, thus it may not appear as illustrated downslope and internally. The structures are dashed based on an assumed continuation downslope and internally.

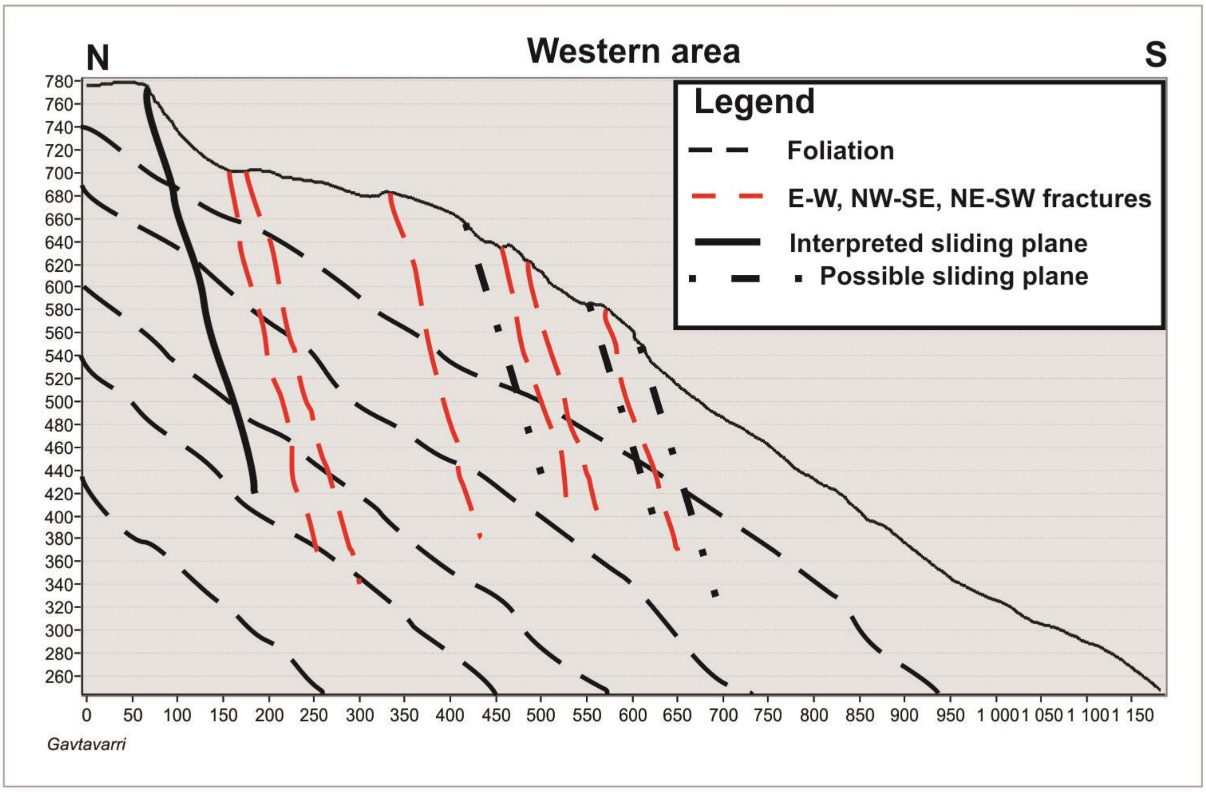

Fig. 16 – Profile B-B' in Fig. 13 of the western area at Gavtavárri. The location of the lower possible sliding surfaces are indicated where depressions and/or trenches locate in-between scarps and counterscarps in the scarp/terrace system below the main terrace. These depressions follow trend of brittle fractures. Fractures and foliation are dashed due to an assumed continuation of these structures measured along the backscarp.

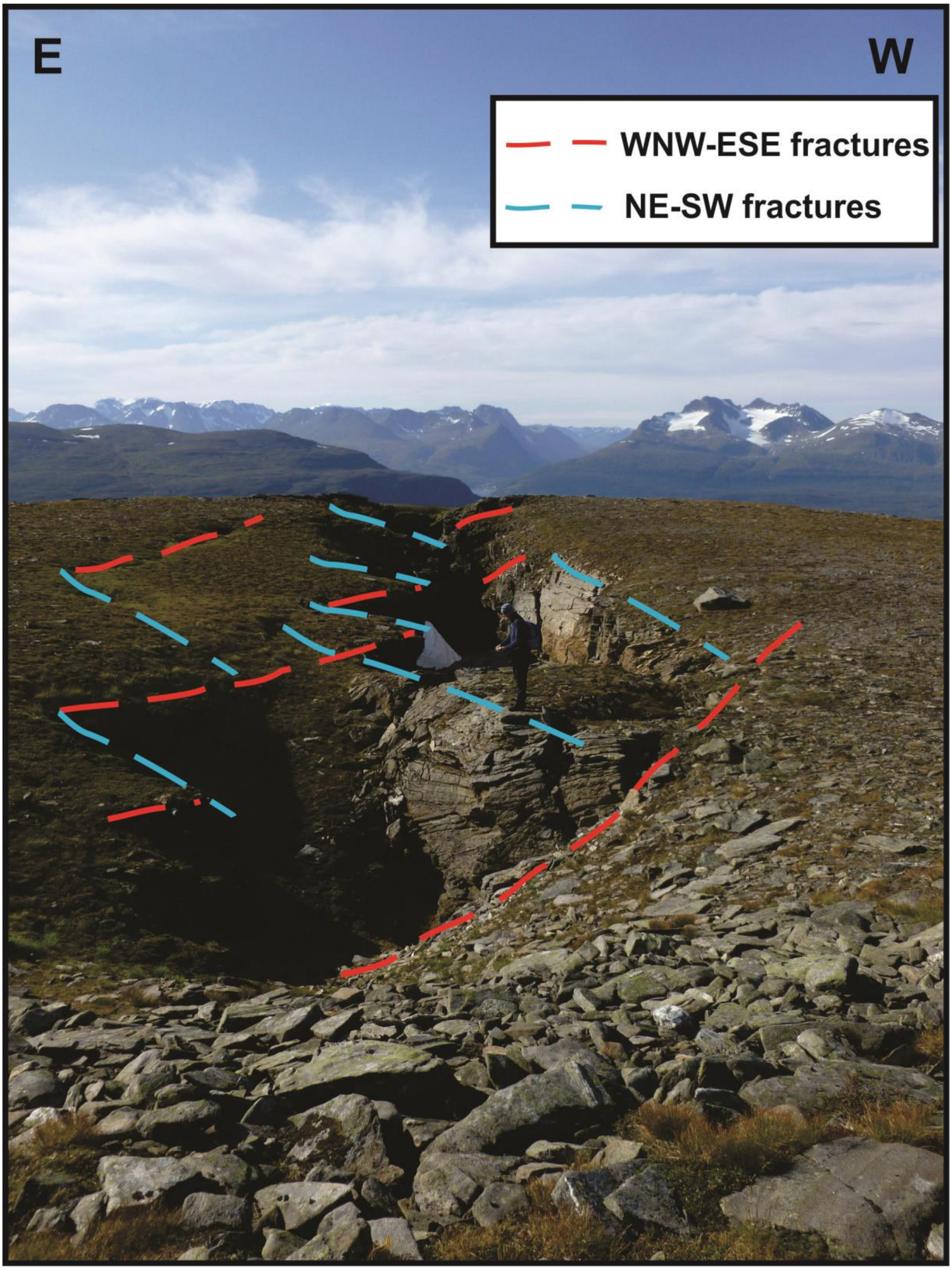

Fig. 17 - Crosscutting fractures forming a large open space trending ENE-WSW made up of intersecting fracture sets striking WNW-ESE (red dashed lines) and NE-SW (blue dashed lines), both sub-vertically dipping. Scale standing on a partly detached block between the intersecting fractures.

5.2.2 Geomorphological elements

The backscarp at Gavtavárri occurs at approximately 900 m.a.s.l. in the eastern part, where it strikes NW-SE and is fully foliation-parallel (Fig. 19A). It can be traced towards WNW-NW for approximately 1 km onto the plateau where it splits. It splits into one linear depression trending NW-SE behind the unstable western area (green dashed line in Fig. 13), and one part following the brittle fractures towards west (Fig. 12 and Fig. 13). The backscarp continues gradually downslope in the western area in a stepping manner following a NW-SE -striking and steeply SW-dipping fracture surface. These fractures intersect with the NE-SW –striking fractures, also steeply dipping oblique to the former, towards SE (Fig. 13 and Fig. 14B).

Several smaller scarps and counterscarps make up a major terrace system in the lower western part of the unstable area at Gavtavárri (Fig. 19B). The main terrace in this system is sub-horizontal with a smooth, yet irregular surface due to presence of linear depressions and ridges adjacent to one another (Fig. 13). The terrace is approximately 350 m across and up to 200 m wide, with the ridges and depressions mainly concentrated in the northern and eastern part. Depressions and ridges crosscut the terrace in the central parts of it, in addition to a structure interpreted as a fracture (Fig. 13). The main terrace is located along the gently-dipping upper part of the profile of the western area (Fig. 16).

Several smaller scarps and opposing scarps of various extent bound the main terrace upslope, to the east – northeast, while the southern extent is cut off by a steep scarp, parallel to strike of the fractures in the eastern area (NE-SW –striking). Downslope, the terrace is bound by a scarp followed downslope by several smaller terraces comprised by scarps, opposing scarps, ridges and depressions (Fig. 13). These smaller terraces have a dip parallel to the foliation, and do locally have a cover of talus blocks (Fig. 19B). The depressions in this system trend parallel to the fractures forming the backscarp in the western area.

Scarps and opposing scarps in the central upper parts, just below the backscarp in the western area, trend parallel to each other, are located a few meters apart and comprise graben-like depressions in-between (Fig. 19A). Bedrocks in some of the opposing scarps have foliation dipping steeper than the scarps, and are locally overturned relative to the host rock foliation in the intact bedrock (Fig. 19C).

Talus material dominate in the steep slopes in the lower parts of Gavtavárri, concentrated in lobes below ca 500 m.a.s.l. In the eastern part of the study area, a thick cover of talus blocks cover most of the slope below the foliation-parallel backscarp, beginning at approximately 700 m.a.s.l.. The mountain slope above the backscarp of the entire study area shows much wider areas of vegetation and some crushed material. In the western area, most of the talus concentrates at the toe of the backscarp and above the main terrace on slopes parallel to the foliation (Fig. 13).

Along the possible NW-SE –trending continuation of the backscarp (Fig. 13), above the stepping part of the backscarp, linear ridges and depressions showing parallel trends to the backscarp exist. These features vary in extent along trend, some depressions are open and delineated by sinkholes, or merge together where sinkholes appear (Fig. 19D). The presence of the sinkholes on this plateau is concentrated along two trends, parallel to the backscarp in the western areas; NE-SW and NW-SE –trending.

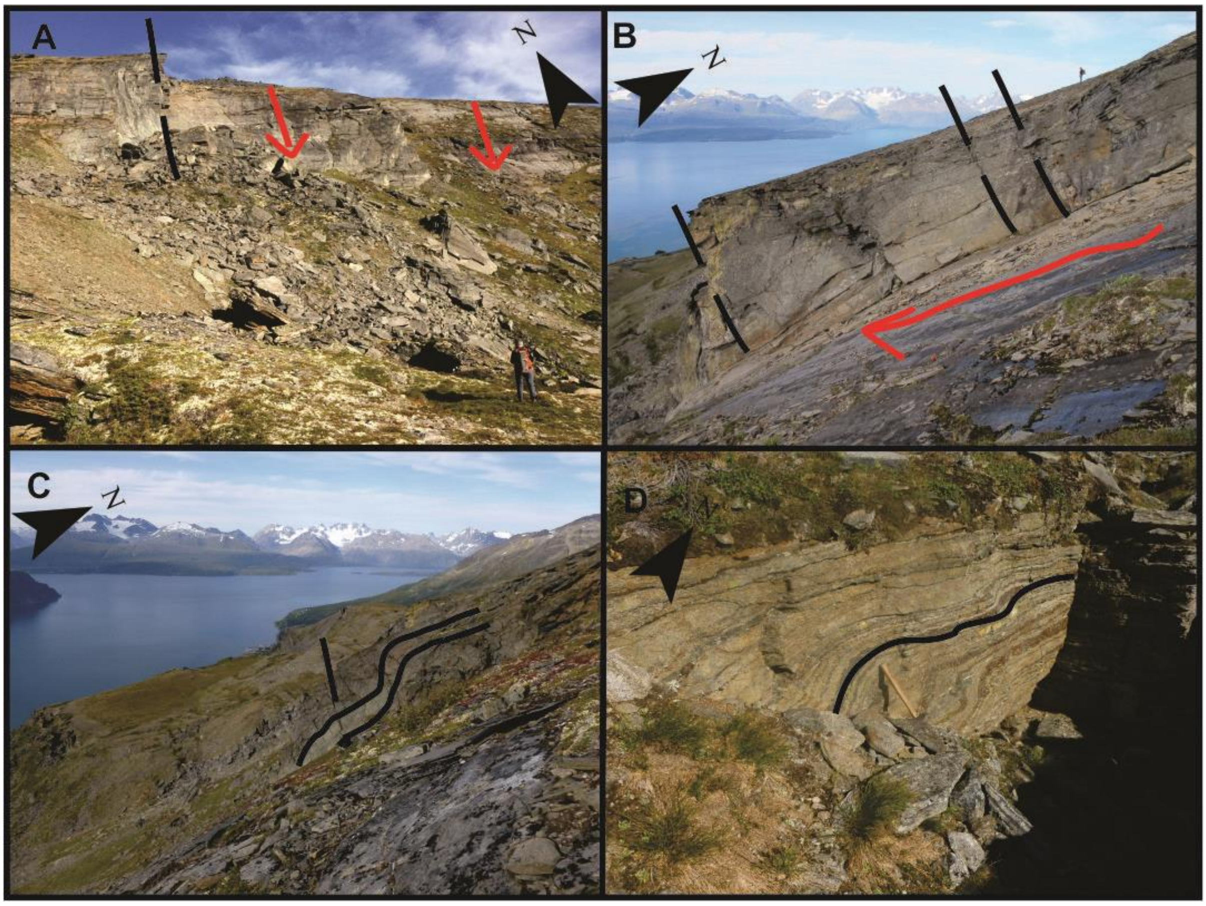

Fig. 18 - Photos showing bedrock structures at Gavtavárri. Black dashed lines are interpreted fractures, and red arrows are foliation surfaces, and sliding direction. A) Parts of the backscarp in the eastern area defined by foliation surfaces. B) An exposed foliation surface in the eastern area and perpendicularly oriented fractures intersecting with the SW-dipping foliation. C) A NE-SW –oriented scarp (fracture surface) with interpreted limb of an exposed asymmetric overturned and SW-dipping antiform. D) Small-scale folds in a garnet mica schist on the plateau behind the backscarp in the western area. The fracture surface strikes NE-SW. Photo A, B and C are by Steffen Bergh.

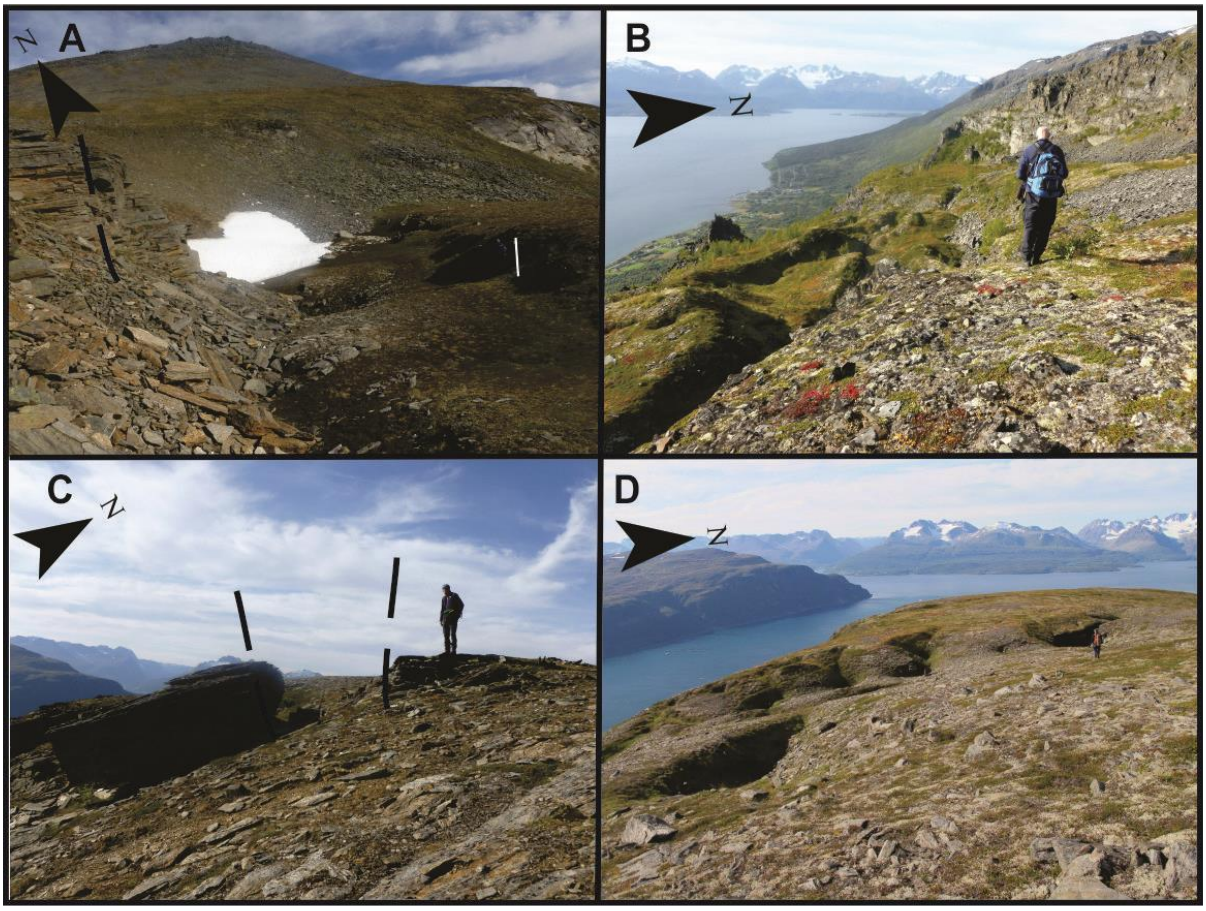

Fig. 19 – Photos showing the bedrock structures and geomorphological elements at Gavtavárri. Black dashed lines are interpreted fractures. A) A graben-like depressions along NE-SW –striking fractures below the backscarp in the western area. White lines indicates size of scale, which is a person. B) Scarps, depressions and opposing scarps below the main terrace. C) Intact bedrock with scale on top, while the lower block is considered collapsed material as the foliation dips steeper. D) Sinkholes and open fractures on the plateau behind the backscarp in the western area. Photo D is by Steffen G. Bergh.

5.2.3 Preliminary interpretation

The backscarp of the rock slope failure at Gavtavárri is interpreted as fully foliation-parallel in the eastern area, with a folded geometry downslope. The eastern part comprises fractures delimiting collapses along strike of the foliation interpreted as scarps in Fig. 13. Presence of small-scale SW-dipping overturned antiforms supply material downslope by rock fall along the axial surface of the folds. Thus, in this eastern part of the failure at Gavtavárri, the foliation is interpreted as the sliding surface, and the overturned fold limbs and axial surfaces are considered the controlling structures of block failure (Fig. 15). Steeply SW-dipping fractures and steeply SE-dipping scarps seem to delimit the area into backscarp- and scarp-controlled segments along strike of the foliation. These observations suggest that the eastern part of Gavtavárri may be considered an *irregular compound slide* that has collapsed along the folded foliation surface. The fractures are controlling rock falls of the remaining unstable parts (Glastonbury and Fell, 2010) (chapter 3.3.2).

In the western area, the backscarp follows two interacting brittle fracture sets, NE-SW- and NW-SE –striking fractures. A collapse along these interacting fracture sets have formed a downdropped, partly intact terrace, the main terrace, with smaller terraces above and below possibly formed due to displacement of the main terrace (Fig. 13). The open fractures and the sinkholes behind the backscarp are considered tensile features. The stability made up by the terrace decreased as the terrace downdropped along the brittle fractures, opening fractures and formed depressions with sinkholes on the plateau. If further displacement occurs, the tensile fractures on the plateau may become the backscarp in the future if retrogressive displacement continues (Agliardi, 2012). The system of scarps downslope of the main terrace is considered formed along the brittle fractures controlling in the western area, NE-SW and NW-SE –striking. This is suggested as the features in the system are parallel to the fracture sets, and the formation of the system was initiated by the displacement of the main terrace. In summary, the failure mechanisms in the western area of Gavtavárri may initially have been a *rock fall slide* of the main terrace along the steeply dipping fractures linked with the backscarp (Braathen et al., 2004, Hermanns and Longva, 2012). This sliding and decrease of stability due to displacement may subsequently have opened fractures and sinkholes on the plateau behind the backscarp.

5.3 Rismmalčohkka and Badjánanvárri

The mountains Rismmalčohkka and Badjánanvárri are located south of Nomedalstind on the northeastern side of Kåfjorden, with a small valley between the two localities. This valley is approximately 100-150 meters lower than the two peaks, which are 1096 m.a.s.l. and 1169 m.a.s.l., respectively. Badjánanvárri is located south of Rismmalčohkka (Fig. 2 and Fig. 20). The work on the localities have focused on the SW-facing slope at Rismmalčohkka and the SSW- to S-facing slope at Badjánanvárri (Fig. 20). Both localities comprise a well-developed mainly NW-SE -striking foliation dipping SW in the meta-psammites (Fig. 21). The unstable area at Rismmalčohkka is defined by a prominent backscarp, an exposed foliation surface, striking E-W to NW-SE with a thick cover of talus below the backscarp. The unstable area at Badjánanvárri has an E-W –striking backscarp, less prominent than at Rismmalčohkka, and a much thicker cover of weathered talus material downslope. The talus material below both backscarps is mostly angular, concentrated in lobate shapes and along sub-linear depressions, and covers most of the bedrock of the unstable areas.

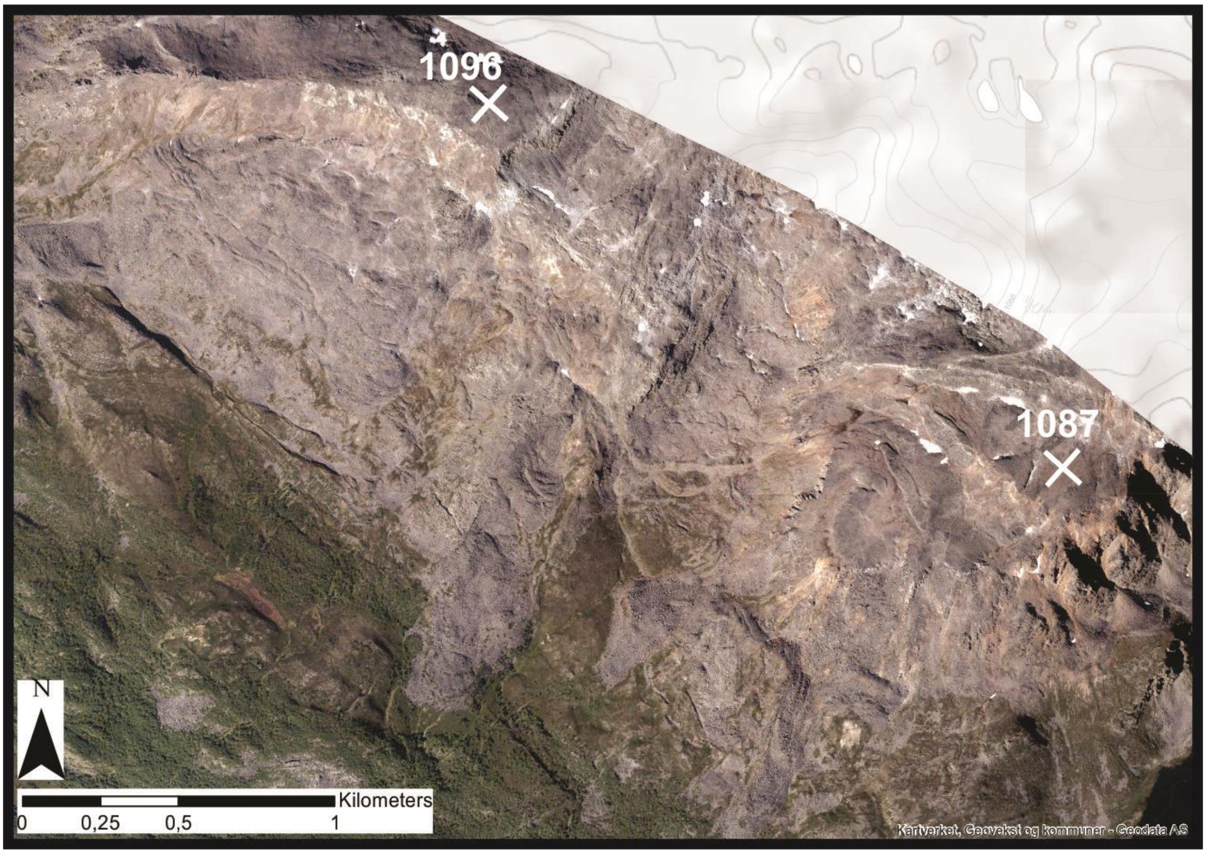

Fig. 20 - Aerial photo of Rismmalčohkka and Badjánanvárri. Rismmalčohkka is to the left (1098 m.a.s.l.) and Badjánanvárri is to the right (1087 m.a.s.l. is a sub-peak). Aerial photo retrieved and modified from www.norgeibilder.no.

5.3.1 Bedrocks and structural architecture

The upper parts of Rismmalčohkka and Badjánanvárri consist of massive meta-arkoses to feldspathic quartzites with various types of micaceous schists and gneisses tectonically below. The lower units contain lenses of amphibolite, with some gabbroic affinities in the gneiss (Fig. 21). The bedrock is assumed to belong to the Kåfjord Nappe (Zwaan, 1988).

