



**GEO-3900**

**MASTER'S THESIS IN GEOLOGY**

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Structural geometry and controlling factors for a rock slope failure area at HOMPEN/VÁRÁŠ, Signaldalen, Troms, North Norway



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May, 2012

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University of Tromsø



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# Preface

## North

*Look more often towards the north.*

*Go against the wind, you get redder cheeks.*

*Find the rugged trail. Hold it. It is shorter.*

*North is best.*

*Winter's flaming sky, summer-nights sun miracles.*

*Go into the wind, travers the rock.*

*Look to the north.*

*More often.*

*It's far this country.*

*Most of it is north.*

*(Modified Rolf Jacobsen)*



**(No terrain is untraversed, Signaldalen 2011)**



# Acknowledgements

I will here use the opportunity to thank the many people who have helped to make this thesis possible. Firstly, I should thank my supervisor, Prof. Steffen Bergh, for the encouragement and guidance through the studies and that he gave me the study area in Signaldalen. I will also thank my co-supervisor Geoff Corner for guidance and efforts to help me with this thesis. I take this opportunity to give my thanks to the other students (nobody mentioned, nobody forgotten), who patiently been listening to a somewhat frustrated fellow student. I would like to acknowledge Jan P at the third floor for helping me with computer challenges with a smile you always helped and supported. To my co-supervisor at Geological Survey of Norway Per Terje Osmundsen, who took time to meet the Hompen angel in Trondheim and to Halvor Bunkholt at NGU who have supported and been in the background as a solid person for help and motivation. A big thank to Bauke Zwaan who provided me with his unique database over Troms and the personal communication during my visit in Trondheim. I can't forget to thank my field assistants, (Gro, Anne and Elisabeth) and to the number one assistant Torben. Without you all, this thesis had not had all field data as it has, sorry the HMS was not always followed. Tusen Takk, to Tina Nielsen who helped me to correct my svengenglish. Thanks to friends and neighbors.

I have saved one of the last acknowledgements to the ones who deserve it most. To my kids Synne (9) and Hedda (5), now mum will try to become a "normal" mum, with not always saying "Jag skall bara.."

The last and most deserved acknowledgement goes to my beloved, most truly man in life Torben Rognmo. This whole student period and the finale year with master work had never ever been possible without you and your unconditional support and patience has been priceless. There will be a totally new star system developed in the sky for you.



# Abstract

This thesis uses a multidisciplinary approach to investigate factors affecting the origin and evolution of a rock slope failure (RSF) at Hompen (*Varas*) in Troms, Northern Norway. These factors include internal existing structures in the bedrock, external factors such as glacial unloading, and changes in fluid pressure affecting the RSF.

The study combines bedrock geology, structural geology, geomorphology, and satellite data and dGPS measurements to analyze and classify the area. Detailed field work, analyses of field data, DEM models and aerial photos are employed to interpret the RSF.

The area has been divided into two domains based on observed structures. Domain I show classical RSF morpho-structures: a major scarp striking NW-SE, lateral scarps striking NE-SW, counter scarps and transfer structures. Domain II is stable but show clear pre-rock slope failure structures, e.g. major tensile fractures, which potentially may enlarge the main RSF area.

Among interpreted movement mechanism, creep occurs at present towards SSW (7-10 mm/year) as indicated by dGPS data. There is also clear evidence of toppling as a failure mechanism, shown by the major graben area filled with toppled rock material. The detachment surface is assumed to be of ramp-flat geometry with several sliding planes, affected by fractures working their way down to a basal detachment.

The initiation of the RSF is likely linked to pre-existing fracture systems inherited from Mesozoic-Cenozoic tectonic regimes, release of stress regimes in the bedrock after deglaciation. Other factors such as permafrost melting and water drainage may have caused changes in the pore fluid pressure in the area.

Today the Hompen RSF can be classified as a complex RSF field and classifies under the deep seated gravitational slope deformations (DSGSD).





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# 1. Introduction

## 1.1 Background for the study

Statistically we can expect 2-3 big rock slope failures (RSF) in Norway the next 100 years, each of them can take about 200 lives. In addition we will experience many smaller rock slides. The national internet based database for avalanches ([www.skrednett.no](http://www.skrednett.no)) gives updates on the latest avalanches and rock slope failures as well as historical events. (Høst et al., 2006)

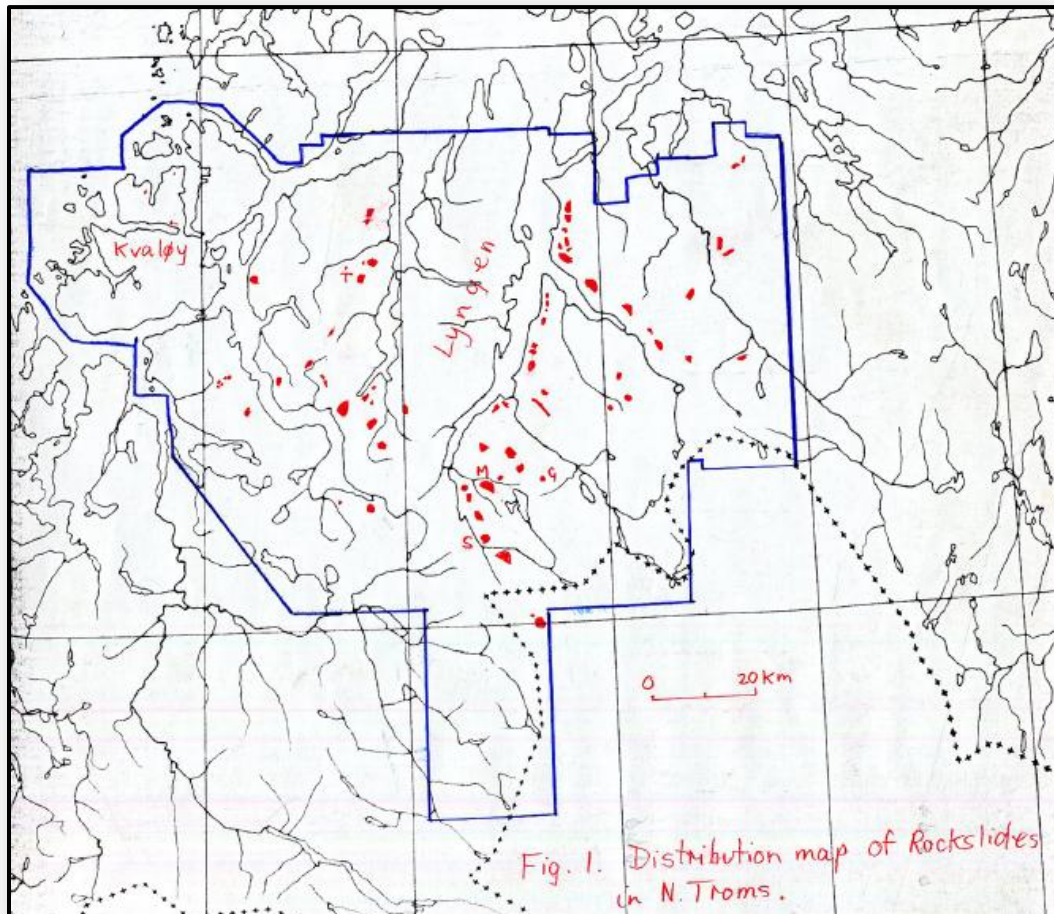
To cope with the hazard of RSF's, there is a need for more knowledge and understanding of e.g. their internal characteristics, kinematics and initiation mechanisms (Bjerrum & Jørstad, 1968; Agliardi et al., 2001; Braathen et al., 2004; Jaboyedoff et al., 2011; Bunkholt et al., 2012 and several others). There have been several fatal rock slope failures of different types in Norway, e.g. in the Loen area in Stryn, Sogn and fjordane, that suffered from severe RSF in 1905 and 1936; these took 174 lives (Furuseth, 2006).

In late 1930 NGU (Geological survey of Norway) started systematic mapping of unstable mountain sides in the southwestern Norway. After the publishing of the review by Bjerrum and Jørstad (1968), regarding the importance of factors for understanding the behavior of RSF in Norway, the interest for RSF started to grow. An unpublished report and map of RSF in the Troms County (Fig. 1.1) shows several of the same identified RSF as those recorded today (Fig. 1.3) (Corner, 1972).

In the late 1990's the NGU (Norwegian Geological Survey) was asked to start investigating areas in the counties of Møre and Romsdal and Troms that may provide a high-risk of RSF ([www.skrednett.no](http://www.skrednett.no)). Certain areas in Norway have a larger potential for landslides; Troms is one of these areas. The reasons are varied, but mainly may be due to the steep mountain sides and accompanying deep, glacially carved valleys characterizing these areas.

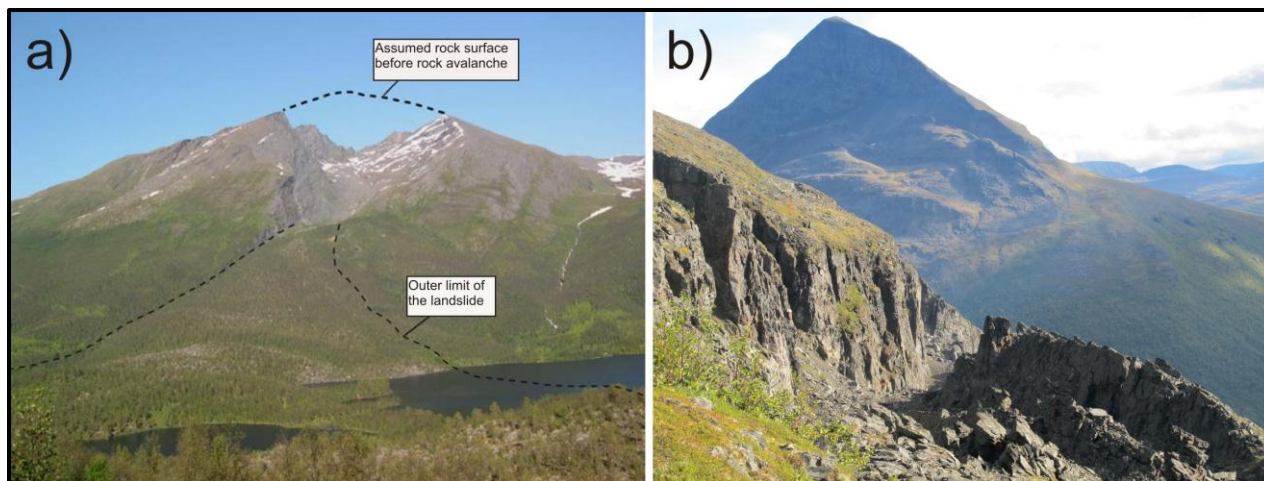
The initiation and mechanisms operating during RSF are poorly understood, but new interests for studying RSF has greatly improved during the last years. It is now generally accepted that the reasons for the initiation of RSF's are numerous and may include, e.g. steep exposed rock faces, overhanging rock, lithology and pre-existing fabrics in the bedrock, as well as the presence of brittle fractures, among others. The importance of fluids and permafrost melting and there effect on RSF areas may be one of the major topics in future, in a climate changing environment.

During the last few years a higher focus have been made on making the RSF research to an interdisciplinary work with more focus on understanding of the development and evolution of RSF's through combining e.g. quaternary geology, geomorphology, structure geology, engineering geology and satellite based research as InSAR and dGPS measurements (e.g. Jaboyedoff et al., 2011; Blikra et al., 2006b).



**Figure 1.1:** Rockslide distribution map of Troms in 1972. Potential “rock slope failures” sites are marked with dots. The investigated area for this thesis is located next to a “S” marked on the map. (unpublished by Corner 1972)

Several mountain slopes in Troms have suffered major RSF, for example Hølen in Balsfjord and Parastind in Signaldalen (Fig. 1.2), next to the investigated area (Henderson et al., 2009). Another major RSF occurred in Pollfjellet in the Lyngen area in June 1810. This is one of the biggest and best documented RSF in north Norway in historic time, here 14 persons died from a tsunami triggered by the rock fall (Furuset, 2006; Blikra et al., 2006a).



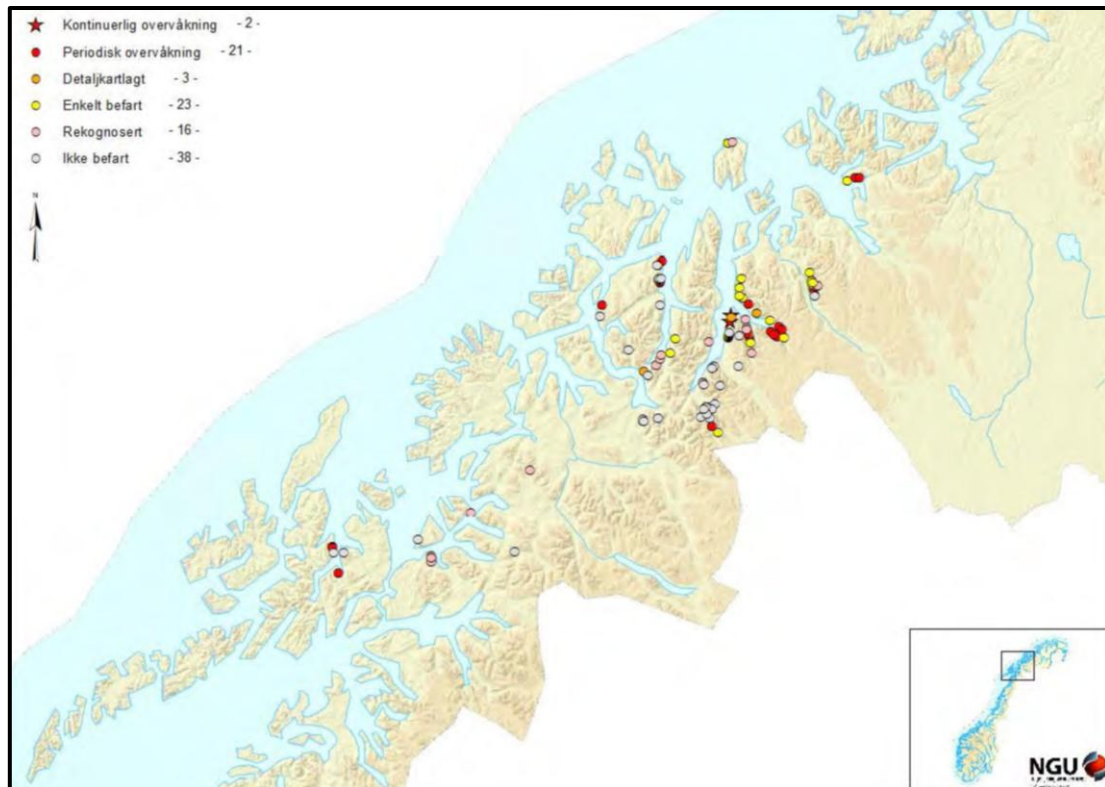
**Figure 1.2:** Examples of big RSF in Troms. (a) Huge triangular cleft in the mountain Hølen, Balsfjord , collapse of 100mill.m<sup>3</sup> (Modified from Blikra et al., 2006a). (b) View of the collapsed northern scarp of the peak Paras (500 million m<sup>3</sup> ) in Signaldalen. View is through the graben at Hompen looking south.

## 1.2 The project: Rock slope failures in Troms

In 1999 the first studies that marked the onset of the onset of mapping large RSF in Troms was done in the area of Nordnes south east of the Lyngen fjord (Blikra & Longva, 2000). In 2003 the Geological Survey of Norway (NGU) mapped and investigated RSF in the Troms County of northern Norway. They found several areas of interest and claimed the need for more work in the area. The project “Fjellskred in Troms” (Rock slope failures in Troms) got established in the spring of 2005.

The NGU-report (2007.041) by Blikra et al., (2007) outlined the status for NGU’s work with the project “Forprosjekt-Fjellskred I Troms.” The project is an inter-municipality project among the municipalities of Kåfjord, Storfjord, Lyngen, Tromsø and Kvæfjord with Lyngen as the leader. Collaboration with Northern Research Institute (NORUT) was started in 2006; GPS measurements are conducted through the University of Oslo (Blikra et al., 2007). Until December 2010, NGU had registered 103 potentially unstable mountain slopes (Fig. 1.3) in Troms (Bunkholt et al., 2011).





**Figure 1.3:** All registered potential landslides in Troms/Nordland, by Dec 2010. (Bunkholt et al., 2011)

The University of Tromsø (UIT) started in 2009 with structurally focused research on RSF. The main goals were to characterize the geometry and inner structure of RSF as a firm basis for discussing the initiation and sliding mechanisms (e.g. Rasmussen, 2011; Husby, 2011).

In the summer of 2009, two master students started work on their project with NGU, one in Laksvatnfjellet in Balsfjord and the other at Nomedalstinden in Kåfjord (Henderson et al., 2010). The third area chosen for these initial studies is the present work at Hompen/Vårås in Signaldalen, Storfjord County (Fig. 1.4). The areas were thought to cover RSF's of three different categories of rock slope failures, based on characteristics, initiation and development mechanisms, e.g. rock fall, rock slide/translational slide and complex fields, as defined by Braathen et al., (2004). The two former largely support this hypothesis (Rasmussen, 2011, Husby, 2011).

The present work has been financially supported by NGU and RDA funds (regionally differentiated employer fee) from the Troms County Council (TCC), given in 2010. The intention of the cooperation between UIT, NGU, TCC and NORUT is to develop a more applicable geological competence at the municipal level based on the ongoing work on different RSF's (RDA, 2010).

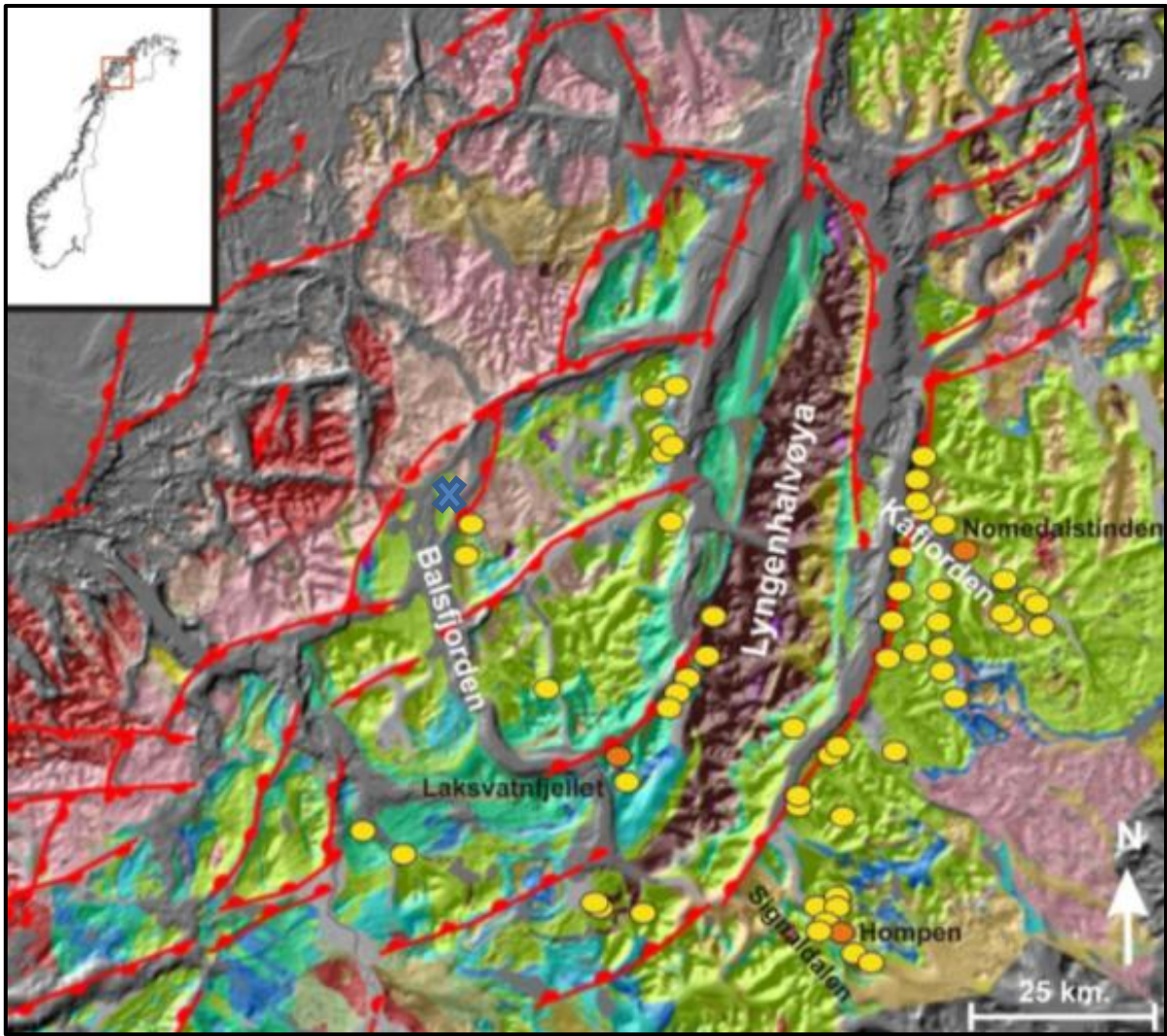


Figure 1.4: Regional DEM image and lineament map showing the studied RSF areas (Laksvatnfjellet, Nomedalstinden and Hompen) in addition to several other RSF's mapped by NGU (labeled by yellow dots). Tromsø is marked with X on the lineament map (Modified from Hansen et al., 2011).

## 1.3 Objectives

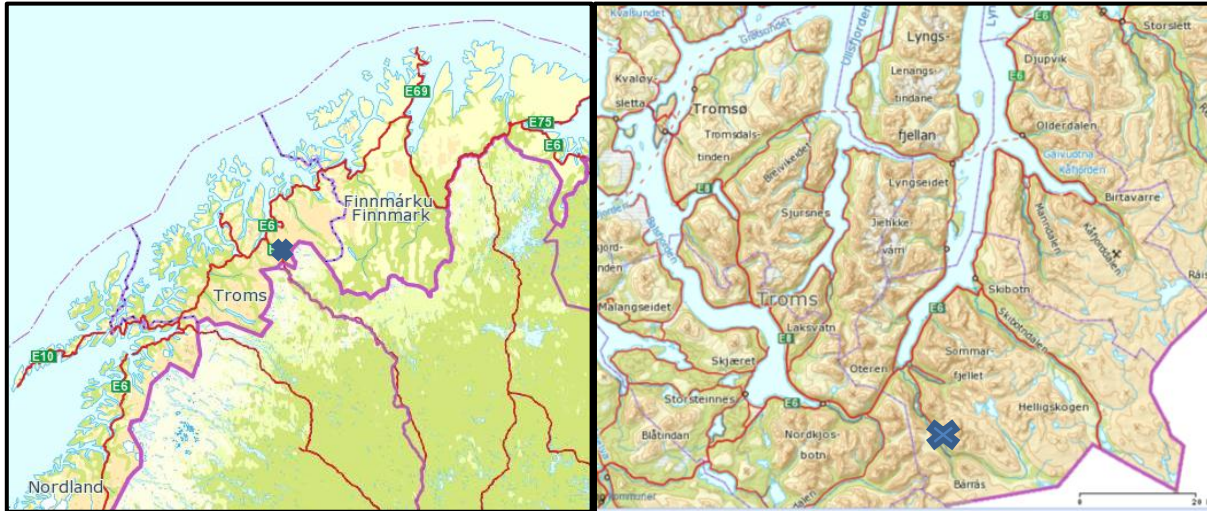
The main objective for this thesis is to obtain an understanding of the morpho structures that develops during the evolution of a potential RSF, through a multidisciplinary study of the Hompen/Varras rock slope failure site in Signaldalen in Troms County. There will be a close integration between structural geology and geomorphology in the study, which includes description and analysis of the morpho-tectonic structures and geomorphological features. In the thesis, the classification by Braathen (2004) will be used. The classification will be supported and complimented by Hutchison (1988). In the present study, a number of methods and tools will be applied, e.g. fieldwork, use of aerial photos, digital elevation models (DEM), and InSAR and dGPS. The main workflow can be outlined as follows:

- Mapping of structures (foliation and brittle fractures) and geomorphological features (e.g. escarpments, counter scarps) of the RSF area, and their orientations, applying field data, aerial photos digital models, InSAR and dGPS. This mapping and characterization of the RSF will be done both inside the RSF and in the more or less intact surrounding bed rocks. In addition, the bed rock lithologies in the RSF area will be described.
- Discuss initiation mechanisms, controlling factors and driving forces/evolution mechanisms of the RSF in the Hompen/Varas area.
- Classification of the rock slope failure area in regard to structure and morphology. The classification will mainly be based on Braathen (2004).
- Discuss possible factors that may have controlled the location, such as pre-existing fabrics and regional fracture/fault patterns in central and western Troms.

Combining information from various methods has previously proven to give good results in understanding deformation in unstable mountainsides and to predict if there is further potential for failure (Jaboyedoff et al., 2011).

## 1.4 Geographic location and topography

The Hompen RSF area is located 65 km southeast of Tromsø in the Signaldalen valley to the south of the Lyngen peninsula, and near the head of Storfjorden (Fig. 1.5).



**Figure 1.5:** Maps showing the location of the investigated area, labeled with an X, Hompen, Signaldalen Troms North Norway (Modified from statkart, 2012).

The study area is situated on a steep southwest-facing mountain side, just above the Signaldalen river. The unstable mountain slope starts on an elevation of c. 200 m a.s.l. (Fig. 1.6). The lower part of the hillside typically consists of talus, which has been vegetated by bushy birch wood, and the lower slope has angles up to  $45^\circ$ . The whole mountainside has an average dip angle of about  $35^\circ$ , up to the back scarp which marks the upper termination of the RSF and being located at c. 550 m a.s.l. The back scarp is an un-traversable vertical wall c. 100 meters high (Fig. 1.6). From the back scarp up to the shoulder, the dip angle is around  $30^\circ$ . The landscape on the top shows a plateau-like morphology. The total RSF area is between c. 0.63-1.5 km<sup>2</sup> (Fig. 1.6).

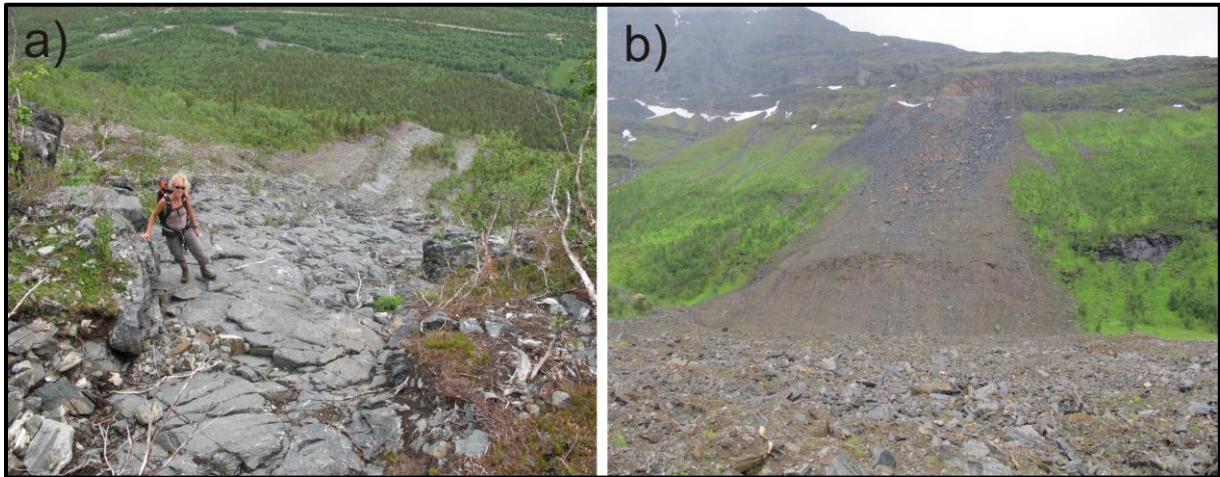




**Figure 1.6:** Photo showing the SW facing slope of the the RSF at Hompen/Varas. The clear back scarp striking NW-SE and the southern scarp striking SW-NE (photo by Bunkholt 2011).

The Lyngen peninsula, situated about 24 km to the west of the investigated area (Fig. 1.4), is classified as a chain of high-relief mountains (Alpine) with its steep slopes formed by glacial cirques and troughs and with many sharp peaks and ridges. Tracing southeastward from the inner part of the Signaldalen valley, away from the Lyngen peninsula, we move into a smoother mountain relief, generally more rounded forms and with moderately steep slopes, broad basins and valleys. The paleic surfaces can be seen in both areas as flat-topped summits (Corner, 2005).

The areas surrounding Signaldalen have recently been in focus for smaller rock falls, e.g the one in June 2008, in the outer part “Skogly farm” of Signaldalen. The rock fall led to a mass of debris (500 000 m<sup>3</sup>) that almost destroyed a farm filled with animals (NVE-report, 11-10). This event has been classified as a thousand-year slide which means that we can expect about 2-4 slides of that size in a 100 years perspective in Norway (nve, 2011). In the spring of 2010, Troms experienced unusually warm weather with intense snow melt, leading to a water saturated snow avalanche with debris that cleared a river gully all the way down to the bedrock next to the investigated area with a thickness of up to 6 meters of local glacial till cover. The bedrock on the south side of the rock slope failure is therefore nicely exposed (Fig. 1.7) (T. Figenschau, personal communication, 2011).

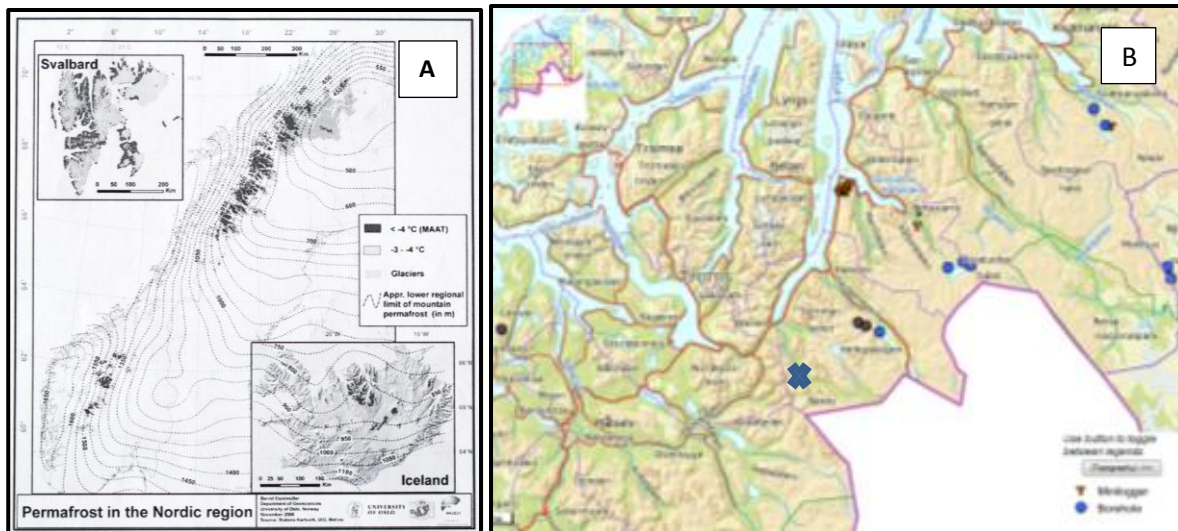


**Figure 1.7:** a) Cleared channel down to the bedrock up to 6 meters of till material, just south of the study area. b) The photo to the right shows the rock fall and the result from it, which happened in the outer part of signaldalen “Skogly farm” in 2008.

Study of aerial photos and models show that several areas in Signaldalen might be potential unstable mountainsides which show clear pre-avalanche structures (norgei3d.no, 2012; Fig. 1.3, Fig. 1.4). One obvious example is the Mannfjellet mountain, located just a few kilometers NW of the investigated site at Hompen (Bunkholt et al., 2012).

The ongoing monitoring project of the Nordnes area termed “Jettan” in Kåfjord, should be mentioned, where an unstable mountainside with a volume as much as 17 mill.m<sup>3</sup>, has a high-risk of falling into the fjord and further, potentially creating a tsunami. Today this area is classified as a high-risk area for RSF hazard and it is monitored by the company Nord Norsk fjellovervåking with cooperation with Åkenes in Sogn and fjordane (Blikra & Kristensen, 2011).

Regarding permafrost conditions in Norway, there is little knowledge and more research should be done. It is known that there is permafrost in the mountains in north Norway (Fig. 1.8A). At Nordnes unstable mountain slope, permanent ice is monitored in cracks at elevations as low as 550 m.a.s.l. (R. Evenes, personal communication, 2011; Brown et al., 2001; Christiansen et al., 2010).



**Figure 1.8:** A) Showing the distribution of permafrost in the Nordic region (appollon.uio.no, 2010) B) sites on which investigation has started in Troms regarding Permafrost; the Hompen area is labeled with a X (Modified tsponsorway, 2012).

## 1.5 Regional geology and previous work

Until 2010, NGU had registered over 103 potentially unstable mountain slopes in Troms County. More than half of these unstable slopes are located on the east side of the Storfjorden (Fig.1.3) (Bunkholt et al., 2011). On the east side of the Lyngen mountain range the Caledonian mountain chain is built up of relatively flat-lying thrust nappes with a smooth topography (Zwaan, 1988), whereas farther west and in the coastal regions of Troms, the bed rock geology comprises variable Caledonian thrust sheets and Precambrian basement rock (Zwaan, 1998; Andresen et al., 1985; Fossen et al., 2006). These regions also display a much more high-alpine topography, due to extensive glacial carving, erosion and deposition during the last 20 000 years. Thus, the variation in structure and character of the regional and local bedrock geology, and the geomorphology, are among the most important factors that could influence where rock slope failures can occur. In the following text, the bed rock (Caledonian) geology and the Quaternary geomorphology of central Troms will be described, briefly.

### 1.5.1 Caledonian bedrock geology in Troms

The Caledonian geology of central Troms is characterized by four major Allochthons, from base upwards, the Lower, Middle, Upper and Uppermost Allochthons (Fig. 1.9). These Allochthons are arranged as an imbricate stack of generally, gently NW-dipping to flat lying nappes or nappe complexes of variable lithology, metamorphic grade and probably also of variable age. The Allochthons lay on top of the Autochthon Precambrian basement, which is



also present to the west of the Caledonian nappes in e.g. in the coastal islands of Senja, Kvaløya and Ringvassøya (Fig. 1.9).

In a section from NW to SE across central Troms, from Kvaløya to Sweden/Finland, the uppermost Allochthon makes up the Tromsø Nappe Complex, which consists of plutonic rocks and various gneisses, including eclogites, metamorphosed at high-grade and whose origin might be exotic fragments of e.g. Laurentia (Andresen et al., 1985; Fossen et al., 2006). The Upper Allochthon series is built up of four separate nappes; the Lyngen nappe (Balsfjordgruppen and the Lyngen gabbro), Nordmannvik nappe, the Kåfjord nappe and Vaddas nappe (Fig. 1.9). The lower and Middle Autochthon, the Kalak nappe complex and the Målselv nappe, both consist of originally sedimentary rocks, deposited on the Fennoscandian margin, but the Kalak nappe show a higher grade of metamorphism. Below the eastern and lowest Allochthon units there is Para-Autochthon and Autochthonous cover (Dividal Group) that rests directly on Precambrian basement rocks (Fig. 1.9) (Binns, 1978; Andresen et al., 1985; Zwann, 1988, 1998; Fossen et al., 2006).

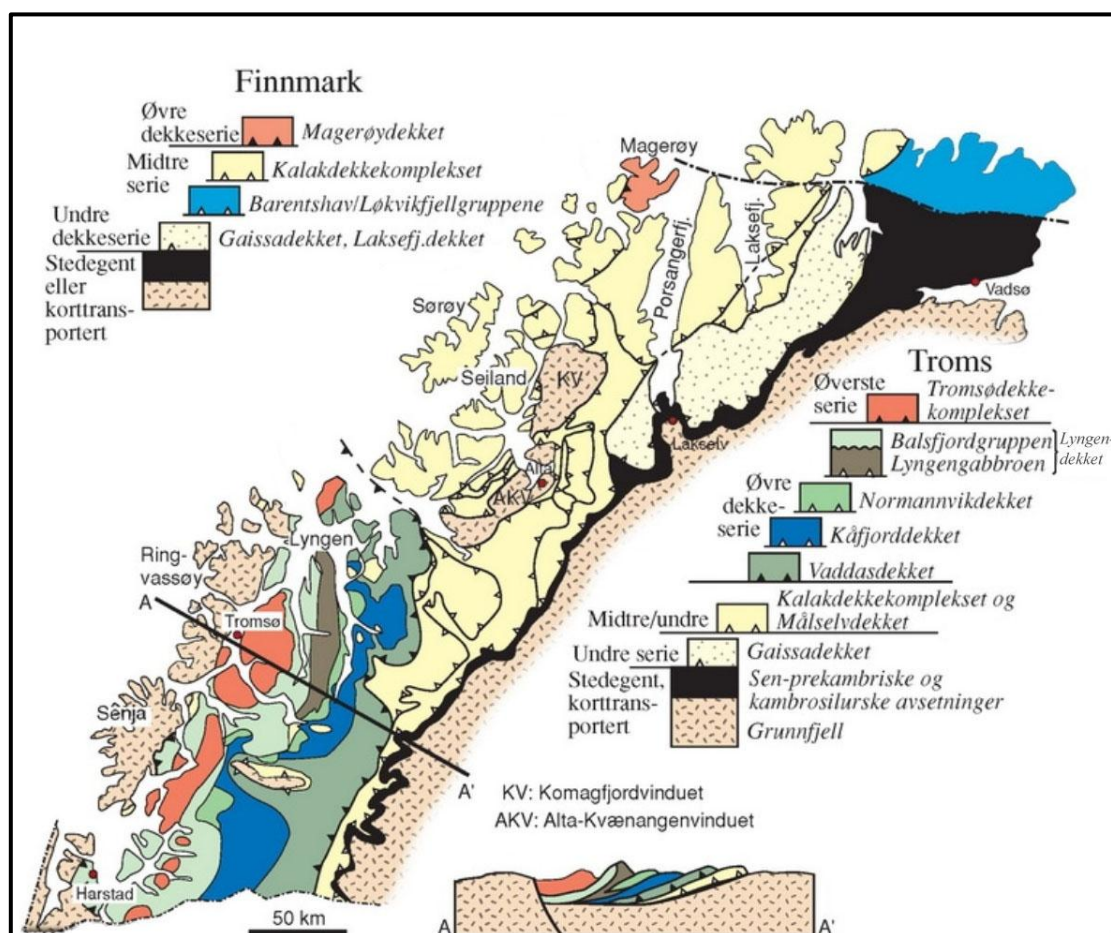
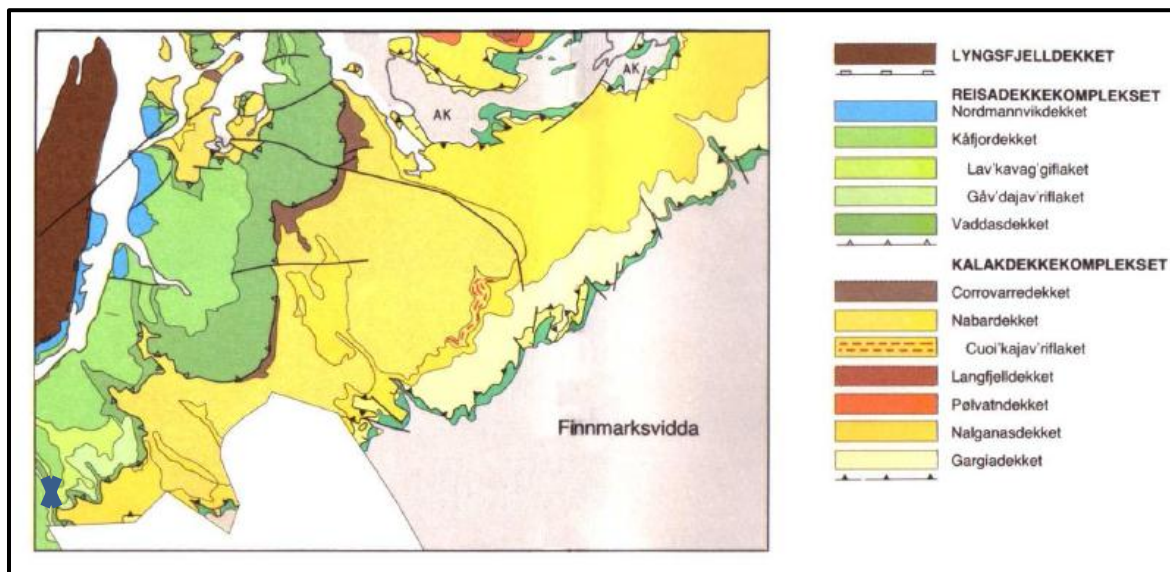


Figure 1.9: Map showing the Allochthons with the different nappe units in north Norway, profile goes across the study area. (Fossen et al., 2006)



The study area is located in the Signaldalen valley, and the bed rocks there belong to the Upper Allochthon, named as the Reisa Nappe Complex (Zwaan, 1988). The Reisanappe complex consists of the Nordmannviknappe, Kåfjordnappe and Vaddas nappe. Between the last two there are the Lavkavagi sheet and Gåvdajavri sheet (Fig. 1.10). The investigated area is located where rock from both the Kåfjord and Vaddas nappe are represented, rock from the Gåv'dajav'ri sheet might also be in the area. The sheet will be described in more detailed in chapter 3. (Binns, 1978; Zwaan, 1988)



**Figure 1.10:** Tectonostratigraphic map showing the two smaller sheets, Lav'kavag'gi and Gåv'dajav'ri which is here seen between the Kåfjord nappe and Vaddas nappe, located in the lower left corner. The study area is marked with an X (Modified Zwaan, 1988).

The Caledonian nappes and corresponding thrusts, folds and ductile fabrics in central Troms were formed during closure of the Iapetus Ocean, i.e. by accretion and collision (Scandian) of Fennoscandia and Laurentia in the early to late-Silurian (Binns, 1978; Andresen et al., 1985; Zwaan, 1988). The Upper Allochthon, including the Kåfjord and Vaddas nappes, comprise rocks formed both in platformal and arc-related settings, including ophiolites, and the rocks suffered multiple tectonic events and a complex deformation history (Roberts et al., 1980; Andresen et al., 1985). The result was nappes with varied bed rock composition and internal structures (see description in Ch. 3.2). It has been suggested that one of the dominant thrusts from the Scandian phase, is positioned just at the base of the Vaddas Nappe (Ramsay et al., 1981; Andresen et al., 1985). Thus, one should expect the rocks of the Kåfjord and Vaddas nappes to be highly heterogenous with respect to composition and internal structure.

### 1.5.2. Quaternary geology and geomorphology

In Troms there have been several glacial and interglacial periods. The area is still strongly affected by these processes, in the mountains we have daily weathering processes and in the low land we can see catastrophic effect of the marine sediments as huge mudflows (Fig. 1.11).



**Figure 1.11:** Photograph showing the outline of a mudslide in marine clay deposits near Lyngseidet. This slide occurred in September 2010 (photo by Andrea Taurisano/NVE).

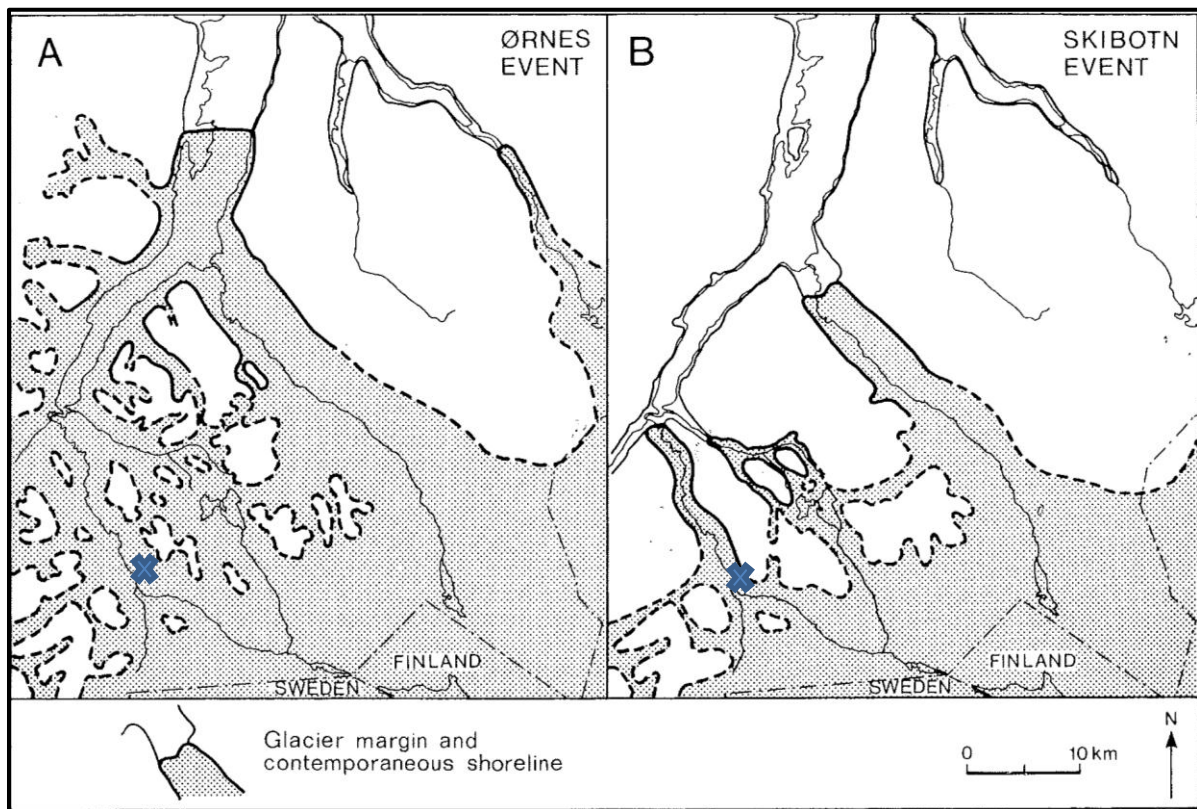
It's in more recent time that the less visible effects, such as Cenozoic uplift, uncovering and weathering effects are becoming more of interest (Dahl & Sveian, 2004; Corner, 2005; Jarman, 2006; Lidmar-Bergström, 2007).

During the Quaternary system we have had series of large scale environmental changes, with large ice sheets eroding and deposition masses. The glacial activity has reshaped the bedrock into the landscape we can see today. The development of big continental ice sheets during glacial stages, and periods with warm interglacial. There have probably been as many as 30-50 interglacial-glacial cycles (Nesje, 1995).

The Weichselian ice sheet, which also can be called the Scandinavian ice-sheet, started to retreat in the Preboreal around 10,000 years ago. It is clear that the big ice sheet that covered most of the Scandinavian countries was at its maximum size 20,000 years ago. About 9,100

years ago it was totally melted away in Troms (Dahl & Sveian, 2004). The position of the ice-sheet has been reconstructed (Fig. 1.12) for the Ørnes (9800-9900±150BP) and Skibotn (9500-9600±150BP) events. The chronology for the retreat of the ice sheet in Signaldalen valley is well documented by Corner (1980). His reconstructions of the retreating of the ice are based on marine limits and ice-front accumulations. The ice retreated from the outer part of Signaldalen (Fig. 1.12B) valley to the head of the valley, in a really fast speed. The 25 km long Signaldalen valley became free of ice in only 300-400 years. The upper Signaldalen show evidence for a marine limit on 96 m.a.s.l, that include wave-washed boulders (Corner, 1980).

The rapid ice sheet retreat of the whole valley and the warmer climate that existed during its retreat will most likely have had an effect on the surrounding mountain sides.



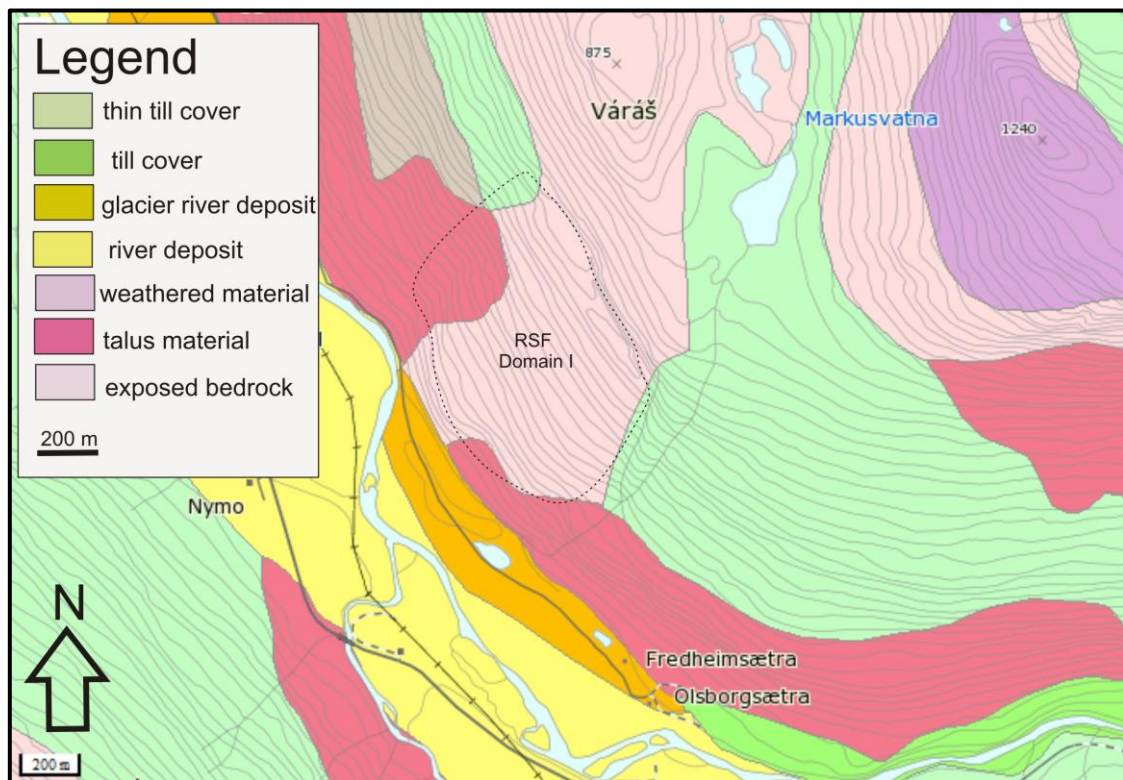
**Figure 1.12:** An modified reconstruction of the extent of the ice- sheets position during the A)Ørnes and B)Skibotn event, The rock slope failure area is marked with an X. (Modified Corner, 1980)

The mountains in Troms are dissected by valleys with floors as low as 300-500 m a.s.l. in the east and down to sea level in the west (Corner, 2005). Signaldalen valley is only one of these valleys (Fig. 1.4). The Signaldalen valley is a U-shaped valley that formed through several glacial periods (Corner, 1977). During the retreat of the Weichselian ice sheet, several marginal features were deposited including the Marginal moraines of the Ørnes and Skibotn



events, which were formed by the ice sheet and several ice-front accumulations in the valley. There are also several features above the head of Signaldalen; the north-east side of Stordalen has a thick till cover. There are several marginal moraines on the west side of Paras valley at 620-640 m a.s.l. There is also a very narrow part in Stordalen, the fluvial valley at the head of Signaldalen, showing a V-valley canyon shape (Corner, 1977).

The evidence of glacial deposits can be identified in today's landscape, as shown in (Fig. 1.13). The investigated mountain slope shows mostly exposed bedrock with a thin cover of talus and glacial river deposits in the lower part (Fig. 1.13). There is a thin cover of moraine, on the SE side of the slide. The moraine is up to 6 meters thick on the mountain slope (Fig. 1.7a) (Lunell, 2001; ngu.no, 2012).



**Figure 1.13:** Quaternary map of the Signaldalen area, with surficial/glacial deposits (Modified from ngu.no, 2012). Note that the steep hillside of the study area (framed) is mostly exposed bedrock with a cover of talus in the lower part.

### 1.5.3 Previous work on rock slope failures in the area

As early as in the 1940's, Geological surveys (Grønli, 1941) described the back scarp in the studied RSF in Hompen/Varas and its upper gorge as a glacial melt water channel (Grønli, 1941; Corner, 1977). A number of previous work has been done on rock slope failures in e.g. central Troms (see Fig. 1.3) and several papers have been published about rock slope failures in international journals and as reports (Corner, 1972; Blikra & Longva, 2000; Blikra et al.,

2006a,b, 2007; Henderson et al., 2008a,b, 2009, 2010; Bunkholt et al., 2011, 2012; Osmundsen et al., 2009, 2010 etc.) and by NGI (1987, 2003, 2008) and many more. There is also popular science work, such as the one in Ottar (Blikra, 2002).

It was through the work by many of these above mentioned authors, that Hompen RSF area were decided as a master thesis subject in the spring of 2010. The work made by Braathen et al., (2004), makes the framework for much of the structure for this thesis.

## **1.6 Definitions and terminology used in the thesis**

So far, no complete and uniform terminology has been established in order to describe rock slope failures. This is because it is a quit new field of subject and the combination of different fields. It is, however, important to promote mutual understanding of terminology between the different branches of geology (structural geology, geomorphology and technicians) that would lead to a better common understanding of the field of subject.

Below are definitions used most frequently in this thesis. Some are modified definitions and some are used because of observed morphologic differences.

Rock slope failure (RSF) is an umbrella term that can embrace many different rock masses and their movements (Table 1). For a more specific description of the different approaches to definitions, refer to Braathen (2004), Hutchinson (1988) and Cruden & Varnes (1996). In Norway the definition of “skred” is a common expression for phenomena’s, where gravitation leads to movement of material. Classification is partly based on the type of material involved in the slide, including bedrock, loose material (fine or coarse) and snow (Høst et al., 2006).

“Fjellskred” is a term defined by Norwegian Water Resources and Energy (NVE) as an event that happens 1-2 times/100 years, with size bigger than 10,000m<sup>3</sup>, and who’s moving mass might have a combination of fall, slide or a fast flow. On its way downhill, the rock splits into smaller fragments and the mass can behave as a mass flow with a long run out (NVE report 14, 2011).

Abbreviations and terms from other subjects fields will also be used, which might have an effect on how the RSF is defined.

**Table.1**

Slope gradients are divided into four categories: gentle ( $<20^\circ$ ), moderate ( $20-30^\circ$ ), steep ( $30-45^\circ$ ) and very steep/vertical ( $>45^\circ$ ).

Accommodation zone

A zone between to overlapping fault segments, where the offset is transferred from one segment to the other. Structures in these zones might also be called transfer structures. (*Modified by Rosendahl et al., 1986*)

Active layer

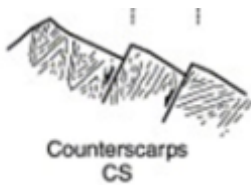
The layer which represent the top of the ground, which is subject to annual thawing and freezing, seen in areas with permafrost. (*Harris et al., 1988*)

Crevasse

A deep fissure, a crack, a cleft and opening in rock, resulting from stress in the rock. The term is mostly used on glaciers. Here it's used as a descriptive type of a wide and steep open fracture. (*Jacksson, 1997*)

Counterscarps/anti-scarp

An uphill facing scarp. (*McCalpin, 1999; Agliardi et al., 2001, 2009; Ambrosi & Crosta, 2006; Kinakin & Stead, 2005*)



D.S.G.S.D-deep-seated gravitational slope deformation

A large gravitational slope deformation, characterized by a large area (multiple  $\text{km}^2$ ), showing a complex and distinctive geometry. The movement rate is low, just a few millimeters per year. Secondary landslides in the area can show on a much higher movement rate. (*Zischinsky 1966; Hutchinsnson 1988; Crosta and Zanchi, 2000; Agliardi et al., 2001, 2009; Ambrosi & Crosta, 2006; McCalpin, 1999*).