The Caledonian ductile foliation has consistent orientation in the bedrock at Rismmalčohkka, striking WNW-ESE and NW-SE, parallel to the backscarp. The foliation is gently dipping (30-35°) towards south to southwest, downslope towards the fjord (Fig. 23, Fig. 22A and Fig. 25C). At Badjánanvárri, the ductile foliation is NW-SE- to NNW-SSE –striking, gently to more steeply dipping (30-60°) towards SW, downslope towards the fjord. The NNW-SSE –striking foliation is the steeper dipping orientation of the foliation (Fig. 22A).

Brittle fractures observed along the backscarp at Rismmalčohkka are planar and have two dominant strikes, WNW-ESE and NE-SW, both steeply dipping to sub-vertical (60-85°). The WNW-ESE –striking fractures dip north-northeastwardly inward the mountain, almost perfectly opposite to the foliation. The NE-SW –striking fractures regularly dip towards northwest, perpendicular to the foliation (Fig. 22B).

At Badjánanvárri, brittle fractures mostly strike E-W and NNE-SSW, with the E-W –striking fractures dipping both north- and southwards; gently (40°) northward and steeply southward (80°). The NNE-SSW –striking fractures dip steeply towards WNW (70°). The fractures at both localities are open, linear in map view, locally intersecting with stepping geometries at the intersections (Fig. 25A and Fig. 25B). The intersecting angle varies, but commonly displays close to 60°, thus may represent conjugate fracture sets (Fossen, 2016).

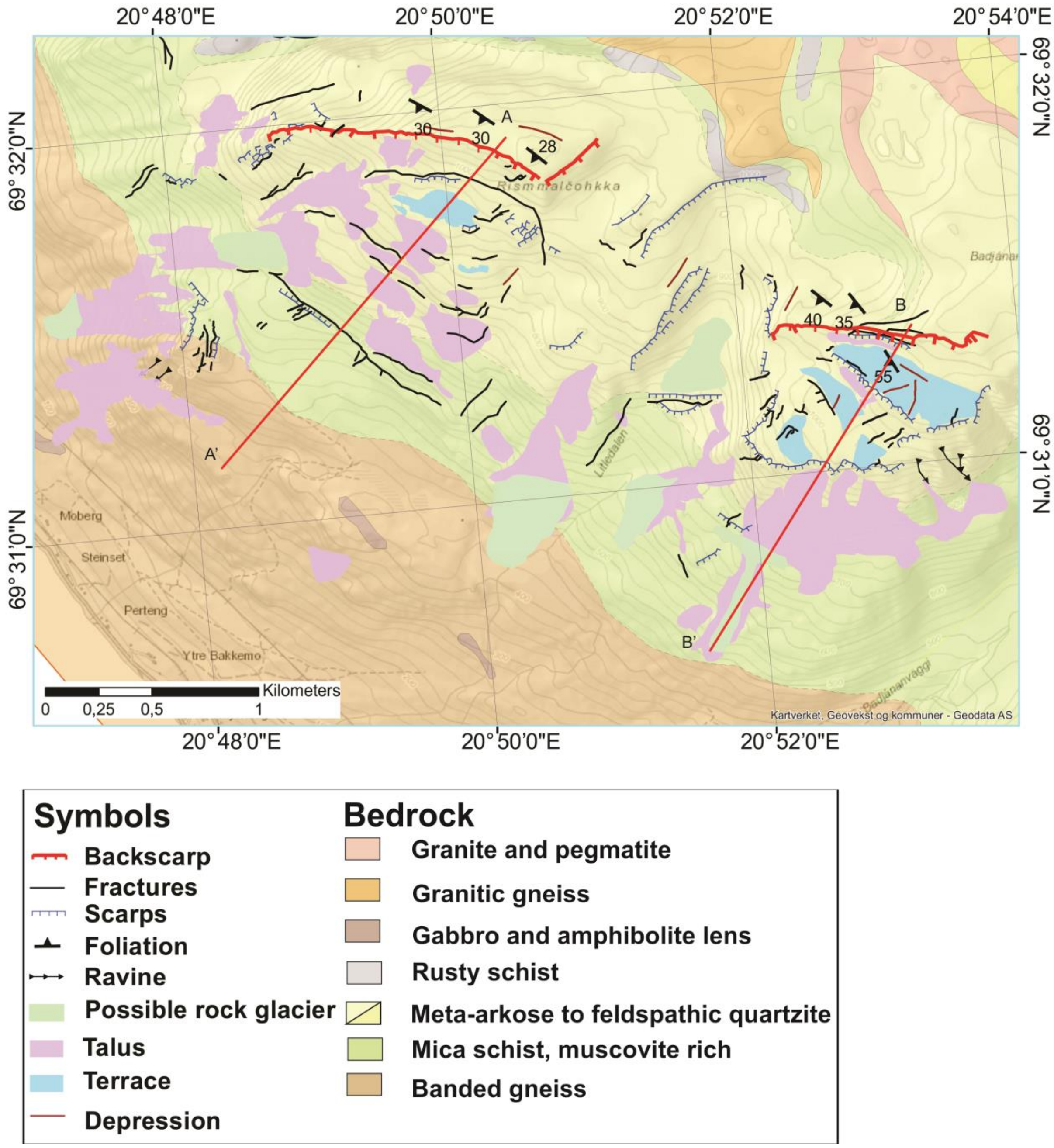

Fig. 21 - Bedrock map of Rismmalčohkka and Badjánanvárri with the observed bedrock structures and geomorphological features. Profile A – A' is located at Rismmalčohkka, and profile line B – B' is located at Badjánanvárri. Bedrock map made available by the Geological Survey of Norway.

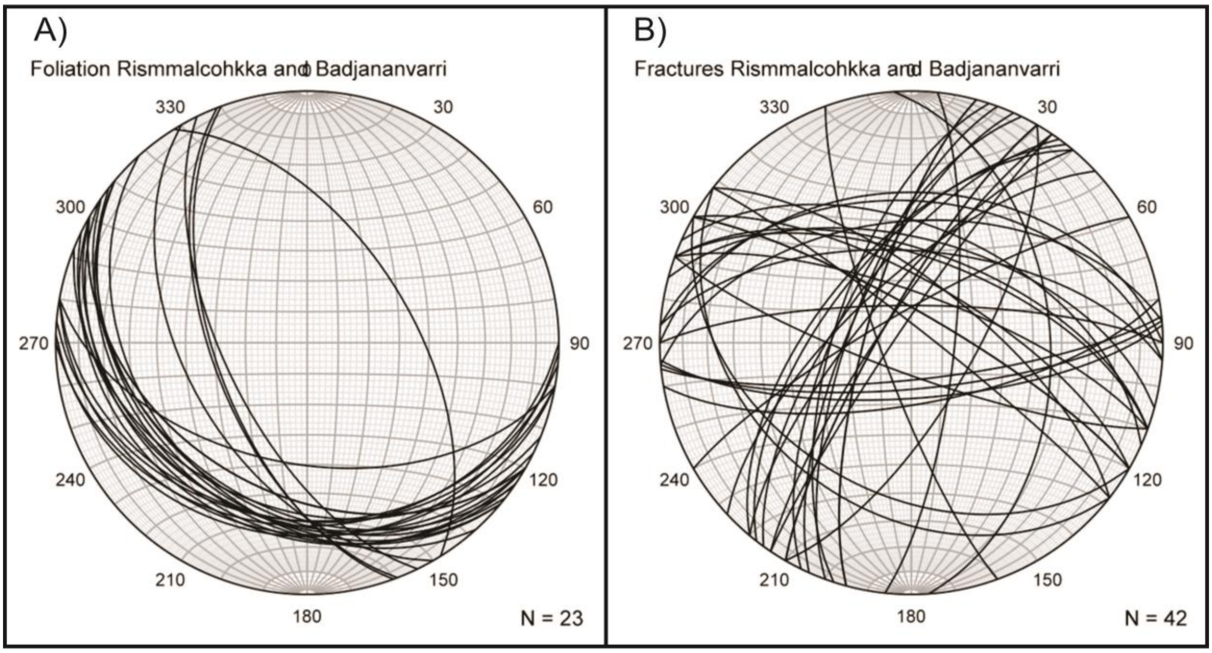

Fig. 22 – Stereographic projections of the bedrock structures at Rismmalčohkka and Badjánanvárri. A) presents the ductile Caledonian foliation, and B) presents orientations of the brittle fractures.

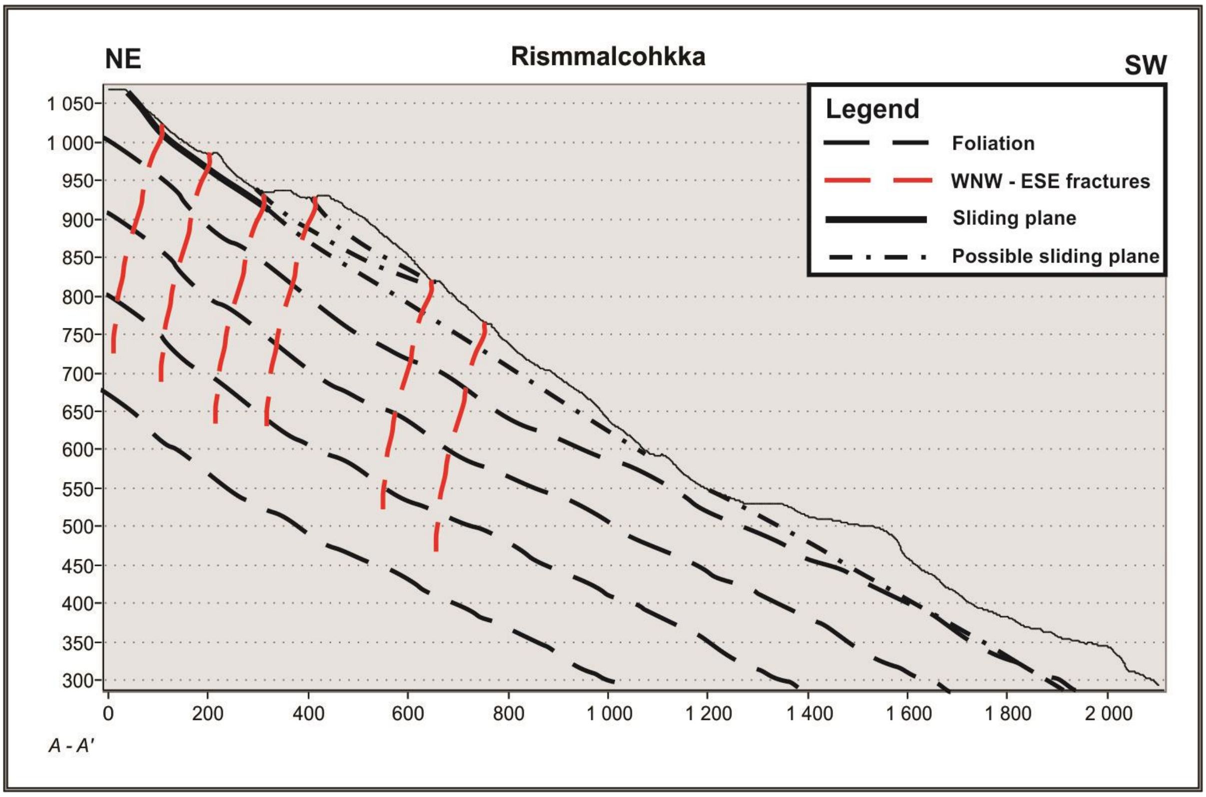

Fig. 23 - Profile A - A' at Rismmalčohkka in Fig. 21. Structures parallel or sub-parallel to the profile are not indicated in the profile. The lines are dashed as the continuations downslope and internally are interpreted, as structures only were measured along the backscarp.

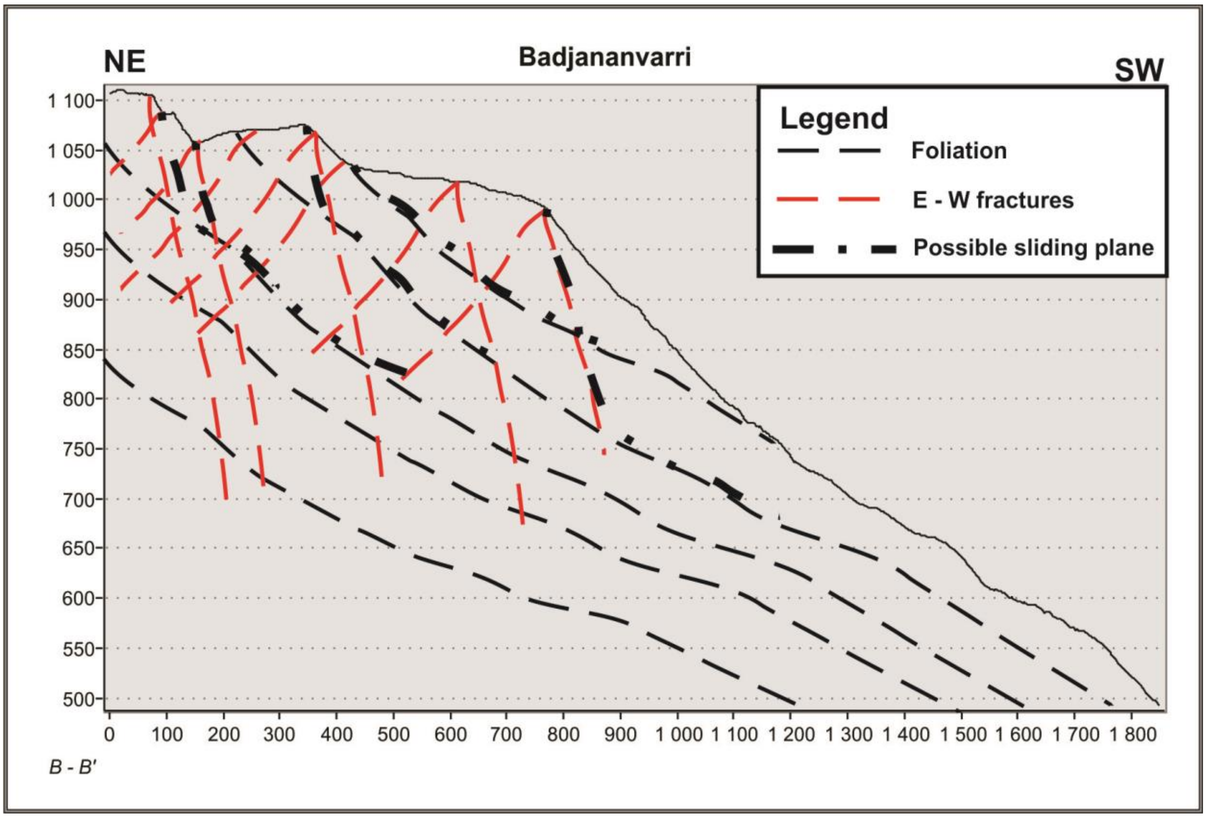

Fig. 24 - Profile B - B' of Badjánanvárri in Fig. 21. Structures parallel or sub-parallel to the profile are not indicated in this cross-section. All lines representing structures are dashed, as the downslope and internal continuations of the bedrock structures are interpretations, and not measured.

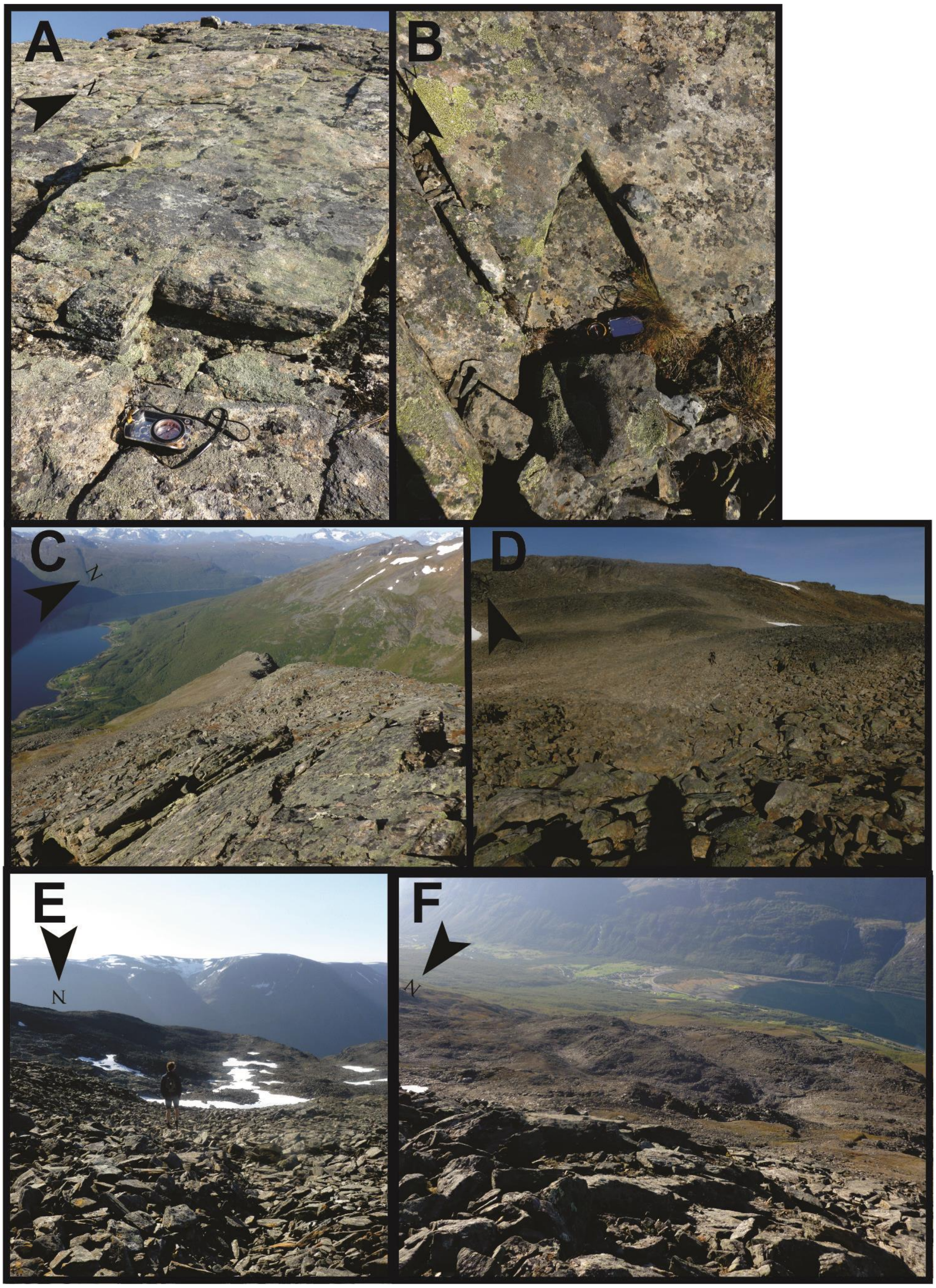

Fig. 25 – Outcrop photos from Rismmalčohkka and Badjánanvárri. A) A steeply dipping NW-SE –striking fracture crosscutting the exposed foliation surface along the backscarp, intersecting with a steeply dipping WNW-ESE –striking fracture. B) Sub-vertical N-S –striking fracture crosscutting the gently dipping foliation along the backscarp, intersecting with a steeply dipping NE-SW –striking fracture. C) The northwestern part of the foliation-parallel NW-SE –striking backscarp at Rismmalčohkka. D) N-S –trending depressions oriented perpendicular to the scarp in the back, located on a terrace at Badjánanvárri. E) A N-S –trending depression located between Rismmalčohkka and Badjánanvárri. F) The lower, talus covered part of Rismmalčohkka. In the center of the photo, a large terrace can be seen. The village of Birtavarre is located where the fjord ends.

5.3.2 Geomorphological elements

The prominent backscarp at Rismmalčohkka is approximately 1.5 km long and 100 m high at the most. It trends WNW-ESE in the eastern part, alternating with a partly stepping geometry westward from an E-W- and ENE-WSW –trend to WNW-ESE and NW-SE (Fig. 21). The backscarp is defined by exposed foliation surfaces along trend (Fig. 25C). A possible continuation of the backscarp in the eastern part strikes NE-SW, is oblique to the foliation and has a thicker cover of talus material at the toe of the scarp than the main backscarp does.

The delimiting backscarp at Badjánanvárri is sub-parallel to that of Rismmalčohkka, trending E-W altering in the eastern part of the unstable area to a stepwise NE-SW- and E-W -trending appearance (Fig. 21). Several depressions are located in immediate vicinity to the backscarp at Badjánanvárri, trending sub-parallel to the backscarp, considered fractures (Fig. 21).

The scarps at Rismmalčohkka show trends parallel to the brittle fractures striking WNW-ESE and NE-SW, and vary in extent from a few meters up to over 100 m (Fig. 21). The scarps comprise partly intact bedrock, but are in most cases covered by talus material in the front. An opposing scarp is located parallel to the interpreted long NW-SE –striking fracture at ca 600 m.a.s.l., appearing as a ridge.

Badjánanvárri is downslope composed of long, near backscarp-parallel scarps covered by a thick cover of talus material, with scarps delimiting some of the terraces (Fig. 21 and Fig. 25F). The trends of the scarps vary, where some sections trend parallel to the brittle fractures and the backscarp, while other sections trend perpendicular. The scarps are prominent features in the topography, as they distinctively separate the terraces at different elevations downslope (Fig. 24). Both of the failure areas comprise several linear depressions (Fig. 25D and Fig. 25E). The depressions are commonly trending parallel to strike of the brittle fractures, N-S to NNE-SSW, often observed on the terraces of the unstable area at Badjánanvárri.

There is a prominent, thick cover of talus material along the slopes of Rismmalčohkka with angular blocks of 10 cm in size up to several meters, some covering the foliation-parallel backscarp. The largest concentrations are located between the backscarp and the sub-backscarp-parallel NW-SE –striking fracture at approximately 600 m.a.s.l. (Fig. 20, Fig. 21 and Fig. 25F). Talus material and possibly rock glaciers, or relics thereof, cover the area located northwest of the ridge/fracture, where material is concentrated in lobate shapes (Tolgensbakk et al., 1988). The same lobate shapes are located on the slope between the backscarp and the ridge, some truncating each other.

The S- to SW-facing slope of Badjánanvárri has a thick cover of talus material that exposes a higher degree of weathering than the material at Rismmalčohkka, with a rusty color (Fig. 20

and Fig. 25D). The size of the material varies from 10 cm up to several meters, and the talus is mainly concentrated on the terraces in the upper part (Fig. 25D). In the lower parts of the unstable area, the talus blocks are concentrated in lobes, with possible rock glaciers or relics of rock glaciers (Fig. 21) (Tolgensbakk et al., 1988).

5.3.3 Preliminary interpretation

The backscarp of the unstable rock slope at Rismmalčohkka follows the exposed foliation surface striking WNW-ESE and NW-SE, dipping gently (30-35°) towards southwest. These exposed foliation surfaces are therefore considered the main controlling structure of the failure in the study area. Most of the smaller scarps at Rismmalčohkka, however, are parallel to the orientations of the brittle fractures, striking NE-SW and WNW-ESE to NW-SE. These scarps are interpreted to have formed along fractures (Fig. 21), partly delimiting some of the terraces. The scarps are covered by talus material downslope, suggesting smaller failures along the fractures delimiting them. The lower NW-SE –striking ridge/fracture at ca 600 m.a.s.l. is interpreted as a fracture with an opposing scarp trending sub-parallel to the backscarp. This system may be a surface expression of the daylighting of the sliding surface, as very little deformation is observed below it. The displacement mechanism at Rismmalčohkka is considered sliding controlled by the foliation, where sliding was initiated along the fully foliation-parallel backscarp (Fig. 23). The smaller failures along the scarps are interpreted to be due to gravitational activation of the fractures delimiting them. The possible daylighting of the sliding surface at 600 m.a.s.l. may, in combination with the mentioned structures, lead to an interpretation of a *planar translational slide* type of mechanism for the unstable rock slope at Rismmalčohkka (Glastonbury and Fell, 2010).

The backscarp at Badjánanvárri strikes E-W, parallel to the steeply southward dipping fractures. The backscarp alternates in a stepping manner eastward, where it follows the brittle fractures striking E-W and NE-SW. The foliation dips downslope, striking NW-SE to NNW-SSE, near perpendicular to the strike of the backscarp. The dip may be favourable for sliding of the rock masses as it intersects with the brittle fractures (profile in Fig. 24). The scarps and terraces at Badjánanvárri are mostly located in immediate vicinity to one another with some depressions on the terraces. Common for the scarps and the depressions is that they trend parallel to the strike of the brittle steeply-dipping fractures. These observations suggest that the failure mechanism at Badjánanvárri is controlled by both the gentler downslope-dipping foliation and the steeply-dipping brittle fractures that intersect with each other, suggesting a *bi-planar compound slide* as the failure mechanism (Glastonbury and Fell, 2010).

5.4 Ruovddášvárri

The unstable rock slope Ruovddášvárri is located south of Rismmalčohkka and Badjánanvárri (Fig. 2). The peak is 1096 m.a.s.l. and defines a vegetation-covered rectangular plateau. The south-facing slope consists of meta-psammites and calcareous marble with dolomitic layers exposed in the frontal vertical cliffs of the mountain. The cliff faces of the mountain represent the backscarps, trending E-W and N-S, respectively, forming an orthogonal pattern (Fig. 26). The backscarp exceeds 100 m at its highest in the northern part, and decreases in height eastward where a few terraces and greater amounts of talus material occur near and along the backscarp. The plateau exposes several N-S –striking open fractures, depressions and scarps, while the eastern part comprises large open fractures striking both parallel and perpendicular to the backscarp. Downslope of the entire backscarp, large lobate shapes of talus are detectable, partly truncating each other.