Fault

Faults can be described in many ways, here its seen as a discontinuity with a large offset,  $>dm$  scale. A fault is often several fractures that are linked. On a scale smaller than  $dm$  scale, the same will be called a shear fracture. (*Fossen, 2010*)

Foliation

Foliation is sometimes used for primary structures such as magmatic layering or bedding. Here, 'foliation' is used for a planar structure, commonly seen as a flattening of minerals that formed during tectonics and metamorphism. (*Fossen, 2010*)

Fracture

A planar discontinuity resulting from stress in the rock. There is a distinction between extension fractures and shear fractures. (*Fossen, 2010*)

### Graben

Graben is a German word for grave. A graben structure is a depression which is bordered by two parallel faults dipping in opposite or vertical direction. (Agliardi., 2001, Fossen, 2010)

### Horst

A stratigraphically elevated area compared to the rock next to it, the elevation is made by normal faults that are vertical or dipping away from the horst. (Fossen, 2010)

### Joint

A planar surface of a potential fracture, without displacement. Often occurs as part of a joint set. (Hawley & Parsons, 1980)

### Landslide

All masses of earth material (rock or soil) displaced by gravity (Cruden and Varnes, 1996.) There is also a *Landslide classification by Hutchinson (1988), which will be used.*

### Lineaments

A linear or sub linear element on the land surface seen on aerial photo, which often represents a weakness, geologic structure or lithologic contact (O'Leary et al., 1976, Fossen, 2010).

### Morpho-structures

The term describes a structure from a morphological point of view, as a deformation structure from gravitative/tectonic origin or both. Examples of morpho-structures are scarps, counterscarps and trench. (Agliardi et al., 2001).

### Permafrost

Soil, ground or rock that stays at or below 0°C, for minimum of two years. It's based on temperature and not necessarily frozen. Can be seen as continuous, discontinuous, sporadic, thaw-stable and thaw sensitive permafrost. (Harris et al., 1988)

### Ridge

Morphologically elevated land surface over the lower situated surrounding. In regard to morpho-tectonic structures we can experience single ridges or doubled ridges, usually sharply crested forming a upland between valleys. When the ridge is in a clear connection with a scarp, it might be described as a counter scarp in this thesis. (Modified Hawley & Parsons, 1980, Agliardi et al., 2001)

### Rock slope instability

An area in the mountain side that has moved from its geologically original place, and has started to move along a weaker surface plane in the crust/bedrock. (Høst et al., 2006)

### Rock slope failure (RSF)

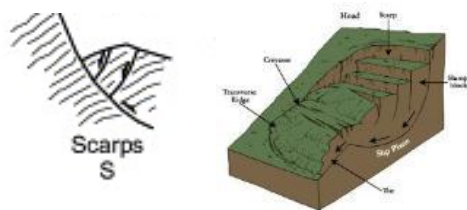
Rock slope failure is a term which can be seen as a umbrella term for the subject. Bedrock mass which is potentially exposed and showing on downslope gravitational movement. The lower cut-off size should be 0.01 km<sup>2</sup> (Jarman, 2006).

## Sackung

The term “sackungen” (from the German verb meaning “to sag”) describes a family of landforms in mountainous areas that include crestral troughs, antislope scarps, and closed depressions. Some authors conclude that sackungen result from a slow mass rock creep and use it synonymously with Deep Seated Gravitational Slope Deformation. (Chigira, 1992; Crosta & Zanchi, 2000; Agliardi et al., 2001; Ambrosi & Crosta, 2006)

## Scarps

In general, a scarp is defined as a escarpment; There are different kinds of scarps: a **back scarp** is a downhill dipping collapse/main failure surface, the crown; a **subsidiary scarp** is the same as a back scarp but not necessary in back. There can also be **lateral scarps** which might work as a boundary scarp.



(Agliardi et al., 2001, Cruden & Varnes, 1996 )

## Sinkhole

A landform caused by weathering or erosion of surface material; normally used in connection with karst, the surface collapses down in depressions that might be fractures or channels. When they cut through vegetation they can be assumed to be active. (Henderson et al., 2011)

## Slope Tectonics

A deformation which is induced or controlled by the morphology in the slope. The features seen can be compared to features seen in tectonic setting. (Jaboyedoff et al., 2011)

## Talus

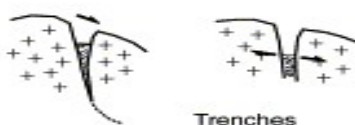
Rock fragments produced by rock failure, can have any size and shape, often angular and coarse. Such material is accumulated at the base of the cliff or as steep rock slope is called talus (Jackson, 1997).

## Terraces

A geomorphological landform that can be horizontal, slightly dipping or have a step-like surface. (Hawley & Parsons, 1980)

## Trench

A trench is a linear and deeper cut form than the surrounding area; it's also an expression of an extensional opening of a vertical or downward dipping surface. Areas which show on a somewhat linear and more consistent topographic depression in the area will be mentioned as trenches, clefts and basins. If it is of major scale it will be referred to as graben structures.

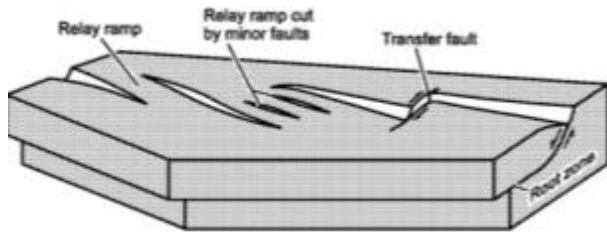


(Modified Agliardi et al., 2001)



### Transfer zone

A transfer zone will here also be called an accommodation zone. A zone between two overlapping segments, where the offset is transferred from one segment to the other. Structures in these zones might also be mentioned as transfer structures or relay ramp structures (*Modified by Rosendahl et al., 1986*).



([gsabulletin.gsapubs.org](http://gsabulletin.gsapubs.org))

### Toppling

A failure which involves a forward rotation and movement of a mass of rock, earth or debris out of its original position in a steep slope/cliff. There are different types of toppling: block, flexure and block-flexure toppling. (*Goodman & Bray, 1976; Varnes 1978; Cruden & Varne., 1996*).

## **2. Methods of Work**

### **2.1 Field work and presentation of data collected**

Fieldwork was conducted in summer of 2010 and 2011; and simplified bed rock sampling was done, to get the impression of the true lithology in the RSF. Morpho-structures and geomorphologic features were observed, mapped in the field, analyzed and interpreted. The orientation of fabrics, including ductile foliation and brittle fractures and joints were measured as strike and dip, applying the right hand rule (RHR-360/90). The hillside slope in the area has an average of 35 degrees in dip. Due to the terrain it is a challenge to get to all good outcrops and not all outcrops are visited. That leaves several areas unmapped, which are either covered with vegetation or loose talus/scree material, or are too exposed. The location of the area is outside mobile coverage, so an Iridium satellite phone was required as a safety precaution.

Structural and geomorphological maps of the study RSF has been made based on the field work. On separate maps of foliation (see Ch. 4), measurements for the symbols are plotted (each symbol have an average of about 10-15 measurements). These measurements are connected to a GPS coordinate (WGS 84, UTM 34), handheld GPS Oregon 450. The collected data have been visualized in ArcGIS (Desktop10) in the Arc Map view and further visualized in stereographic projections (lower hemisphere) and in rose diagrams (e.g. Fig. 4.1, Fig. 4.9, Fig. 4.10). The same procedure was performed for fractures (e.g. Fig. 4.12, Fig. 4.14, Fig. 4.16). Fractures measured are the main visual trends seen; all measurements are taken in order to make sure that all trends are presented. Statistically, these data sets may not be correct because the whole area consists of fractured rock.

A subdivision of the rock slope failure area has been proposed, based on different morpho-tectonic structures seen in the different areas. The data are analyzed with respect to the smaller areas and the total area (Fig. 4.10), and according to the different morpho-structures described in chapter 4. The measurements of the fractures, crevasses and actual trenches/clefts are all taken into account when visualized in the different stereo plots, if not otherwise mentioned. Fractures measured may show extensional displacement, with either total failure of one side or just displacement, either horizontally or vertically or both. Trenches are often started with a plane structure in the cleft's orientation. This might not be the best way statistically to present the data, but it will hopefully show us the main trend and pattern for the

area. A more descriptive presentation of fractures and clefts is given in the presentation of the morphological structures (see Ch. 4).

## **2.2 Aerial photographs and digital elevation models**

The internet site [www.norgei3d.no](http://www.norgei3d.no) has been used in the planning stage of the field work and for location of structure elements. This visualization application has the best resolution for the area; [www.norgebilder.no](http://www.norgebilder.no) and [Google earth.no](http://Google earth.no) were also tried but with less success.

NGU has supplied the project with geographically referred aerial photographs. DEM-files (Digital elevation model) have been the basis for most of the maps, they are geographically referenced and connected to the coordinate system using UTM WGS84 zone 34 (coordinated marked in meters east and north from a reference point in each zone).

Structures and morpho-structures are documented through old photos and digital photos by me and other contributors, most of the photographs are taken with a Canon G11, Digital Camera. I have also used a more informal drawing, as a 3D model of bedrock in the surrounding area from 1969 (Corner, 1969).

## **2.3 Software and map analyses**

Software used for this thesis is ArcGIS version 10 consisting of two main components, ArcMap10 and Arc Catalog. Arc Catalog is the data base where the collected data are stored and shape files are created. The shape files are then used in Arc Map for making maps and visualizing profiles. The software Arc GIS is a geographic information system developed by ESRI, Geodata, [esri.no](http://esri.no). The data collected are stored in GPS system, Garmin Basecamp (2008-2011) and excel files. Reference coordinate system used is UTM WGS84 zone 34.

Stereographic program, Geo Orient version.4.1.5 developed by Holcombe, R., at the University of Queensland Australia has been used in the start of the work with the thesis. Further in the process stereo analyses program, Dips Version 5.103, 1998-2003 Rockscience Inc. Canada; a plotting, analysis and presentation program were used to present the collected data in stereo plots in connection to the figures and text.

Coral DRAW4, a vector-based drawing and graphic design program, was used for photographs/maps and other illustrations.

## 2.4 Maps

Maps used in the thesis are bedrock map 1:250 000 for Nordreisa, with descriptions by Zwaan (1988), topographic map 1:50 000 Signaldalen (Statens kartverk 2007). Digital maps from Norwegian geological Society ([www.ngu.no](http://www.ngu.no), [Statkart.no](http://Statkart.no)) both bedrock, sediments and topographic maps are available there.

Other maps used are a structural map (unpublished) by Binns, the bedrock map by the same (Binns 1969,1978), glacial and sedimentary maps made by Corner (1972) and Lunell (2001), and an unpublished rockslide map of Troms (Corner 1972)

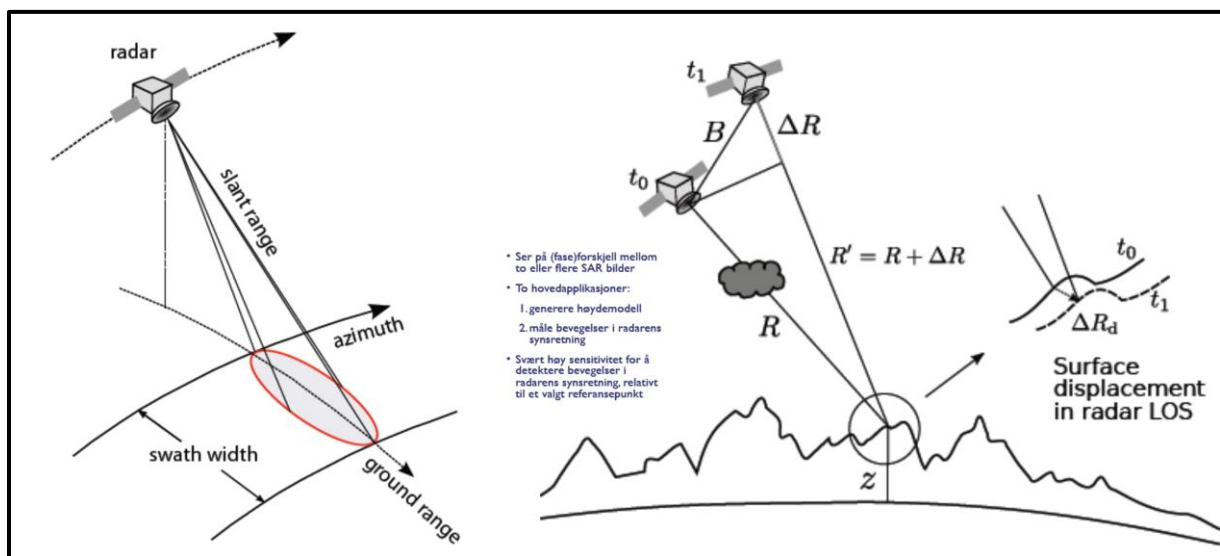
## 2.5 In-SAR data

In-SAR (Interferometric synthetic aperture radar) methods are based on a comparison of information from two or more SAR (synthetic aperture radar) images. The images are produced at different times. The images are taken either while the satellite is descending (south) or ascending (north), depending on the location of the investigated area (Fig. 2.1). The technique can measure millimeter-scale changes in deformation over timespans of days to years. These will potentially detect millimeter to centimeter scale ground deformation patterns. This method was first presented by Gabriel (1989). Current and earlier In-SAR data have been used for studying potential landslides by several different authors in countries other than Norway, e.g. (Hilley et al. 2004; Strozzi et al. 2005; Colesanti and Wasowski 2006,;Rott and Nagler, 2006). In Norway this is a relatively new technique. Challenges in Norway are the long winter season, the snow cover limits, and the number of SAR scenes available for analyses. Steep topography is another factor which can give In-SAR atmospheric stratification effects as Hanssen (2001) points out (Lauknes, 2010).

Interferometric synthetic aperture radar, space born InSAR offers the ability to survey large areas in rare and remote places. The data used in this thesis are from the satellite ERS-1 (1992-2000) from ESA (European Space Agency). These data were made available for the ROS-project. The analyses here are made with a new data set from ENVISAT satellite data taken during, 2002-2010 and provided by NORUT in Tromsø. There are more detailed satellite data Terra SAR-X which can detect much faster velocities, which might be masked with ERS-1 or ENVISAT Satellite wave length which is 5.6 cm and a turnaround of 35 days. To get a true impression of velocities it's important to get the best satellite data available. The

study area Hompen/Varas in Signaldalen is located just to the south of the available Terra SAR-X Satellite images.

InSAR data can help us detect unstable mountainsides; either they are showing down or up movement. The data is a relative movement referred to as (mm/year) in line of sight (LOS) to the satellite. Data can be used to see if there is a correlation between structures we find in the topography through the field investigations and a relative movement on the ground (Lauknes, 2010; Lauknes, personal communication 2012).



**Figure 2.1:** Illustrations simplifying how InSAR works; it collects data every 11-46 days. When the satellite descends (south) or ascends (north), depending on the location of the study area. (Illustrations from NORUT)

## 2.6 dGPS- differential General Position System

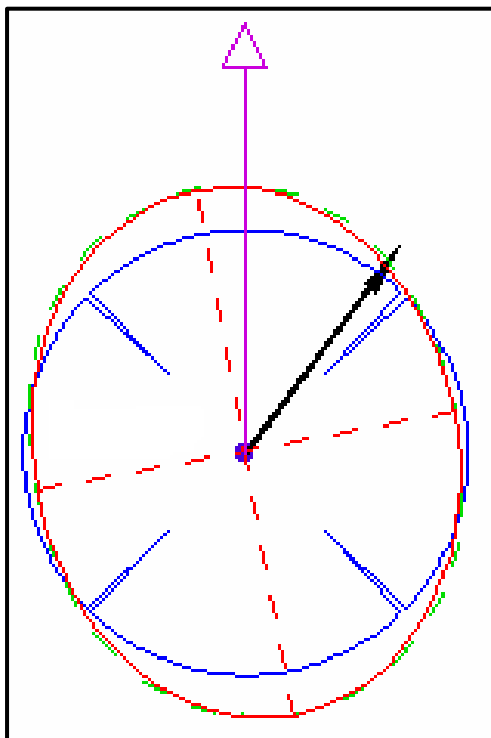
Differential Global Positioning System determines its position by using the signals that it receives from different satellites. Four satellites (one for time and the others for position) are required for positioning. The differential component is added for better accuracy. It uses two satellite receivers, the reference station and rover receiver. Reference station is set up at a known position where the mountain side is stable. Because of this known reference station calculations can be made for improved accuracy.

The measuring equipment used here are Javad/Topcon two frequency PS-receivers, measured by GLONASS satellites, a Russian GNSS system similar to GPS. GNSS (global navigation satellite system) is a system with monuments placed in the terrain, allowing either continuous or periodic measurement of surface motion. The measuring points are marked with screws which are glued to the bedrock. The measuring method is a statistically relative phase measurement, measuring a network of vectors between points (interval is five seconds with a

measuring time of at least 30 minutes per vector). An optimal network should be built up so that every point has connection to three other points. The vectors are calculated using either TPS-Pinnacle or GrafNet (Eiken, 2012) programs.

The results used in this thesis are taken from a preliminary report (Eiken, 2012) made by Eiken at the University in Oslo.

The measurements are given in changes in the coordinates over time as direction and distance of the change. This is visualized in tables and in graphic figures. The figures might need a short presentation here to be read correctly. The figure shows changes in (N, E) and elevation or all three dimensions in one figure (Fig. 2.2). The figure also takes into account a confidence level, meaning how big a change is needed in order to be statistically significant. Changes are displayed with a black arrow, and the significance level is the red circle. If the change arrow goes outside the circle then it's a significant change. Elevation change is visualized through the circle; blue circle with tags towards the center means that its subsidence (movement down), red circle with tags outwards means uplift (movement upwards). The significance levels are shown with the vertical arrow; if the circle goes outside the arrow's point then it's a significant change. This also tests if it's movement of the points or if it's just variations in the coordinates related to other errors (Eiken, 2012).



**Figure 2.2:** Illustration explaining the changes in North and East, and elevation. All three dimensions are presented in one figure. If the black arrow goes outside the red circle the change is significant. Elevation change is marked with blue circle and tags in-movement down and a red circle with tags outwards mean movement up. The vertical arrow pointing straight up and if it is going outside the circle the movement is significant.

## **3. Bedrock Fabrics in the Rock Slope Failure Area**

### **3.1 Introduction**

It is well known that the character of the bed rocks, including lithology and the presence of fabrics such as, e.g. bedding and bed contacts, foliation, faults and fractures may be important factors in controlling the potential hazard for initiating rock slope failures at any scales (e.g. Braathen et al., 2004; Agliardi et al., 2009; Saintot et al., 2011; Henderson et al., 2011; Henderson & Saintot, 2011). In particular, such inherited fabrics may define zones of weakness that easily can be reactivated if their orientation is favorable for, e.g. gravitational sliding or rock fall to appear, and failure planes established along such fabrics can lead to development of unstable mountain slopes (e.g. Braathen et al., 2004; Saintot et al. 2011). In the following chapter, the Caledonian bed rock fabrics and presumed Mesozoic-Cenozoic brittle fractures (see Ch. 1.5) of the studied area will be described in more detail in order to discuss these aspects.

The composition of the bed rock and the orientation of bed rock fabrics may also influence hillside (slope) stability, foliation can work as weaker areas which can be exposed for fractures and further weathering (see Ch. 3.5.2 & Ch. 4.4.1). Some lithologies are more susceptible for fracturing than others, and can therefore be more exposed for landslides (Saintot et al., 2011).

### **3.2 Caledonian bed rock and structures**

The investigated mountain slope is situated in the Upper Allochthon of the Caledonian nappe stack in central Troms (Zwaan, 1988) in the contact zone where both the Kåfjord and Vaddas nappes is represented, in an area that includes as well parts of the Gåv'dajav'ri thrust sheet (see Ch. 1.5, Fig. 1.10). Together we can say that Kåfjord and Vaddas nappes of the Upper Allochthon forms the base of this Allochthon above the middle/lower Allochthon the Kalak nappe Complex (Fig. 1.9). These Allochthons are overlaying the Pre Cambrian basement (Ramberg et al., 2006). The Vaddas nappe represent a volcano-sedimentary sequence of the Upper Ordovician Silurian age while the overlaying Kåfjord nappe contains a more medium to high grade with marbles, quartzites and mica gneisses of a more unknown origin and age.

The Allochthonous units have most likely been transported and thrust several hundred kilometers eastwards during the pre-Silurian and Scandian Caledonian deformation and metamorphism (Binns, 1978; Andresen et al., 1985; Andresen, 1988). The area is bounded by

the Stordalen thrust below, which is the base of the Vaddas nappe against the Kalak Nappe Complex. The Vaddas nappe has a tecto-stratigraphic sequence of first a continental sequence (shallow water sediments) overlain by a late Ordovician-Silurian transgressive succession which has been dated by fossils, this may have been deposited on the Baltic edge (Lindahl et al., 2005). The Kåfjord nappe consists mostly of garnet mica schists, amphibolites, mica schists and numerous pegmatite inclusions. The Vaddas nappe consists of meta-sedimentary rocks such as meta-greywackes, quartz-feldspathic gneisses, banded mica schists and mafic meta-volcanic rocks (Andresen, 1988; Zwaan, 1988). The Gåv'dajav'ri sheet is one of the smaller imbricated thrust sheets in the contact zone and consists of calcite marble, rusty quartzite and black schist (Zwaan, 1988, 1997).

The existing bedrock map (Fig. 3.1A) of the Signaldalen (Nordreisa 1:250 000) area specifies that the RSF area consists of meta-greywacke and the upper part consists of hornblende schists and represent the lower part of Kåfjord nappe and parts of Vaddas nappe (Fig. 1.9) (Zwaan 1988).

In the area where Hompen RSF are located the Vaddas nappe does not display a successive stratigraphy. This area has been subject for several deformations resulting in a complex geometry with e.g. large-scale tight over-folds, open folds, thin thrust sheets as intranappe thrusting and several lithological units may not even be represented in the area. The metamorphism has mostly been in amphibolite facies. There are parts that are magmatic and others approach granulite facies in grade (Binns, 1978; B. Zwaan personal communication, 2012).

### **3.3 Bed rock in the study area**

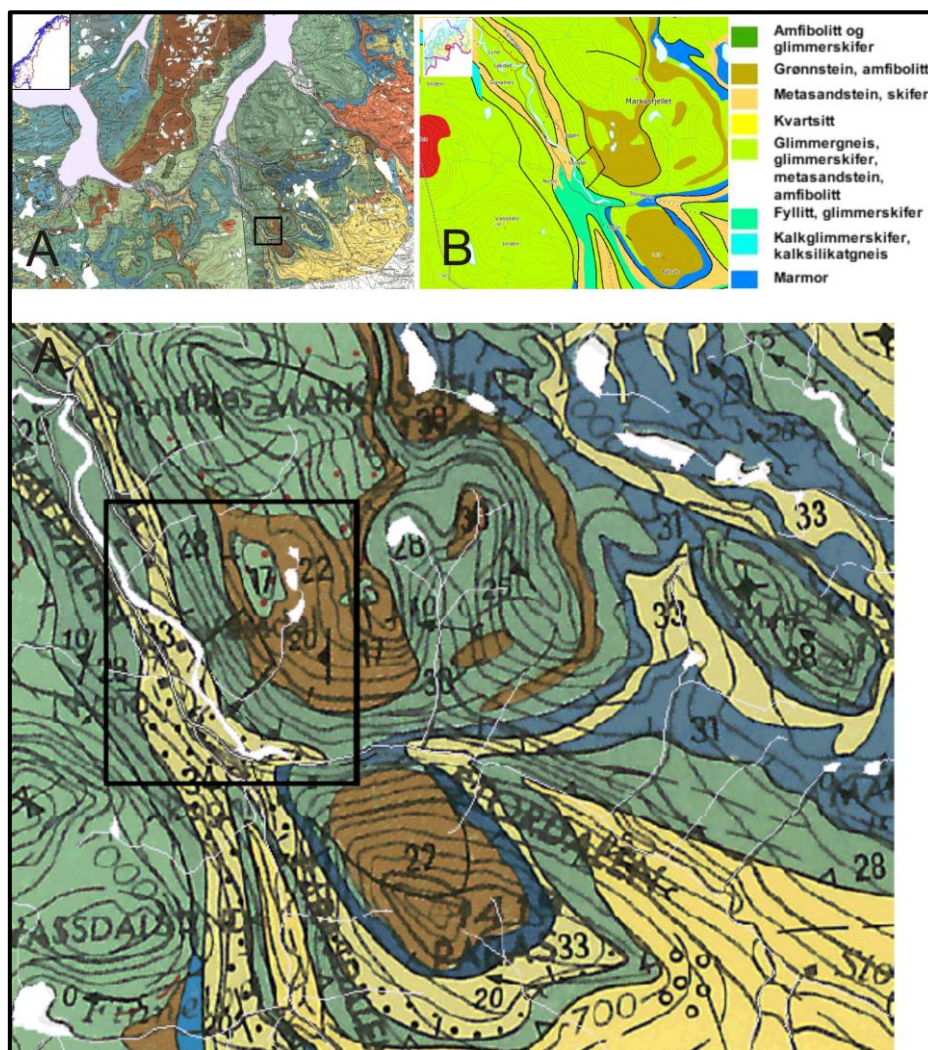
#### **3.3.1 Lithology**

In more detail, the meta-greywacke portion of the Vaddas Nappe (Zwaan 1988) in the study area can be subdivided into conformable units of alternating metamorphic rocks (Fig. 3.1, Fig. 3.2) (Binns 1978; Zwaan, 1988; B. Zwaan, personal communication, 2012). The name meta-greywacke is used as an overall description of the gneisses in the area. If the origin of the greywacke are sedimentary or magmatic is uncertain. The Hompen RSF tectono-stratigraphy according to (Fig. 3.1a; Zwaan, 1988) consist of meta-greywackes and the upper part hornblende schist's and according to (Fig. 3.1b; ngu.no, 2012) the stratigraphy comprises



mica gneiss, mica schist's , meta-sandstones and amphibolites and the upper part of the area is greenstone and amphibolite.

According to Andresen (1988) the upper part of the Vaddas nappe a relatively thick sequence consist of green schist and amphibolites, there is also the “Cappis” thrust which separates the Vaddas nappe terrane from the overlaying Kåfjord nappe (Andresen, 1988). Within the thrust area it is difficult to establish a lithostratigraphy/tectonic stratigraphy, because the area has been subject for high strain, combined with extensive mylonization and several internal thrusts. In the lower part of the Kåfjord nappe which may be affected of this, dominates of marbles, meta-psammities and garnet mica-schists (Andresen, 1988).

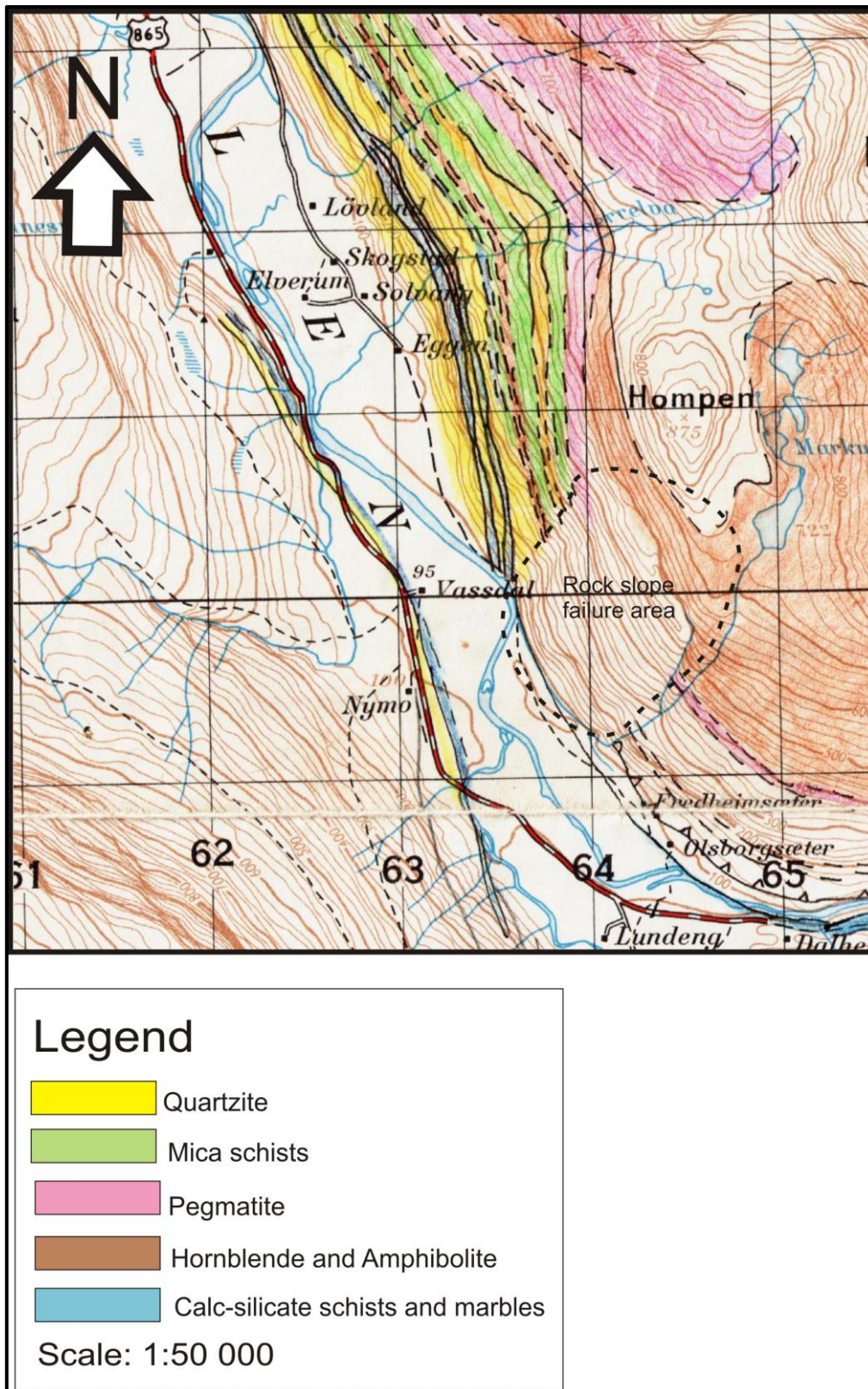


**Figure 3.1:** Bedrock maps A) shows the main rock slope failure consisting of nr: 28 meta greywacke, nr: 22 hornblende schist. The map B) shows that the lower part of the area consists of mica gneiss, mica schist, meta sandstone and amphibolite and the upper part is greenstone and amphibolite (ngu.no, 2012; Zwaan, 1988).

According to map description of the Hompen area (Fig. 3.2) by Binns (1978), the lower-most units of Hompen marked quartzite (Fig. 3.2), represent quartz-feldspathic rocks or meta-greywackes alternating with mica-schist's with various contents of biotite and muscovite. Calc-silicate schist's and marbles are also locally present in these rocks. The mica schist's contain significant quantities of hornblende and epidote. Foliation-parallel units of amphibolite, can be seen as 80-150 m thick zones of dark hornblende schist's, often finely inter-banded with epidote-rich layers, and these lithologies often occur as mega-lenses and boudins (see Ch. 3.3.3). There is also a characteristic horizon of a medium to fine grained, brown and quartzitic biotite garnet schist with carbonate, giving rusty spots and a pitted appearance. Conglomerate found in the brown quartzitic schist contains quartzite clasts and quartzitic schist (Binns, 1978). All these units in combination belong to the upper-most part of the nappe (Fig. 3.1) (Binns, 1978).

The characteristic horizon of biotite garnet schist is not labeled on the map (Fig. 3.3), but the area above the hornblende schist conforms to the description (Binns, 1978). As seen in map (Fig. 3.2) the RSF area were not mapped.





**Figure 3.2:** Bedrock map of the area surrounding the RSF area (marked on map). The map shows that the area north of the RSF has a repetition of lithologies of mostly quartzite and mica schist. (Modified map by Binns, (1977) and description from Binns, (1978)).

### **3.3.2 Lithological variations in the study area**

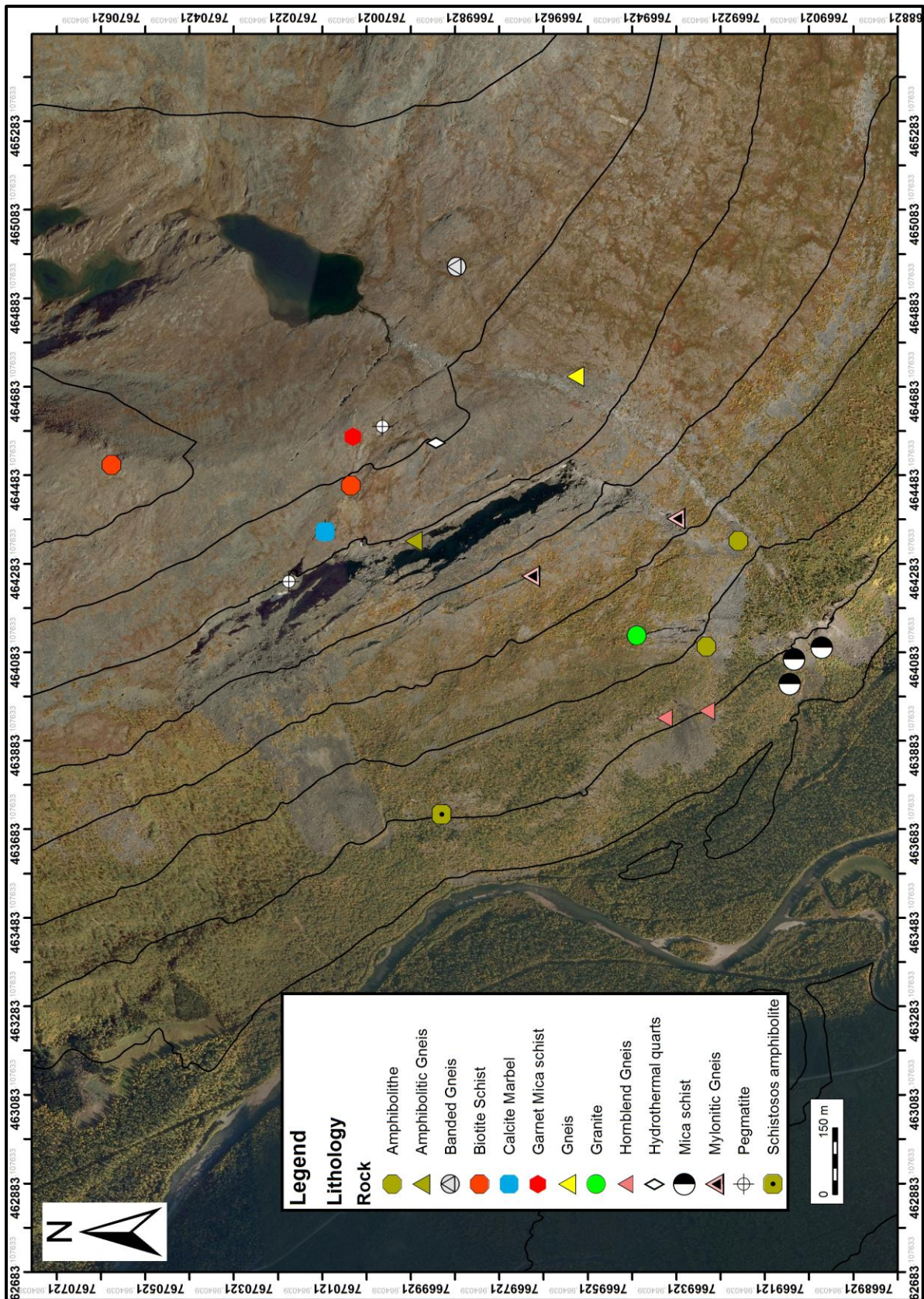
During field work, many different lithologies were observed in the RSF area. A small and sporadic sampling of representative bedrock types were taken from intact bedrock the rocks were classified and named accordingly. The samples were taken from areas which represent a stratigraphy for the RSF area, from lowest down and up to the summit of Hompen.

The result of the bed rock sampling in the RSF area is shown in (Fig. 3.3). The base of the unstable mountain slope consists of unit of mica schist, with sub horizontal foliation (Fig. 3.3, Fig. 3.4a) with fine debris between the layers (mica or clay minerals). This is overlain by a unit of hornblende schist's (Fig. 3.3, Fig. 3.4c). The hornblende schist contains bodies of amphibolite's and areas of granite pegmatite (Fig. 3.3, Fig. 3.4b). In the northern part of the RSF area, the amphibolite's has a well-developed schistose foliation (Fig. 3.3, Fig. 3.10). In the amphibolitic host rock, small lenses of pre-tectonic unspecified minerals are preserved from earlier metamorphic events. In the more central areas of the RSF and in the southern lateral scarp, zones of mylonitic gneisses alternate with banded gneisses in parts (Fig. 3.3, Fig. 3.9).

The back scarp of the RSF consists of a mixture of amphibolite gneisses with pegmatite dikes/veins. Above the back scarp we find calcite marble, biotite schist's, garnet mica schist's and several hydrothermal veins of quartz (Fig. 3.3).

The field mapping indicates that the more detailed and alternating stratigraphy map made by Binns (1978) (Fig. 3.2) match best with what is observed in the area, even if the upper part in the RSF does have more amphibolite's than mica schist's (Fig. 3.2, Fig. 3.3).





**Figure 3.3:** Lithological overview showing the distribution of identified rock samples in the RSF area made in Arc GIS. As seen in the description there are lithological variations all over the RSF.





**Figure 3.4:** Illustration showing a) sub horizontal layers of mica schist's in the lowest part of the RSF area; b) the granite rock in the crevasse area above the toe zone scarps; c) the toe zone scarp consists of hornblende which is located on top of mica schist's.

A distinct lithological contact is located high up on a scarp in the northern part of the RSF area, this is an area which show on slipped rock material (Fig. 3.5, see Ch. 4.4.3.1). The hornblend schists display a fractured appearance compared to the massive amphibolite below (Fig. 3.5).





**Figure 3.5:** The photo shows a lithological contact between the more competent amphibolite and the fractured hornblende schist. Notice that the bedrock in the upper part of the scarp displays a more fractured appearance than the lower amphibolites. Photo is taken looking up from the talus area in the north of the RSF area.

From the sampling of bed rocks from the base to the top of the RSF area, it can be concluded that different lithology's exist. The lithology's may follow each other in a stratigraphic context and represent the local and alternating metamorphic bed rocks beneath, but they may also be stretched or even absent in this area (Binns, 1978).

### 3.4 Ductile Structures

The literature describes observed ductile structures as isoclinal folds, open folds, boudins, and elongated lenses, planar and irregular foliation (Fig. 3.6, 3.8) (Binns, 1978; Zwaan, 1988).

The bedrock in the RSF area are defined to be part of the Upper part of the Vaddas nappe, this nappe does not show a right way up stratigraphy in this area as described by Lindahl et al., (2005). The situation is strongly effected of deformation in the area (see Ch. 3.3.1).

The area has a complex history with several orogeny stages, including an early period of isoclinal folding, with thrusting (Binns, 1978; Lindahl et al., 2005; B. Zwaan personal communication, 2012).

#### 3.4.1 Folds

Major folds and thrusts are well displayed on a map of the Signaldalen area (Fig. 3.6: Binns 1967). The folds are fairly open, more or less symmetrical and with a dominant NW-SE trend. They define a system of larger-scale antiforms and smaller-scale synforms (Fig. 3.6). Open

upright cross-folds with trend NE-SW occur locally (Binns, 1967), whereas major fold trends in the nearby areas also include WNW-ESE, NW-SE and WSW-ENE directions (Zwaan 1988), likely due to complex tectonic interactions during the emplacement of the nappes (Lindahl et al., 2005; B. Zwaan personal communication, 2012). During field mapping open folds were observed in domain II of the RSF area. Above the major scarp that bounds the RSF area (i.e. back scarp) another open fold system exists, trending NW-SE and with axial surfaces dipping 20° NW. Similar folds were also observed in the bedrock south of the southern scarp with fold axes striking N-S.

Based on the outline and geometry of folds in the Signaldalen area, a block diagram was made that shows the complex folding in the Hompen and surrounding area (Fig. 3.7) (Corner, 1969, based on data from Binns, 1967).

The orientation of the dominant foliation in (domain II), of the study area is NNE-SSW striking and with a gentle dip to the NW (see Ch.4 for more details). The lithology's in the area varies and may be effected of the regional folding in the area, part of the RSF area may be located on the western limb of major open anti-form (see Ch. 5.2)(Binns, 1967).

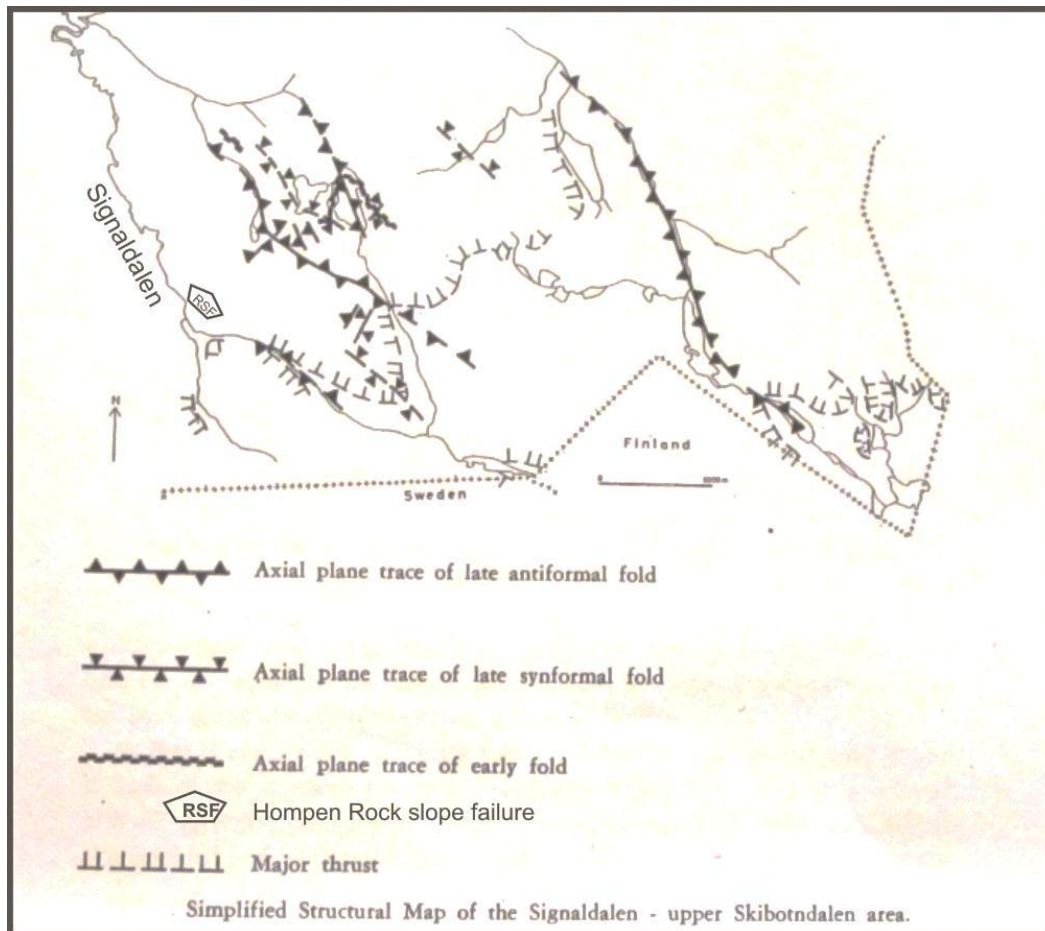


Figure 3.6: Structure map, several NW-SE trending fold systems. Hompen RSF are labeled (Modified from Binns, 1967)

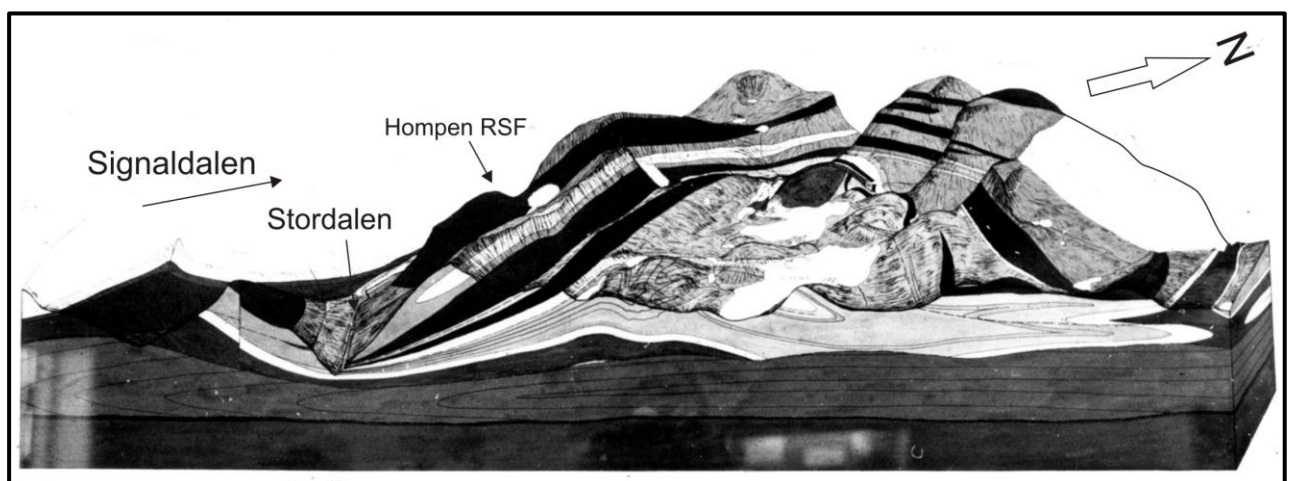


Figure 3.7: A block diagram showing on the complex and varied bedrock in the area; notice the tight isoclinal folding. The investigated area is located behind the mountain, view arrow (Modified from Corner, 1969).

### 3.4.2 Gneiss foliation

Most of the bed rocks in the RSF area comprise a well-developed ductile fabric, or foliation. This foliation has various expressions in the different lithologies. For example, in the quartz-feldspatic meta-greywackes and in the amphibolites the foliation is a planar metamorphic gneiss foliation made up of colorful banding of alternating lithologies and metamorphic minerals (Fossen, 2010).

Other gneisses show migmatite foliation which is highly irregular and undulating, a mixed rock (Fig. 3.8), migmatites are formed due to partial melting the new material crystallize to a leucosome and another part of the old material a mesosome which may have resisted the melting. These together form the new fabric, which gives a foliation to the rock. It is often seen that the new material is folded; local partial melting is one of the characteristics (Blatt et al., 2006).

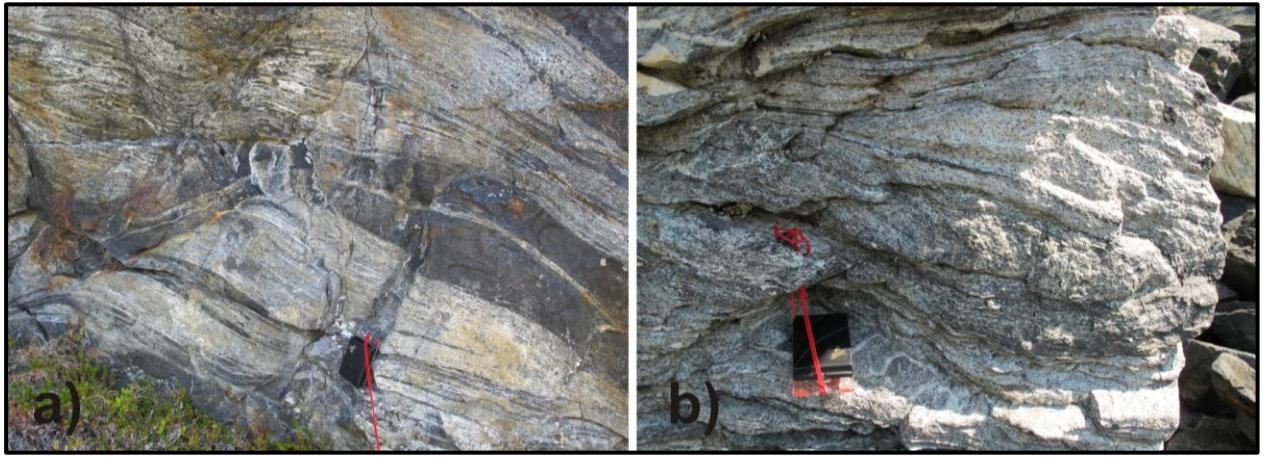
That the gneiss or schist have a mylonitic foliation (Fig. 3.9) mean that the rock is deformed, and consist of planar aggregates and fine-recrystallized minerals. Mylonitic foliation is commonly localized in bands or zones, in areas which have experienced tectonic stress as high strain e.g. shear zones (Fossen, 2010).

Mica schist's can be displayed in an infinite of variations, schist means split and gives the character for the rock. Schist's are formed by both high temperature and high pressure. The mica grains are aligned as well as hornblende and other flat or elongated minerals; this is what makes up the foliation. The percentage of aligned minerals decides if it will be called a schist or gneiss. If the texture has a very large amount of micaceous minerals, the rock will get a flaky texturing with easy cleavable layers the rock will be presented as having a schistose foliation (Fig. 3.10) (Fossen, 2010).





**Figure 3.8:** The photo illustrates a typical gneiss texture, with mylonitic and migmatic texture from the Hompen area.



**Figure 3.9:** a) and b) mylonitic outcrops. Both photos are from the middle part of the RSF area.

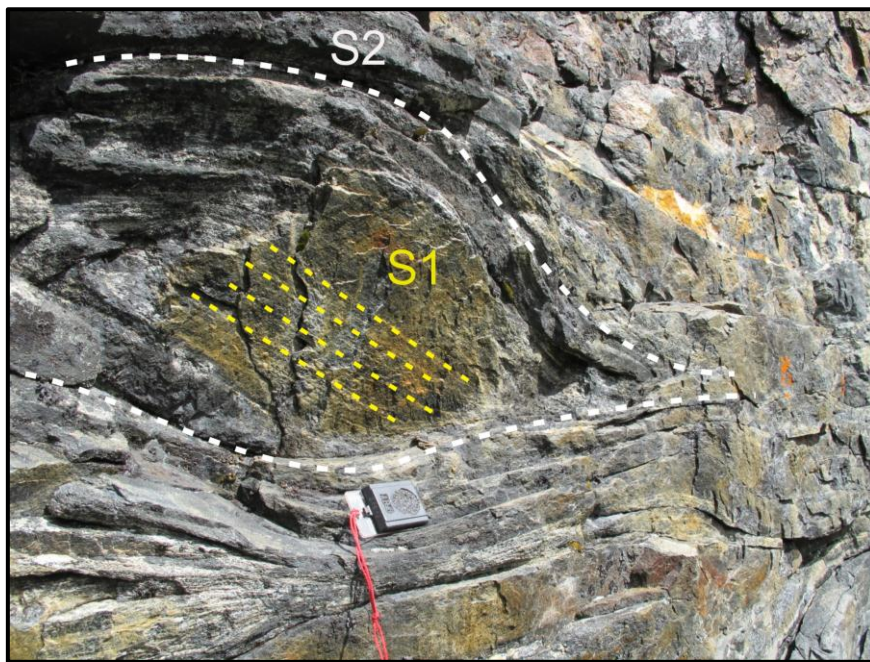




**Figure 3.10:** Amphibolite showing a high schistose foliation a flaky texture, the host rock has preserved older small lenses of an unspecified lithology this location is labeled (Fig. 3.3).

The foliation gets coarser when the rock has been metamorphosed in high temperatures.

When studying a gneissic rock, we can often see more than one foliation; this is referred to as composite foliation. Lenses formed tectonically with an internal foliation (S1), are bent into a younger Caledonian foliation (S2) in the main bedrock (Fig. 3.11) (Fossen, 2010).



**Figure 3.11:** Photo showing foliation in several generations-composite foliations, a preserved older foliation (S1) in the lenses which are not deformed by the younger Caledonian foliation (S2).

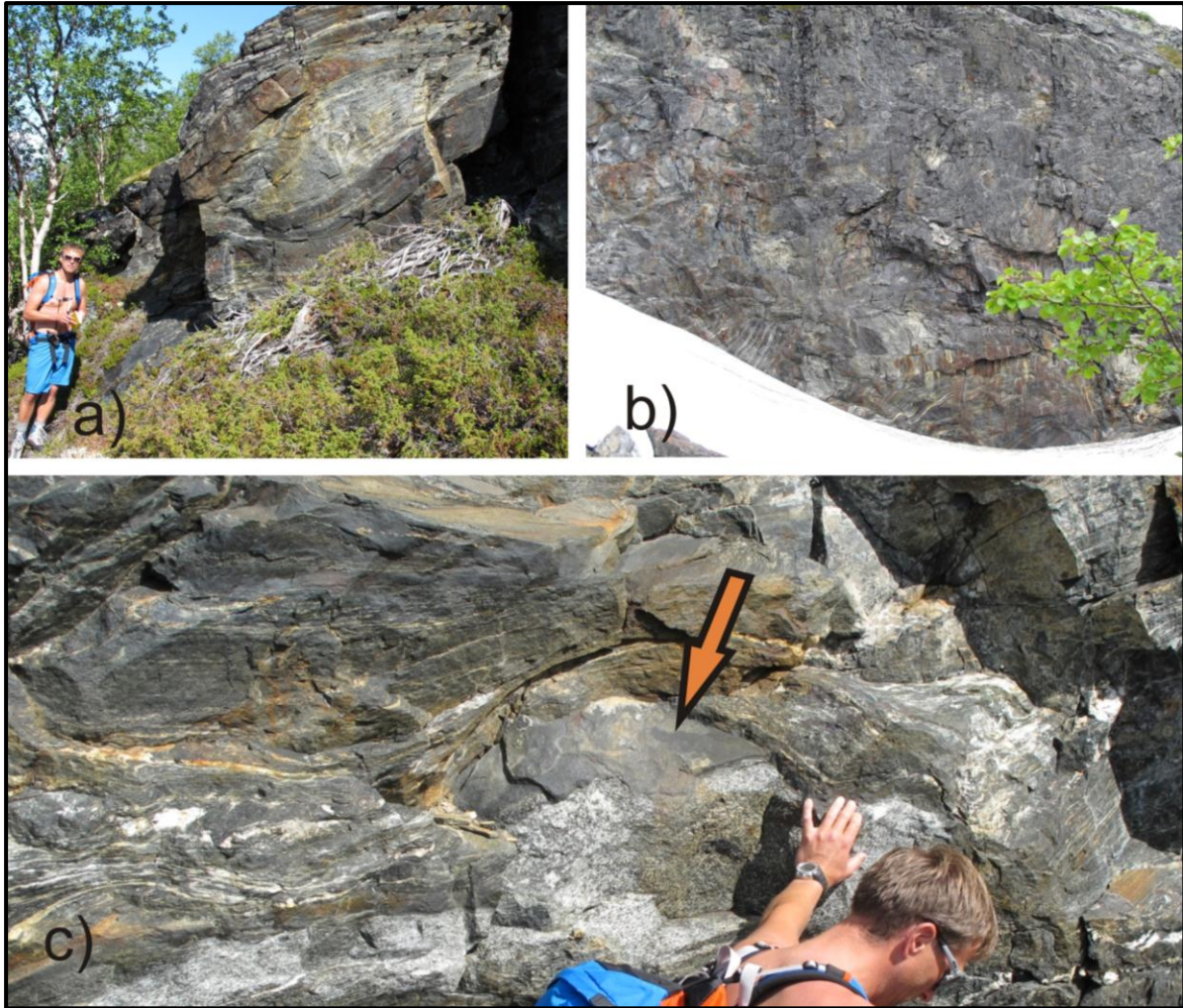
### **3.4.3 Heterogeneous ductile fabrics (boudins and lenses)**

The bed rocks in the RSF area comprise various foliations in different lithologies e.g. in the isotropic or massive amphibolites may have a structure less appearance. Several areas in domain I in the RSF show boudins and lenses, a different lithology between host rock and boudin/lenses are common in the more gneissic rock (Fig. 3.12a). Lenses of a more competent material show older preserved foliation while the new Caledonian foliation is formed around the lenses (Fig.3.11).

Boudins are commonly formed in extensional settings, formed by stretching of competent layers or foliations, they can be seen as separated structures or without separation then they are called pinch-and-swell structures. There is a enormous varieties of boudin structures depending on what type of extension the area have experienced and what type of deformation mechanisms (brittle versus ductile) they been developed under. Boudins can also be formed as a result of strongly deformed foliated rock as foliation boudinage, these may be separated by fractures or shear bands (Fossen, 2010) (Fig. 3.12c).