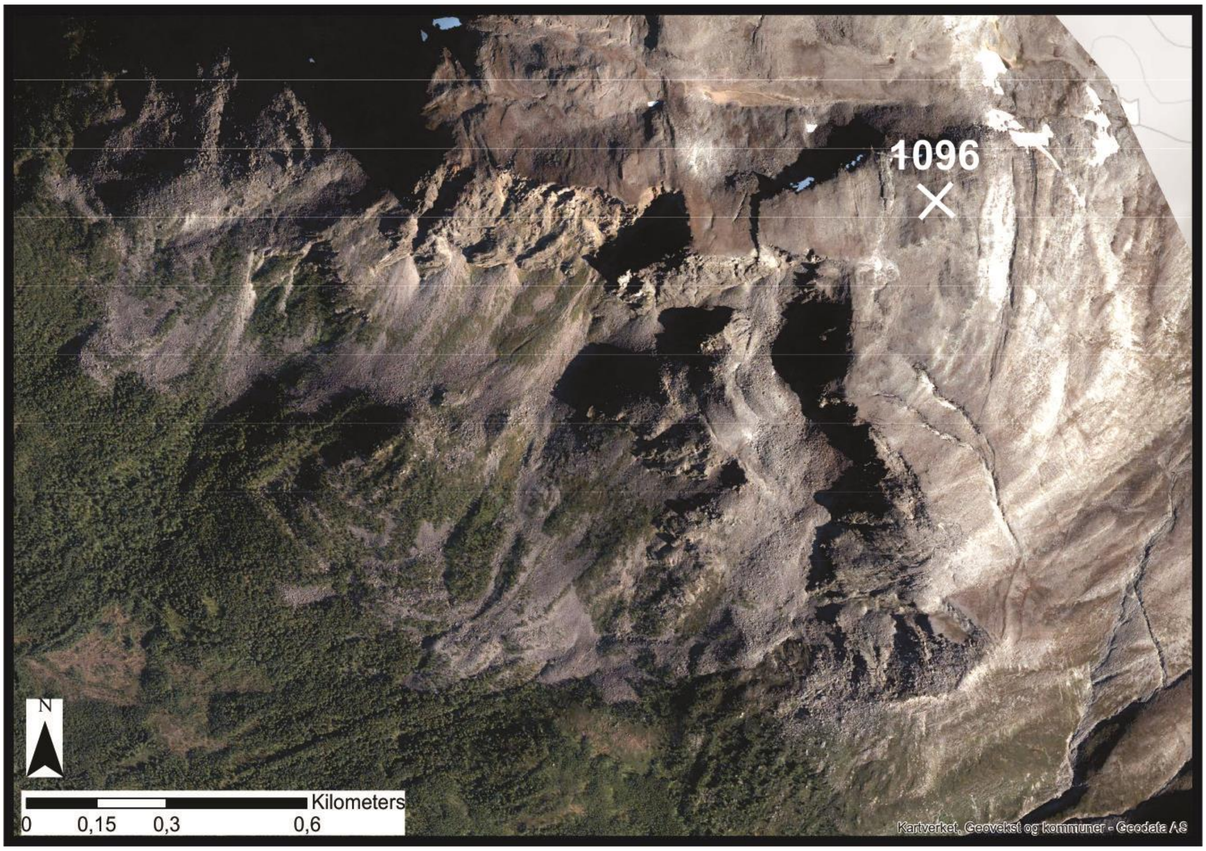

Fig. 26 - Aerial photo of Ruovddášvárri with the highest point indicated with a cross. Note orthogonal fracture sets bounding the top plateau striking E-W and N-S, respectively. Note also the several talus lobes in front of the cliff. Retrieved and modified from www.norgeibilder.no.

5.4.1 Bedrocks and structural architecture

The bedrock at Ruovddášvárri consists of meta-psammites, meta-arkoses and locally some calcareous and dolomitic layers of marble (Fig. 27). Structurally below these units, micaceous and amphibolitic schists and gneisses appear with varying content of muscovite and biotite. The bedrock at Ruovddášvárri is considered rocks from the Kåfjord Nappe. The Caledonian ductile foliation at Ruovddášvárri commonly strikes NNE-SSW to NE-SW with a generally uniform, gentle dip (10-30°) towards ESE and SE (Fig. 28A).

Most brittle post-Caledonian fractures observed in the intact bedrock of the study area at Ruovddášvárri strike E-W and N-S with a steep dip (Fig. 28B, Fig. 29 and Fig. 30). The E-W –striking fractures dip both north- and southwards, 85° and 65-70° respectively, and the N-S –striking fractures dip steeply to sub-vertical (50-80°) to the west (Fig. 28B). At intersections, the fracture form orthogonal patterns, which are observed large scaled along the stepping backscarp, but also smaller intersections, e.g. along the central N-S –trending scarp on the plateau (Fig. 31A).

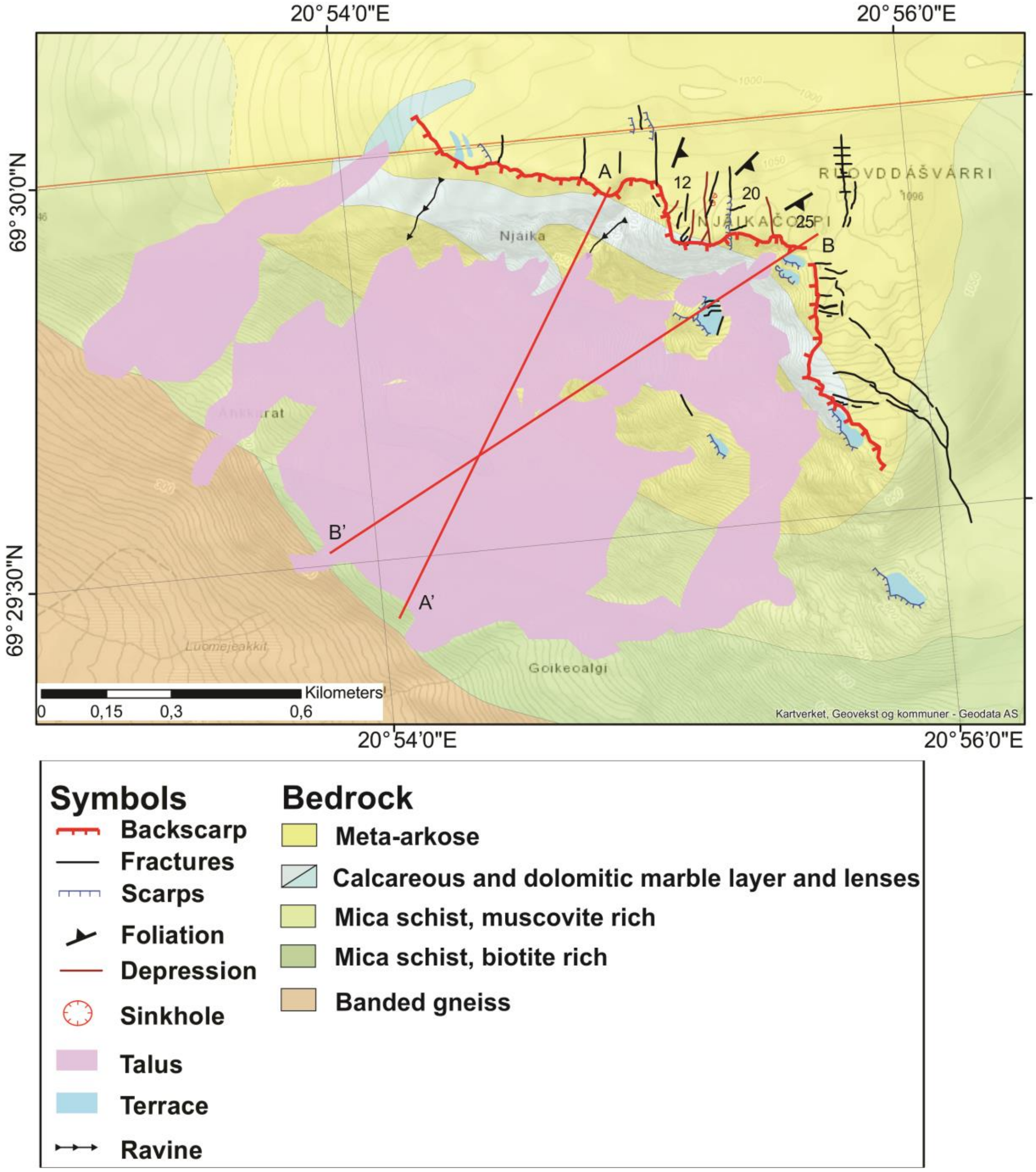

Fig. 27 – Bedrock map with structural and geomorphological features at Ruovddášvárri. Profile line A – A' and profile line B – B' are indicated. Bedrock map made available by the NGU.

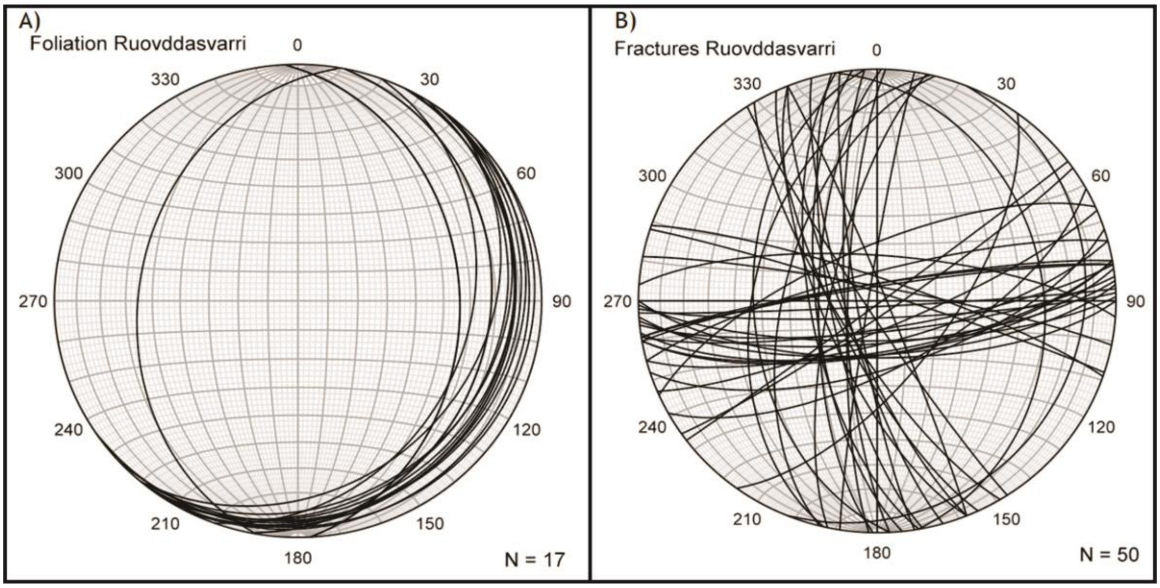

Fig. 28 – Stereographic projections of bedrock structures at Ruovddášvárri. A) Represents the ductile foliation, and B) presents the brittle fractures of the locality. The data are from own fieldwork and complimented by data obtained by the NGU.

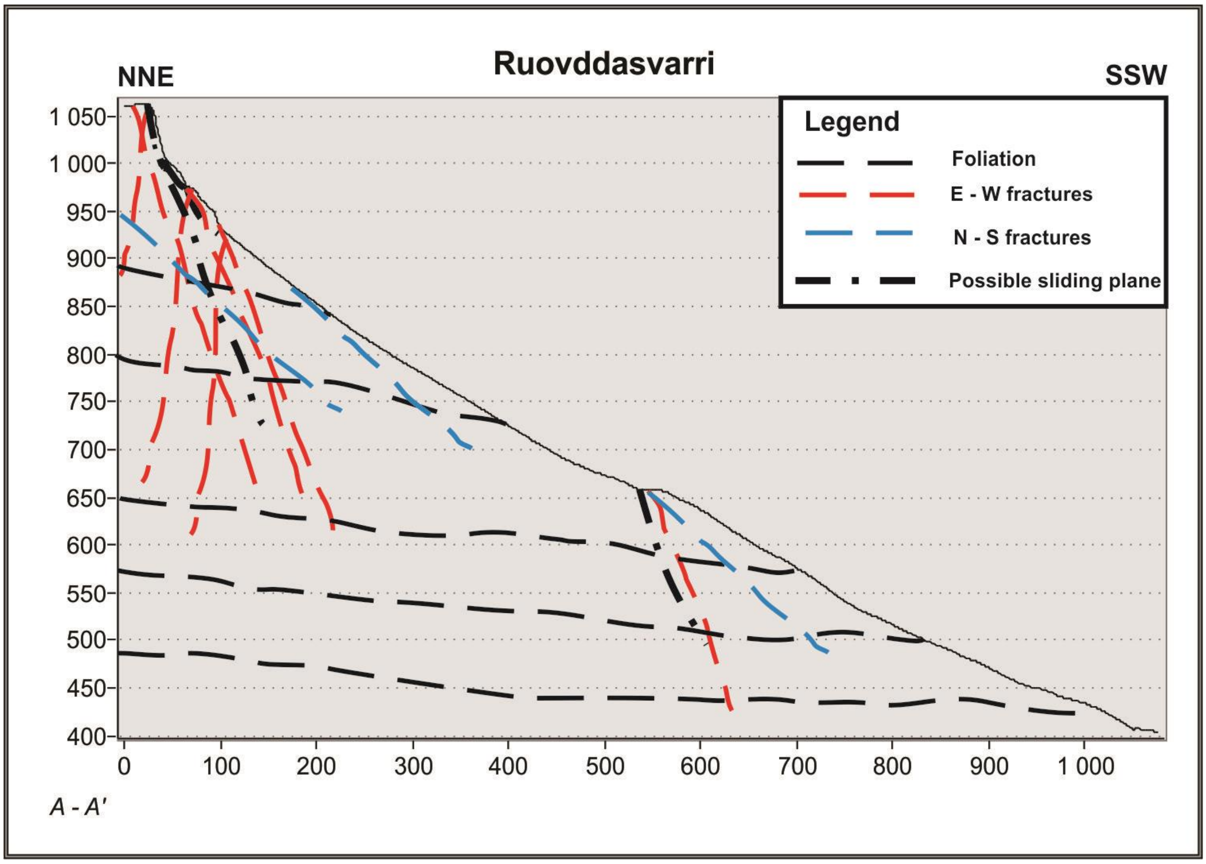

Fig. 29 – Interpreted cross-section A - A' with presumed, main failure-controlling structures. As the foliation is parallel and the N-S –striking fractures are sub-parallel to the profile, the apparent dip is utilized in the profile. This profile is along the A – A' line in Fig. 27. The interpretations downslope and internal continuations are based on field observations, and not certain.

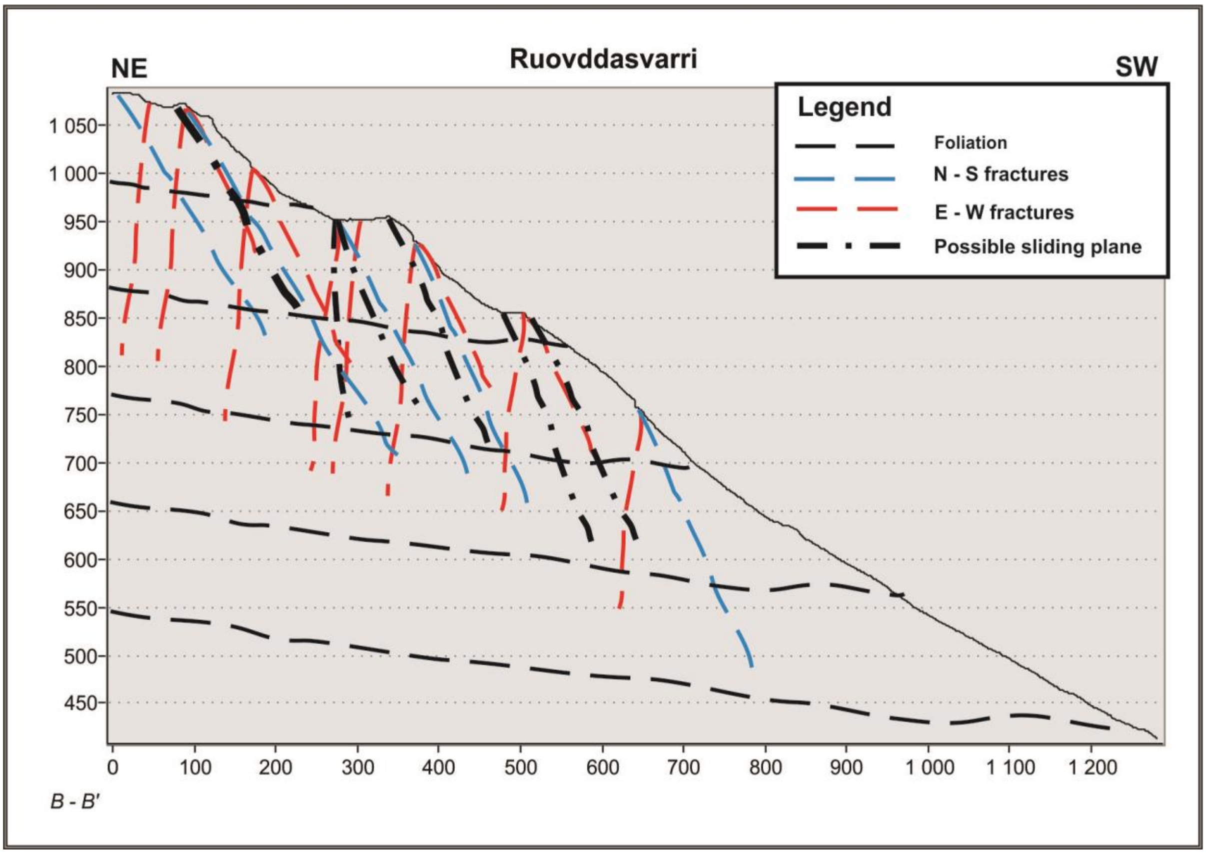

Fig. 30 – Interpreted cross-section B – B' with presumed, main failure-controlling structures. For the foliation and the N-S –striking fractures, the apparent dip of the structures is applied. Profile line is indicated in Fig. 27. Interpretations downslope and internally are not certain, as they are based on orientations of structures along the backscarp.

5.4.2 Geomorphological elements

The delimiting backscarp at Ruovddášvárri appears in a stepping manner of orthogonal steeply-dipping fracture surfaces striking N-S and E-W, altering to NW-SE –trending in the lower eastern part (e.g. Fig. 27, Fig. 31B and Fig. 31C). The overall orientation of the backscarp is WNW-ESE, sub-parallel to the orientation of the Kåfjorden valley. The backscarp is up to 120 m high, higher in the west than in the east. In the western part, the backscarp appears as cliff faces, whereas the eastern part has a slope-like appearance, with talus material covering the backscarp (Fig. 26). The two cross-sections, Fig. 29 and Fig. 30, illustrate well how different the backscarp appears within the unstable rock slope area.

The scarps observed at Ruovddášvárri do frequently trend parallel to the strike of the brittle fractures, N-S and E-W. In contrast, the scarps on the plateau itself trend perpendicular to trend of the backscarp, i.e. scarps trend N-S where the backscarp trends E-W. A long, prominent N-S –trending 5 m high scarp extends from an E-W –trending segment of the backscarp and crosses the entire plateau (Fig. 27 and Fig. 31A). The scarps below the backscarp in the eastern part delimit the few terraces in the study area, where the scarps trend sub-parallel to the backscarp. Smaller terraces also are located in the western part on the plateau, which are 'delimited' by slopes and not distinct scarps (Fig. 27).

In the western and central parts, talus concentrates in ravine-like depressions in the steeper parts, fanning out forming lobes where the gradient decreases below the cliffs forming the backscarp. The eastern part has a more chaotic appearance; talus material dominates more of the upper parts closer to the backscarp, where large blocks have collapsed forming terraces. Below the entire south-facing slopes and cliffs of Ruovddášvárri, a thick cover of talus material is concentrated in lobes that locally truncate each other (Fig. 27). Several depressions trending N-S are located on the plateau (Fig. 31D), some linking up with each other and comprising sinkholes, with on-lapping depressions trending NNW-SSE and NNE-SSW. The observed sinkholes vary in size, but several are aligned in a N-S –trending orientation (Fig. 27), with some of the sinkholes containing year-lasting snow-fill.

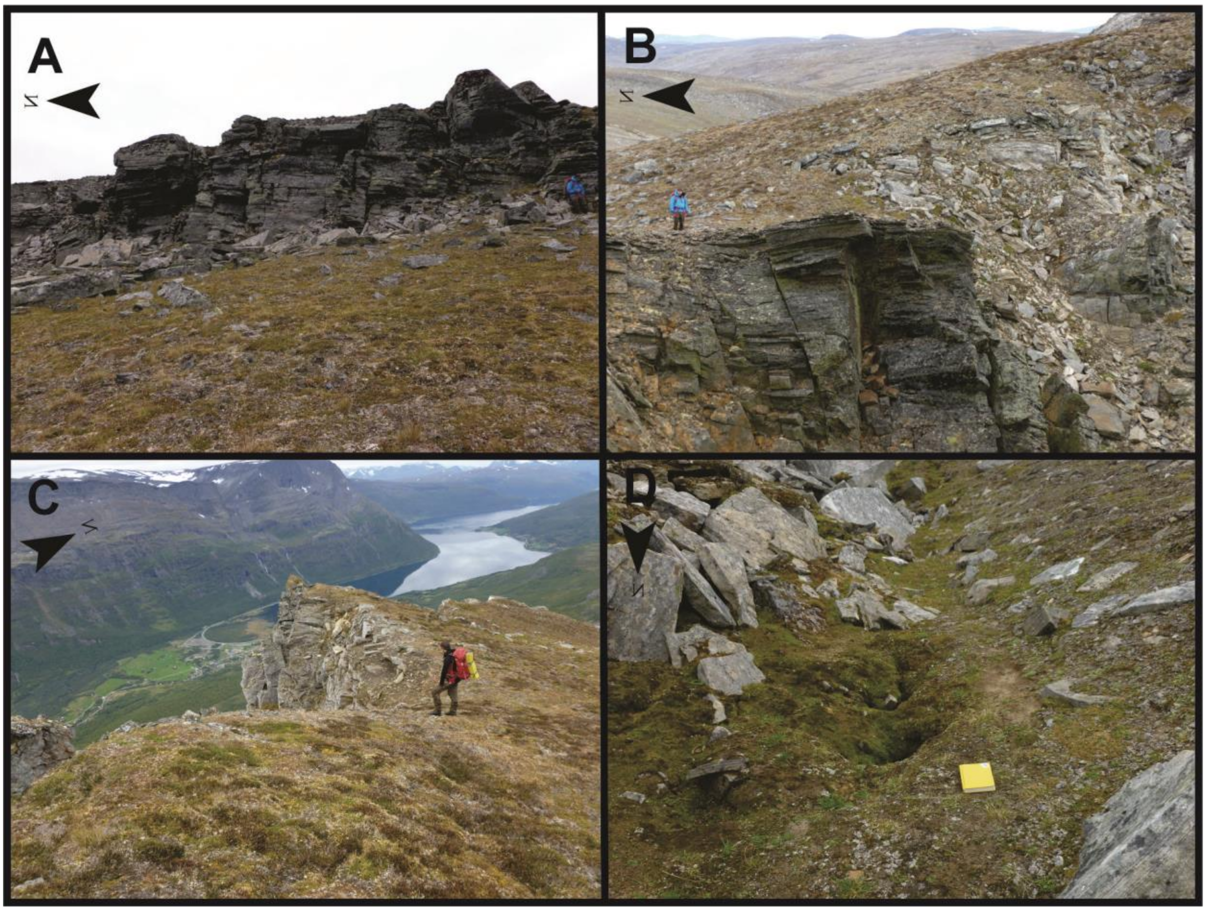

Fig. 31 – Photos of structural and geomorphological features at Ruovddášvárri. A) The elevated N-S -striking scarp on the plateau in e.g. Fig. 27. B) Parts of the backscarp showing the orthogonal appearance due to intersection of N-S- and E-W –striking fractures. C) A part striking E-W of the backscarp in the western part of the study area. D) Exposed sinkholes along a depressions, interpreted as a structural lineament striking N-S.

5.4.3 Preliminary interpretation

The backscarp is interpreted as a feature formed of zigzag shaped orthogonal brittle fractures, and it appears along lines of intersections striking N-S and E-W. The plateau comprises scarps and depressions trending parallel to the fractures, suggesting that the plateau is controlled by similar oriented fractures (Fig. 31A and Fig. 31D). The Caledonian foliation of the locality dips gently towards ESE and SE, and intersects with the brittle fractures that mainly dips perpendicular to and oppositely to the foliation. At the intersections of the fractures and the foliation, sliding may be enhanced along the gently dipping foliation, with fractures delimiting these failures. The large open fractures in the east are interpreted as tensile, and may continue to open causing failure of material in front.

The scarp across the plateau may have down-faulted the western part, as there is a distinct height difference between the western and eastern side of the scarp. The backscarp is steeper in the western and central parts, and appears more gentle and slope-like in the eastern part with downdropped terraces that follow trend of the backscarp and the brittle fractures. This suggests that the sub-vertical N-S- and E-W striking brittle fractures controlled the displacement of the terraces. Sliding along the foliation is considered possible in interaction with the southward-dipping E-W –striking fractures (Fig. 28B) daylighting in the face of the cliffs. Several of the downslope deposited talus lobes of heavily disintegrated material truncate each other, evidencing several events of failure, possibly at different times. In combination, the heavily disintegrated material and the steeply-dipping fractures may indicate a rockfall –type of failure. Because the geometry of the foliation may favor sliding, the overall failure type of Ruovddášvárri is considered a *slide topple* type of failure mechanism (Goodman and Bray, 1976, Braathen et al., 2004, Hermanns and Longva, 2012).

5.5 Nomedalstind

The mountain Nomedalstind is located between Gavtavárri and Rismmalčohkka, and has its highest point at 1051 m.a.s.l. (Fig. 2 and Fig. 32). The unstable area occurs on the southwest facing slope consisting of mica-schists and meta-psammites. The rocks comprise a well-developed foliation striking consistently NW-SE and dips ca 30° downslope towards southwest, the fjord (Fig. 32 and Fig. 33). The unstable area is defined by a foliation-parallel backscarp striking NW-SE in the west and NNW-SSE in the east. The locality comprises downslope several terraces of partly disintegrated bedrock, backscarp-parallel scarps and talus material concentrated in lobate shapes (Fig. 32).

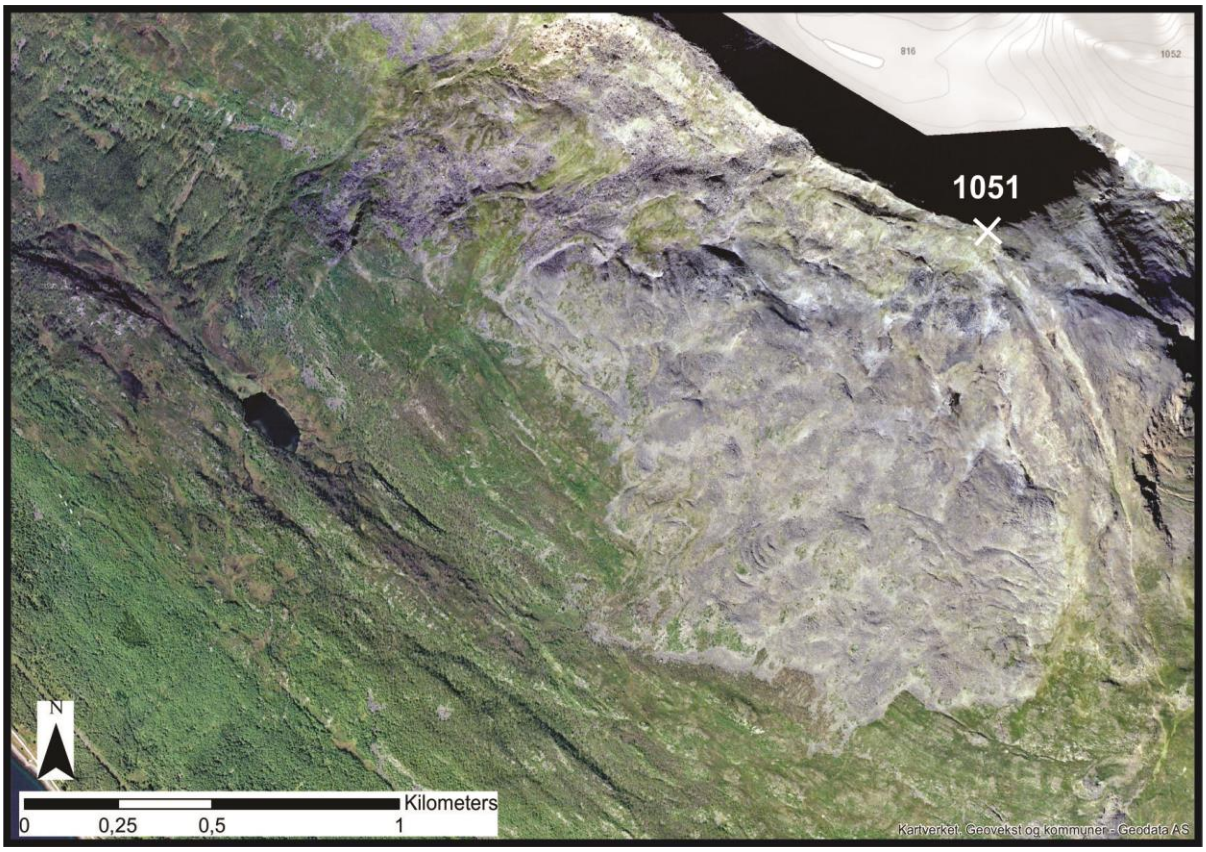

Fig. 32 - Aerial photo of Nomedalstinden with scale to the bottom left. The cross and point 1051 indicates the peak of the mountain. Aerial photo retrieved and modified from www.norgeibilder.no.

5.5.1 Bedrocks and structural architecture

The bedrock at Nomedalstinden consists of rocks from the Kåfjord nappe (e.g. Andresen, 1988), mainly meta-psammites and muscovite-rich mica schists in the upper part, while the lower part comprises various types of gneisses. Lenses of gabbro and amphibolite are detectable in all tectono-stratigraphic units of varying size. The lenses are flattened parallel to the lithological boundaries (Fig. 33).

The Caledonian ductile foliation at Nomedalstind acts as the main backscarp, which on average strikes NW-SE with a uniform dip (35-40°) towards SW, downslope towards the fjord. The foliation surfaces within the collapsed area are undulating, locally sub-horizontal, but in the intact upper part of the failure area, the foliation is perfectly coinciding with that of the backscarp. The foliation is prominent in the intact bedrock and fully exposed along the backscarp due to a high mica content, which makes the rocks schistose and more easily disintegrated. Slickensides occur locally in the northwestern part of the foliation-parallel backscarp, oriented parallel to the direction of failure, thus perpendicular to the strike of the backscarp, plunging southwestward.

Post-Caledonian brittle fractures at Nomedalstinden dip steeply to sub-vertical (75-80°) to N, S and SW, striking E-W, NE-SW (vertical) and NW-SE in the intact bedrock behind the collapsed area. The same orientation of fractures are located within the failure area where for instance scarps trend parallel to the strike of the fractures. Fractures strike both parallel (NW-SE – striking fractures), perpendicular (NE-SW –striking fractures) and obliquely (N-S – and E-W – striking fractures) relative to the foliation-parallel backscarp (Fig. 33). The fractures are all planar, thinner and smaller in extent in the less disintegrated upper part of the failure, whereas they are more irregularly shaped, open and often deep in the lower part of the failure area (Fig. 33). Some of the fractures in the lower parts of the failure area comprise year-lasting snow-fill.

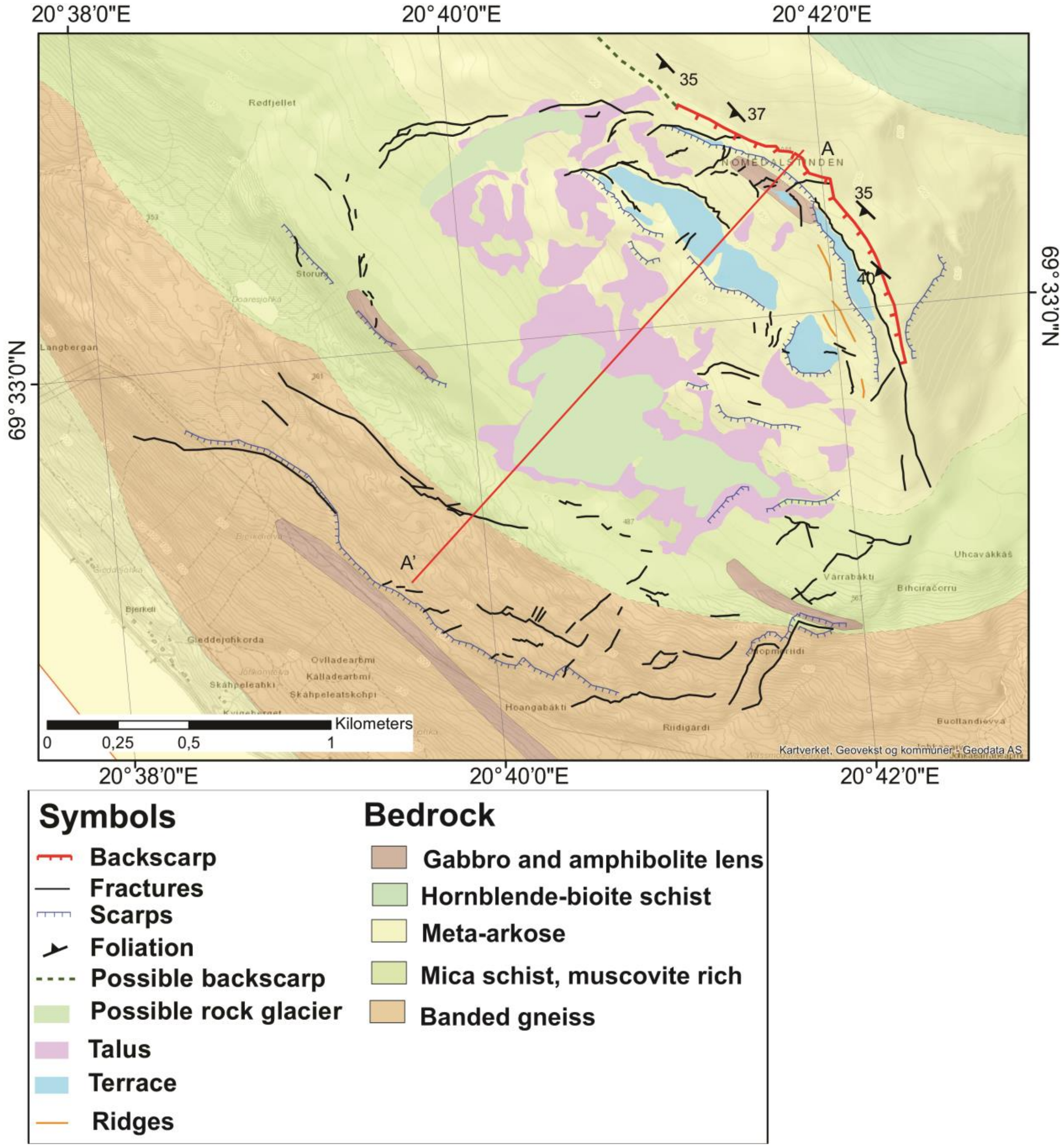

Fig. 33 - Bedrock map of Nomedalstinden with profile line A – A' drawn. The bedrock and legend, bedrock structures and geomorphological features are included. Bedrock map made available by the Geological Survey of Norway. Modified after (Husby, 2011).

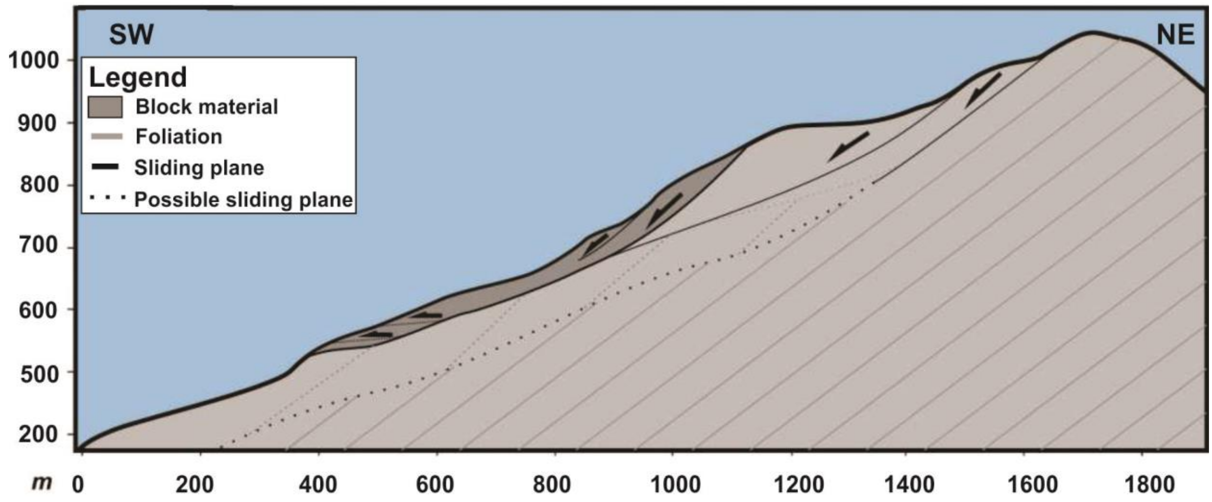

Fig. 34 – Interpreted cross-section of bedrock structures at Nomedalstind, where the profile is located along line A - A' in Fig. 33. Modified after (Husby, 2011).

5.5.2 Geomorphological elements

The backscarp at Nomedalstind is parallel to the foliation, dipping gently (30°) downslope to SW (Fig. 34), trending NNW-SSE in the eastern part bending to a NW-SE-trend in the central part of the unstable area, which it continues as further to the NW. The exposed backscarp is approximately 1.5 km long with a possible extension further towards northwest (green, dashed line in Fig. 33). Talus material is locally covering the exposed foliation surface representing the backscarp (Fig. 33 and Fig. 35).

There is a prominent scarp below the backscarp oriented similarly, which indicates that this scarp is also foliation-parallel. The scarp is an obvious feature (Fig. 35), has a parallel to sub-parallel surface to that of the backscarp, and seems partly delimited by a small depression in the back. There is a greater cover of talus material along this lower scarp than along the backscarp, and the surface of the lower is more irregular (Fig. 33).

The entire failure area has considerable amounts of talus material with several areas of block fields. The size of the block fields vary, but they all show topographic variations from the surroundings, and mainly consist of larger fragments than elsewhere along the slope. In the lower parts of the failure area, the talus material appears in lobes that vary in size. The lobes are mostly found in the central and southeastern part of the study area, and truncating patterns are common. The lobes do often show compression in the toe, where material appears stacked and pushed upwards. Some of the lobes in the lower central part and upper northwestern part of the study area are considered rock glaciers, possibly relics of rock glaciers (Fig. 33) by Tolgensbakk et al. (1988).

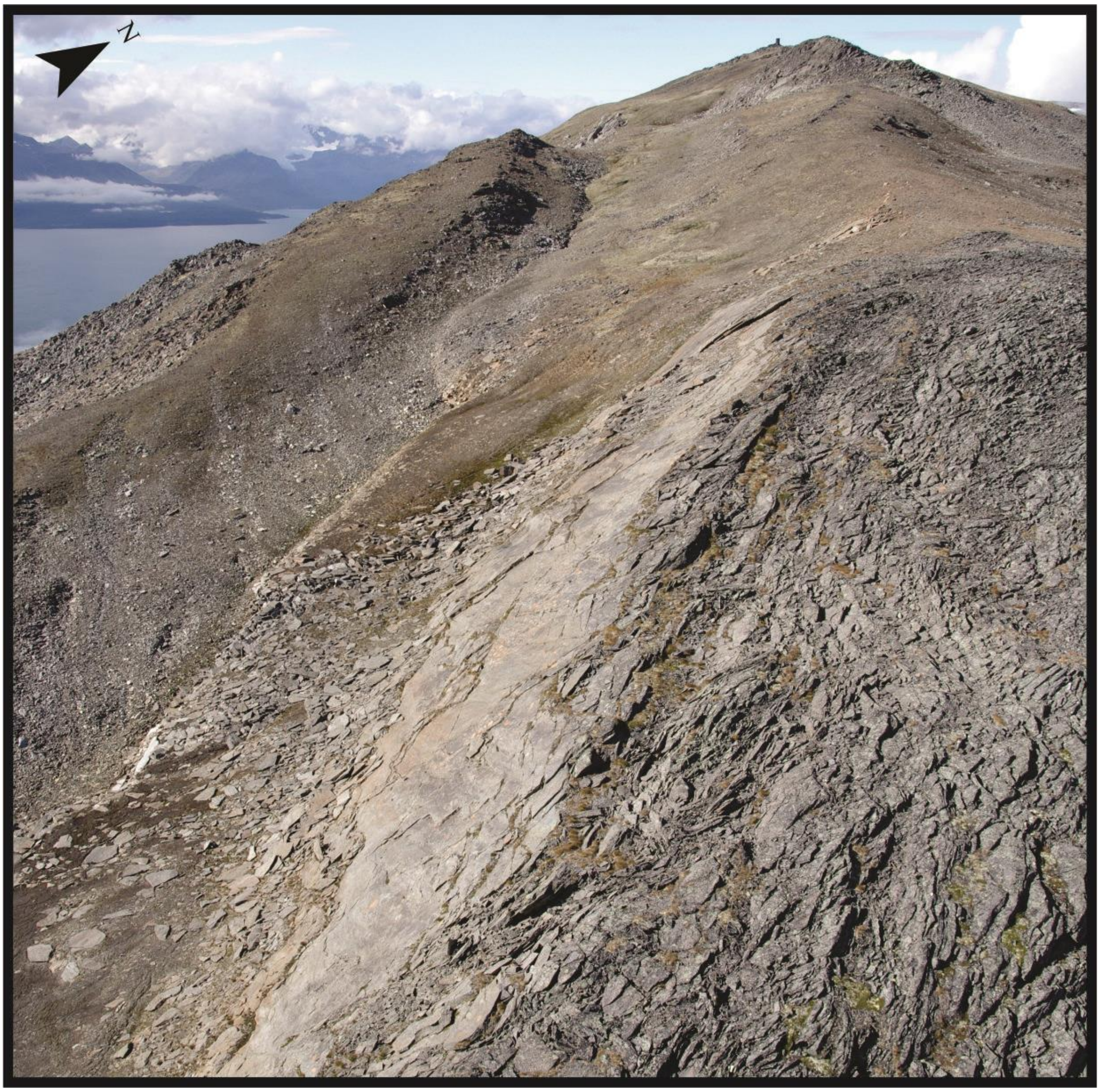

Fig. 35 - Photograph of the foliation-parallel backscarp at Nomedalstind. The scarp downslope of the backscarp trends and dips parallel to the backscarp. The top of the mountain is seen in the far back with the landmark on top. Photo by R. Hermanns (NGU).

There are several linear ridges parallel to the NW-SE –trending backscarp in the upper eastern part of the failure, and the same features, yet not as prominent, are located in the lower southern parts. These ridges crosscut the foliation in the rear parts and are composed of a thick cover of talus, while the front of the ridges are foliation-parallel with a thinner cover of talus in the bottom parts.

Below the backscarp, a major terrace system exists at ca. 850-900 m.a.s.l., comprising smaller and larger terraces in immediate vicinity to one another. Talus-covered scarps delimit them in the front, linear depressions delimit the terraces laterally, and the system is widest in the central parts (Fig. 33). The lateral segmentation of the terraces follow trend of the NE-SW –striking fractures, while the delimiting scarps trend parallel to the NW-SE –striking fractures and the foliation-parallel backscarp. The foliation is observed to be sub-horizontal within these terraces.

5.5.3 Preliminary interpretation

Nomedalstinden has a prominent backscarp, which is an exposed foliation surface dipping 35-40° southwestward (Fig. 35). The scarp below the backscarp is parallel to it, and is considered separated from the backscarp along a sliding surface, likely the foliation, as the backscarp follows the exposed foliation. Large terraces occur in the front of the lower scarp, are laterally segmented by the NE-SW –striking fractures and the front of the terraces comprises scarps trending parallel to the NW-SE –striking fractures. As the terraces appear at different elevations, downfaulting along the lateral delimitations is plausible. Downslope, the talus material defines lobes that are stacked against each other in the toe, suggesting toe compression (profile in Fig. 34). Several of these lobes truncate each other, evidencing several events of failure, or deposition at different times. The terraces, the presumed rock glaciers and the overall lobe-shape of the talus material are considered surface features of a DSGSD, with compression of material in front due to failure. Overall, the foliation is considered the dominant controlling structure of the failure at Nomedalstind, and the compression of the talus material may possibly be due to regional gentle folding of the foliation, making the sliding surface folded within the study area. The toe-buckling of the material is interpreted occurring as the sliding surface's angle decreases, at approximately 350 m.a.s.l., along the lowermost scarp (Fig. 33). Thus, the failure type of Nomedalstind is considered a *toe-buckling translational slide* (Glastonbury and Fell, 2010).

5.6 Oksfjellet

Oksfjellet is the southernmost locality, located on the southwestern side of the Kåfjord valley, a few kilometres south of Birtavarre (Fig. 2 and Fig. 36). The peak is among the higher in the area, 1151 m.a.s.l., located on a plateau, while the study area comprise the steep cliffs representing the backscarp. The slopes of the mountain are steep sub-vertical cliffs facing north to northeast consisting of well-foliated micaceous schists with varying content of muscovite and biotite.

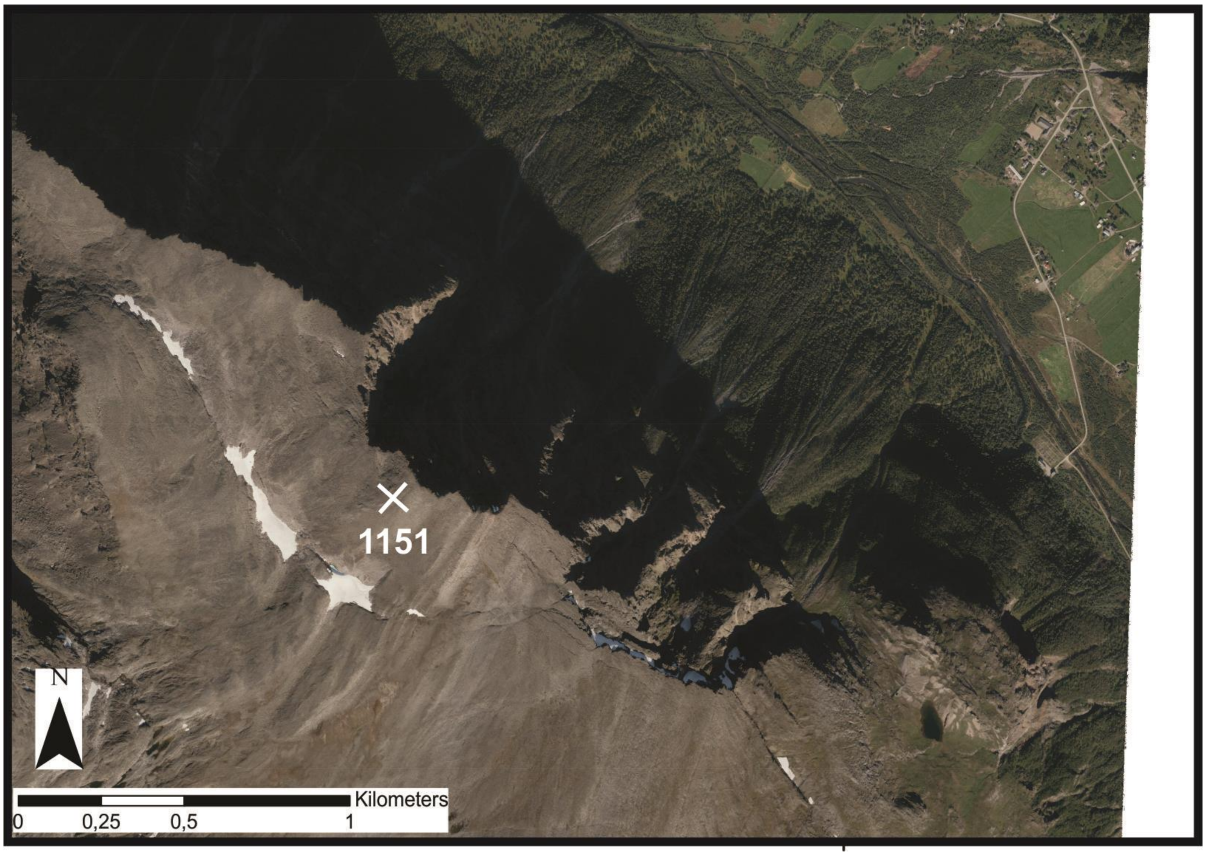

Fig. 36 - Aerial photo of Oksfjellet. The large open fracture, locally filled with snow, on the plateau and the alternating backscarp are prominent features of the locality. The point 1151 m.a.s.l. is the peak of the mountain. Retrieved and modified from www.norgeibilder.no.

5.6.1 Bedrocks and structural architecture

Units of alternating muscovite-rich and biotite-rich mica schists make up the bedrock at Oksfjellet, where the biotite-rich schists are enriched in garnet and have a rusty colour in the upper part along the backscarp. Some lenses and layers of amphibolite and calcite marble appear, which are parallel to foliation and lithological boundaries, and the lower southern part may comprise quartzite, marble and some pegmatite veins (Fig. 37).

All units at Oksfjellet comprise ductile Caledonian structures. The schists are well foliated, with foliation striking parallel to the lithological boundaries, mostly NE-SW to NNE-SSW with a variable dip (15-40°) to the WNW and NW (Fig. 39A and B). In combination, the foliation dips parallel to Kåfjorden valley, and out towards the valley. The foliation dips steeper in the southern part of the study area, seemingly due to the large scale folding of the lithologies forming a ramp above an interpreted thrust fault (Fig. 37 and Fig. 41).

The brittle post-Caledonian structures in the intact bedrock at Oksfjellet strike NW-SE to NNW-SSE and NE-SW to NNE-SSW with a steep dip to sub-vertical (70-85°), parallel and perpendicular to the backscarp, respectively (Fig. 39A and B). Subordinate fracture sets strike E-W and N-S. The fractures dipping towards northeast dip outward the cliff face towards the valley, while the SW-dipping fractures dip into the mountain. The NE-SW and the NW-SE striking fractures may represent conjugate fracture sets, as both fracture sets have opposite dipping directions forming angles at approximately 60° to one another (Fossen, 2016).

A large open fracture, or normal fault (Bredal, 2016), can be traced from the backscarp onto the plateau, changing strike from NE-SW to NW-SE. The feature is distinctively visible in the aerial photo (Fig. 36) with a discontinuous cover of snow. This arc-shaped fracture displays a similar geometry in map view as the backscarp itself, and a similar attitude of the bedrock foliation is apparent near the fracture (Fig. 37).