During an orogeny event, the area experienced high ductile strain during several periods. This can be preserved, but also masked by flattening and extensional strain. Periods of ductile strain might explain why we see so many lensoid, mega-boudin structures (Fig. 3.11, Fig. 3.12), this might also explain why some nappe units are so washed out or do not even exist (Roberts & Sturt, 1980).





**Figure 3.12:** a,b) Lensoide structures in the bedrock, b) lenses of different lithology the surrounding rock can work as a sliding surface, as seen here.

The lenses may be of different lithology than the host rock or that there is a small shear planes which may work as a weaker zone. Fractures in connection with the weaker zone can get reactivated; the lenses might work as small sliding planes (Fig. 3.12c). Different lithologies may be differently exposed for fracturing (Saintot et al., 2011).

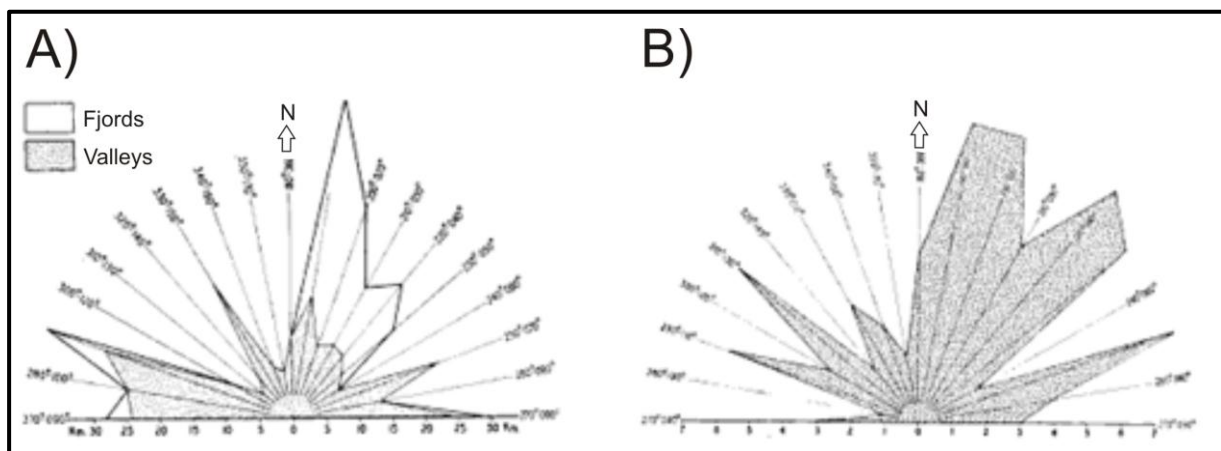
### 3.5 Brittle structures

#### 3.5.1 Regional fracture pattern

The ductile structures in the RSF area are truncated by brittle structures such as joints and fractures. These fractures may have its origin (see Ch. 5.5.3) from the complex tectonic history for the area (see Ch. 1.5.1)(Roberts & Sturt, 1980; Andresen et al., 1985; Zwaan, 1988; Binns 1967, 1969, 1978).

Through fracture analysis in the RSF area and surrounding areas, it is shown (see Fig. 4.12, Fig. 4.15, Fig. 4.16) in combination with aerial photographs and existing lineament maps (see Fig. 4.1, Fig. 4.2), that the main fracture trend is WNW-ESE and NW-SE, subordinate NE-SW trending linear features also exist. The NE-SW trend is mostly observed in the coastal areas of Troms (see Ch. 4.2 and Fig. 4.2). The lineament pattern seen in the RSF area largely corresponds with regional trends of fractures and fault systems in western Troms (Fig. 1.4, Fig. 5.19) (Gabrielsen et al., 2002; Hansen et al., 2011; ngu.no 2011). In addition, lineaments trending NNE-SSW do occur, corresponding with the trend of Storfjorden which is parallel to the Lyngen peninsula (Fig. 1.4).

A study by Randall (1959) showing the direction of the valley's/fjords and fractures in the Lyngen area (Fig. 3.13). Vector and strike frequency diagrams (Fig. 3.13) show a clear connection between the main directions seen in the topography (Fig. 4.2), with valleys and fractures striking NE-SW (Fig. 3.13). This similarity of main fjord-valley trends in the Lyngen area (Fig. 3.13: Randall 1961) with regional fracture maps may support that the fjord-valley may be structurally controlled (Fig. 5.19). (Randall, 1961)



**Figure 3.13:** A) Vector diagram of valleys and fjords. B) Strike frequency diagram of fractures, both in south Lyngen (Modified Randall, 1961).



## **4. Description of the Rock Slope Failure Area**

### **4.1 Introduction**

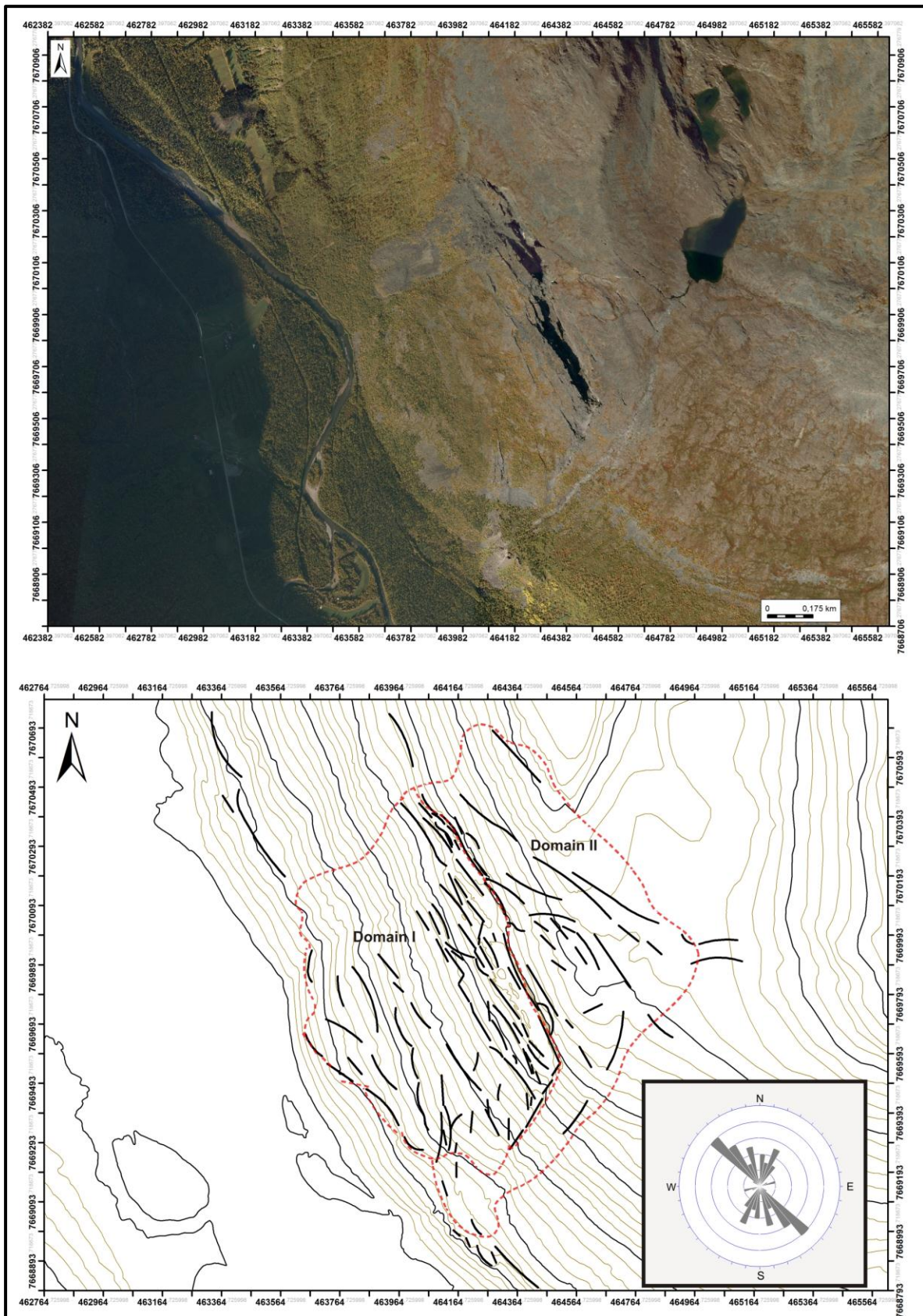
In this chapter, the studied rock slope failure area (RSF) will be described in successive order from the macro scale, using satellite data and DEM terrain images, to the mesoscale, applying photographs and direct field observations. The description of the studied rock slope failure area will focus on various aspects of the internal structure, e.g. bed rock fabrics as foliation and fractures, their geometry and orientation and possible relationship to geomorphological elements (see Table 1) in the RSF area. Fractures in the intact bed rock (footwall), relative to the slide area (hanging wall) will also be described and compared with the internal structures (see discussion).

At the end of the chapter, possible hydrological features that may be of importance for the migration of water and freeze thaw processes in the fracture systems, will be described and used for later discussion (Chapter 5). There will also be descriptions of the dGPS and In-SAR data that are available for the area.

### **4.2 Lineaments inside and outside the rock slope failure area**

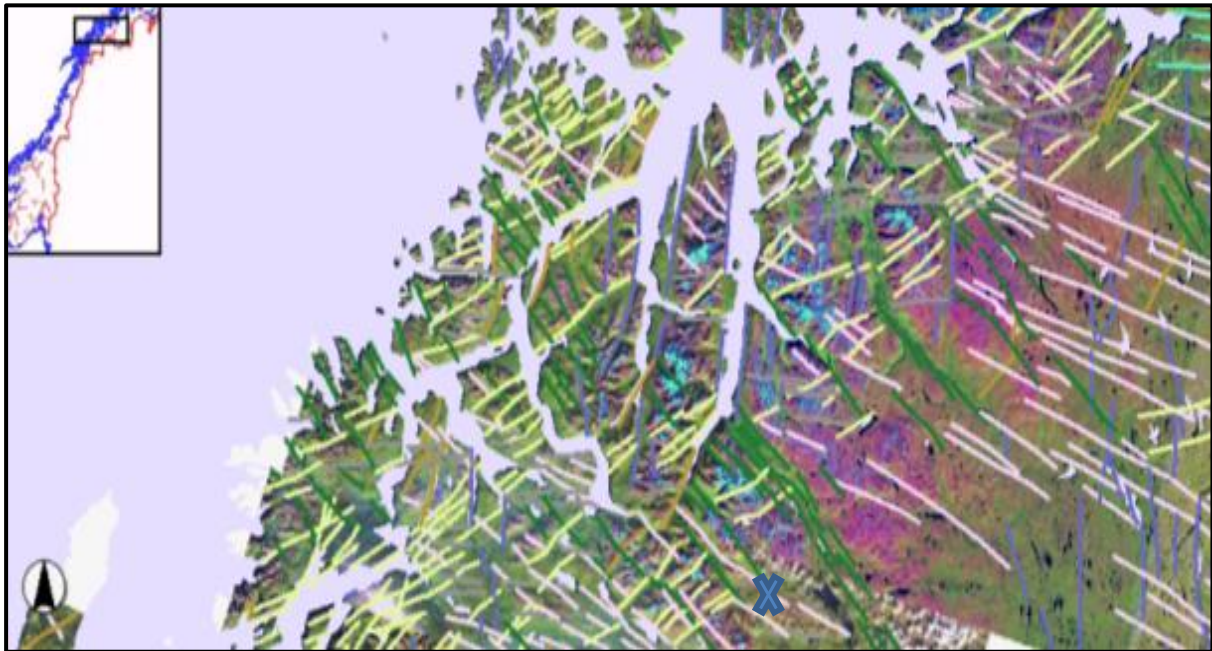
The aerial image of Hompen shows a dominant lineament pattern in the bed rocks, striking NW-SE, but additional and subordinate NE-SW, N-S and WNW -ESE striking linear features also exist (Fig. 4.1). These lineaments consist likely of both structural and geomorphological features, including e.g. the dominant gneiss foliation and secondary, brittle fractures. It can be hard to locate all lineaments seen in the aerial photo in the field; however the most important ones can be easily recorded and classified (see Chapter 4.4).

The above patterns seem to correspond with regional trends of fractures and fault systems in Troms (Fig. 4.2; Gabrielsen et al., 2002). NW-SE striking lineaments exist on the east side of the Lyngen peninsula, WNW-ESE directions are common inland, while NE-SW lineaments are mostly seen in coastal areas of Troms (Fig. 4.2). In addition the NNE-SSW striking lineaments occur on both sides of the Lyngen peninsula (Fig. 4.2) (Gabrielsen et al., 2002; Hansen et al., 2011; ngu.no, 2011).



**Figure 4.1:** Orthophoto over the RSF area; Topographic map illustrating observed lineaments in the RSF area (Domain I and Domain II), rose diagram showing dominant NW-SE striking lineaments. Several of the lineaments are easy to see in the field but others are hard to identify. The lineaments in the upper part of domain I are parallel with the back scarp striking NW-SE, lower down the lineaments are striking N-S oblique to the back scarp and NE-SW.





**Figure 4.2:** Lineament map that illustrates the dominant trends in western and central Troms, a dominant WNW-ESE and subordinate NW-SE and NE-SW trends. Note also a NNE-SSW trend parallel to the Lyngen peninsula in central part of the map. The RSF area is marked on the map with a X. (Modified from: Gabrielsen et al., 2002; Hansen et al., 2010; ngu.no 2011).

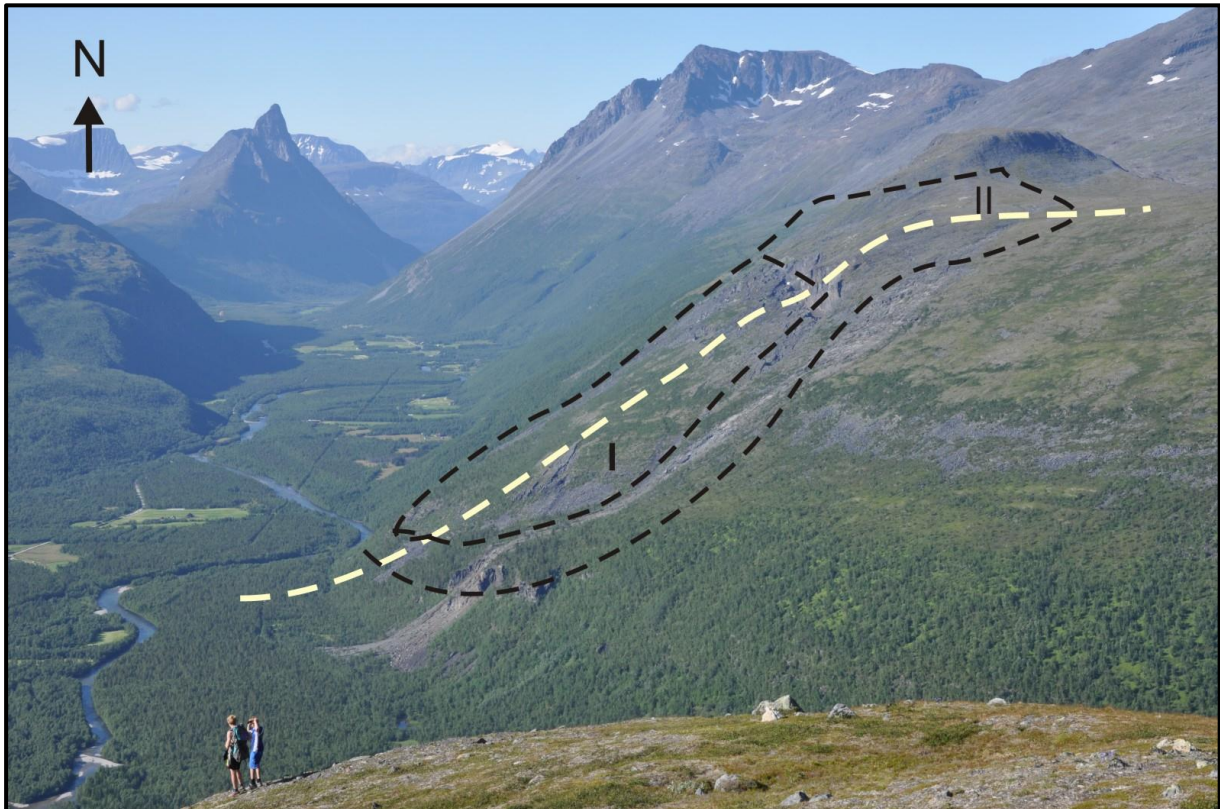
The NNE-SSW striking lineament on the east and west side of the Lyngen peninsula (Fig. 4.2) has recently been proposed to be a regional Mesozoic-Cenozoic fault that bounds a major horst system (Osmundsen et al., 2009) and may be traced southwards to link up with similar faults in Lofoten and Vesterålen (Bergh et al., 2007). The lineaments striking NW-SE and WNW-ESE also has a regional extent and can be traced up with the major glacial valleys and ridges in inner Troms, e.g. the Signaldalen valley, Kåfjord valley and Skibon (Fig. 4.2).

### **4.3 Morphological overview of the rock slope failure area**

The RSF area is divided into two different domains (Fig. 4.3, Fig. 4.4) domain I and domain II, the division is based on the presence of different rock slope failure structures such as counter scarps, trenches and are described separately from the two domains. Domain I has also been divided into smaller subareas (cf. Fig. 4.10), depending on the topography and structures seen in the different subareas.

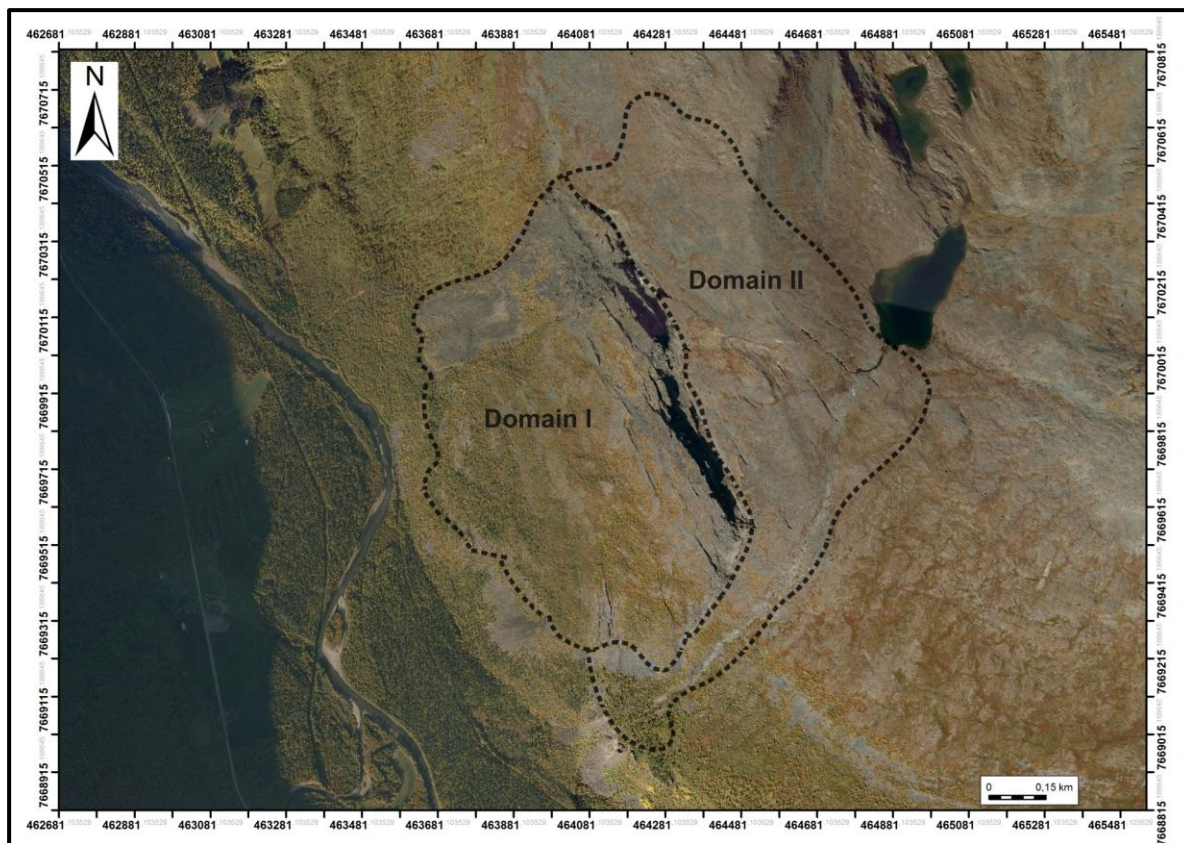
A dominant steep escarpment striking NW-SE is called the back scarp; and a deep trench defined as a central graben is located in connection to this. An *en-echelon* stepping scarp system striking SW-NE, comprising several pre-rock failure features and talus areas, together

with the back scarp frame the Domain I of the RSF area and separates it from Domain II behind the back-scarp. The area to the east and south, mostly above in the slope profile (Fig.4.3) show some potential instabilities in the rock mass as several sets of open fractures exist there, otherwise, it is dominantly a more or less stable area similar to that of Domain II (Fig.4.4). The plateau above is surrounded by higher peaks (1550 m.a.s.l) and a cross-valley that covers a small lake system that drains down section into the RSF area (Fig. 4.6). The total estimated square area of the RSF is between c. 0.63-1.5 km<sup>2</sup>.



**Figure 4.3:** Overview photo of the RSF area showing the typical glacial U-shaped valley topography (Signalaldalen valley) and the steep slope of the east side of the valley, where the studied area is located. The Domain I and II are labeled. The photo is modified from Blikra (2011), and the view is toward north.



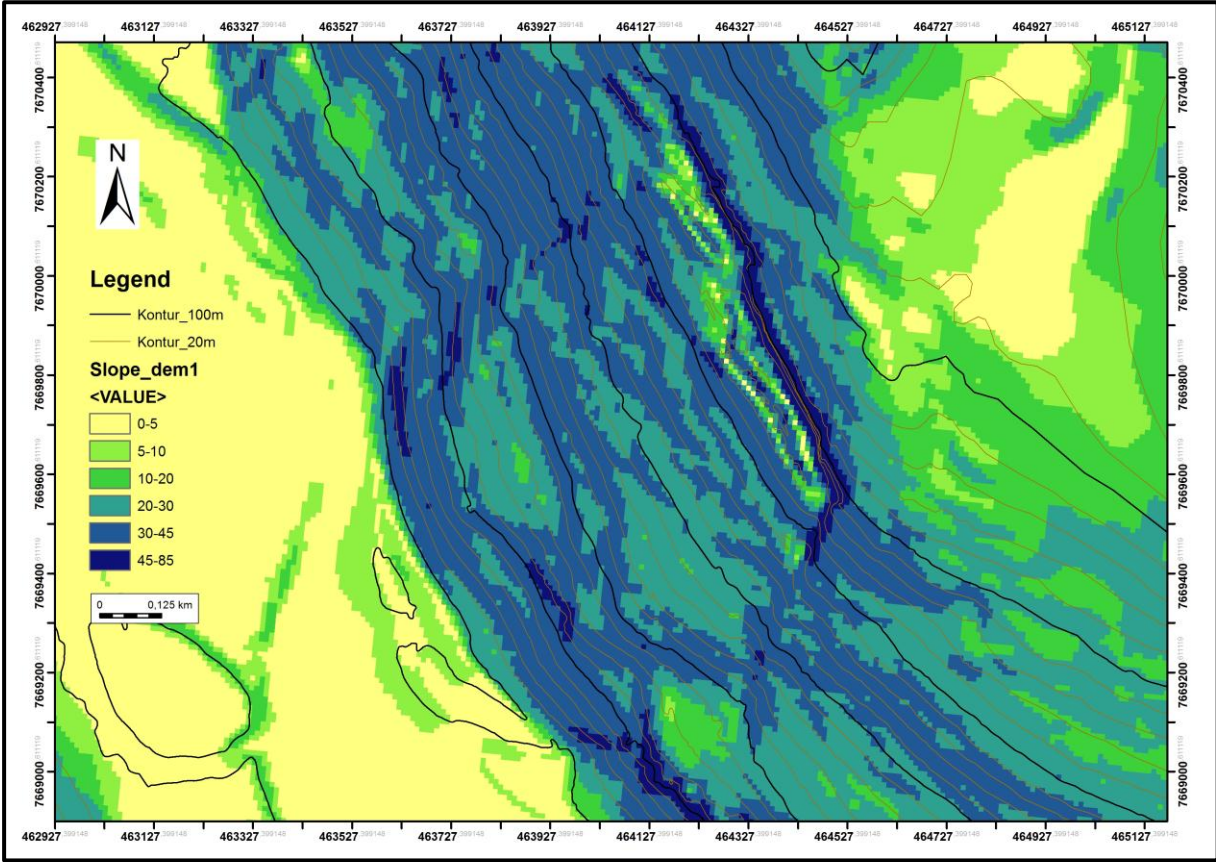


**Figure 4.4.** Orthophoto displaying an overview of the RSF area, the subdivision into Domain I and II are labeled. Note that Domain I is the main rock slope failure area.

The RSF area is located on a west face of the Signaldalen U-valley, which is oriented NW-SE (Fig. 4.1). The location of the studied RSF area is just NNW of the relatively sharp V-valley Stordalen (Fig. 4.3; coming in from right on photo), with orientation SE-NW connects with Signaldalen valley (Fig. 4.3). The RSF area has a clear steep escarpment, the back scarp (540 m.a.s.l), which separates Domain II from Domain I by a big trench. The southern margin is a steep and planar scarp with *en-echelon* right-stepping character, which is SW-NE trending and named, informally as the southern scarp, forming a border to the south (Fig. 4.6). On the northern side, the RSF area is bound by a big talus field (Fig. 4.6). The failure area is located just on the shoulder of the hillside.

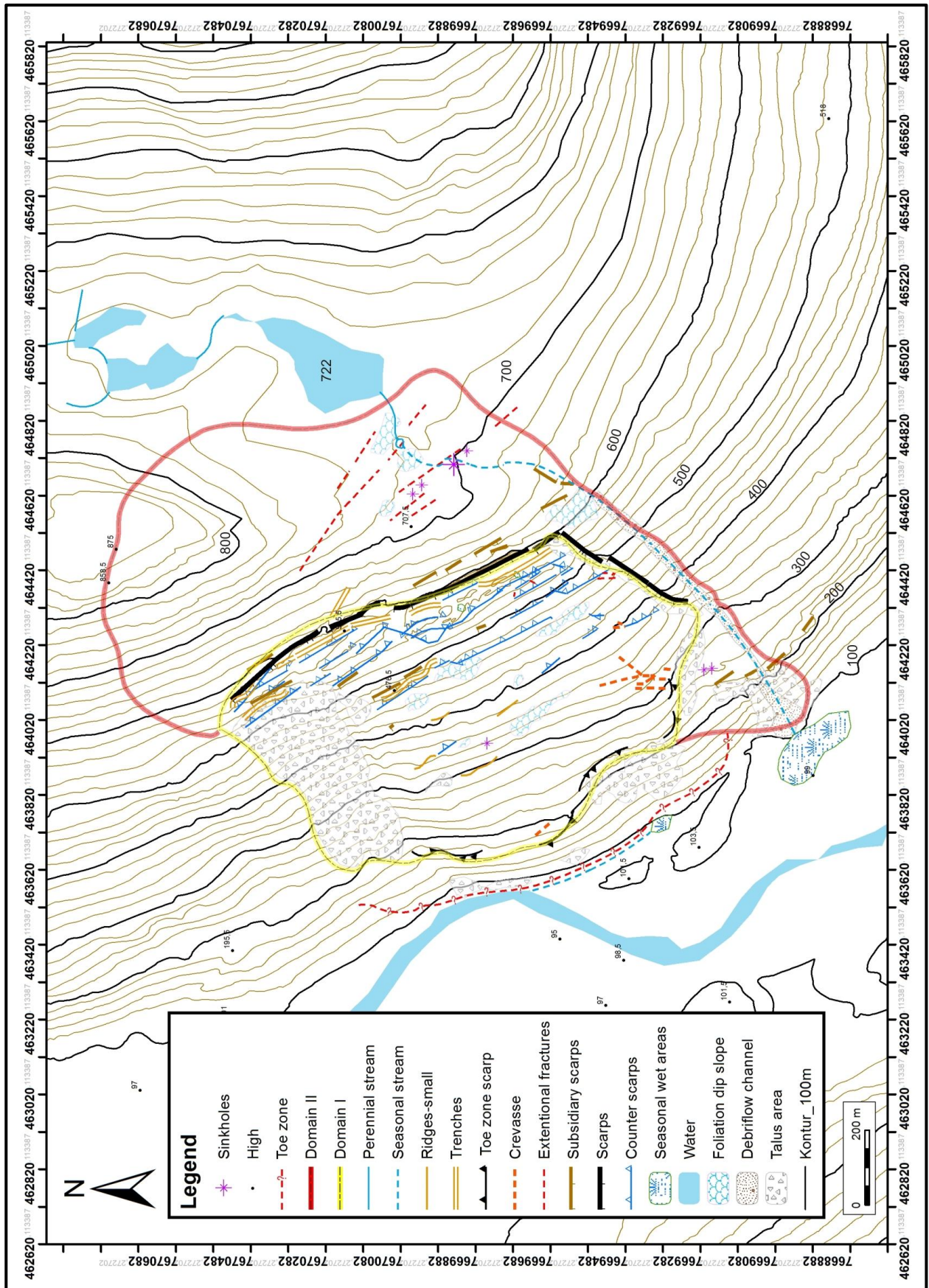
The lowest part of the RSF area consists of talus material both vegetated and without vegetation here the slope angle is between 30-55° (Fig. 4.5). Above this lower part and in the middle part of Domain I, a bigger bench/terrace area occurs where the bedrock is quite undisturbed and polished by glacial erosion (Fig. 4.5, Fig. 4.6). The terrace consists of a number of geomorphological smaller ridges, trenches and terraces (Fig. 4.6). The slope angle in this middle area is moderate (<30 degrees), (Fig. 4.5) but in the upper part of Domain I, the slope angle gets steeper (>35 degrees). This upper part of Domain I are the place where most

of the rock failure structures are located (Fig. 4.6). In all the levels of the slope profile there are several talus fields and talus slopes. Above the back scarp the slope profile is still quite steep (>30 degrees), but when passing the mountain shoulder it flattens out and gets almost horizontal (Fig. 4.5). On this horizontal plateau several deep and open fractures are exposed (Fig. 4.6, 4.39). In the following subchapters (i.e. Chapters 4.4-4.6), structural and geomorphological features of the entire RSF area, including Domain I and Domain II, will be described in detail and form the basis for the discussion in Chapter 5.



**Figure 4.5:** Slope map of the RSF area at Hompen. The mean inclination is around 35°. The Back scarp is displayed with the dark purple color, in the middle of the map striking NW-SE. Map is made in Arc GIS.





**Figure 4.6:** Morpho-structure map of the RSF area; the map is made in Arc GIS. Note the abundance of structures in the upper part of the RSF area and the parallel fractures draining the small ponds above the back scarp.

## 4.4 Structural and morpho-tectonic elements

Morpho-tectonic elements are those which on first impression look like morphological elements, but may have a link to a kind of a tectonic event, therefore the expression morpho-tectonic (Table.1). These are elements with an overlap between structural geology and geomorphology (Agliardi et al., 2001). The studied RSF area shows many clear examples of morpho-tectonic/pre-rock failure structures, for example foliation-controlled escarpments, brittle fractures that appear to link up with regional fractures, fracture-controlled escarpments, counterscarps, anti-scarps, ridges, trenches, clefts and graben structures (see Ch. 4.4-4.6). Some of these morpho-tectonic structures are shown on the map (Fig. 4.6).

Foliation-controlled elements are common in areas where the intact foliation of the gneisses has been preserved, and in the RSF some areas display a well-developed foliation, while other areas have a more undefined foliation. In most areas the foliation is irregular, folded and banded producing mega-lenses (of mafic rocks) and boudins in the bedrock. Ductile shear zones and thrusts bounding thrust sheets of variable compositions (mafic, quartzitic and gneissic units) are abundant (see Chapter 3) and characteristic of the pre-rock failure structures of the area.

The variation in orientation of the bedrock foliation between the more intact footwall and the hanging wall can give us an understanding of how much the bedrock has failed within the RSF area, how the failure may have occurred and about the processes operating during the failure.

### 4.4.1 Caledonian Foliation (ductile structures)

Foliation data have been collected from domain I of the RSF area, from bedrock which seems more or less intact, not loose blocks, though inside the slide area this can be hard to fully validate.

The Caledonian rocks above the RSF area in **Domain II**, mostly have preserved their pre-rock fabric, but the foliation varies somewhat in orientation. The bedrock has a well-developed foliation in many places, which is easy to measure and document. Other places, the same bedrock just a few meters away the foliation is undulating and is banded in other structures. The foliation in the back scarp is sub horizontal (Fig. 4.7), but undulating when viewed in cross-section due to open folding and the presence of boudinage structures (Fig. 4.8). This is common when the bedrock have different competence as with different lithology, mafic lenses and gneisses. Foliation data from the area above the back scarp in cross-sections inside



wide open fractures. Foliation here shows an average strike SW-NE with dip of about 20 degrees to the NW (Fig. 4.7). The area also shows foliation in strike NW-SE with average dip (20 degrees) to the SW (Fig. 4.7).

There is an open synform just above the back scarp which has limbs dipping SW and NW and with a gentle W-plunging axis (Fig. 4.7).

The variation in strike and dip of the rock failure structures in Domain II will be compared with those of Domain I and discussed further in chapter 5.

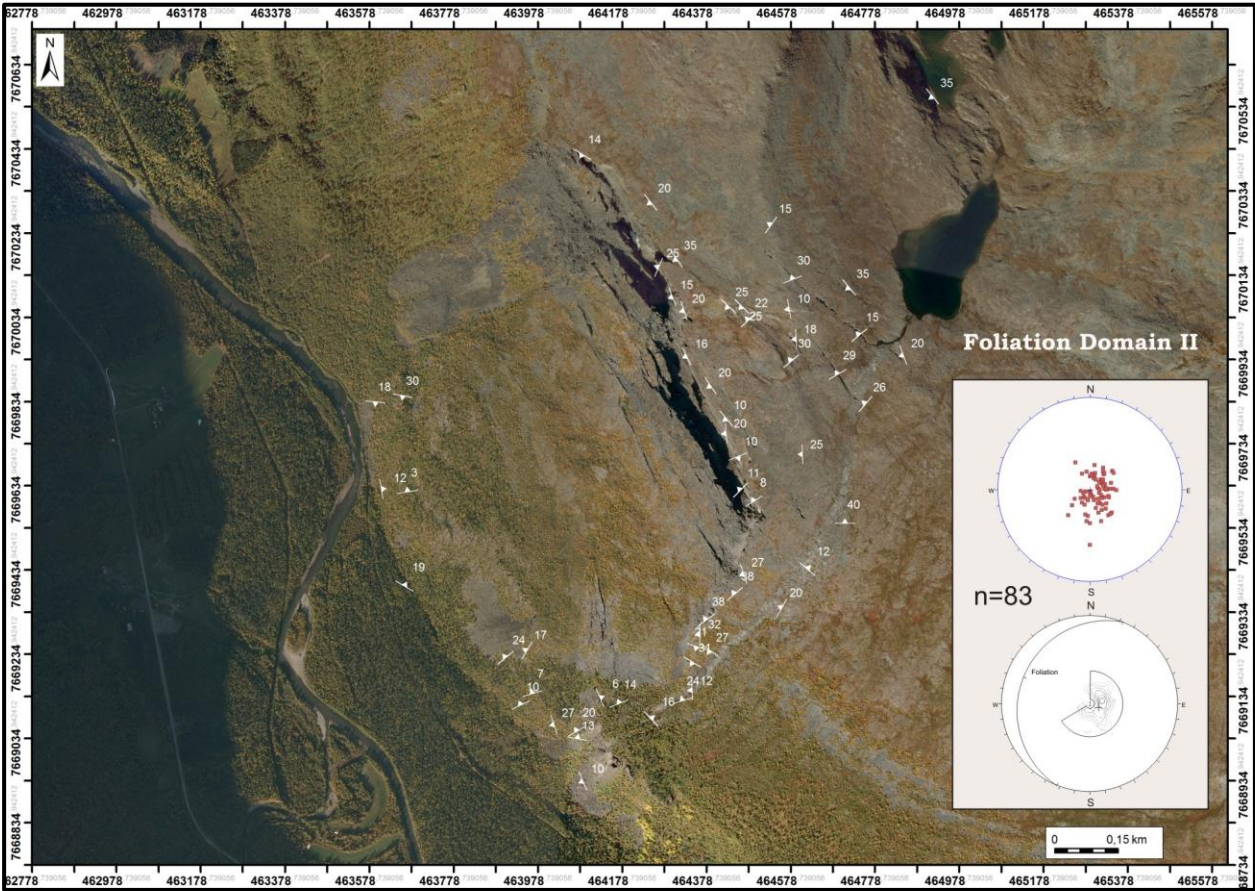
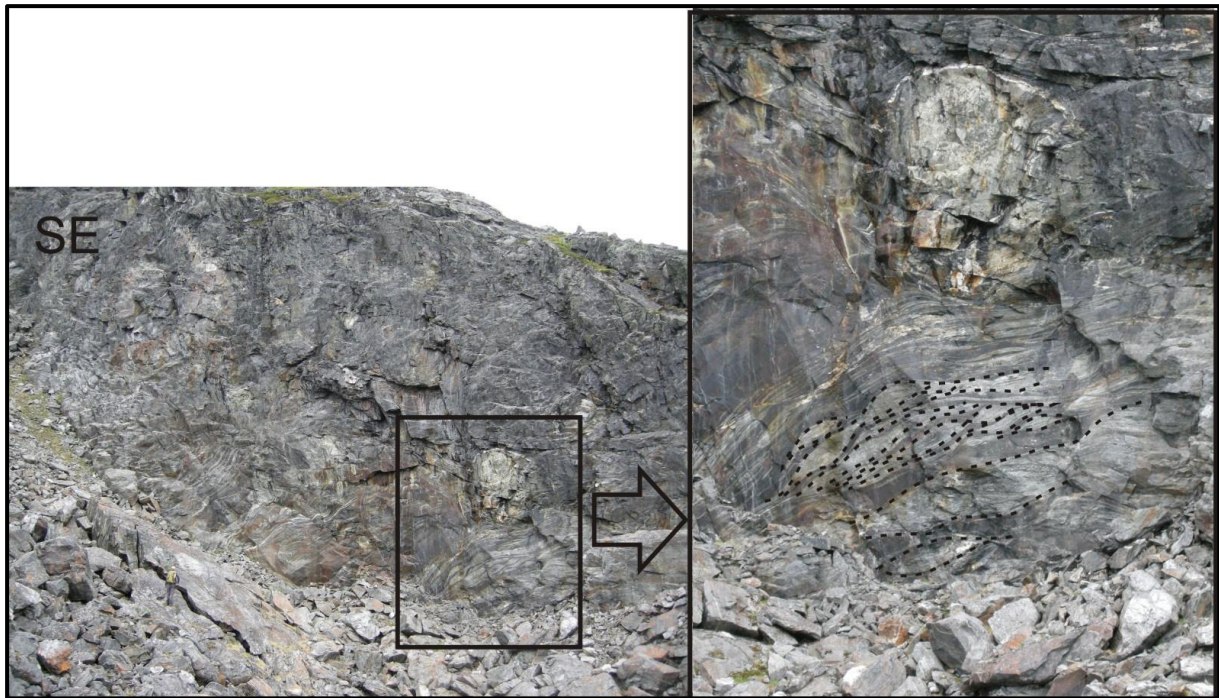


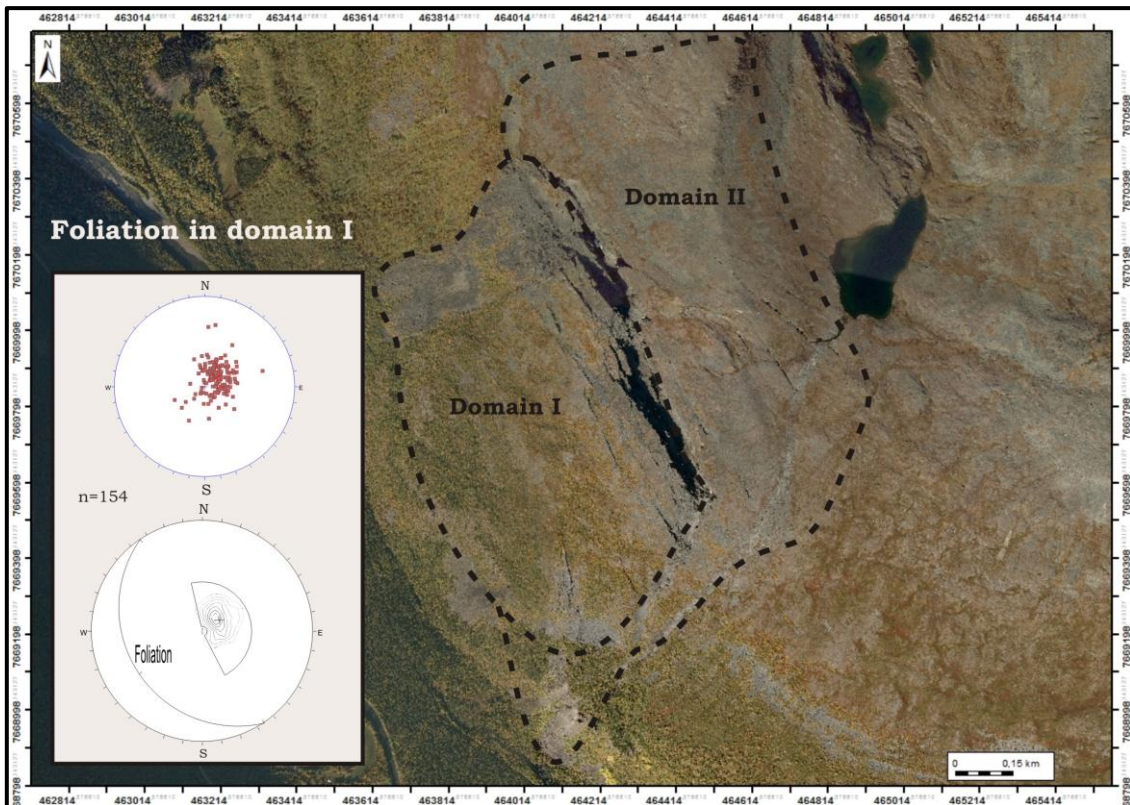
Figure 4.7: Ortho-photo of the RSF area showing attitudes of the main gneiss foliation in Domain II of the RSF area (there are also some measurements below the RSF in the view).



[Figure 4.8:](#) The southern scarp shows an undulating foliation, due to boudinage structures. For scale view the man on the left photo, left corner.

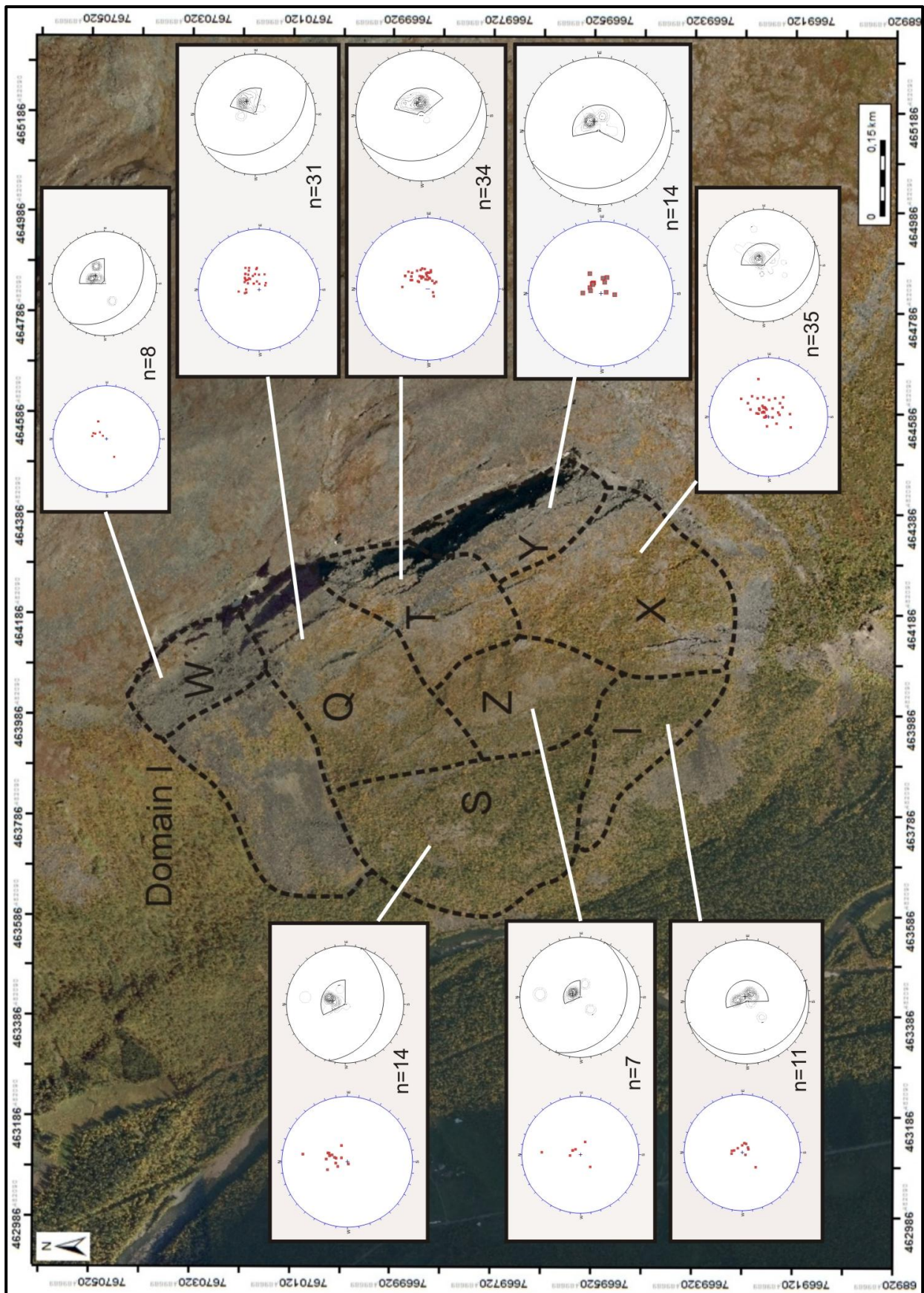
The foliation in **Domain I**, the RSF area, displays a more systematic orientation of the foliation. The mean strike is NW-SE with a gentle dip of about 20 degrees to the SW (Fig. 4.9). The foliation is however slightly undulating in areas due to open folding and the presence of boudinage structures (Fig. 4.8). This is particularly common when mafic rocks occur in between the quartz-felspathic gneisses. In the upper part of the rock slope failure area, the bedrock foliation is well preserved and partly overlaps in orientation with gently dipping geomorphological surfaces. Most scarps truncate the foliation with a high angle (Fig. 4.9).





**Figure 4.9:** This illustration shows the poles of the foliation and main trend in plane in Domain I; foliation strike NW-SE and dip of average 20 degrees to SW.

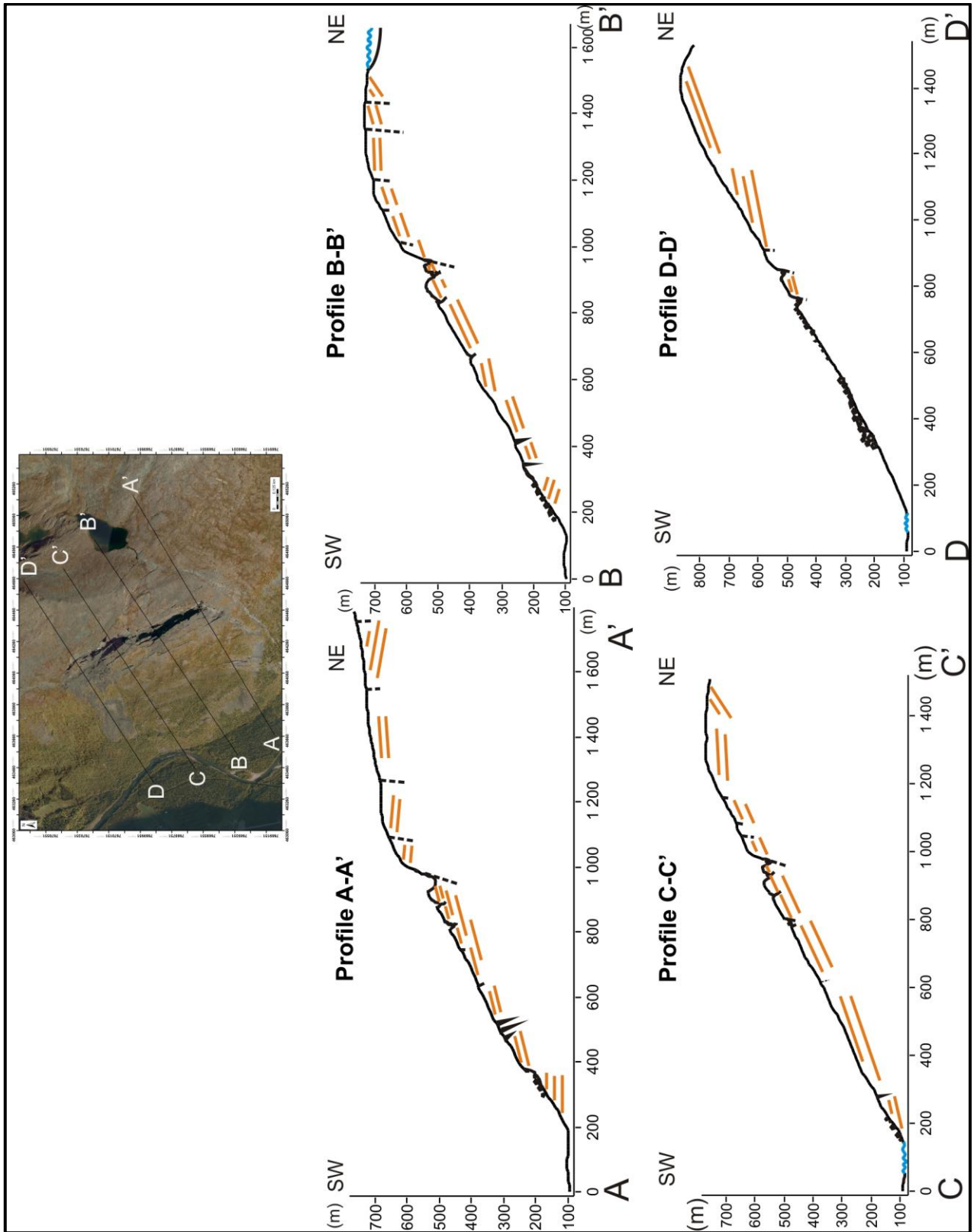
In the upper part of the RSF in domain I, starting in the north with area W, the foliation has NW-SE strike with a gentle dip to SW, while others show the opposite NE dip direction towards the back scarp. The NE dipping foliation, there is situated on a major collapsed counter scarp block in the area. In area Q the foliation strikes NW-SE with a gentle dip to SW. Further into area T, the strike of the foliation varies from NNW-SSE to WNW-ESE, with dip direction to the W and SW (Fig. 4.10). In the southern part of domain I in area Y, there is a dominant NW-SE striking foliation with a gentle dip to the SW, and subordinate NNE-SSW and WNW-ESE striking foliation (Fig. 4.10). Area X displays almost the same variation in attitude as area Y, although a more pronounced NW-SE strike of the foliation is visible, and the dip angle gets steeper (Fig. 4.10). In the middle part of domain I, area Z, the foliation shows a predominant WNW-ESE strike, but variations occur in between different blocks and scarps of the area (Fig. 4.10). In the area labeled S, defined as the lower part of domain I, a uniform WNW-ESE strike and gentle dip to the SW is apparent, while foliation in the area I shows a strike NW-SE with variable dip directions (Fig. 4.10).



**Figure 4.10:** Foliation data from the various subareas of Domain I plotted as poles and an analysis is made as contour plot in Dips (Rockscience, 2011).



Interestingly, the strike of the foliation in the entire RSF area to some extent seems to correspond with the orientation of scarps and topographic elements, as illustrated by four profiles across the RSF area (Fig. 4.11). These profiles show well both the strike and dip variations, i.e. as apparent dip in the different areas of Domain I and II. Major fractures and morpho-structures are drawn on the same profiles and will be described later in this chapter. As seen in the profiles the dip direction of the foliation in the lowest part of profiles A-A' and B-B' is to the NNE, i.e. toward the RSF area (Fig. 4.10, Fig. 4.11), whereas the average foliation in Domain I is NW-SE striking and dip to the SW (Fig. 4.9, Fig. 4.11). In Domain II which is the area above the back scarp in the profile, the strike shows some variations (Fig. 4.7, Fig. 4.11a), the foliation strikes almost E-W with dip to the N, this same orientation is seen in the uppermost parts of the profiles (Fig. 4.11b,c). The average orientation in Domain II however, is more constant, with strike NW-SE and dip to the SW (Fig. 4.7, Fig. 4.11b,c,d).

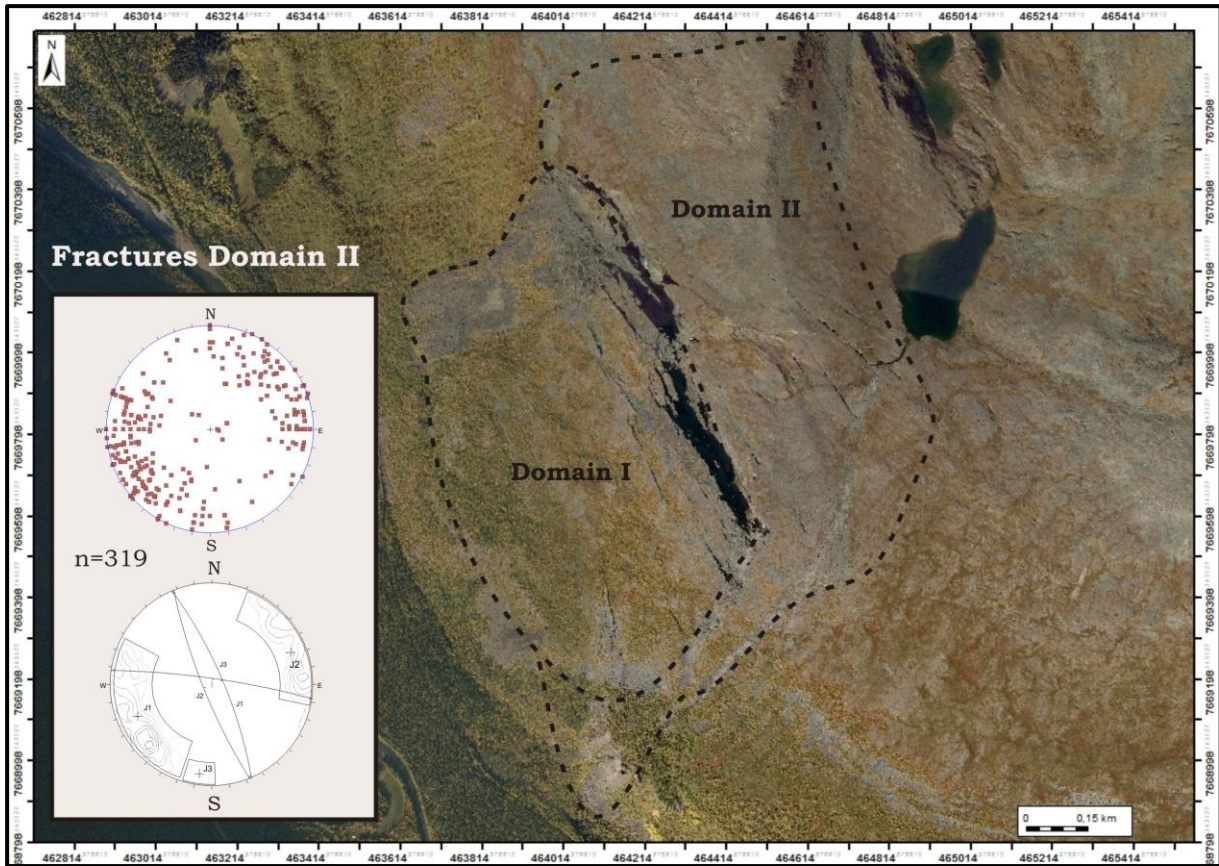


**Figure 4.11:** Profiles A-D, showing the small variation in foliation in the rock slope failure area. The measured foliation is here visualized as apparent dip in respect of the profiles direction.