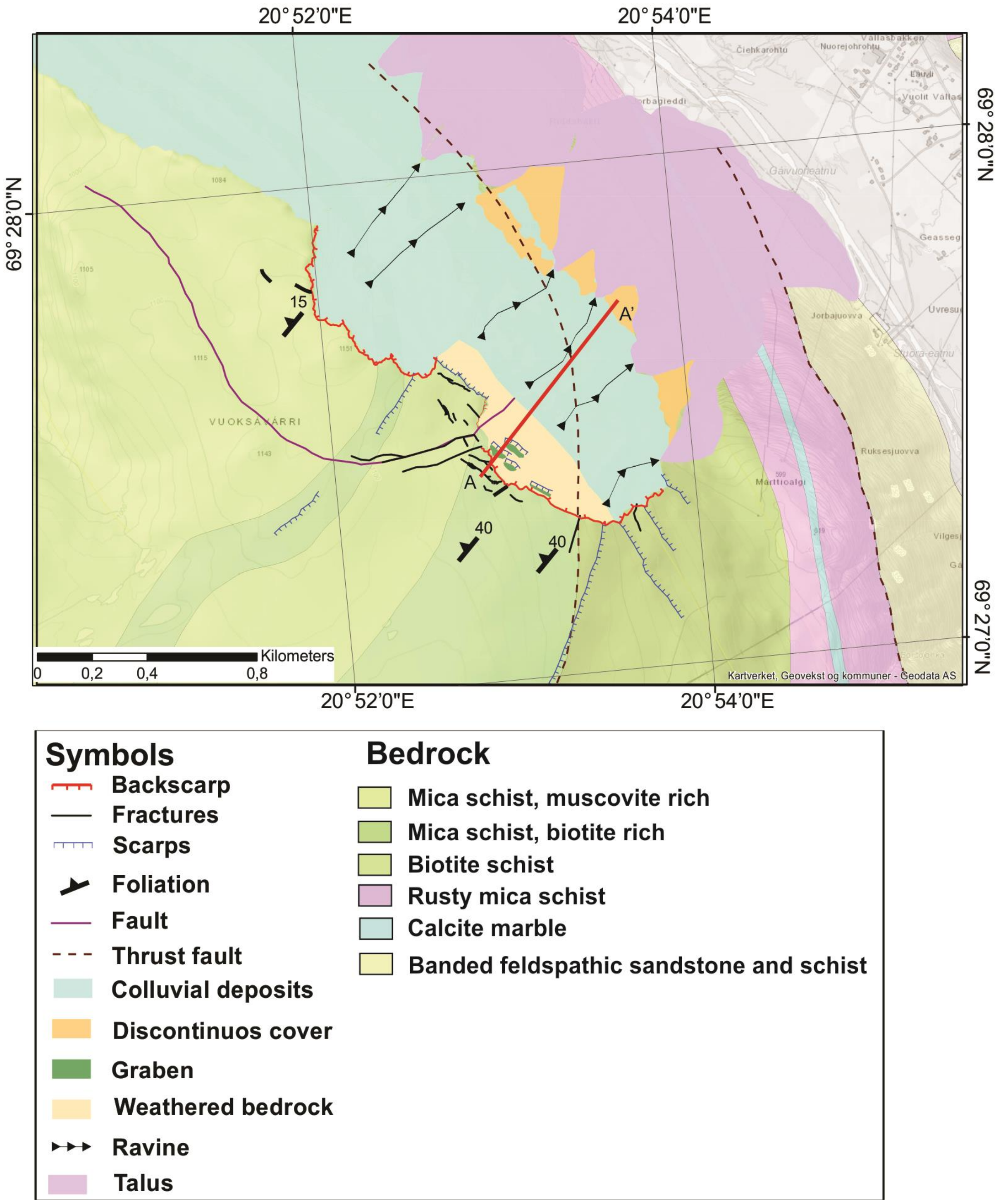

Fig. 37 - Bedrock map of Oksfjellet with interpreted geological bedrock structures and geomorphological features. Profile line A – A' is indicated. Bedrock map made available by the NGU. Modified after (Bredal, 2016).

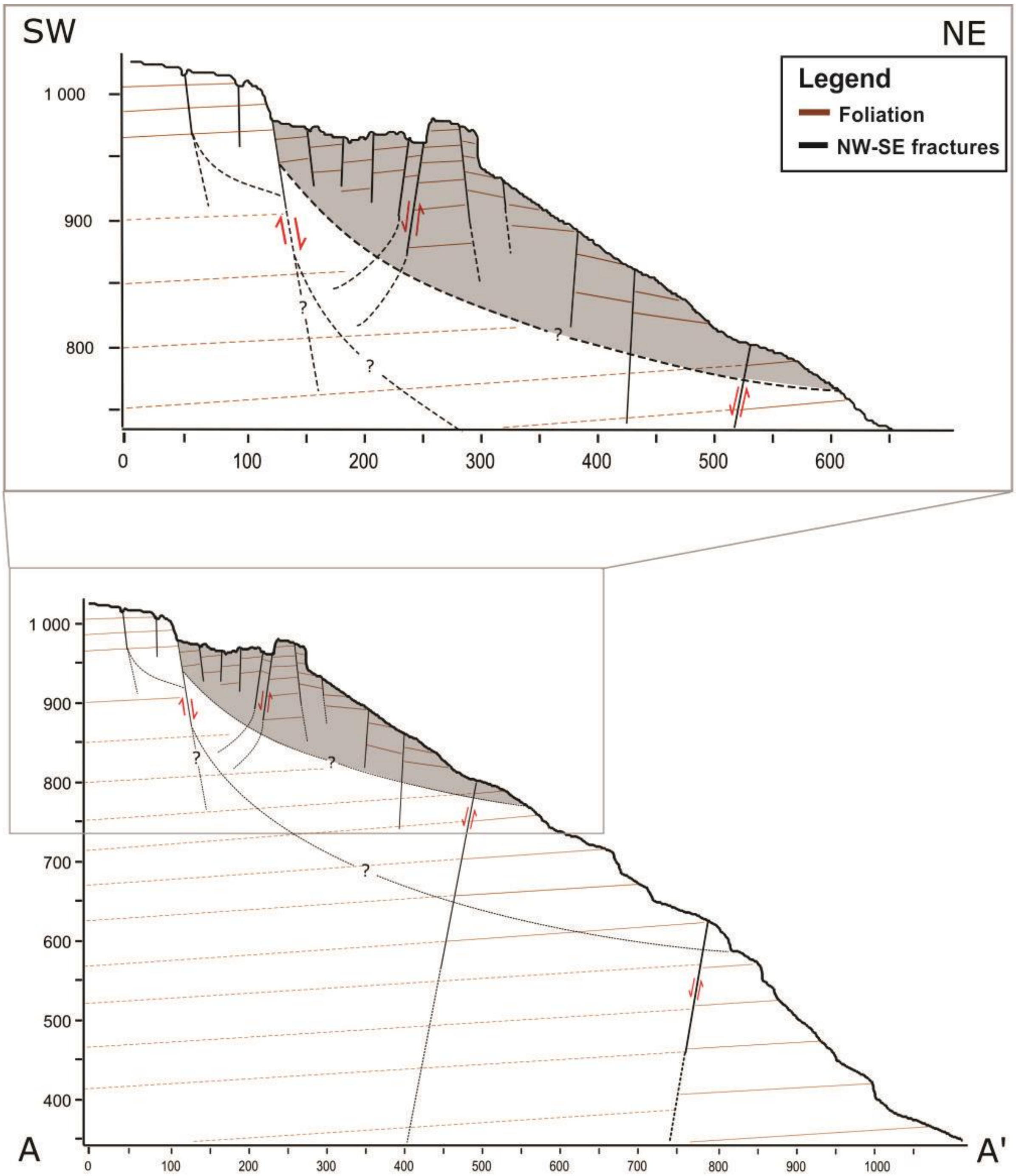

Fig. 38 - Profile A - A' of Oksfjellet. The fault in the interpreted cross-section is the same as the uppermost fault in Fig. 37. Modified after (Bredal, 2016).

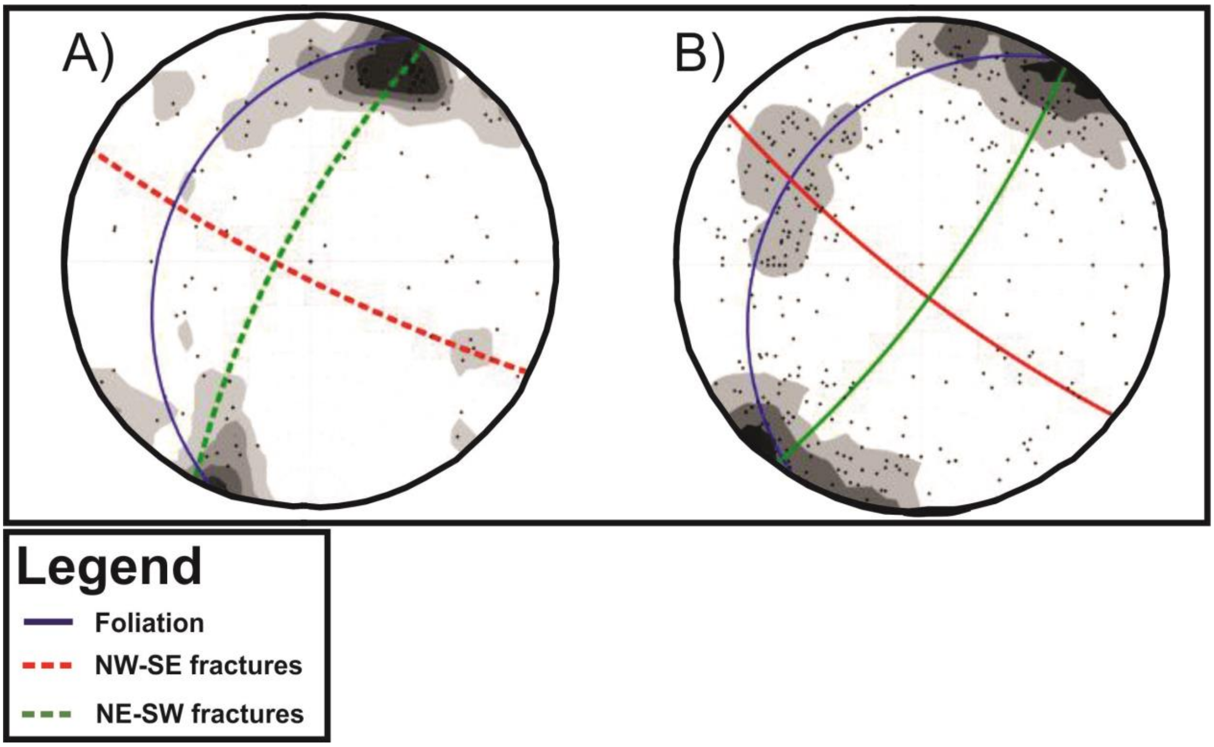

Fig. 39 - Stereographic projections of structural elements at Oksfjellet. A) Represents structures within the unstable area, and B) represents structures outside of the unstable area. Modified after (Bredal, 2016).

5.6.2 Geomorphological elements

The backscarp delimiting the unstable area at Oksfjellet is a prominent feature with an overall strike of NW-SE, parallel to the valley. The backscarp has a zigzag geometry in map view due to interaction of steeply dipping (70-85°), partly orthogonal fractures striking parallel and obliquely/perpendicularly to the valley, respectively. Maximum height of the backscarp is approximately 50 m in the central parts, decreasing towards NW and SE, with a system of graben structures, scarps and counterscarps in front (Fig. 37 and Fig. 38). The system of scarps and counterscarps follows strike of the brittle fractures, with trenches up to 100 m wide. The trenches (grabens in Fig. 37) are observed between the backscarp and the uppermost counterscarp consisting of crushed, angular material covering the surface. The fault on the plateau has a system of smaller scarps along strike trending parallel to the fault itself.

Most of the downslope talus at Oksfjellet is located below 400 m.a.s.l., defining truncating lobes where the slope gradient decreases below the cliffs. Upslope and in between the lobes, several ravines are traceable uphill to the intact bedrock (Fig. 37 and Fig. 40). Several large boulders (> 200 m^3), angular in shape, are present on the lobes close to the valley floor and settlements, especially in the northern part of the unstable area (Fig. 40). The talus cover is defined as it was classified by Bredal (2016) (Fig. 37).

Fig. 40 - Photo of the cliffs at Oksfjellet. Notice the large boulders to the left in the picture, considered derived from the exposed backscarp/cliff. Photo: Håvard L. Haukenes.

Fig. 41 - Photograph of the steep cliffs of Oksfjellet showing the interpreted monocline folding of the Caledonian foliation above the ramp. Modified after (Bredal, 2016). Photo by Martina Böhme.

5.6.3 Preliminary interpretation

The unstable area at Oksfjellet is bounded by a WNW-ESE to NW-SE -striking backscarp, alternating in orientation along average trend. In the southeastern part, the backscarp consists of steeply dipping to sub-vertical fractures striking NE-SW and NW-SE in a zigzag geometry in map view. The northwestern delimitation is where the backscarp follows the N-S- and the NE-SW –striking steeply-dipping fractures (Fig. 37).

The steeply dipping orthogonal, backscarp-parallel and backscarp-perpendicular fractures delimit the unstable area to the northwest, while the NW-dipping (40°) foliation delimits the unstable area in the southeast. The interaction of the scarp-related brittle fractures and the NW-ward dipping foliation favour wedge-failure sliding (Braathen et al., 2004). The presence of a failure-controlling sliding surface at Oksfjellet was inferred by Bredal (2016) based on field observations and data from satellite InSAR. The location of the sliding surface is constrained to the intersecting line of the foliation along the ramp thrust and the steeply dipping fractures (Fig. 38).

The complex geomorphology with scarps, counterscarps and trenches (grabens in Fig. 37) within the unstable area, in addition to the estimated volume (maximum 35 Mm^3) of the failure area and the steeply dipping fractures indicate that the failure was a combination of several mechanisms. The NE-SW –striking fractures crosscutting the NW-ward dipping foliation, and the NE-dipping fractures may likely have enhanced a wedge type of failure where the structures intersect (Fig. 39A). If there is a deeper-seated sliding surface controlling the collapse, a slide topple type of mechanism may be more likely, with sliding along the foliation. The unstable area was by Bredal (2016) classified as a *complex field* based on the theory presented by Braathen et al. (2004). A possibly more nuanced view is that it can be classified as a *slide topple* type of failure mechanism, with *rock fall sliding* due to NW-SE –striking fractures, and *wedge failure* reflecting the local, and possibly, initial failure mechanisms (Goodman and Bray, 1976, Braathen et al., 2004, Hermanns and Longva, 2012).

5.7 Langsnøen

The unstable area of Langsnøen is located along a cliff face north of Oksfjellet, just above the village of Birtavarre in the valley (Fig. 2). The work on this locality has focused on the NE-facing slope of the steep mountain side where the unstable area is located at ca 700-450 m.a.s.l. Langsnøen is the only one out of the studied localities that does not have the backscarp on the top of the mountain (Fig. 42). The unstable area is dominated by a distinct NW-SE –striking backscarp with minor scarps downslope.

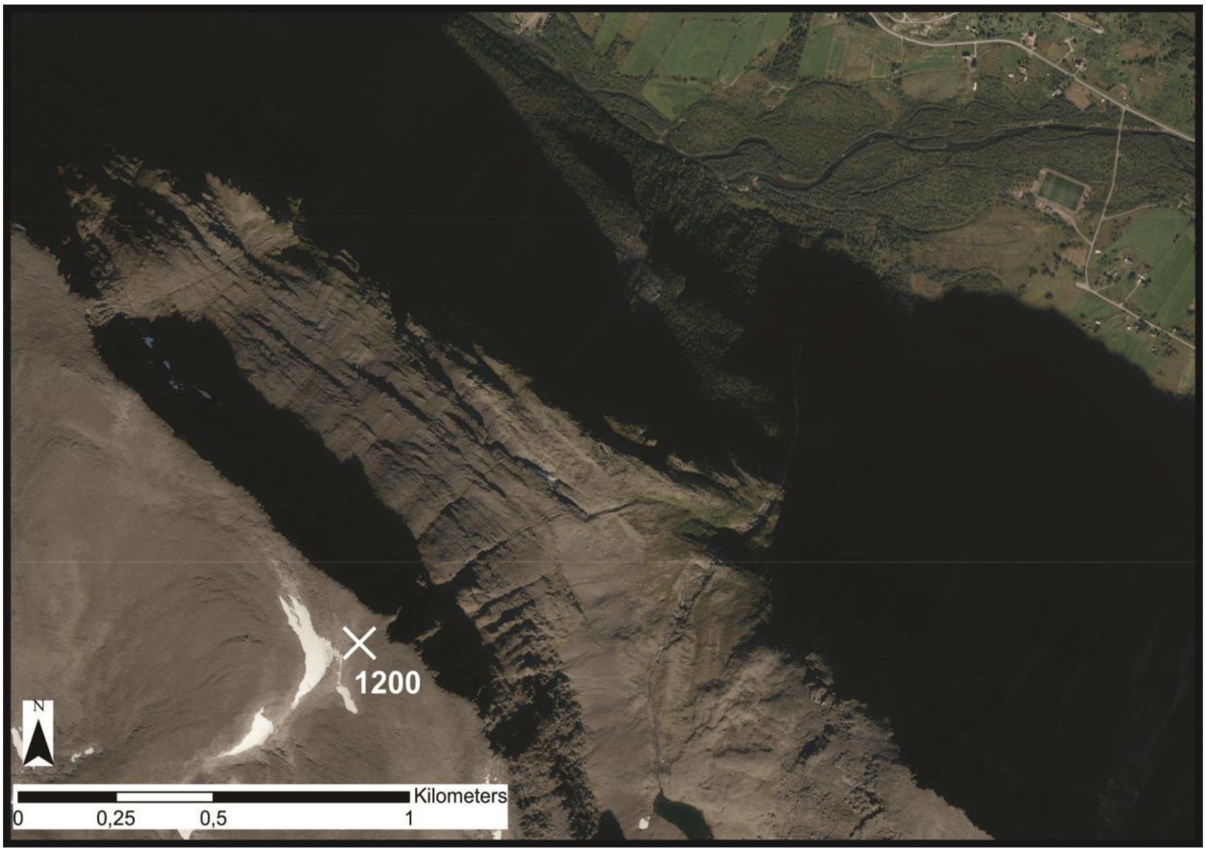

Fig. 42 - Aerial photo of Langsnøen. The cross indicates the highest point in the photo; however, the highest point is further to the southwest. Retrieved and modified from www.norgeibilder.no.

5.7.1 Bedrocks and structural architecture

The bedrock in the unstable rock slope of Langsnøen consists of various mica schists. The tectonically uppermost unit is enriched in muscovite, successively followed downslope by alterations of biotite-rich and muscovite-rich units of mica schist (Fig. 43). Both the muscovite-rich and the biotite-rich mica schist contain layers and/or lenses of amphibolite. The bedrock comprises rocks from the Kåfjord Nappe (Zwaan, 1988).

The ductile foliation is sub-horizontal to gently dipping (10-30°) towards SSW to S and NW to NNW, oppositely and perpendicularly to the slope, respectively (Fig. 44A). The most prominent brittle fracture sets strike NW-SE, parallel to the slope, and subordinately NE-SW and E-W (Fig. 44B). The NE-SW –fractures strike perpendicular to failure direction, while the E-W –strike obliquely on the slope. The fractures are steeply dipping to sub-vertical (60-85°) in both possible directions for each fracture set (Fig. 44B). However, a downslope dip direction is most common for the slope-parallel fractures. Most fractures are planar and open.

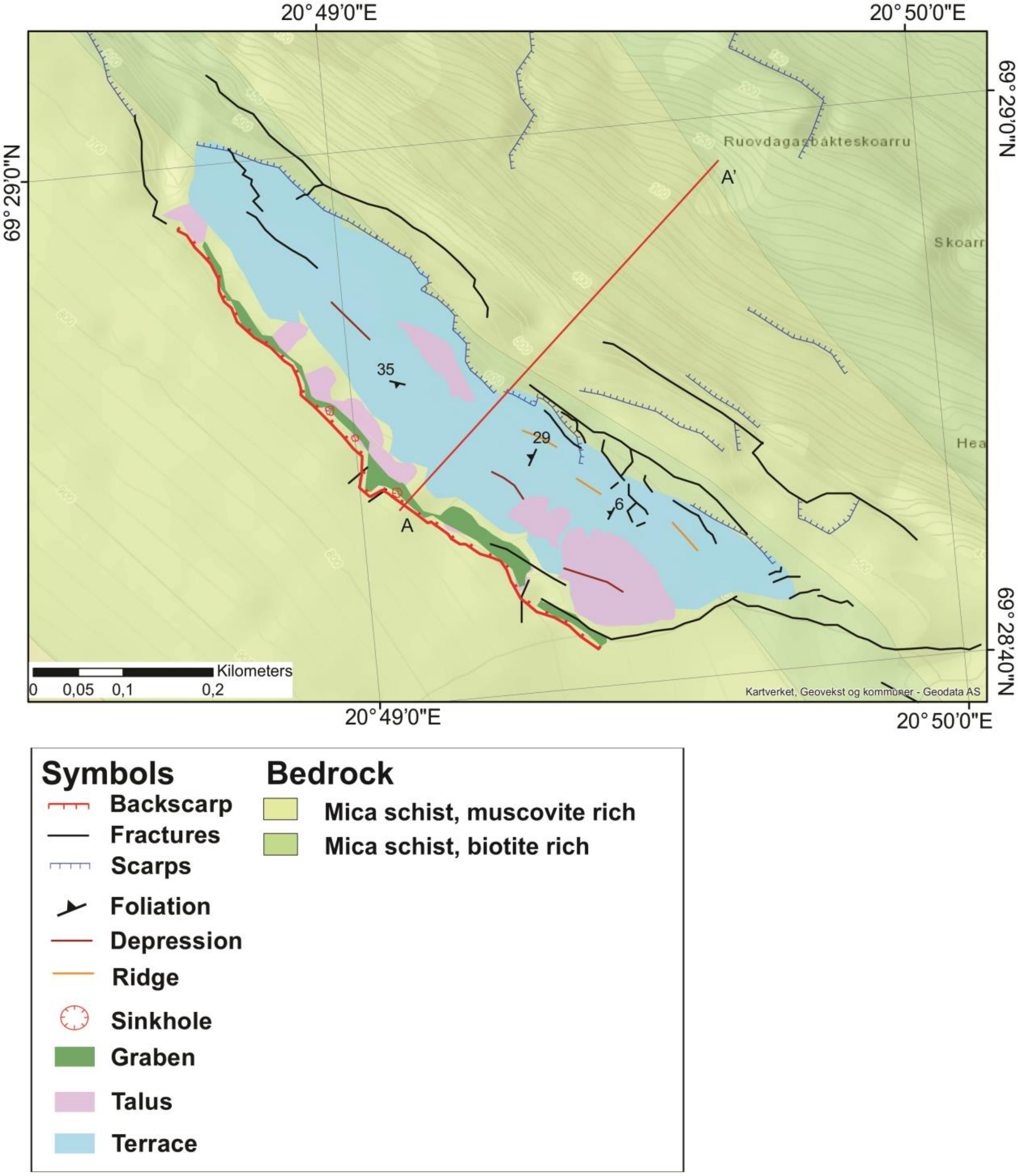

Fig. 43 - Bedrock map of Langsnøen with structural and geomorphological features. Several sinkholes are located in the graben parallel to the backscarp. Bedrock map made available by NGU. The cross-section along profile line A – A' is illustrated in Fig. 45.

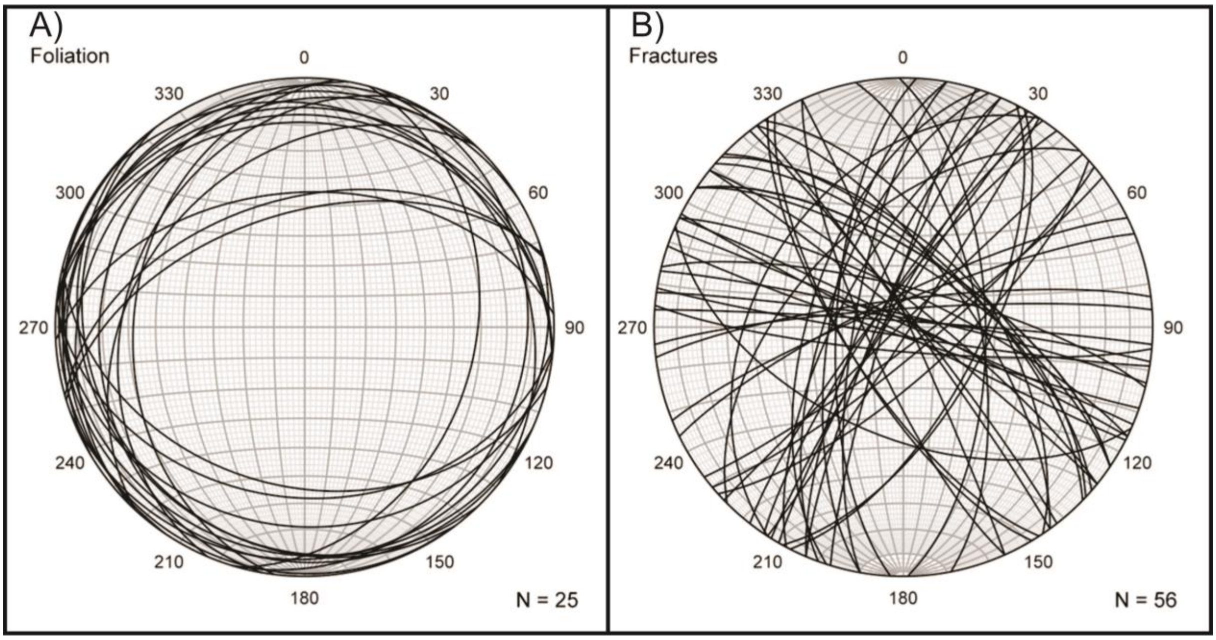

Fig. 44 - Stereographic projections of the bedrock structures at Langsnøen. A) represents the ductile, Caledonian foliation, and B) represents the brittle post-Caledonian fractures. The Geological Survey of Norway provided the data.

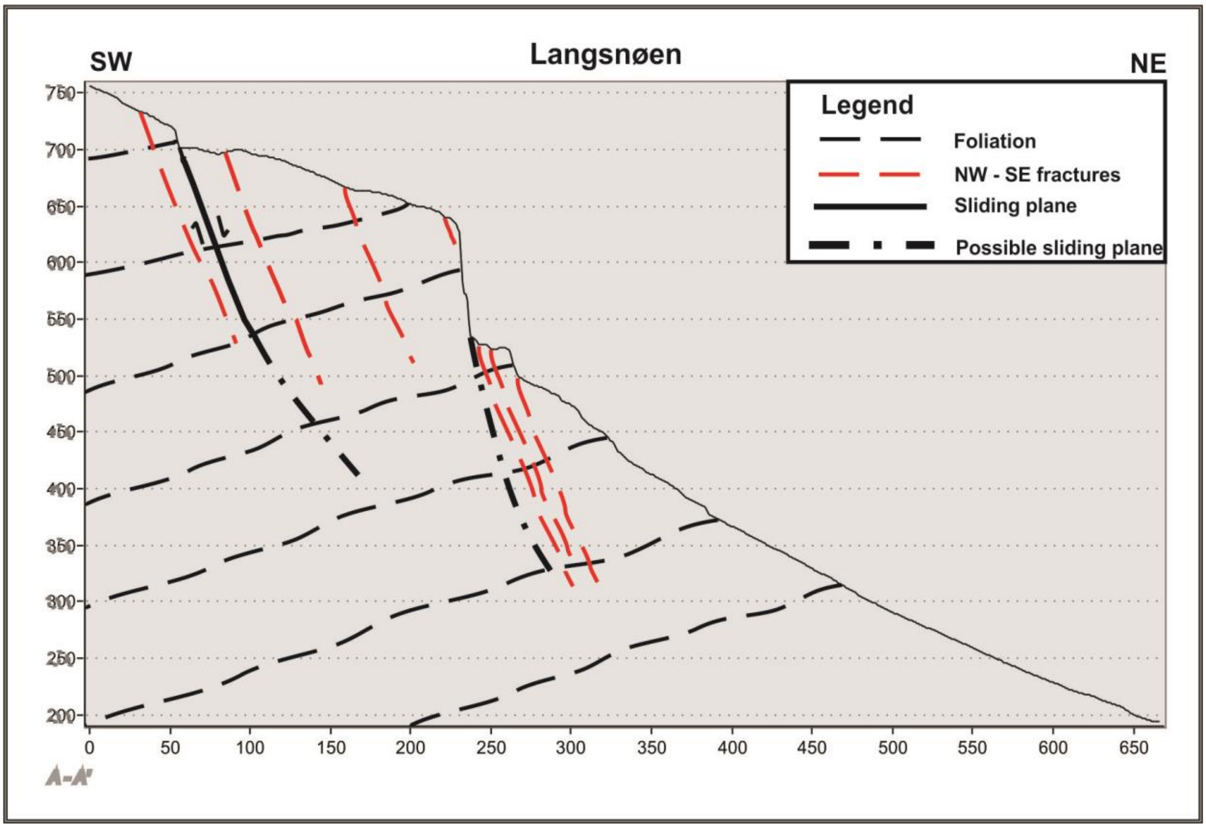

Fig. 45 - Profile A - A' of Langsnøen and its structural features. The fractures parallel and sub-parallel to the profile are not drawn. The profile is made based on data provided by the Geological Survey of Norway. All lines are dashed, as they are interpreted from structures measured at the surface.