#### 4.4.2 Brittle structures (fractures)

The terminology used for the description of brittle structures in the RSF area is obtained from Fossen (2010) and Twiss & Moores (2006). Brittle fractures include structures formed as a planar or sub planar discontinuity, either representing an extensional fracture, a shear fracture or a hybrid fracture (Davis & Reynolds 1996). With respect to fractures in the RSF area, they will be described as well based on the morphology of the fracture. Fractures which show no evidence of movement are termed **joints**; if the fracture has an infill, they are called **veins**. Open fractures with an extensional character of cm-1.5 m scale will be described as **fractures**. If the fracture displays one planar surface it will be classified as a single fracture, joint or fracture plane. When the fracture is wider than 1.5m (>1.5), and the geometry of the fracture is often V-shaped in cross-section view, or when it has an uneven character, it will be called a **crevasse** (Table 1). There will also be mentioned different fracture systems as e.g. en-echelon fractures, stepping fractures and fracture pattern (Eig & Bergh, 2011).

Pre-rock failure fractures seem to have played an important role in the genesis (see Chapter 5) and the resulting geomorphic character of the studied RSF area. An outline of the total amount of fractures measured in the RSF area is shown in (Fig. 4.12, Fig. 4.15). Two dominant trends of the fracture surfaces are apparent, a main NW-SE (Fig. 4.12) trend and a subordinate NE-SW (Fig. 4.14) trend, in the RSF area of domain II, the one which is defined as more or less stable. The dip of most fractures is steep ( $\geq 70^\circ$ ) to sub vertical (Fig. 4.12). The fractures show a slight bending geometry in NE direction (Fig. 4.13a). Some of the fractures are vegetated, others are vertical with clean rock walls (Fig. 4.13b,c). The fractures on this plateau show a deep and almost vertical character. Snow from earlier years is located in the fractures and does not melt. The fracture system on the plateau functions as drainage from the small lake. The drainage can be viewed (see Chapter 4.6), where we can see the drainage event has happened.



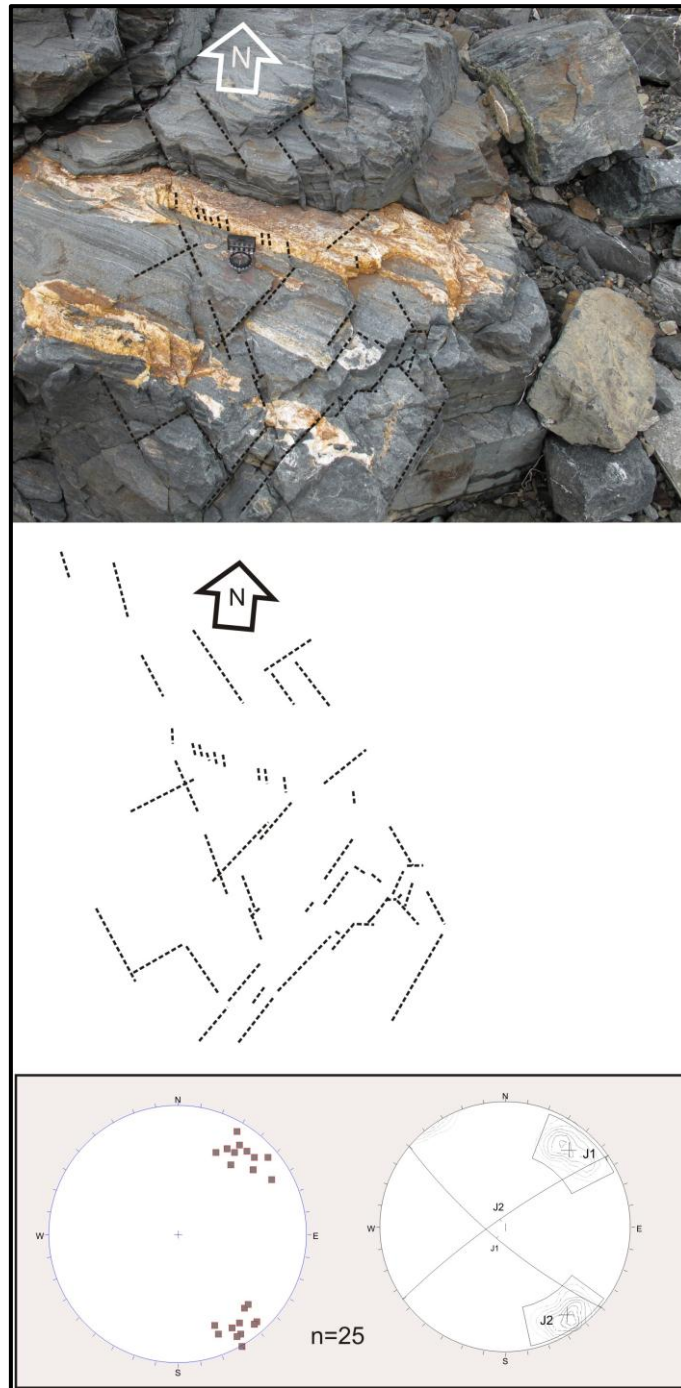
**Figure 4.12:** Stereo plot as poles and contoured plot showing us the fracture trends in Domain II, outside the main slide. Here the measurements are mainly taken east of Domain I in the area above the back scarp.





**Figure 4.13:** Photos showing various fractures in the studied RSF area: (a) Extensional fractures showing a slight bending geometry towards NW (b) Some are vegetated with ferns (c) Open fractures in Domain II, above the main rock slope failure area. The deepest ones have almost an “A” shape, narrow on top and widening deeper; they are so deep and cold that the snow does not melt in them 20 meters down.

On a smaller scale, fractures covering e.g. an area of  $1.5 \text{ m}^2$  within partly intact bed rock of the RSF show a similar trend as the large-scale pattern of Domain II, with a dominant NW-SE trend and a subordinate NE-SW trending fracture set (Fig. 4.14). Typically, the NW-SE fractures also show en-echelon geometries in map view and comprise small-scale transfer zones in between right-stepping fractures (Fig. 4.14). Notably, the south-bounding scarp of the RSF area (Fig. 4.21) seems to correspond in orientation with this NE-SW trending fracture system (Fig. 4.14).



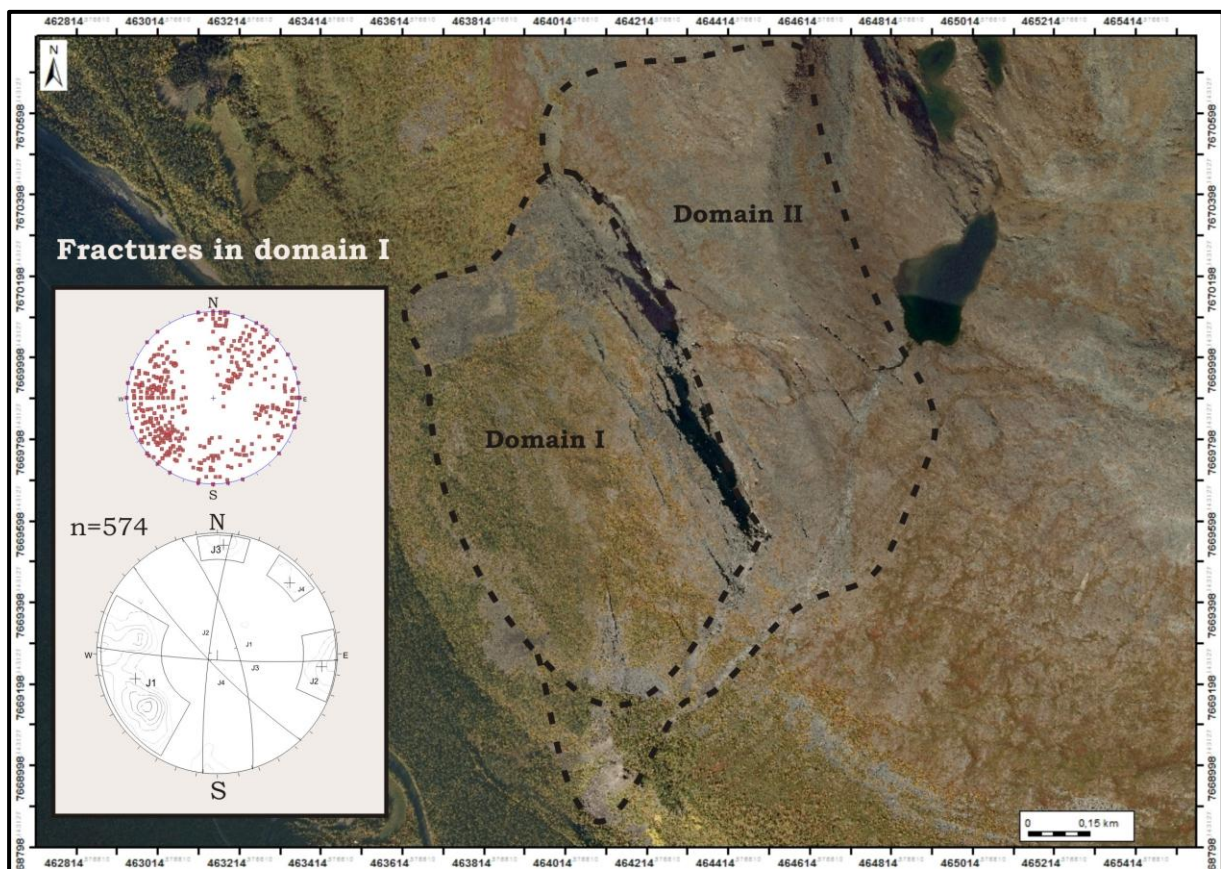
**Figure 4.14:** A Small scale; fracture analyses in Domain II (34W 464183/7669042), showing the two trends NW-SE and NE-SW.

Fractures inside domain I of the RSF show considerable variation in the attitude (Fig. 4.15). In this area several sets of strike directions are represented and in different areas they seem to correspond with the orientation of morpho-structures as linear scarps and counter scarps (Fig. 4.6, Fig. 4.16). The area has been divided into smaller sub areas, because through dividing it is easier to see the trends and to use the data sets for analysing e.g. the nature and movement direction of the rock slope failure and as a framework for detailed discussions (see Chapter 5).



The division is made in response to structural elements found in the different areas (Fig. 4.16).

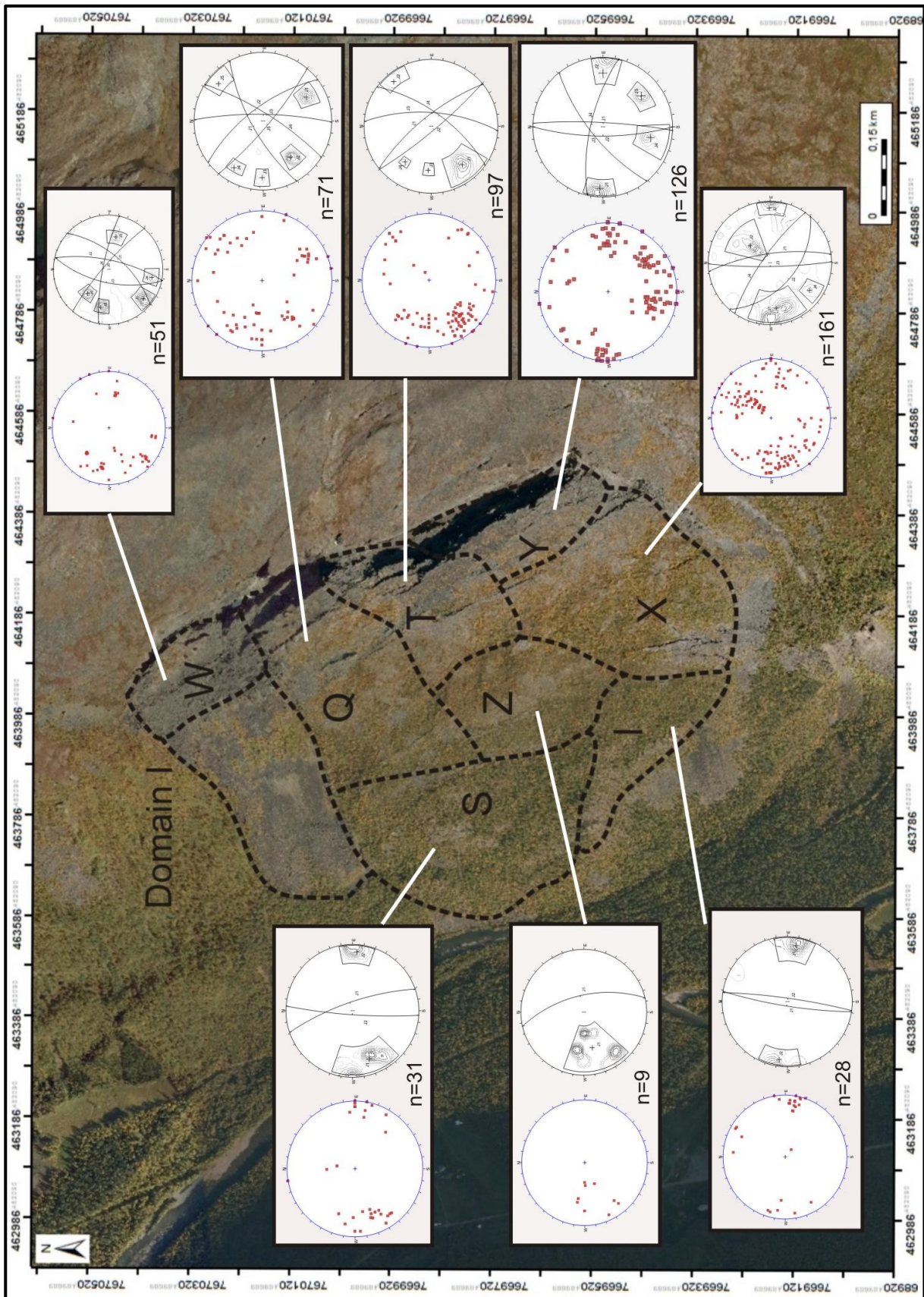
The area shows multiple fracture surfaces and orientations, with major fracture sets striking NW-SE, NNE-SSW and W-E (Fig. 4.15, Fig. 4.16) The dominant fracture trend is NW-SE, parallel to the back scarp (Fig. 4.15, Fig. 4.16, Fig. 4.17a). There are also fractures trending oblique to the back scarp with strikes NNE-SSW and NNW-SSE (Fig. 4.15). Fractures trending SW-NE are the once that occur perpendicular to the back scarp, meaning that they stand ca.  $90^\circ$  normal to the back scarp. These perpendicular fractures, however, do not show up very clearly in the stereo plot (Fig. 4.15).



**Figure 4.15:** Stereo plot over poles and main fracture planes in Domain I the main trend is NW-SE.

In the southeastern part of Domain I, i.e. subarea Y, fracture set with a distinct orientation exist, striking E-W, NNE-SSW and NW-SE, respectively. Notably, the NW-SE fracture trend in this domain overlaps with the orientation of major ridge-like back-scarps and counterscarps (see Chapter 4.4.3.2) which all have a NW-SE trend (Figs. 4.16, Fig. 4.17b). The counterscarps with strike NW-SE are also cut by subvertical orthogonal fractures (Fig.4.17c,d), as well as by oblique fractures in the area (Fig. 4.18).





**Figure 4.16:** Orthophoto with the subdivision of (Domain I) the RSF area into smaller sub areas, and which allow fracture orientations to be evaluated in a spatial outline. Fractures are plotted in stereo diagrams as poles and analyses are made as contour plot in Dips (Rockscience, 2011).





**Figure 4.17:** a) The upper part of the southern scarp has several joints striking SE-NW, parallel to the back scarp. b) Counter scarps in area Y show orientation NW-SE (Fig.4.13 and Fig. 4.19). c) Tensile fractures in Y, striking NE-SE perpendicular to the back scarp going downslope into area X; both show clear displacement and the fractures are up to 15 meters deep. d) Perpendicular fracture to the back scarp striking NE-SW filled with talus material.

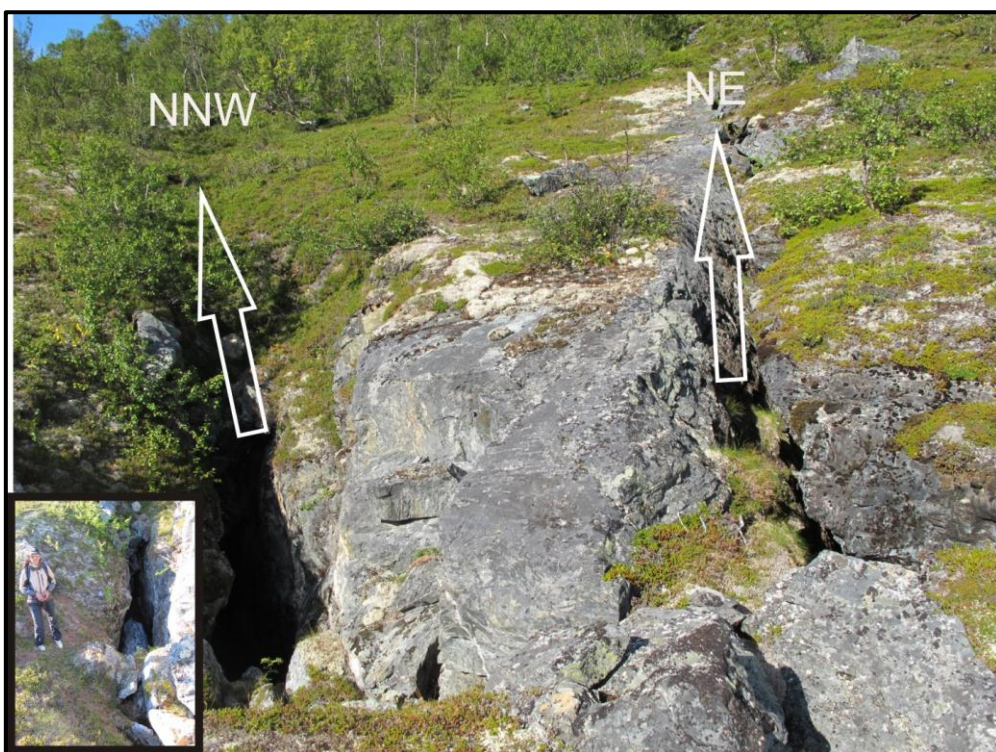
Subarea T represents an important area that marks a transition zone between the *en-echelon* and right-stepping major back-scarp (Fig. 4.6, Fig. 4.10) as a transition area. In this area the NW-SE trending back-scarp is off-set and/or partly bent along an oblique, NNE-SSW-trending fracture system (Fig. 4.6), which is also outlined by mesoscale fractures (Fig. 4.16). These fractures strike NE-SW and dip to the SE. Scarps that dip opposite direction of the



major back scarp are termed counter-scarps (Fig. 4.17b) (Table 1), where as scarps that are oblique to the back-scarp represent transfer scarps. The transfer plane bends into several of the counter-scarps strike NW-SE dip to NE (see Chapter 4.4.3.4).

In the two northern areas W and Q the fractures show a main strike NW-SE and NNE-SSW (Fig. 4.16); fractures with strike N-S also exist.

**Area X**, the southernmost and central portion of the RSF area, has fractures with strike NW-SE and N-S (Fig. 4.16). This area consists of mostly birch vegetation on a big terrace-like surface sloping gently ( $<30^\circ$ ) to SSW. This well exposed foliation surface comprises fractures that differ markedly from those of area Y, farther up. In the more slab and vegetated area we can find deep, open fracture systems that cut the terrace both oblique and perpendicular relative to the back scarp (Fig. 4.17d). The perpendicular fracture strikes SW-NE with a moderate dip to the SE. The oblique systems are more vertical (Fig. 4.18) but bend into a crevasse system striking NNW-SSE and parallel to the back scarp NW-SE (Fig. 4.18).



**Figure 4.18:** Perpendicular and oblique fractures in relation to the back scarp in upper x-area, striking NE-SW and NNW-SSE. Note the inserted picture fore scale and to visualize that there is snow in the fractures in late summer.

The crevasses are a form of open fractures. The vegetation-covered surface cut by open and partly-open crevasses is very chaotic and shows a somewhat uneven displacement form, with steep scarps and steep ridges (Fig. 4.19). The fractures do not show the same lateral extents,

they display elevation differences and make several step-like moves. They resemble crevasses found in a glacier fall, but here they cut into solid bed rock. This crevasse system can be traced from area X and northeastward into the Z-area; this area consists mostly of vegetated birch trees and polished slabs. In the Z-area there are fractures striking N-S and NNW-SSE (Fig. 4.16).



**Figure 4.19:** Crevasse system with orientation NNW-SSE. The small inserted pictures show the steep and exposed topography in the area.

In the **lower part** of the RSF area, the areas **S and I** have fractures with strike NW-SE dip to NE, N-S and NNE-SSW with more vertical dip (Fig. 4.16). The fractures striking NW-SE are located just under the tree line at an elevation under 200 m.a.s.l, unmelted snow is seen in the fractures even in late summer (Fig. 4.18, Fig. 4.20). These fractures are parallel to the backscarp and can be followed for several tens of meters; they are located just on the shoulder of the lower hillside before its gets steeper down into the lower part of the rock failure area. The fractures split into a complex fracture system in NW, ending with a vertical cliff (Fig. 4.19).





**Figure 4.20:** Fracture seen in the upper part of S-area just above the steep lower part of the RSF. The fractures strike NW-SE with a steep dip NE. Several of the fractures have snow even in late summer, where the elevation is 200 m.a.s.l. The fracture enters in a chaotic cliff area in the NW, the upper inserted photo.

### 4.4.3 Structurally controlled morphologic elements

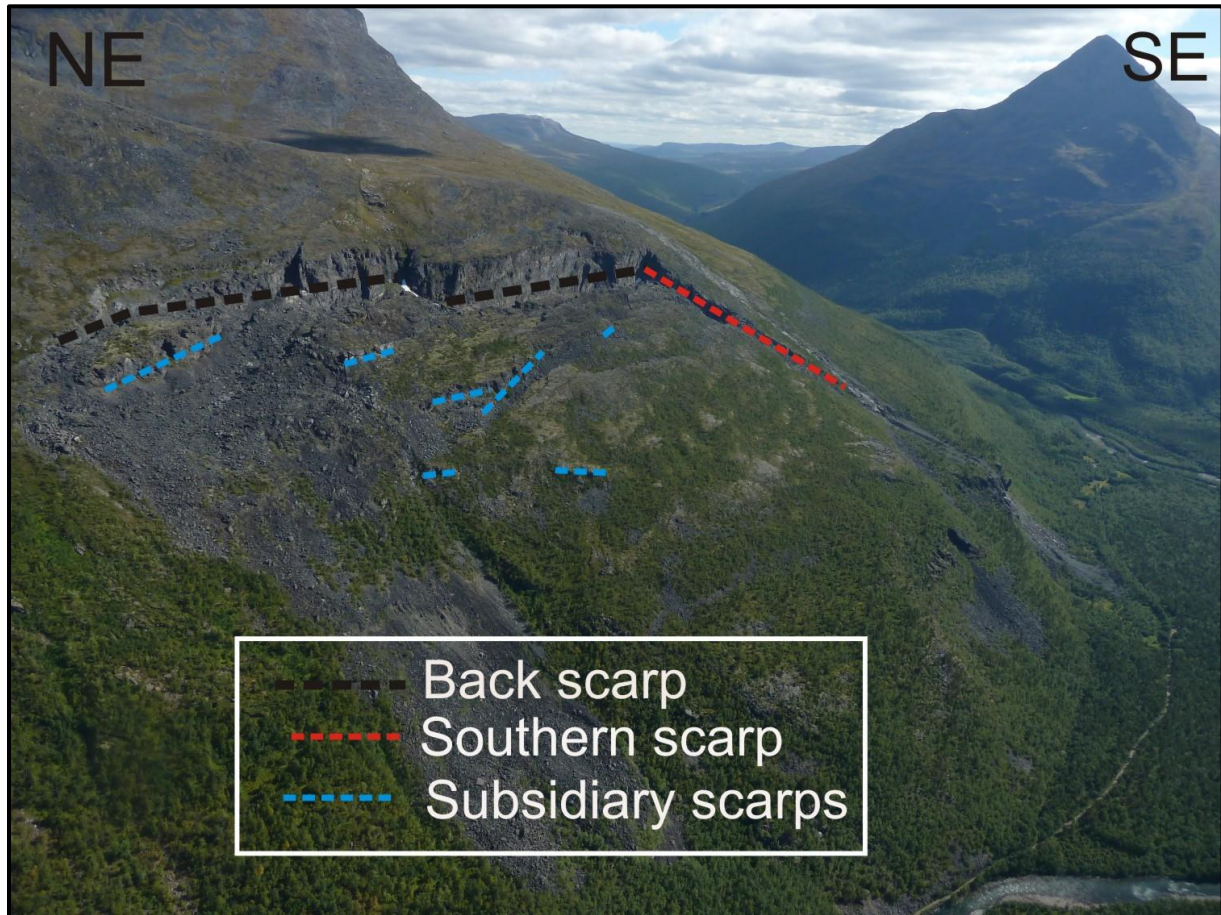
Structurally-controlled morphologic elements are those that show an obvious relation to the ductile and brittle structures described in section 4.4.1 and 4.4.2. These elements are all shown in the map (Fig. 4.6), and will be described successively in this section. Examples of structures shown on the map (Fig. 4.6) include (see Chapter 1.6 for definition of the terms):

- Escarpments; Back scarp, southern scarp and subsidiary scarps
- Counter-scarps/anti-scarps and ridges
- Trenches; Depressions and clefts
- Oblique structures

#### 4.4.3.1 Escarpments

There are several scarps in the area, including the back-scarp, the southern scarp and subsidiary scarps (Fig. 4.21). The described scarps are all located within Domain I. There are also several smaller scarps in Domain II (Fig. 4.6). The scarps described are of the size of a few meters to tens of meters. Scarps of smaller size will not be taken account.

The studied RSF area is framed by a main back scarp, generally striking NW-SE with a steep almost vertical dip to the SW, and a boundary scarp to the south, termed the southern scarp, which strikes SW-NE and has a steep dip to the NW (Fig. 4.21).



**Figure 4.21:** The photo illustrates the domain I, of the rock slope failure. The back scarp strikes NW-SE and the southern scarp strikes NE-SW. Subsidiary scarps are marked with blue lines (Modified photo Bunkholt, 2011)

### **The back-scarp**

The main scarp of the RSF area, the back scarp, strikes NW-SE to NNW-SSE and dips to the SW. The scarp is a sub vertical wall ( $> 85^\circ$  dip), with a height of about 30 meters in the northern part and almost 100 meters high in the south. The total length of the back scarp is around 950 meters.

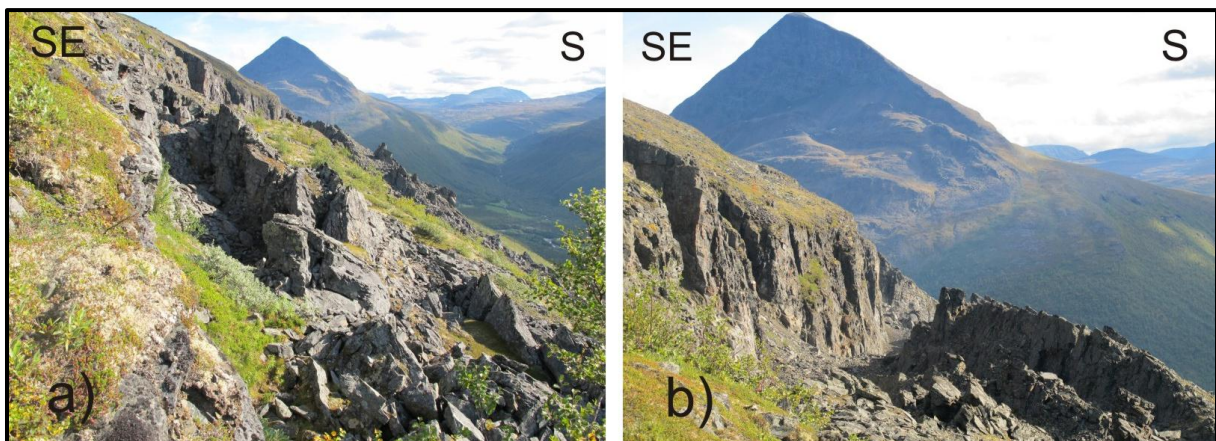
The back-scarp cuts with a high angle, the sub-horizontal or gently SW-dipping foliation of the bed rock in Domain II above (Fig. 4.9), and is itself cut by major fractures/scarps striking NE-SW with dip ( $>60^\circ$ ) to the SE (Fig. 4.22b, Fig. 4.24). The surface/wall of the back-scarp has some major steep scarps with strike W-E; these are located in the northern part (Fig.