5.7.2 Geomorphological elements

The backscarp is a prominent 750-800 m long NW-SE -trending feature along the slope of an internal terrace parallel to the Kåfjord valley, at approximately 700 m.a.s.l. The backscarp follows traces of the dominant NW-SE –striking fractures dipping downslope (NE), and the backscarp is up to 10-15 m high (Fig. 45). There are also fractures striking perpendicular and obliquely to the backscarp locally delimiting smaller unstable blocks and talus below (Fig. 43). A graben located parallel to the backscarp is approximately 700 m long and varies in width, about 30-50 m across, and is generally covered by talus material, but some sinkholes appear along trend of this graben.

In front of the graben, there is a terrace oriented parallel to the backscarp and the graben that dips gently downslope towards the valley (Fig. 43). The terrace has a cover of vegetation and some rock material, and is narrower in the northwestern part of the unstable area. In front of the terrace, there is a vertical scarp in the northwest, and several downward-stepping scarps oriented parallel to the backscarp in the central and southern parts of the terrace.

In the southeastern part of the unstable area, several blocks are separated from the intact bedrock. These blocks vary in size, and show separation parallel and perpendicular to the backscarp and the valley. Ravines filled by debris exist downslope from the terrace, fanning out, and material has been deposited where the slope gradient decreases, at approximately 200 m.a.s.l. (Fig. 42). Several linear depressions and smaller ridges are detectable within the unstable area that mostly trend NW-SE, which is parallel to the backscarp and the Kåfjorden valley.

5.7.3 Preliminary interpretation

The unstable area of Langsnøen has a prominent backscarp clearly delimiting a terrace in front from the intact bedrock behind. The graben in front of the backscarp is an obvious sign of displacement towards northeast, and the controlling structure of the failure at Langsnøen is considered the NW-SE –striking and NE -dipping (downslope) fracture surfaces parallel to the backscarp. The orientation of scarps and fractures at Langsnøen largely overlap and are both parallel and perpendicular to the slope face. The foliation dips similar to that of Oksfjellet, gently (10-30°) toward northwest and southwest, which may have enhanced sliding as the foliation intersects with the steeply-dipping fractures (Fig. 45). Little talus material exist within the unstable area, a thin cover appears on the terrace, but mostly is deposited further downslope due to the large topographic variations of the hillside area, as in Oksfjellet.

In combination, the fractures that dip steeply toward the valley, e.g. toward NE and those dipping to the NW (slope-perpendicular) may cause sliding when they intersect with the gently dipping (10-30°) foliation. The steep fractures parallel to the backscarp found elsewhere in the unstable area might control a rock fall slide of the terrace, with local slide toppling where these fractures intersect with the foliation. The unstable area at Langsnøen is therefore considered a *slide topple* with minor *rock fall slides* (Goodman and Bray, 1976, Braathen et al., 2004, Hermanns and Longva, 2012).

5.8 Regional trends of lineaments

One of the goals of this thesis is to evaluate pre-existing regional structures (lineaments) in the bedrock as controlling factors for the studied unstable rock slopes in Kåfjorden. In this sub-chapter, regional lineaments (Fig. 46) assumed to be of structural origins, mainly brittle faults and fractures (cf. Indreværet al., 2013) are described and compared with those found at the studied localities.

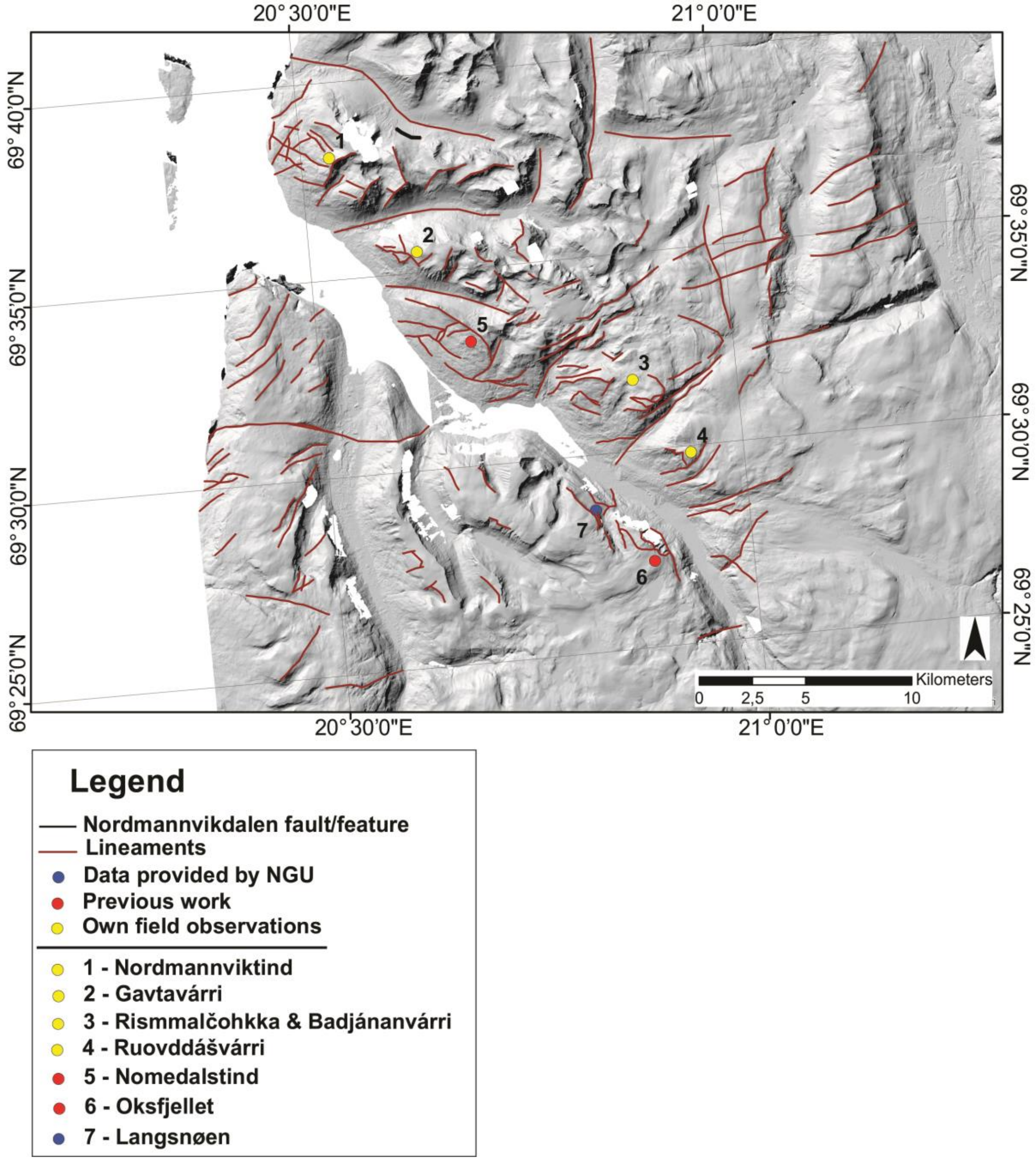

Fig. 46 - Structural lineaments in the bedrock of the study area. The locations of the study areas are indicated, as well as the backscarps of each locality. The presented Normannvikdalen fault/feature is drawn with a black line NE of Nordmannviktind, locality 1 (Redfield and Hermanns, 2016).

In the study area of Kåfjorden, the dominant structural lineament trends are NW-SE, NE-SW and E-W. Lineaments trending ENE-WSW, WNW-ESE and N-S (i.e. at Ruovddášvárri) also appear; however, these orientations are considered subordinate ones, or splays of other lineaments (Fig. 46). The regional lineament pattern interpreted mostly corresponds to the observed brittle fractures of the localities, and the main characters of these are presented below.

5.8.1 NW-SE –trending brittle structures

In coastal and central Troms, NW-SE –trending lineaments are observable along e.g. major ductile shear zones in Precambrian basement rocks, e.g. the Bothnian-Senja Fault Complex (Fig. 4), and these features segment the entire continental margin along strike (Indrevær et al., 2013). The previously mentioned Nordmannvikdalen fault/feature also trends NW-SE.

The NW-SE –trending lineaments (Fig. 46) are located along several of the backscarps of the studied unstable rock slopes, and within the studied localities. Examples include Nordmannviktind, Gavtavárri, Nomedalstind, Oksfjellet and Langsnøen. Among these localities, Nordmannviktind, segments of the backscarps of Gavtavárri west and Oksfjellet, and Langsnøen are all localities with fracture-parallel backscarps, while Nomedalstind has a foliation-parallel backscarp. These lineaments also trend parallel to the orientation of the Kåfjorden valley, as well as the southern and northern parts of the fjord itself. Pre-existing NW-SE –striking fractures appearing at the mentioned localities, and their close relation to the backscarp in these areas, suggest they controlled the location of all these unstable rock slope failures. That is with the exception of Nomedalstind, where this fracture set is interpreted to only delimit the terraces within the failure area.

5.8.2 E-W –oriented brittle structures

Lineaments trending E-W, and subordinate ones trending ENE-WSW and WNW-ESE, are traceable along segments of the Troms-Finnmark Fault Complex. The faults are found to, for instance, separate parts of the Nordkapp basin from the Finnmark Platform (Koehl, 2018). Regionally in Troms, E-W –trending lineaments can be observed in aerial images west of the Lyngen peninsula (Fig. 5), at Senja crossing the island from east to west, and across Reisadalen east of the study area, towards Birtavarre. E-W –trending lineaments in the study area are observed e.g. in Olderdalen, between Nordmannviktind and Gavtavárri, along Nomedalen, north of Nomedalstind, and northwest of the peak at Rismmalčohkka (Fig. 46). The central part of Kåfjorden also trends E-W, while the northern and southern parts trend NW-SE.

The backscarps of Badjánanvárri and Ruovddášvárri do both comprise segments of E-W –trending orientations (Fig. 21, Fig. 27). Segments of intact bedrock at Nordmannviktind are dismembered and partly collapsed along such steeply-dipping fractures (Fig. 11A and B), and they are locally segmented into half-grabens at Gavtavárri (Fig. 13).

5.8.3 NE-SW –trending brittle structures

NE-SW –trending lineaments presumed to be brittle faults and fractures in coastal and central Troms are traceable from the Vestfjord-Vanna Fault Complex bounding Precambrian basement rocks against Caledonian rocks (Olesen et al., 1997), via Breivikeidet (Fig. 1) and eastward to Lyngen (Indrevær et al., 2013). Similar NE-SW –trending lineaments mapped in Kåfjorden (Fig. 46) are located along several side valleys on the northeastern side of the Kåfjorden, e.g. south of Nomedalstinden, and along the valley between Badjánanvárri and Ruovddášvárri. This lineament is also verified by Zwaan (1988) along the western part of Kåfjorden where it intersects with the N-S –trending Lyngenfjorden (Fig. 46). Several unstable rock slopes are present on the eastern side of the Lyngenfjord, amongst others, Nordnesfjellet (e.g. Skrede, 2013).

NE-SW –trending fractures define the southern scarp at Nordmannviktind (Fig. 8), the sidescarps to the foliation-parallel backscarp in the eastern part of Gavtavárri (Fig. 13) and segments of the zigzag-shaped backscarp in the western area of Gavtavárri (Fig. 13). Segments of the fracture-parallel backscarp of Oksfjellet also trend NE-SW, as well as the scarps south on Badjánanvárri (Fig. 37 and Fig. 21, respectively). The small valley between Rismmalčohkka and Badjánanvárri (Fig. 20) trends NE-SW, parallel to the possible continuation of the backscarp of Rismmalčohkka. Similar fracture sets are mapped on the southwestern side of Kåfjord, at Oksfjellet and Langsnøen.

In summary, NE-SW –striking fractures are present at most of the studied localities, and may be interpreted as one of the main-controlling bedrock structures for failure along Kåfjorden (further discussion in chapter 6.4.3).

6 Discussion

This chapter discusses the results and preliminary interpretations of the studied unstable rock slopes in Kåfjorden (chapter 0), trying to relate the unstable areas to controlling pre-existing bedrock structures (chapter 3.1), rock slope failure types (outlined in chapter 3.3) and regional lineament patterns of Central Troms (chapter 0 and 5.8). Table 2 summarizes the key features of the studied localities, and Fig. 49 and Fig. 50 illustrate the interpreted failure mechanisms in relation to the mapped regional lineaments.

6.1 Bedrock structures

This sub-chapter will outline the key characteristics of the different bedrock structures introduced in chapter 3.1, and relate them to the studied unstable rock slopes.

6.1.1 Lithology

All the studied unstable rock slopes in Kåfjorden are located within the Caledonian Upper Allochthon (Nordmannvik Nappe and Kåfjord Nappe within the Reisa Nappe Complex; see chapter 2.3.1), which comprises various meta-psammites and mica schists (Corfu et al., 2014). This includes the studied localities of Nordmannviktind, Rismmalčohkka, Badjánanvárri, Ruovddášvárri and Nomedalstind (Fig. 8, Fig. 21, Fig. 27 and Fig. 33). These areas have backscarps exposing meta-arkoses and feldspathic quartzites, with varying degree of exposed foliation, and all located on the northeastern side of the fjord/valley. Various types of micaceous schists dominate at Gavtavárri, Oksfjellet and Langsnøen (Fig. 13, Fig. 37 and Fig. 43). Alternating hornblende-biotite schists and gneisses with pegmatite dykes dominate the backscarp at Gavtavárri, and the backscarp at Oksfjellet crosscuts lithological boundaries of altering muscovite-rich and biotite-rich mica schists. The backscarp at Langsnøen exposes mica schists containing more muscovite than biotite.

The observed bedrock within the study area of Caledonian origin (chapter 2.3.1) shows different degree of deformation and metamorphism. All localities located on the northeastern side of the fjord comprise, amongst other lithologies, meta-arkoses, while the localities on the southwestern side of the fjord mainly comprise micaceous schists with varying biotite- and muscovite content. Nordmannviktind and parts of the western area at Gavtavárri are located within the Nordmannvik Nappe, which is metamorphosed in amphibolite facies with relicts of granulite facies rocks, which is evidenced by the observation of kyanite (Andresen, 1988, Faber, 2018). Thus, this nappe is of higher metamorphic grade than the other localities of the Kåfjord Nappe (Fig. 13).

Lithological variations such as e.g. feldspathic quartzite in the Nordmannvik Nappe versus dominantly micaceous schists in the Kåfjord Nappe may explain differences in frequency and nature of foliation surfaces (Earle, 2016). For example, a larger quartz content in the meta-psammites at Nordmannviktind may explain the less prominent backscarp, and why collapsed boulders and blocks are more massive there. Feldspathic psammites require a higher shear strength than mica schists in order to (re-) active a pre-existing fabric/weakness (Wyllie and Mah, 2004). This suggests that, without well-developed foliation the pre-existing brittle fractures are more likely to control the failure area.

The meta-psammitic bedrocks of the western area at Gavtavárri have a well-developed foliation, but due to orientation of the foliation relative to the failure direction of the main terrace, the foliation is considered to have less influence on the failure than the brittle fractures (Fig. 16). By contrast, the eastern slope of Gavtavárri comprises micaceous schists with a favorable orientation of foliation relative to failure, and foliation-controlled failure occurred (Fig. 15).

According to Agliardi et al. (2013), well-foliated micaceous schists are more prone to failure (DSGSD) than massive and competent bedrocks. This is partly consistent with observations in the study area, where some localities contain various types of well-foliated micaceous schists along the backscarps (Zwaan, 1988). Several other studied unstable rock slopes in Troms, e.g. Gámanjunni 3, Jettan and Indre Nordnes, Adjet (Eriksen, 2013, Skrede, 2013, Hernes, 2014, Bakkhaug, 2015), comprise well-foliated mica schists, supporting the conclusion by Agliardi et al. (2013).

In the studied areas along Kåfjorden, both lithological boundaries and the contacts between the boudinaged lenses and layers of gabbro and amphibolite are parallel or sub-parallel to the main foliation. The units of calcareous and dolomitic marble at Ruovddášvárri are locally sub-parallel, while the various types of schists in Langsnøen and Oksfjellet show foliation-parallel trends. These observations suggest that the dominant host rock foliation formed during the emplacement of the Caledonian nappes, locally resulting in a stacked NW- and SW –dipping foliation is oriented favorably for controlling some of the failure areas in Kåfjorden. However, the lithological contacts are not assumed to represent any of the failures' sliding surfaces, except for possibly the contact-parallel ductile thrust faults at Oksfjellet (chapter 6.1.4).

Lithology alone is not considered a controlling factor for any of the studied rock slope failures; rather no evidences are found proving that lithology controlled the slope gradients. Because the rocks have undergone several Caledonian orogenic events with folding and thrust nappe emplacement, and later upright and asymmetric folding, back-folding and back-thrusting (chapter 2.3.1 and chapter 2.3.2), these ductile fabrics provided controlling effects on location and the displacements of the unstable rock slope failures in the study area of Kåfjorden.

6.1.2 Foliation

The ductile, Caledonian foliation of the localities on average dips 35-40° SW with local variations. The three southernmost localities, Ruovddášvárri, Oksfjellet and Langsnøen (Fig. 47); however, show a gentler dip than the other localities (10-30°), and the foliation dips E to SE in Ruovddášvárri, and SW- to NW in Oksfjellet and Langsnøen.

In the localities where the foliation dips uniform 35-40° downslope, the slopes are found to always be sub-parallel or parallel to the foliation. Three of these localities, Gavtavárri east, Rismmalčohkka and Nomedalstind, are considered unstable rock slopes that are moving along a foliation-parallel surface. The backscarps of these localities are fully foliation-parallel, and the exposed foliation surfaces are interpreted as the sliding surfaces for these rock slope failures. The conclusion by Henderson et al. (2006) on rock slope failures with foliation dipping towards the valley/fjord usually have sliding surfaces parallel to the foliation, corresponds with some of the localities in this project as well. All the studied localities, except for the western part of Gavtavárri, are interpreted to have, of varying degree, some sort of sliding movement along the foliation.

The localities with foliation-parallel backscarps are not necessarily formed by the same failure mechanisms. This is based on observations of a large-scale folded foliation surface at Gavtavárri east, where the foliation becomes steeper downslope than in the upper part (Fig. 19A and Fig. 19B). The foliation downslope is assumed to have a dip up to 60°, making the Gavtavárri east unstable rock slope area similar to the *irregular compound slide* (see Fig. 6H and profile in Fig. 15).

Rismmalčohkka also has a foliation-parallel backscarp (Fig. 25C). However, the foliation downslope is considered more uniform in dip angle than for Gavtavárri east, as the sliding surface foliation daylights at approximately 600 m.a.s.l. Here, the foliation intersects with steeply-dipping fractures forming a system of scarps, open fractures and counterscarps (Fig. 21 and profile in Fig. 23). This suggest that the failure mechanism at Rismmalčohkka is a *planar translational slide* (cf. Fig. 6C) (Glastonbury and Fell, 2010).

The rock slope failure at Nomedalstind, previously studied by Husby (2011), was interpreted to have a sliding surface with a ramp-flat geometry made up by a regional scale, gently folded foliation, which became sub-horizontal beneath and within the partly intact terraces in the upper part of the failure area (profile in Fig. 34). As these terraces obviously are located within the failure area, the orientations of bedrock structures should be interpreted carefully.

Therefore, this study addresses an alternative idea on the failure mechanism and sliding surface. Instead, the terraces may have failed along the foliation, but because the foliation-parallel sliding surface decreases in dip at the NW-SE –trending feature at ca 350 m.a.s.l., the partly collapsed masses above this feature along the sliding surface are compressed. Due to this compression, masses upslope may be rotated inward, thus the foliation in the terraces is sub-horizontal. Therefore, the failure mechanism at Nomedalstind is considered a *toe-buckling translational slide* (Fig. 6D), with sliding fully along the SW –dipping foliation (Glastonbury and Fell, 2010).

For the other localities with slope-parallel foliation, the controlling structures are thought to be a combination of foliation and brittle fractures when they have favorable intersecting geometries. For these localities, the intersecting line is out towards the valley/slope (further discussed in 6.1.4). The localities with oblique to perpendicular dipping foliation relative to the slopes, e.g. Ruovddášvárri, Oksfjellet and Langsnøen, are likely controlled by a combination of fractures and foliation. In general, rock slope failures with foliation dipping into the mountain slope are *not* structurally controlled by the foliation, but more likely by brittle fractures, possibly a combination if orientation of the foliation relative to the slope is favorable for sliding. As concluded by Böhme et al. (2011) from their studies on 28 unstable rock slopes in Sogn and Fjordane, western Norway, foliation dipping into the mountain or obliquely to the valley/fjord is not favorable for activation as a sliding surface. This is the case for the three mentioned localities as well, as no sliding surfaces were found parallel to the foliation. A sliding type of displacement may still occur along the foliation of these localities, even though the sliding surfaces are not defined by the foliation.

A foliation dipping into the slope may delimit failures along the face of the slope if fractures are slope-parallel, which is the case for a *rough translational slide* (Fig. 6B) (Glastonbury and Fell, 2010). However, this failure type was not observed within the study area. For Ruovddášvárri, the gently-dipping foliation sub-parallel to the E-W –trending parts of the backscarp (Fig. 27), may have enhanced sliding where the sub-vertical fractures of the backscarp intersect with the foliation. The sliding direction will then be parallel to the dip of the foliation, E to SE (Fig. 50).

For Oksfjellet (Fig. 37), the foliation dips perpendicular and sub-perpendicular to the slope, the slope faces NE and the foliation mainly dips gently (15-40°) to the NW to NNW (Fig. 39A and B). Notably, the foliation dips steeper in the southern part of the locality than in the northwestern part (Fig. 37), and this was interpreted as due to folding of the lithologies and the foliation above a thrust ramp (Bredal, 2016). The friction angle for mica schists is 20-27°, suggesting sliding along the foliation along favorable oriented parts of the backscarp is possible for this locality as well. Favorable orientations of the backscarp will be along the NW to NNW –facing parts. Due to the shallow-dipping foliation in the northwestern part of the failure area, the steeply-dipping brittle fractures are considered controlling. However, sliding along the foliation delimited by brittle fractures is also possible in the northern part of the locality.

The dip of the bedrock foliation at Langsnøen is mostly uniform (10-30°), but varies in strike from slope-perpendicular and NW-dipping (dominant), via slope-parallel to slope-inward dipping (Fig. 44A). The orientations of brittle fractures at Langsnøen are similar to those at Oksfjellet, thus the controlling structures of these localities are considered the same; i.e. a combination of foliation and fractures (Fig. 44B).

The Randa rockslide in Switzerland may be comparable to Langsnøen and Oksfjellet, as the foliation at the well-known Swiss rockslides dips into the mountain slope. The controlling structures of the Randa rockslide are the steeply-dipping slope-parallel brittle fractures, which is similar to that of Oksfjellet and Langsnøen (Eberhardt et al., 2004).

A study of more than 40 potential unstable rock slopes in Møre and Romsdal (Henderson et al., 2006), concluded that localities where foliation dips towards the fjord (or the valley floor) usually have sliding surfaces parallel to the foliation. This conclusion fits well with our results in localities that have valley/fjord-dipping foliation; Nordmannviktind, Gavtavárri (east), Nomedalstind, Rismmalčohkka, Badjánanvárri and Ruovddášvárri. For all these localities, the foliation is either the dominant controlling structure or subsidiary with brittle fractures. The sliding surfaces of Gavtavárri (east), Nomedalstind and Rismmalčohkka failures are considered foliation-parallel, as the backscarps of these localities are fully exposed foliation surfaces. At Nordmannviktind, Badjánanvárri and Ruovddášvárri, the backscarps of the failure areas are along strike delimited by steeply dipping fractures, but the sliding movement of these localities is considered along the foliation.

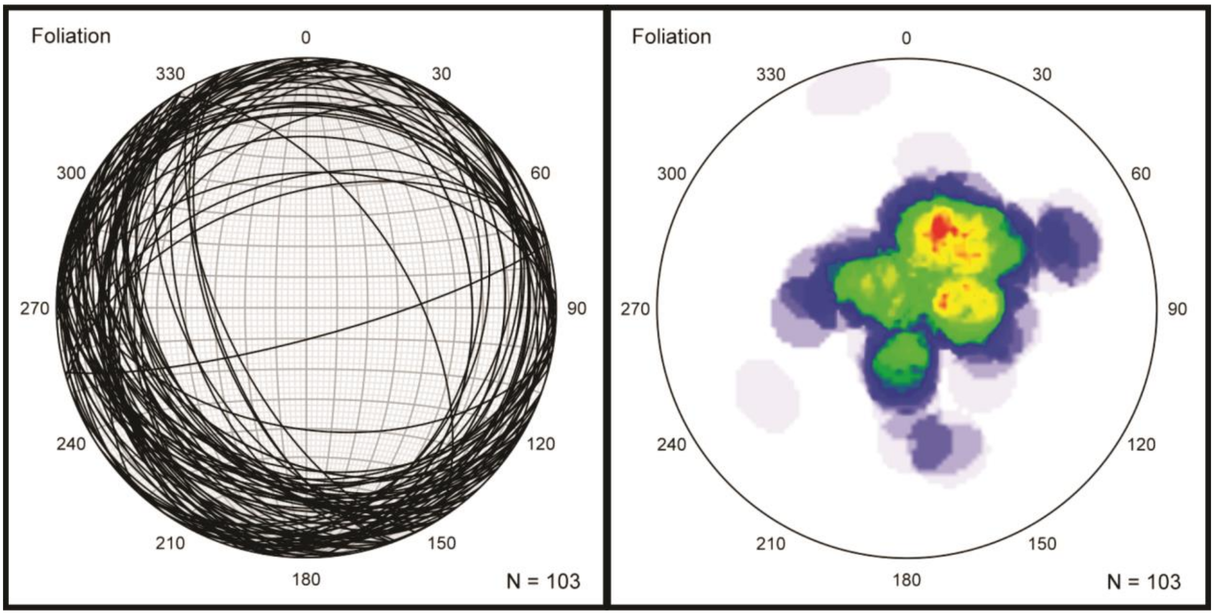

Fig. 47 – Compilation of all stereographic projections previously illustrated. Measurements of foliation from Nordmannviktind, Gavtavárri, Rismmalčohkka, Badjánanvárri, Ruovddášvárri and Langsnøen. The Geological Survey of Norway has provided data from Langsnøen.

6.1.3 Folds

The Reisa Nappe Complex underwent considerable folding and thrust emplacement during the main Caledonian shortening event (Zwaan and Roberts, 1978). Both large-scale and small-scale isoclinal asymmetric and open upright folds are preserved, but few mesoscale folds are visible in outcrops in the studied areas. That is with the exception of the mesoscale asymmetric to overturned folds at Gavtavárri (Fig. 19C and Fig. 19D). These large-scale folds however, may have exerted important controlling effects on the location of rock-slope failures in Kåfjorden. For example, large-scale open folds in the region may be responsible for variable dips and dip directions of the main foliation, such as the southwestward dipping foliation in Kåfjorden. This is considered the limb of a regional antiform plunging southeastward, and with the foliation of Ruovddášvárri evidencing a plunging fold in the southern part of the study area. Nordmannviktind, with foliation dipping SW- to W-ward may be the northern limb of another, open upright fold plunging westward. Similarly, the bedrocks in Oksfjellet and Langsnøen are interpreted to have SW- and NW- dipping foliation due to imbricate movement of the thrust above a ramp below Oksfjellet. As several folding events are considered to have affected the rocks in the area, a changing foliation along the limb of the antiform is reasonable (Zwaan, 1988).

The mesoscale folding along the exposed fracture-parallel sidescarps at Gavtavárri east have backlimbs dipping downslope, sub-parallel to the foliation and the slope. Locally, the folds are cut off by steeply-dipping fractures and by smaller folds, located as talus material downslope

(Fig. 19C). These failures may be a small-scale scenario of the larger failure of the eastern part of Gavtavárri, where the foliation is interpreted to be folded, and the backscarp, the exposed foliation surface, is a larger limb of an overturned antiform, than those observed along the sidescarps. Thus, the folding of the foliation is controlling of the *irregular compound slide* of Gavtavárri east.

The monocline bedrock foliation exposed along the frontal cliffs at Oksfjellet is considered to follow a thrust fault located in the footwall below (Fig. 37 and Fig. 41). This folding and upward bending of the foliation makes it steeper in the southern part of the locality where it dips up to 40° forming a ramp thrust. This angle exceeds the frictional angle for mica schists (20-27°), suggesting that sliding is possible along the foliation in the southern part as the bedrock comprise micaceous schists (chapter 3.1.1). As the foliation dips obliquely to the mountain slope, this bend-up of the foliation requires an additional favorable fabric to support rock slope failure (chapter 6.1.4)

6.1.4 Brittle faults and fractures

Brittle structures within the study area are numerous and pre-existing in the bedrocks (chapter 6.4) and considered mostly of post-Caledonian origin linked to the Mesozoic-Cenozoic rift-margin extension (cf. Indrevær et al., 2013). Some are brittle normal faults and related fractures, while others may be tensional joints opened and/or activated during Quaternary glacial rebound. In addition, others may have formed by reactivation during recent rock slope failures. Most of the observed structures nearby the studied rock slope failure areas in Kåfjorden are fractures with planar geometries striking parallel, perpendicular and obliquely to the Caledonian foliation. The fractures vary from thin and small, only a few millimeters wide and a few centimeters long, up to several meters across and several hundred meters along strike (e.g. Fig. 19D and Fig. 25A and Fig. 25B).

The dominant strike of the fractures observed within the study area are NW-SE, NE-SW and E-W (cf. chapter 5.8, Fig. 48). The NE-SW –striking fractures typically interact with NNE-SSW –striking sets, at least locally, and the E-W –striking fractures merge into WNW-ESE –strikes and ENE-WSW –strikes, resulting in rather complex fracture geometries in map view (e.g. Fig. 13, Fig. 21). Few other orientations of the brittle fractures are observed, however they do appear (e.g. Fig. 28B and Fig. 44B). The fractures are mostly steeply dipping (ca 60-85°) to sub-vertical, except for the westward dipping (15°) N-S –striking fractures at Nordmannviktind, the northward dipping (40°) E-W –striking fractures at Gavtavárri and the northward-dipping (40°) E-W –striking fractures at Badjánanvárri (Fig. 48).

Brittle fractures appear to have fully controlled the western part of the unstable area at Gavtavárri (Fig. 13 and profile in Fig. 16). For this locality, the foliation dips at a high angle to the main fracture sets, and therefore, is unfavorable as a sliding surface, and the exposed backscarp follows the NW-SE- and NE-SW –striking fractures. In addition, the main terrace below, and bounding scarps are interpreted to have failed along these intersecting steeply-dipping fractures based on their geometries (Fig. 13 and profile in Fig. 16). An open fracture behind a moving block is thought to be one out of several critical factors for development of an unstable rock slope failure, according to Henderson et al. (2006). The backscarp at the western part of Gavtavárri clearly separates the main terrace from the surrounding intact bedrock to the north and northwest. This gives the failure area a complex geometry, with structures internally in the failure area trending parallel to those of the brittle fractures along the backscarp. As the fractures are steeply-dipping, the failure is considered a *rock fall slide* (Fig. 6I).

Fractures in combination with foliation are inferred to be the main controlling bedrock structures at the unstable sites of Nordmannviktind, Badjánanvárri, Ruovddášvárri, Oksfjellet and Langsnøen. This conclusion is based on the favorable orientations of the steeply dipping fractures intersecting with the foliation, where sliding is possible along the foliation surfaces, and the fractures have delimited and controlled the extent of the failures. Except for Badjánanvárri, the four other localities are interpreted to have a *slide topple* type of failure mechanism (Fig. 6J) (chapter 5.3.3).

For Nordmannviktind, the foliation dips downslope, ca 30° to the west and southwest (profile in Fig. 10, Fig. 11A, Fig. 11B). These columns are delimited by the steeply-dipping fractures, where the spacing of the fractures is interpreted to control the amounts of rock falls. As the foliation at this locality is not as well developed as for other localities, less sliding is considered to occur at this locality than for the other slide topple type of failure areas. However, several exposed foliation surfaces are observed in the intact bedrock in the study area, and many of the collapsed blocks show geometries created by the interaction of the fractures and the foliation (Fig. 11C and D). Therefore, sliding along the (poorly-) developed foliation seems possible.

The unstable areas at Ruovddášvárri, Oksfjellet and Langsnøen show steeply dipping fractures forming scarps and backscarps of the localities, hence partly controlling the failure areas. The obliquely-dipping foliation relative to the slopes, interacting with these steeply dipping fractures may enhance wedge sliding locally, along the intersection line of the cross-cutting fractures. These localities have similar backscarp geometries, with Langsnøen assumed to have experienced less failure than the two other. This interpretation is based on the fact that the terrace in front of the backscarp shows little displacement, and is still nearly intact. Oksfjellet shows higher degree of failure and more subsidence of collapsed material, still located along the backscarp, and some talus blocks clearly deposited in front of the scarps. Oksfjellet also has a thicker cover of talus and larger extent downslope than Langsnøen. Ruovddášvárri comprises no intact material in front of the backscarp, only a few smaller terraces of considered partly intact bedrock, however interpreted to have failed along the backscarp. The southern, lower part in front of the large, open fractures show similarities with Oksfjellet; displaying partly detached blocks of the bedrock subsiding downslope.

Rock failures along Oksfjellet and Langsnøen occur not only by the *slide topple* type of mechanism, but also as *rock fall slides*, and Oksfjellet may develop *wedge failures* as well. These assumptions are based on the brittle fractures dipping steeply downslope, striking NW-SE (Fig. 39A and Fig. 44B). If these fractures daylight in the slope, columns of bedrock may fail (cf. Fig. 6I). The interpreted wedge type of failure at Oksfjellet may have initiated where the foliation, the thrust fault, or the NW- to NNW –dipping fractures intersect with the NE- to NNE- steeply-dipping fractures, forming a wedge eligible for sliding. Therefore, the total failure mechanism at Oksfjellet is more complex than for Langsnøen, with the possibility of three failure mechanisms (Fig. 38).

The backscarp at Langsnøen overlaps with the steeply NE-dipping fractures (Fig. 43), while the slope failure at Ruovddášvárri has a zigzag shaped backscarp of orthogonally intersecting E-W- and N-S –striking fractures. Oksfjellet comprises intersecting orthogonal NW-SE and NE-SW –striking fractures, with the NW-SE –striking ones being parallel to that of Langsnøen and the valley slope (further discussion in chapter 6.4).

The unstable area at Badjánanvárri is bounded by gently to steeply dipping foliation surfaces, and brittle fractures delimiting smaller collapsed blocks downslope, evidenced by the down-stepping terraces delimited by fracture-parallel scarps (Fig. 24). The intersections of the foliation and fractures are interpreted to delimit local unstable areas, forming the downward-stepping geometry of the slope, thus allowing both the foliation and the fractures to have controlled this failure area, suggesting a *bi-planar compound slide* (Fig. 6E) (Glastonbury and Fell, 2010). As the slope locally is sub-parallel to the foliation, an alternative explanation is that the foliation controlled the lower parts of the failure area, while the brittle fractures controlled the upper part (see profile in Fig. 24).

The unstable areas in western part of Gavtavárri, Ruovddášvárri and in Oksfjellet have the most extensive open fractures. These presumed tensile fractures are located on the plateaus behind the backscarps of the unstable rock slopes (Fig. 13 to the left, Fig. 27 and Fig. 37). If retrogressive displacement is possible for any of the unstable localities within the study area, these three are the best candidates (Agliardi, 2012). This is because the extensive fractures mostly have attitudes parallel and/or sub-parallel to the backscarps, suggesting they formed due to failures of the rock slopes, generating open tensile fractures. If continuous movement occurs in front, or major failures of the localities occur, the tensile fractures (interpreted as a fault at Oksfjellet) on the plateaus may become future backscarps.

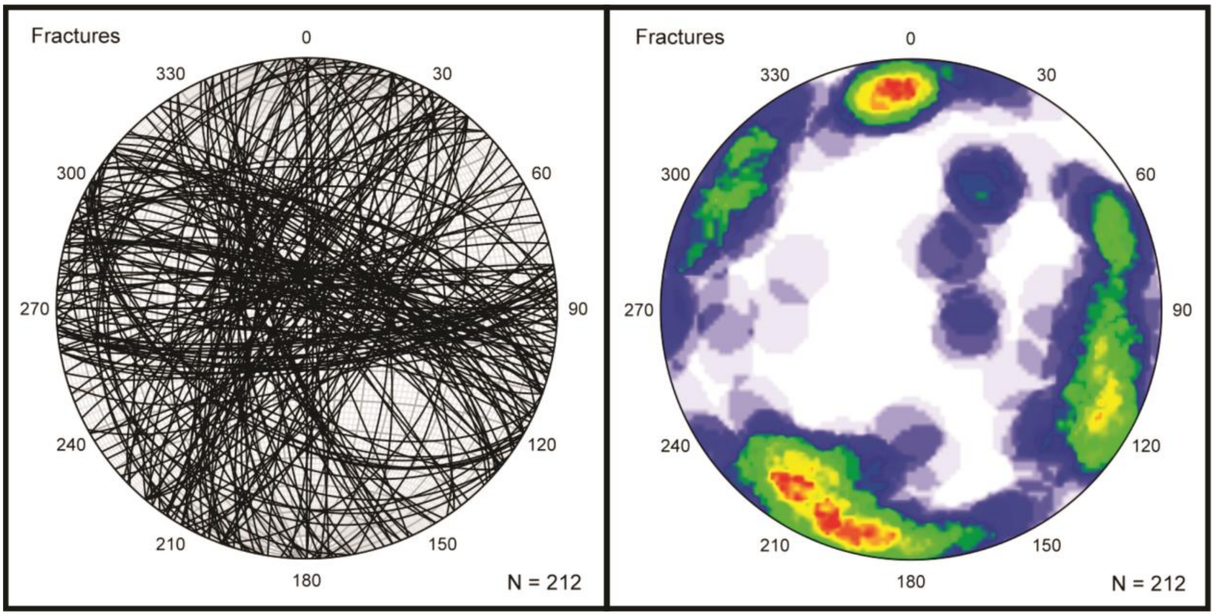

Fig. 48 - Stereo plot of all the measured fractures in the study areas of Nordmannviktind, Gavtavárri, Rismmalčohkka, Badjánanvárri, Ruovddášvárri and Langsnøen. Measurements from Nomedalstinden and Oksfjellet are not included. The Geological Survey of Norway provided measurements from Langsnøen.

6.2 Geomorphological features and their relation to bedrock structures

Several of the mapped geomorphological features within the studied unstable areas of Kåfjorden overlap with structural features in the bedrock, and are thus considered *morphostructures*, e.g. scarps lining up with pre-existing brittle fractures, terraces reflecting the attitude of underlying foliation, depressions following open fractures, etc. (Agliardi et al., 2001). The geomorphological features are important elements, and help to classify the unstable rock slopes, and for the understanding of movement mechanisms along the slopes.

Backscarps

The backscarps of the studied unstable rock slopes failure areas in Kåfjorden vary in appearance, but in most cases, the structures forming them are brittle fractures and/or foliation surfaces. Most prominent examples include backscarps that are linked to SW-dipping open fractures. This is the case for Gavtavárri west, Oksfjellet and Langsnøen, and possibly

Nordmannviktind, Badjánanvárri, and Ruovddášvárri. Nordmannviktind contains loose material on top of thr bedrock, so no obvious delineation of any moving block is apparent, except for the depressions in front of the columns, interpreted as surface features of brittle fractures. These depressions may therefore be the surface expression of a controlling open fracture in the bedrock behind the moving parts of Nordmannviktind.

Similarly, the backscarp at Ruovddášvárri is interpreted as open fracture-controlled, and the orthogonally intersecting fractures observed there, yielding a zigzag shaped geometry of the backscarp, may be linked to at least two major open fracture systems. By comparison, open fractures behind a moving block was concluded as a critical factor to generate backscarps on the surface along unstable rock slope sites in Møre and Romsdal (Henderson et al., 2006).

Badjánanvárri, Gavtavárri west, Oksfjellet and Langsnøen have large portions of partly intact bedrocks failed along fractures forming the backscarps of the localities. All localities show displacement in front of these open fractures, and both Oksfjellet and Gavtavárri west have open fractures even behind the backscarps. This suggest that these localities also have a moving block in front of their fracture-controlled backscarps (cf. Henderson et al., 2006).

On the other hand, the failures at Gavtavárri east, Nomedalstind and Rismmalčohkka have fully foliation-parallel backscarps, interpreted to be the main sliding surfaces.

Scarps and counterscarps

All the studied localities comprise subsidiary scarps mostly in front or downslope from the backscarps, but some also expose scarps in the more intact bedrock behind the backscarps (e.g. Ruovddášvárri and Oksfjellet). When present, these scarps are more extensive and are oriented both parallel and perpendicular to the main backscarps of the failures, but in general, they follow traces of pre-existing fractures.

The scarps and counterscarps observed in the study area have dominant trends parallel to the observed brittle post-Caledonian fractures, suggesting the geomorphological features formed along these pre-existing inherited bedrock structures. Several of the scarps do also trend parallel to the backscarps, suggesting that the orientations of the backscarps follow the dominant bedrock structures. Notably, the scarps have talus material downslope, often accumulated at the toe of the scarps. This talus material is interpreted as rock fall material derived from the scarps, as the scarps often show a smooth front, e.g. a fracture or a foliation surface.

Terraces

Terraces are widespread in all the studied failure areas below the main backscarps in various parts of the localities, except the eastern part of Gavtavárri and Oksfjellet. The terraces show smooth surfaces often covered by vegetation, and are delimited in the front by either foliation or fractures surfaces, giving topographic variations along the slopes. Such terraces are in all cases considered to have moved downslope from their pre-failure location. This interpretation is based on the orientation of bedrock structures relative to the orientations of the rear parts of the terraces, as they in all cases trend parallel to each other. Nordmannviktind, Gavtavárri west, Badjánanvárri, Ruovddášvárri, and Langsnøen have terraces that are assumed to have failed/subsided along the pre-existing brittle fractures of the localities.

The terraces at Rismmalčohkka and Nomedalstind are, on the other hand, interpreted to mark gentle steps in bedrock blocks that have moved along the foliation. The sub-horizontal foliation of the terraces at Nomedalstind is interpreted to be a result of inward-rotation of the material due to toe-buckling of imbricate slices of bedrock as the sliding surface dips at a lower angle in the lower part of the failure area (Glastonbury and Fell, 2010). Subsequently, the toe-buckling provides a barrier for further downslope movement, and the terraces shows evidences of a sub-horizontal foliation due to the inward rotation (cf. Husby, 2011). The variable orientation of many terrace surfaces relative to orientation of the foliation in intact bedrock at these localities suggest complex internal rotation, which is common for some failure mechanisms (e.g. Braathen et al., 2004)

Not all terraces within the study area have been investigated in the field, giving the possibility of more terraces showing differently oriented foliation than those at Nomedalstind. A varying foliation internally in a failure area is considered caused by the failure itself, but as the study area of Kåfjorden is highly deformed, the deformational events may also cause internal variations within an unstable area (chapter 2.3.1 and 2.3.2) (e.g. Zwaan, 1988).

Ridges, depressions, grabens and sinkholes

All the studied localities on the northeastern side of Kåfjorden, except Badjánanvárri, expose linear depressions within the unstable areas. These elements consistently line up with the inherited bedrock structures, commonly along the observed brittle fractures. This suggest that the depressions follow the pre-existing fractures that have opened up during, or due to failures, thus interpreted as tensile fractures. The opening of the fractures is perpendicular to strike, but not necessarily parallel to failure direction. The localities comprising ridges expose them as parallel oriented to the depressions, and they are located in immediate vicinity to each other. This is inferred to be because the depressions follow the brittle fractures that have opened up during failure, compressing material in front forming the linear ridges.

At Gavtavárri west, the depressions located behind the backscarp are considered formed due to successive failure of the main terrace. Some of the depressions at Gavtavárri are covered by vegetation, while others are situated above open fractures exposing intact bedrock and deep sinkholes, thus supporting the controlling effect of brittle fractures. The sinkholes are often located where the brittle fractures intersect, producing sub-surface gaps and several meters of open fractures (Fig. 17). The orientation of the depressions are parallel to that of the backscarp, in favor of a possible retrogressive movement mechanism of the locality. Two graben structures are located downslope of the backscarp in the upper part, further supporting the idea of removal of support in the toe leading to a retrogressive displacement (Fig. 13 and Fig. 19A).

At Ruovddášvárri, the depressions situate on top of the plateau perpendicular to the orientation of the backscarp, suggesting two dominant orientations of controlling fracture orientations (N-S- and E-W –striking). These depressions also comprise sinkholes (Fig. 31D), possibly also enhancing a retrogressive displacement of the backscarp as the depressions intersect at near 90° to the backscarp. The linear depressions at Nordmannviktind are parallel to the strike of the fractures delimiting the columns along the backscarp (Fig. 8 and Fig. 9B). This may suggest that the fractures controlling the failures along the backscarps also controlled movement downslope of the backscarp (cf. Henderson et al., 2006). The graben-like feature at Nordmannviktind is interpreted as an extensional graben, not a depression, as the surface is sub-horizontal, and several meters across.

Langsnøen has several sinkholes located in a linear depression in front of the backscarp, many are covered by talus material. Since the depression is aligned parallel to the strike of the NE-dipping backscarp and corresponding brittle fractures in the bedrock, this feature is interpreted as a real, extensional graben. Similarly, the features interpreted as true grabens at Oksfjellet all occur closely related to scarps and counterscarps, and thus are interpreted to be fracture-controlled. The term graben used to interpret linear depressions may as well be referred to as *trenches*, as a criteria for a graben is the downfaulting of a segment of bedrock (Kearey, 2001, Sigmond et al., 2013). Possibly, not all ‘grabens’ in this study are downfaulted segments, but rather trenches.

Talus

The talus material present below major scarps and steep slopes are likely formed by gravitational rock fall and/or scree deposits, and thus share a common origin. Nordmannviktind differs some from the other localities. All localities have talus material concentrated in lobate shapes downslope, and most localities have a loose cover on the slopes rather than localized deposits there. The investigated localities all show truncating lobes, evidencing deposition at different times, which possibly can be inferred as several events of failure.

At Langsnøen and Oksfjellet talus and block material were transported far downslope from the backscarp because the slopes are too steep for deposition (cf. Table 2). The talus material at Nordmannviktind has larger blocks due to a more massive lithology (meta-psammites). The blocks are angular shaped along fracture- and foliation surfaces in the bedrock structure, thus individual blocks are inferred to be due to rockfall or collapse from the intact bedrock. Failure areas with dominantly mica-schists comprise more disintegrated talus, e.g. Badjánanvárri that displays higher degree of weathering than localities with competent bedrocks.

Rock glaciers

Some of the talus deposits in the study area may comprise internal ice cores thought to reflect the permafrost, thus may be interpreted as rock glaciers (Tolgensbakk et al., 1988, Gisnås et al., 2017). They are however, considered of non-glacial origin, and thus, they have formed due to presence of permafrost. Some of the mapped surface deposits may, in fact be rock glaciers as they are located above where permafrost has been found as sporadic and discontinuous within the study area (Gisnås et al., 2017). Others of the interpreted rock glaciers may be talus lobes without presence of any ice, but this is not known. At several other unstable rock slopes in Troms, rock glaciers have been detected, e.g. Adjet, near Skibotn south of Kåfjorden (Rouyet et al., 2015), Njargavarri, north of Ruovddášvárri and Gámanjunni 3 in Manndalen (Eriksen et al., 2017). As several other localities comprise rock glaciers, some of the mapped rock glaciers by Tolgensbakk et al. (1988) may also be rock glaciers.

6.3 Rock slope failure types

In this subchapter, the interpreted rock slope failure types of the studied areas in Kåfjorden (chapter 5) will be discussed in terms of their controlling bedrock fabrics: (i) Caledonian ductile fabrics including foliation and folds, (ii) combination of foliation and brittle post-Caledonian fractures, and (iii) brittle fractures alone. Understanding the location of rock slope failures, failure mechanisms and movement history, are critical for any kind of rick analysis of potential rock slope failures in Kåfjorden.

(i) Rock slope failure controlled by foliation

The three localities Gavtavárri east, Nomedalstind and Rismmalčohkka are slope failures controlled only by the foliation; however, the inferred failure mechanisms are different in these areas. This is thought to be due to the orientation of the foliation relative to the slopes varies, the daylighting of the sliding surfaces vary, and the depth of the assumed sliding surfaces vary.

These three localities all have fully foliation-parallel backscarps, which are considered the sliding surfaces of these rock slope failure areas. The daylighting of the sliding surface is difficult to establish for Gavtavárri east, but for Rismmalčohkka it is interpreted based on the geomorphological and structural features. As for Nomedalstind, a toe-buckling translational slide, no daylighting of the sliding surface will occur.

For Rismmalčohkka, the sliding surface may daylight at ca 600 m.a.s.l., where the interpreted backscarp-parallel fracture is located between a scarp and a counterscarp (Fig. 21). Considering the profile of the locality, if the foliation is uniform downslope within the study area of Rismmalčohkka, as interpreted, the sliding surface is likely to daylight here and can be considered as shallow for this locality. For Nomedalstind, the sliding surface *may* daylight at ca 350 m.a.s.l. where a fracture-parallel scarp trends parallel and sub-parallel to the backscarp (Fig. 33). One of the criteria for a *toe-buckling translational slide* is that the sliding surface does not daylight (chapter 3.3.1), thus this scarp system is interpreted to represent the location of where the sliding surface dips gentler, and toe-buckling is initiated. Toe-buckling of material occurs upslope of the decreasing sliding surface dip due to large masses failing, causing the inward-rotation of partly intact bedrock as buckling occurs at the toe. As the foliation at Rismmalčohkka and Nomedalstind is quite similar, the sliding surface at Nomedalstind is interpreted to be deeper-seated, thus the failure mechanisms are different. The failure mechanism of Rismmalchokka is therefore interpreted as a *planar translational slide* with a mostly shallow-seated sliding surface, while the failure mechanism of Nomedalstind is a *toe-buckling translational slide*, with a deeper-seated sliding surface (Fig. 6C and Fig. 6D, respectively). Gavtavárri east differs from the two other foliation-controlled localities due to the folding of the sliding surface, concluding on an *irregular compound slide* type of failure mechanism (Fig. 6H). The sliding surface's dip varies downslope further supporting this type of failure mechanism (cf. chapter 3.3.2).

(ii) Rock slope failures controlled by foliation and brittle fractures

The five localities considered to be controlled by a combination of foliation and fractures, Nordmannviktind, Badjánanvárri, Ruovddášvárri, Oksfjellet, and Langsnøen, are all unstable rock slopes with a *slide topple* type of failure mechanism, except for Badjánanvárri. The localities with *slide topple* types of failures are located on both sides of the fjord/valley with different bedrock composition (Nordmannvik Nappe and Kåfjorden Nappe, cf. chapter 2.3.1) and differently oriented foliation and fractures. However, as the foliation dips favorable relative to the slopes to enhance sliding, the mechanism is viable for all of these localities. The steeply-dipping fractures delimiting the sliding often strikes parallel to the backscarps, e.g. the perfectly fracture-parallel backscarp of Ruovddášvárri (combination of N-S- and E-W –striking) and Langsnøen (NW-SE –striking). The backscarp at Oksfjellet alternates along its average trend, but steeply-dipping fractures are interpreted to control the failures along the backscarp.

Badjánanvárri is interpreted as a *bi-planar compound slide* with interaction of steeply-dipping fractures controlling in the upper part of the failure delimiting sliding along the shallower-dipping foliation (Fig. 6E). As the profile of Nordmannviktind illustrates (cf. Fig. 10), this is possible also at this locality. Thus, these two localities vary from the others. Nordmannviktind is interpreted as a combination, but the sub-vertical fractures delimiting the columns parallel to the depressions along the backscarp, are considered the dominating fractures controlling the failure.

(iii) Rock slope failures controlled by brittle fractures

The western part of the unstable rock slope failure at Gavtavárri is the only (sub-) locality controlled only by the pre-existing brittle fractures. The backscarp follows traces of the NE-SW – and the NW-SE –striking fractures dipping steeply and intersecting with each other (cf. Fig. 12). The main terrace below the backscarp appears to have slid along these fracture surfaces causing opening of fractures forming depressions and sinkholes behind the backscarp. The terraces are fully delimited downslope by scarps following trace of the SW- and SE –dipping fractures of the locality, thus fractures are fully controlling the displacement. The locality shows similarities with the cross-section illustrating a rock fall slide (Fig. 6I and Fig. 16), suggesting *rock fall slide* as the failure mechanism.

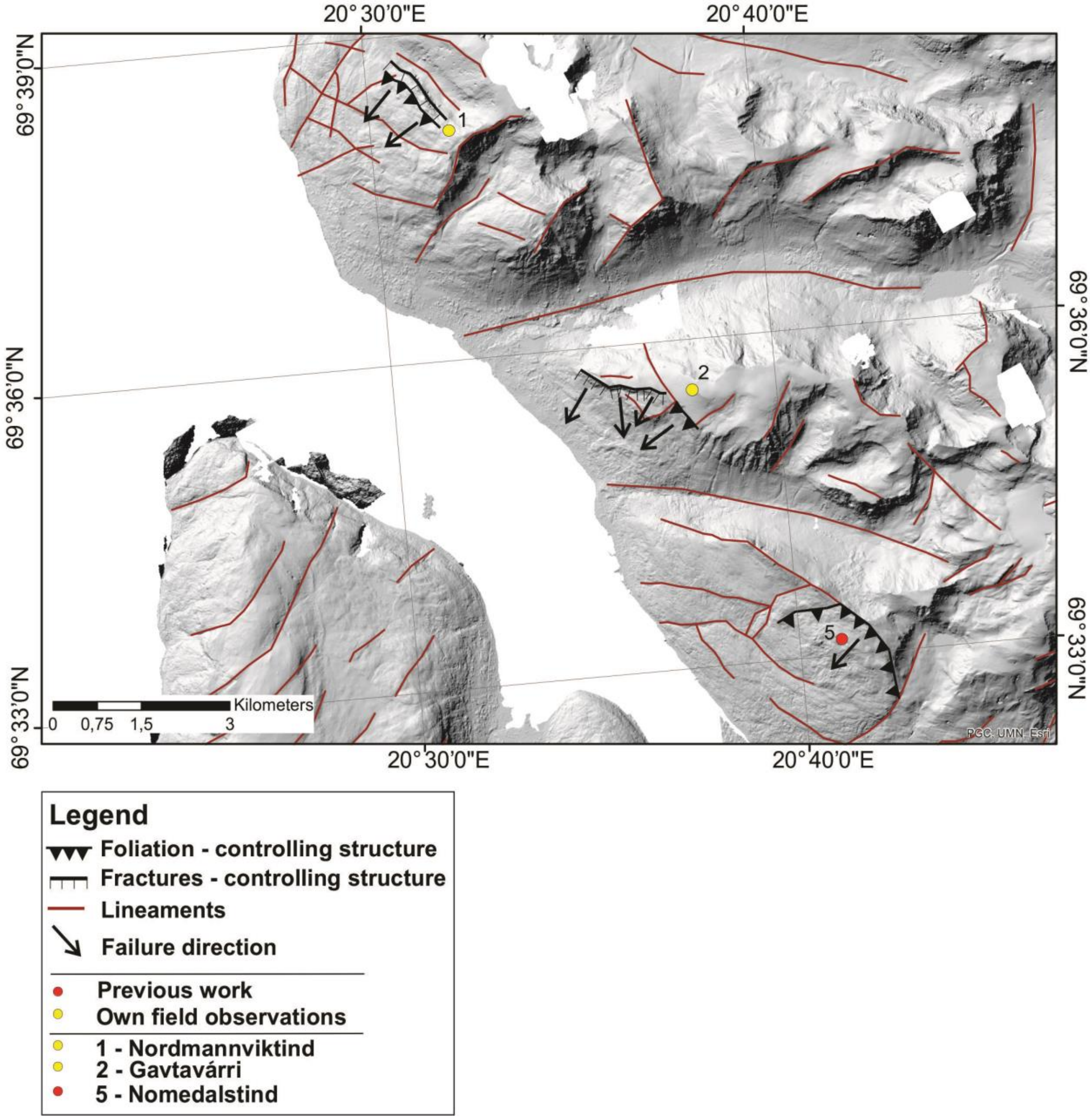

Fig. 49 - Lineament map with the inferred controlling bedrock structures of the three northernmost localities, Nordmannviktind, Gavtavárri and Nomedalstind. The foliation of the localities trace parallel to NW-SE –trending lineaments, while fractures alternate more. The localities with arrows indicating failure directions in more than one direction illustrates the interaction of differently oriented bedrock structures controlling the failures (e.g. western area of Gavtavárri).

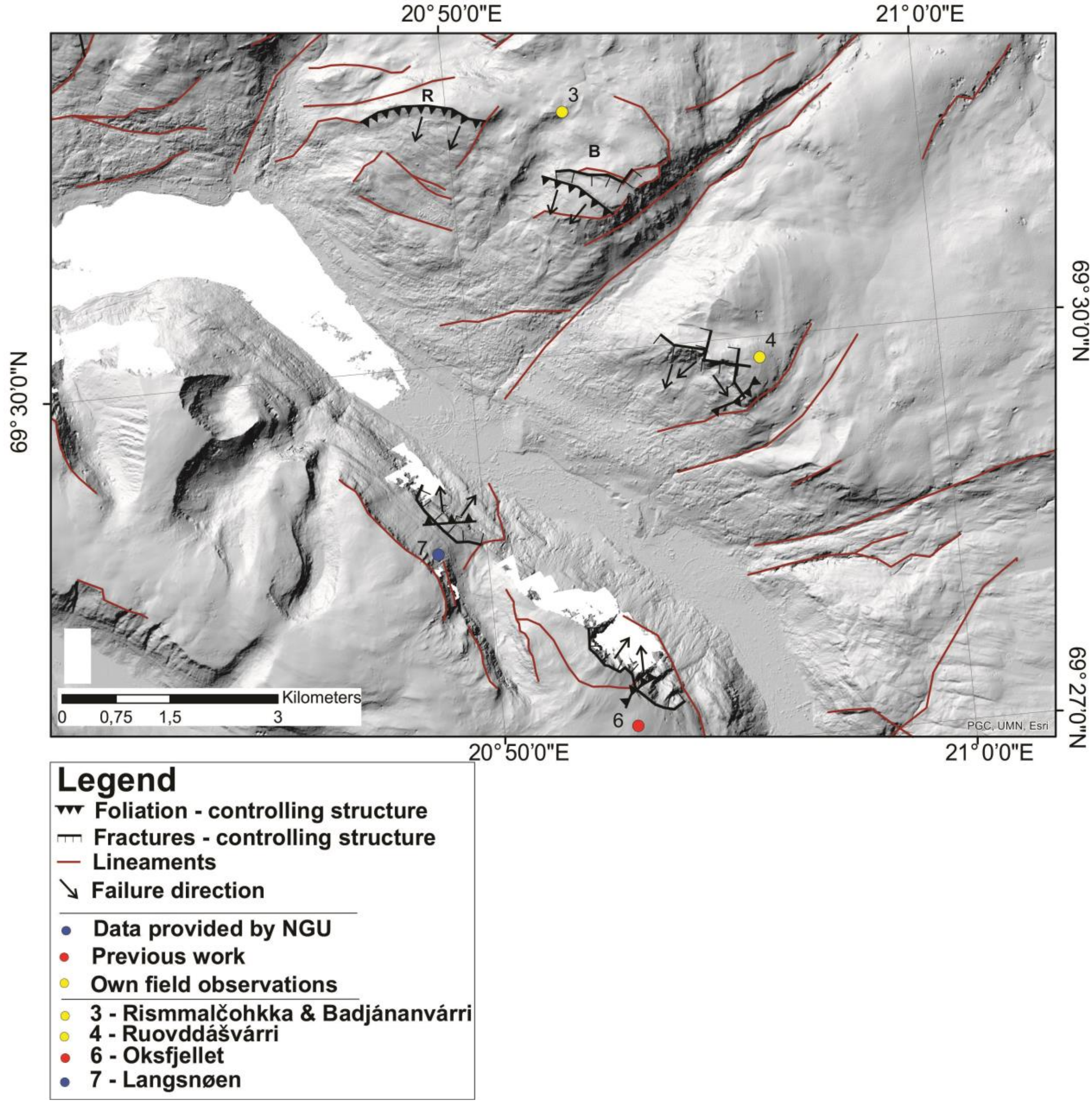

Fig. 50 - Lineament map with the inferred controlling bedrock structures of the southern part of the study area of Kåfjorden with Rismmalčohkka marked with an R, Badjánanvárri marked with a B, Ruovddášvárri, Oksfjellet and Langsnøen. Localities with failure directions in more than one direction, e.g. Ruovddášvárri, illustrate different bedrock structures interacting causing failures in different directions due to favorable orientations of the structures.

Kinematics and movement patterns

The movement directions and nature of movement vary a lot in the study area. The main controlling factors for movement are based on which bedrock structures that are present in the unstable areas, their orientation relative to the slopes, and how they interact. Common for the foliation-controlled failures, Gavtavárri east, Nomedalstind and Rismmalčohkka, the failure directions are towards SW and SSW (Fig. 49 and Fig. 50). This is almost perfectly perpendicular to the strike of the gently dipping foliation of the localities.

The localities controlled by two fabrics, fractures and foliation, vary more in failure direction (Fig. 49 and Fig. 50). One possible reason may be that blocks not only move perpendicular to the strike of the fractures, but along the intersecting line of the controlling structures, as during a wedge failure (chapter 3.3.3). The localities on the southwestern side of the fjord, Oksfjellet and Langsnøen, show similar failure directions, where foliation and one of the controlling fracture orientations mostly are parallel, NE-SW -striking (cf. Fig. 39 and Fig. 46). This is similar to the other foliation- and fracture-controlled failures, e.g. Ruovddášvárri (Fig. 50). Failure directions at Oksfjellet and Langsnøen are therefore mostly towards NNW and NNE for both localities depending on the dominant controlling bedrock fabric.

At the two other foliation- and fracture-controlled localities, Nordmannviktind and Badjánanvárri, the foliation strikes sub-parallel to one another, NW-SE and NNW-SSE to NW-SE, respectively (Fig. 9A, Fig. 22A). In addition, the dominant controlling brittle fractures are sub-parallel to the foliation at Nordmannviktind (Fig. 10), while they strike near perpendicular to the foliation at Badjánanvárri (Fig. 24). In these cases, the failure directions are also similar, i.e. perpendicular to strike of the brittle fractures downslope, which is similar to failure direction of the foliation-controlled localities on the northeastern side of the fjord (Fig. 49 and Fig. 50).

Regarding failures that are controlled by only the post-Caledonian brittle fractures, Gavtavárri west is the best (and only) example. The failure direction is interpreted to be at an angle to both controlling fracture sets, i.e. NW-SE and NE-SW, thus the average failure direction is towards south (Fig. 49). This corresponds to movement direction in a wedge failure, as the fracture sets dip to the SE and SW, respectively (Fig. 14B, Fig. 49).

All the geomorphological features discussed are features formed due to movement within the unstable areas. Features parallel or sub-parallel with the backscarps, e.g. the ridges and depressions at Nordmannviktind (Fig. 8), are interpreted to have formed during the main failure events forming the backscarps of the localities. Features perpendicular to the backscarps, e.g. the scarps in the upper, southern part of Rismmalčohkka (Fig. 21), which dominantly follow trace of inherited bedrock structures, are interpreted to have formed when the fractures were activated during the main failure events.

Various methods regarding monitoring have been utilized in Kåfjorden by the NGU, including monitoring campaigns on some of the localities in this study. Data from these campaigns would better constrain the failure directions of the localities, possibly narrowing down which bedrock structures that are more/less controlling for each failure site. This has not been the focus of this study, but such data could compliment the presented data and interpretations made in this thesis.

Control of deglaciation

Kåfjorden, and central Troms, comprise highly glacially eroded areas, with several NW-SE – trending glacially eroded valleys, e.g. the Skibotn valley and Kåfjord valley. Several of the mountain slopes within the study area are steepened due to glacial erosion presumably along favorable oriented bedrock structures, e.g. fractures (cf. chapter 2.3.3).

The angle of the valley slopes in Kåfjorden is generally relatively steep, cf. Table 2. By contrast, the ductile bedrock structures are gently dipping, while brittle fractures are mostly steep to sub-vertical. On the northeastern side of the fjord, Nordmannviktind, Gavtavárri, Nomedalstind, Rismmalčohkka and Badjánanvárri, comprise slopes dipping with an average of 40°, whilst the three southernmost localities are steeper (ca 70-80°) (Table 2). This is what should be expected as a result of dominant Quaternary glacial erosion in the valley of Kåfjorden, but some slopes are clearly oversteepened (Ruovddášvárri, Oksfjellet and Langsnøen) (chapter 2.3.3). In the southernmost localities, erosion may thus be prevalent along pre-existing brittle structures in the bedrock, and follows these steep inherited fractures (Böhme, 2014). For the northernmost localities, most of the valley have slopes dipping sub-parallel to the foliation, thus glacial erosion is inferred to have followed the weakness made up by the foliation in these slopes.

Thus, the slope angles may indicate that in the southern parts of the study area (Ruovddášvárri, Oksfjellet and Langsnøen); fractures have been the favorable structure regarding erosion. For the northernmost parts (Nordmannviktind, Gavtavárri, Nomedalstind, Rismmalčohkka and Badjánanvárri), foliation is considered the favourable structure for glacial erosion.

Dip directions of the local valley sides vary, but common for the localities on the northeastern side of the fjord is that the slopes face in same direction as the foliation dips, except for Ruovddášvárri (E to SE dip of foliation, and S-facing slope), while steep valley sides include steep brittle fractures. Thus, a likely interpretation is that the dip/slope of mountains in Kåfjorden are controlled by the pre-existing bedrock structures.

External factors

Several external factors are known to contribute to the destabilization of rock slopes. These include, amongst others, water and permafrost, seismic activity and glacial processes. Seismic activity and water and permafrost will briefly be introduced here.

Regarding seismic activity, earthquakes are found to initiate different types of landslides, whereas the minimum magnitude of triggering rock slope failures is 6.6 M (Keefer, 1984). Neotectonic activity was, by Dehls et al. (2000) interpreted to have formed the Stuoragurra reverse fault in Finnmark and the Nordmannvikdalen normal fault (/feature) (chapter 2.3.2.1). However, few earthquakes greater than 5-6 M occur in Norway, thus the controlling effect they might have on failure areas are probably not that great in Norway compared to e.g. the Andes Mountains. Therefore, seismic activity is not interpreted as an enhancing force of the studied unstable rock slopes.

Water is known to lubricate surfaces, may increase the driving forces of failures and the pore pressure will increase with its presence (Braathen et al., 2004). All these situations may further contribute to a destabilization of unstable rock slopes, and attempts on forcing failures with increased input of water have been done, e.g. at Veslemannen in Møre and Romsdal, during the fall in 2017. Increased rainfall and periods with great melting of snow are in several cases found to increase the acceleration of unstable rock slopes, thus an expected acceleration may occur during late summer – late fall before temperatures drop below the freezing point (Skrede et al., 2016). This may also be the case for the studied rock slopes, with Oksfjellet as the greatest threat to fail based on previous studies (e.g. Bredal, 2016).

During winter, presence of permafrost may increase the stabilization of unstable rock slopes, as the water freezes, and will not e.g. lubricate bedrock surfaces. The study area may comprise permafrost (Gisnås et al., 2017), and the findings of several snow-filled sinkholes in August/September may confirm the existence of permafrost.

6.4 Regional lineaments and their relation to the failure areas

In order to discuss possible regional inheritance of bedrock structures, in particular brittle faults and fractures, as controlling factors for the studied unstable rock slope failures in Kåfjorden, the mapped lineaments within the study area will be discussed and interpreted (Fig. 46). As a starting hypothesis, the local trends of bedrock fabrics in the study area coincides well with the regional lineaments in Troms (Fig. 49 and Fig. 50). This hypothesis will be outlines and argued for below.

6.4.1 NW-SE –oriented brittle structures

Along the coastal margin of Troms, few of the major faults or fault complexes trend NW-SE, but ductile shear zones show trends of this orientation. Thus, this orientation of lineaments are margin-oblique (cf. Fig. 4).

Within the study area, all the localities except Badjánanvárri and Ruovddášvárri comprise backscarps fully or partly trending NW-SE where three are foliation-parallel, and the rest follow trace of brittle fractures. This may indicate that the backscarps of the localities follow trace of a larger, dominant lineament orientation, now exposed as fracture- and foliation surfaces. On the northeastern side of the fjord, all localities except Ruovddášvárri has foliation striking NW-SE dipping down towards the fjord. In addition, several of the localities comprise fractures striking NW-SE, steeply dipping towards the fjord (SW). This suggest that the NW-SE –trending orientation of lineaments is highly controlling for development of failures within the study area of Kåfjorden.

Comparing with other unstable rock slopes in Troms, e.g. Adjet near Skibotn (e.g. Bakkhaug, 2015, Eriksen et al., 2017) which also comprises a backscarp mainly following NW-SE –striking fractures of varying dip. The Skibotn valley also trends NW-SE, parallel to the Kåfjorden valley. At the Nordnes peninsula, east of Lyngenfjorden, two of the localities that are under permanent monitoring are located, Jettan and Indre Nordnes (Skrede, 2013, Hernes, 2014). These rock slope failures are located along the N-S –trending Lyngenfjorden, but Jettan comprise controlling fractures parallel to the NW-SE –trending ones observed within the study area of Kåfjorden. However, the N-S –trending lineament (fault) along Lyngenfjorden may have activated the fractures as tensile structures causing destabilization of the rock slope. This gives the Jettan locality a N-S –trending lineament as controlling, which is aligned with several coastal/margin-parallel fracture systems.

Within the study area, the Nordmannvikdalen fault/feature is the most prominent and the most studied NW-SE –trending lineament (e.g. Dehls et al., 2000, Redfield and Hermanns, 2016). Whether this is a neotectonic post-glacial fault, a scarp, a result of creep of topsoil or a

DSGSD is not the focus in this project; however, it may confirm the NW-SE –trending orientation of lineaments as a controlling regional trend. Kåfjorden and the Kåfjord valley also trend NW-SE, except for the central parts of the fjord, suggesting the NW-SE –trending orientation as controlling.

This suggest that on a regional scale, NW-SE –trending lineaments are pervasive in the bedrock of central Troms, and they are thought to be controlling for development of rock slope failures. N-S –trending lineaments, especially the fault along Lyngenfjorden, are also considered controlling, with the several unstable rock slopes along the eastern part of the Lyngenfjord evidencing this (e.g. Jettan, Indre Nordnes, Midtre Nordnes and Revdalsfjellet) (NGU, 2018). The NW-SE –trending lineaments with both foliation and steeply-dipping fractures dipping SW are considered failure-enhancing within the study area of Kåfjorden.

6.4.2 E-W –oriented brittle structures

Considering the larger regional faults and fault complexes in Troms, few show trends of E-W (cf. Fig. 4 and Fig. 5), except segments of the Troms-Finnmark Fault Complex that trend ENE-WSW and WNW-ESE (Koehl et al., 2018). Within the study area of Kåfjorden, the central parts of the fjord trend E-W, in addition to some of the side valleys to the fjord. Therefore, this orientation of lineaments might be inferred as less controlling; however, some structures within some of the failure areas may prove these lineaments as controlling.

All of the studied unstable rock slopes comprise fractures of E-W -striking orientation, except for Oksfjellet. Segments of the backscarps at Ruovddášvárri (Fig. 27) and most of the backscarp at Badjánanvárri trend E-W. These unstable rock slopes are located aligned with, and east of, the E-W –trending segment of the fjord of Kåfjorden. This suggests that the E-W –trending part of the fjord and the backscarps of the localities follow a regional trend that may have formed the fractures the backscarps follow. Regarding failure mechanisms, some of the studied rock slopes comprise the E-W –striking fractures as controlling. Ruovddášvárri, a slide topple type of failure, comprise the E-W –striking fractures as the delimiting structure along the backscarp (Fig. 29 and Fig. 30). The failure at Badjánanvárri is also controlled by the E-W –striking fractures, as they are considered the sliding surface in the upper part of the failure area (Fig. 24).

In combination, the orientation may be a regional extensional weakness, with Badjánanvárri and Ruovddášvárri being the only localities clearly controlled by the E-W -oriented fractures. As these rock slopes are located in vicinity to the E-W –trending segment of the fjord, they may comprise an elongation of the lineament. Thus, the lineament may enhance failure development, however, not as dominant as the NW-SE –trending ones.

6.4.3 NE-SW –oriented brittle structures

The regional lineaments in the study area trending NE-SW are interpreted to be of a structural origin, and they trend parallel to fault systems in the coastal areas of Troms of Mesozoic-Cenozoic age (Indrevær et al., 2013). Thus, this is considered a pervasive bedrock structure in Troms, and several side valleys to Kåfjorden trend NE-SW (e.g. Fig. 46, Fig. 49 and Fig. 50).

In addition, many of the studied unstable rock slopes comprise brittle fractures of this orientation, e.g. segments of the backscarps at both the western area of Gavtavárri and at Oksfjellet. It is for these two localities the NE-SW –trending lineaments are favorable for development of failures. This is inferred as these failures occur along the NE-SW -striking fractures in interaction with other bedrock structures; other brittle fractures at Gavtavárri and in a combination with foliation and fractures at Oksfjellet (Fig. 16 and Fig. 38). At the unstable rock slope of Langsnøen, the NE-SW –striking fractures are interpreted to partly control the failure, but in combination with sliding along foliation surfaces or with other brittle fractures (chapter 5.7.3).

Some localities comprise these as delimiting structures of smaller failures, e.g. as side scarps trending perpendicular to the main backscarp at Gavtavárri east, and as a structure delimiting the terraces at Nomedalstind (Fig. 13 and Fig. 33). This suggest that the NE-SW –trending lineaments within the study area of Kåfjorden are *not* the main controlling orientation of lineaments for development of unstable areas. However, they partly control some localities, suggesting these lineaments as subsidiary lineaments inherited as a bedrock weakness that may be activated.

7 Conclusions

A total of seven unstable rock slope failure areas in Kåfjorden, Troms, have been studied and analyzed with purpose to better explain bedrock structures, their controlling effect on failure areas and failure mechanisms. A focus has also been how or if the various structural trends in the study area may be inherited from regional lineament trends (brittle faults). The main conclusions of this study can be summarized as follows:

- The bedrock in Kåfjorden is highly affected by the Caledonian orogeny, evidenced by a commonly well-developed foliation, which is a result of several events of folding and ductile thrusting.
- The foliation has variable dip direction and dip angle due to imbricate Caledonian thrusting towards SE. The dip varies within the study area, dominantly SW (slope-parallel) in localities on the northeastern side of Kåfjorden. On the southwestern side, the foliation dips towards NW. The foliation itself has fully controlled three of the unstable areas, Gavtavárri east, Rismmalčohkka and Nomedalstind, where rock masses have failed along now exposed foliation surfaces forming the backscarps. The resulting failure mechanisms for these localities include *irregular compound slide*, *planar translational slide* and *toe-buckling translational slide*, respectively.
- The local trends of post-Caledonian brittle fractures in the study area only partly coincides with the regional rift-margin faults in western Troms. In the study area, brittle fracture systems have three dominant trends, NW-SE, NE-SW and E-W.
- Several of the studied rock slope failures are controlled by a combination of the Caledonian foliation and post-Caledonian brittle fractures. These include Nordmannviktind, Badjánanvárri, Ruovddášvárri, Oksfjellet and Langsnøen. Sliding is interpreted to occur along the foliation of these localities, while the steeply-dipping fractures control the extent of the failures, thus limiting sliding along foliation surfaces. Badjánanvárri is considered a *bi-planar compound slide*, while Nordmannviktind, Ruovddášvárri, Oksfjellet and Langsnøen are all interpreted to fail as *slide topple* types of failures. Oksfjellet is also considered to fail as smaller *wedges* and/or *rock fall slides* along the backscarp. Langsnøen shows similar features with the possibility of minor *rock fall slides*.
- The western area at Gavtavárri is the only locality controlled by brittle fractures alone, which is interpreted a *rock fall slide* type of failure mechanism controlled by intersecting NE-SW- and NW-SE –striking fractures.
- In relation to regional trends of lineaments, the NW-SE –trending lineaments are thought to be the dominant failure-inducing fabrics, including the SW –dipping

foliation and the steeply dipping NW-SE –striking fractures. The backscarps of the slide topple types of failures, except Ruovddášvárri, have dominant trends NW-SE. In addition, the E-W –trending fractures largely control the development of failures at Badjánanvárri and Ruovddášvárri, failure area located aligned with the E-W –trending part of the Kåfjorden. The NE-SW –trending lineaments well-developed along the margin are concluded to *not* be failure-enhancing in Kåfjorden. These data suggest regional inheritance of brittle faults/fractures and foliation, as controlling factors for the studied unstable rock slope failures in Kåfjorden.

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