4.24). These scarps are connected with fracture systems in Domain II, on top of the back-scarp (Fig. 4.6, Fig. 4.30b).

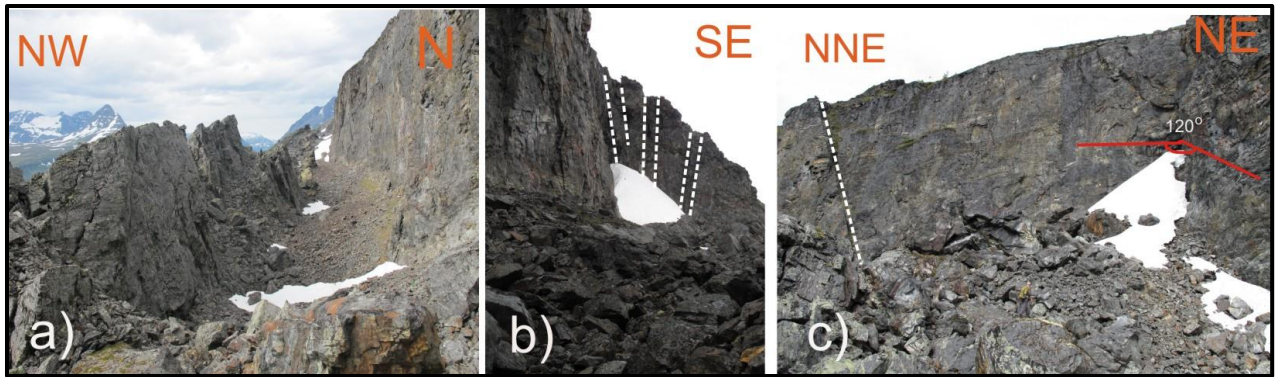
In the middle part of the back-scarp is a zone where the wall makes a step, outlined by a steep, oblique transition zone. In front of the back-scarp is a deep talus filled cleft/trench, and a major counter-scarp that in combination, makes this portion of the RSF look like a graben system (see later description Fig. 4.29c). The cleft has a width of about 20 meters in the transition zone. In north the cleft below the scarp is about 15 meters wide while in the southern part it is much wider, about 50 meters (Fig. 4.22a,b). In the south the back-scarp, including the graben system, joins in a 120° angle with the southern scarp, making a sharp cross-wall (Fig. 4.23).

The relative displacement between the surface of the back scarp and the related counter scarp is a cumulative value taken from the back scarp over the crack and displacement of counter scarps, there is uncertainties of how deep the planes of the back scarp and counter scarps goes down in the loose rock material filling the graben (Henderson et al., 2006). The total horizontal displacement from back-scarp and the surface at counterscarp are calculated to be between 60-80 meters (most in south and less in the north). Total vertical displacement at Hompen RSF is estimated to be c. 20 meters in the back scarp compared to were the counter scarp are located today. These are values measured through DEM models, ortho-photos in Arc GIS and profiles, so these should be seen on as interpretative values.



**Figure 4.22:** The back scarp a) looking from the far north, here the back scarp is less pronounced and the cleft in front is not that wide. b) An overview of the more southern part of the back scarp, there the wall gets higher and the cleft in front gets wider.





**Figure 4.23:** Back scarp; a) looking north from the far south along the back scarp. b) The joints in the southern scarp are marked, showing a parallel strike NW-SE as the back scarp. c) The back scarp joins in a corner to southern scarp the angle between the scarps is  $120^{\circ}$ .



**Figure 4.24.** The scars in the back scarp; a) this deep cut in the back scarp are linked to a talus trench in SE direction, view description for trenches for further information. b) A scar looking from the back scarp side, this scar might be linked to a subsidiary scarp striking parallel above the back scarp, view (Fig. 4.19) map in Domain II.

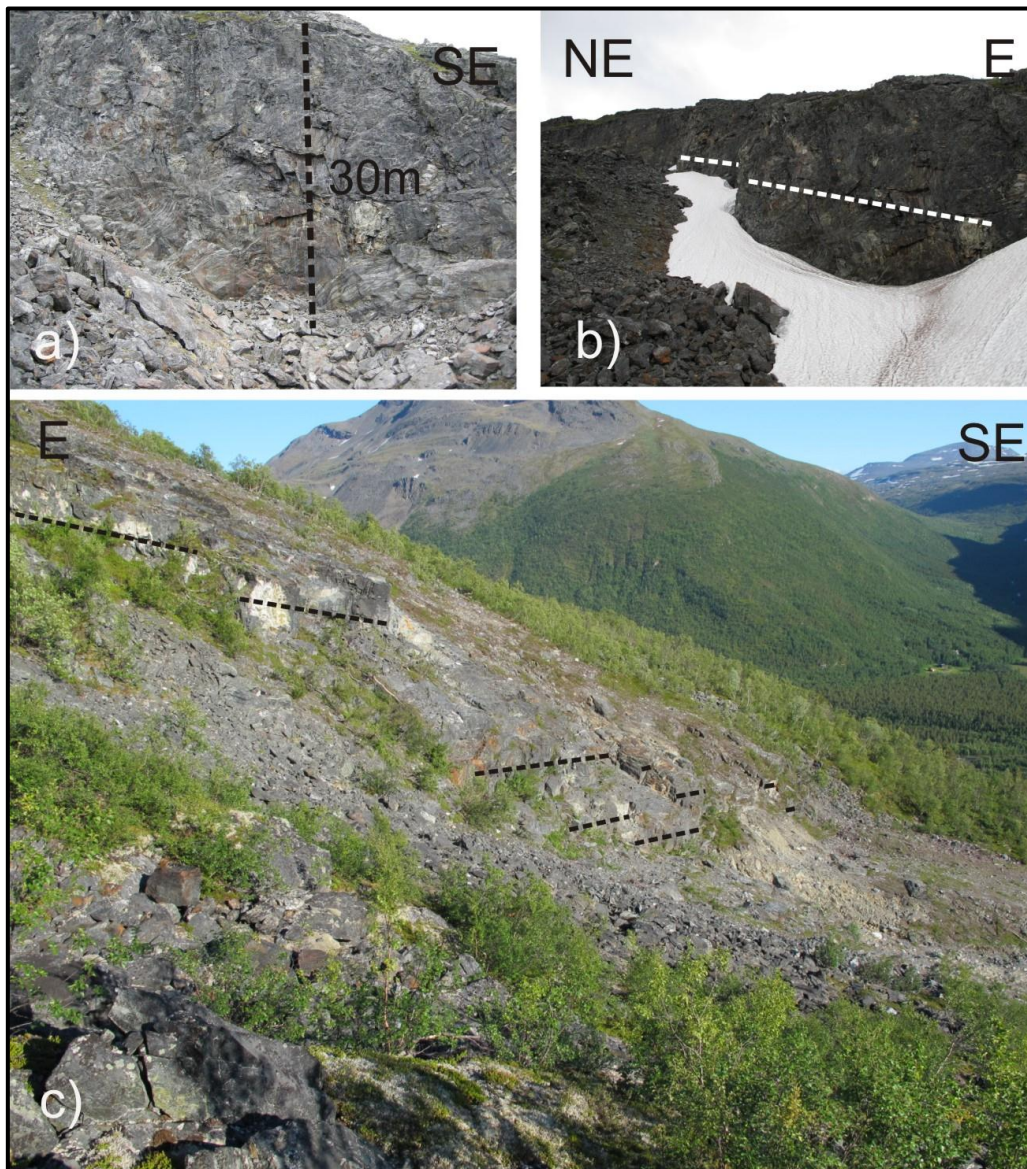
### **The southern lateral scarp**

The southern scarp works as a border scarp, to the south striking NE-SW with a steep dip to NW (Fig.4.21, Fig. 4.25, and Fig. 4.26). It is a scarp with less continuity, with *en-echelon* geometry when traced downwards along the mountain slope. Half way down, the scarp dies out in a south eastern direction (Fig. 4.25c). The southern scarp has a height of around 45 meters in the upper part of the RSF area but lowers as it follows the hillside (Fig. 4.25a,b,c). In the middle part it's 5-10 meters high and then vanishes and dies out to the south (Fig. 4.21, Fig. 4.25c). The cleft below the southern scarp is not so pronounced, but filled with loose talus material of variable sizes (Fig. 4.25b). The total length of the scarp is around 470 meters.



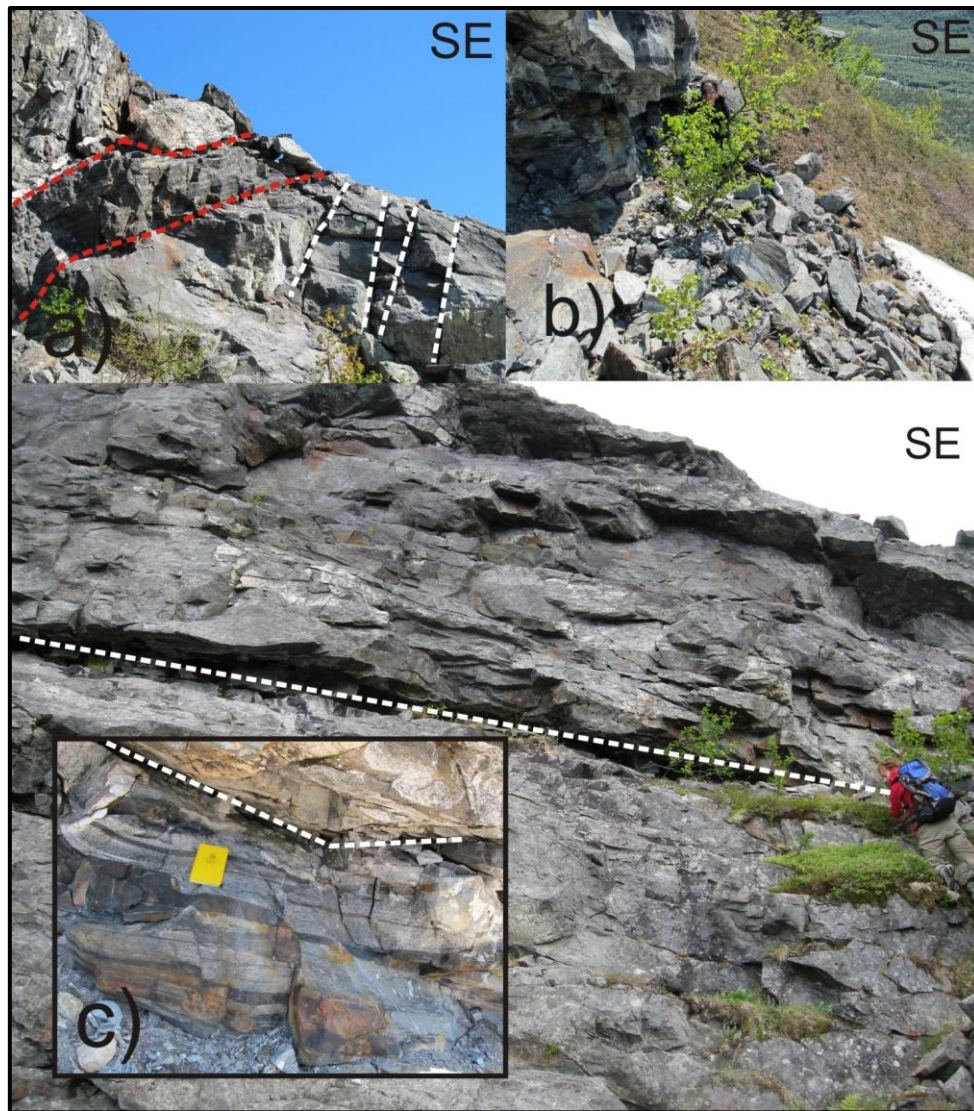
The foliation in the southern scarp is hard to define in the upper part, due to an undulating character outlined by mafic boudins and lens-shaped structures that make the scarp wall look chaotic (Fig.4. 25a, Fig. 4.26a). In the middle and lower areas of the southern scarp the foliation strikes NW-SE with dip ( $<20$  degree) to the SW (Fig. 4.7).

In the upper part the southern scarp is cut by several vertical fractures striking NW-SE, i.e. a direction parallel to the back-scarp (Fig.4.23b). In the middle area just before the scarp dies out, several sets of fractures that strike NW-SE to NNW-SSE direction become more dominant (Fig. 4.26a). The southern scarp also displays some sub horizontal fractures, and these fracture surfaces appear to be located within mylonitic zones of the bedrock gneisses (Fig. 4.26c).



**Figure 4.25:** Southern scarp; a) A vertical 30 m high wall, follow downhill SW b) taking some echelon steps, the height of the scarp is lowering. C) In the middle of the slope, the scarps are vanishing out to the south east.





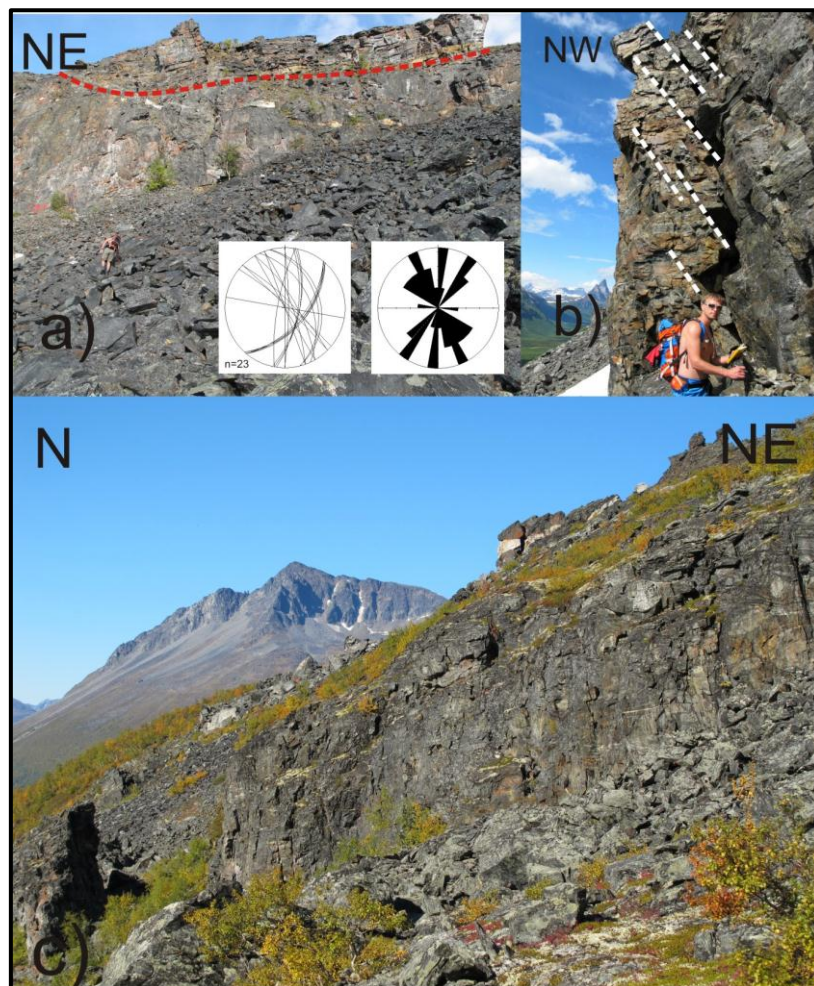
**Figure 4.26:** a) The southern scarp showing the irregularities with mafic lenses (stippled red) in the bedrock, and fractures striking SE, parallel to the back scarp. b,c) The sub horizontal fracture plane in Mylonitic rock following the same orientation as foliation strike NW-SE dip to SW. c) A close up of what might be a local detachment, Mylonitic rock might here work as the weak zone.

### **Subsidiary scarps**

Subsidiary scarps are defined as those having a vertical face of between 5 and 25 meters and that are located inside domain I. There are several scarps of this size in domain II as well, but they will not be described here. Subsidiary scarps of this size are abundant in the northern part of the RSF area. Above the huge talus field in area W (Fig. 4.21, Fig. 4.27a), one such scarp strikes NW-SE, is 200 m long and displays a vertical cliff face of ca. 30 meter. Below this scarp there is a talus filled trench, with an elongated ridge-like structure (Fig.4.6, Fig. 4.32b). In area-Q, there is a steep to sub-vertical scarp striking NW-SE. This scarp has a length of about 300 meters; the height is approximately 20 meters in the north and 5-10 meters in the



south. In connection to this scarp there is a pronounced counter scarp (Fig. 4.27c, Fig. e scarp but not so dominant in the terrain. The scarps in area Q are clearly linked to vertical fracture systems striking NE-SW, and the walls also display fractures standing oblique and vertically to the strike of the wall (Fig. 4.27b). The foliation in intact bedrock nearby these scarps consistently strikes NW-SE and dips gently to the SW (average 140/25) (Fig. 4.10). Similar scarps in area W display two sets of fractures: NE-SW strikes and dip ( $60^\circ$ ) to the SE, and a set striking NNW-SSE dip (85 degree) to SW (Fig. 4.27a). The bed rock foliation in these scarps strikes NW-SE with a gentle dip to the SW (120/25) (Fig. 4.10). A subsidiary scarp in area W is formed cutting the contact between the massive amphibolite gneiss and the hornblende schist (Fig. 3.5, Fig. 4.27a).



**Figure 4.27:** a) Subsidiary scarp in W-area; note a lithological difference in the bedrock, marked with red. b) Oblique fractures towards a scarp, can induce rock failure as toppling (see Ch. 5). c) Subsidiary scarp in Q-area, this scarp has a counter scarp connected to it (also view Fig. 4.28Bc).

#### **4.4.3.2 Counterscarps/Anti-Scarps and Ridges**

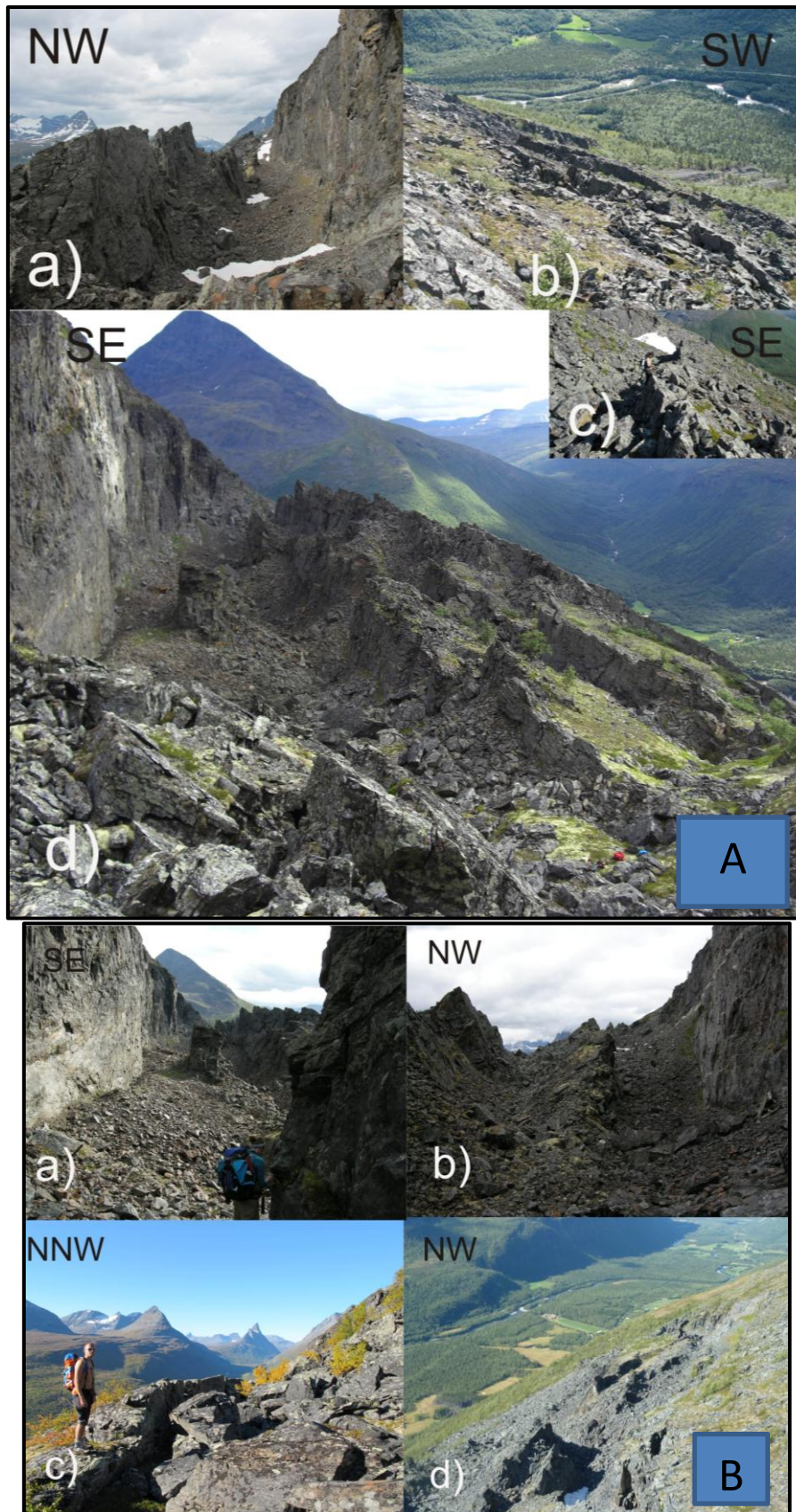
Counter-scarps or anti-scarps are defined as uphill-facing scarps that vary a lot in height, from 0,5 meters to as much as 8 meters (Fig. 4.17b, Fig. 4.28). Most of the upper part of the RSF area of domain I consist of these structures, as shown on the map (Fig. 4.6). These scarps can be followed in the terrain and on DEM images as elongated ridges bounded by fracture plan/cracks and inclined foliation. There is an overlap regarding the definition and presentations of counterscarps/anti scarps and ridges. As a clear morphological structure these can be defined as elongated ridges.

The elongated counter scarps are more or less parallel to a subsidiary scarp that dips downhill. They occur either as sets of counter scarps or just single ones standing alone, together forming “half graben-like” asymmetric troughs in connection to a scarp, (Agliardi et al., 2001). These ridge-like structures, which through observation, have a clear connection to a scarp; will here be described as counter scarps (see Ch.1.6).

The more gently dipping downhill-facing slope of counter scarps typically, is made up of the bed-rock foliation (Fig. 4.28) and the dip angle seem to vary a lot. In the southern part of the RSF area counter-scarps strike on average NW-SE and dip  $75^{\circ}$  to the NE (Fig. 4.28Ad in areas Y and X). The foliation and downhill-facing slopes in these counter scarps strike NW-SE and dips gently SW in the upper areas and in the lower areas the dip changes to SSW (Fig. 4.10, Fig. 4.11). In the northern area (Fig. 4.28B), the strike of the counter scarps are NW-SE, and the foliation is NW-SE with a c. dip  $20^{\circ}$  to the SW. In this area there are counter scarps that dip in the opposite direction i.e. NE-ward  $40^{\circ}$  (Fig. 4.10). All the counter scarps have been truncated of several fractures (Fig. 4.16).

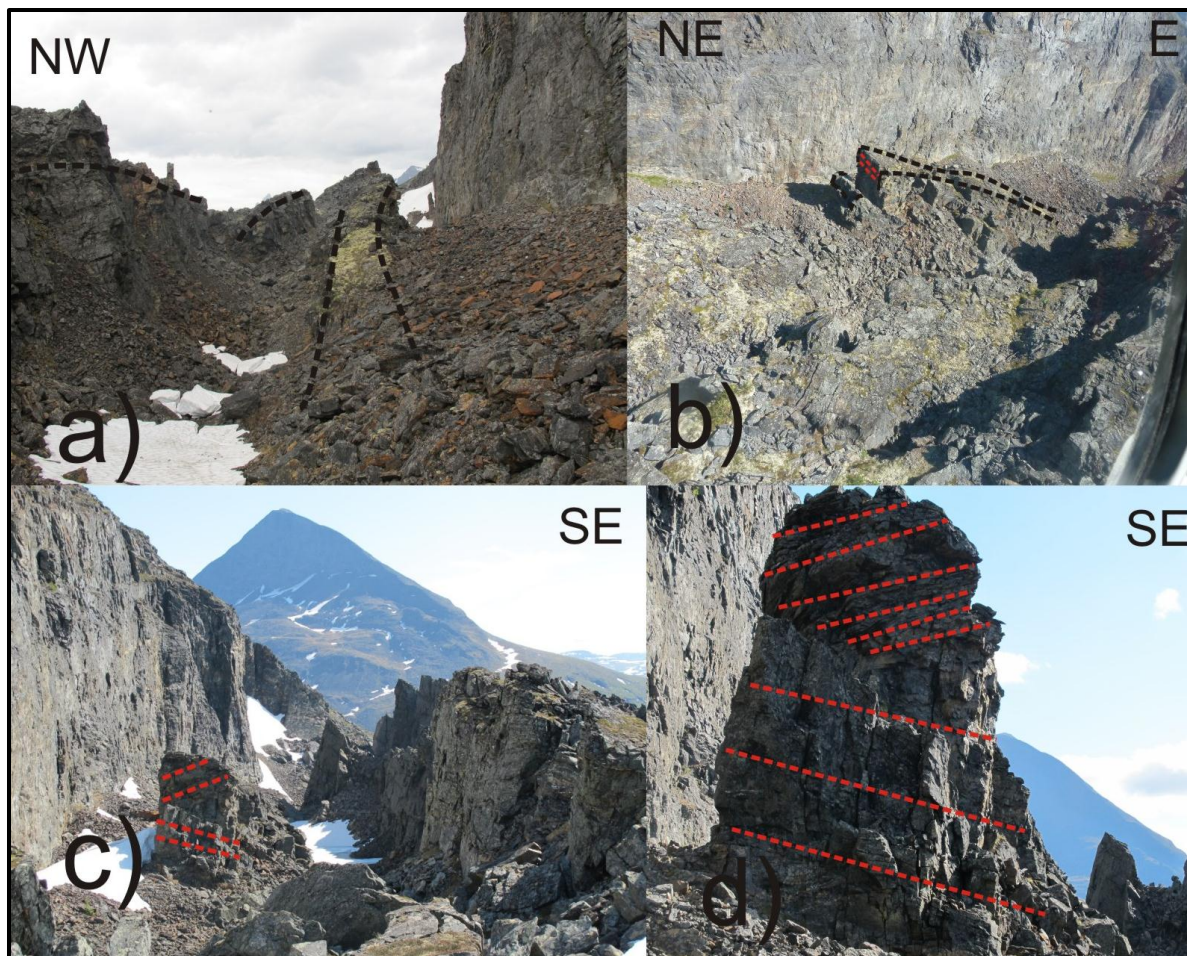
In connection to the back-scarp in the southern part, a narrow ridge bounded by two oppositely dipping fractures defines a structural ridge resembling a horst (Table.1) (Fig. 4.29c). This ridge is about 15 meters high, and in cross-section viewed from the north, the upper surface is shaped by the sub-horizontal foliation, which dips very gently inward (Fig. 4.29c,d). In view from the south, the ridge has another character, from here it looks like a counter-scarp/ridge (Fig. 4.29a,b).





**Figure 4.28:** A) Counter scarps in the southern part of the RSF area. B) Counter scarps in the northern part; a) looking south, b) a counterscarp which has subsided into the back graben, c) a smaller counter scarp in the more northern part of RSF d) talus covered counter scarps showing talus-like ridges in the terrain. The foliation plane is the same plane as the surface plane dipping down valley on most of the counter scarps.





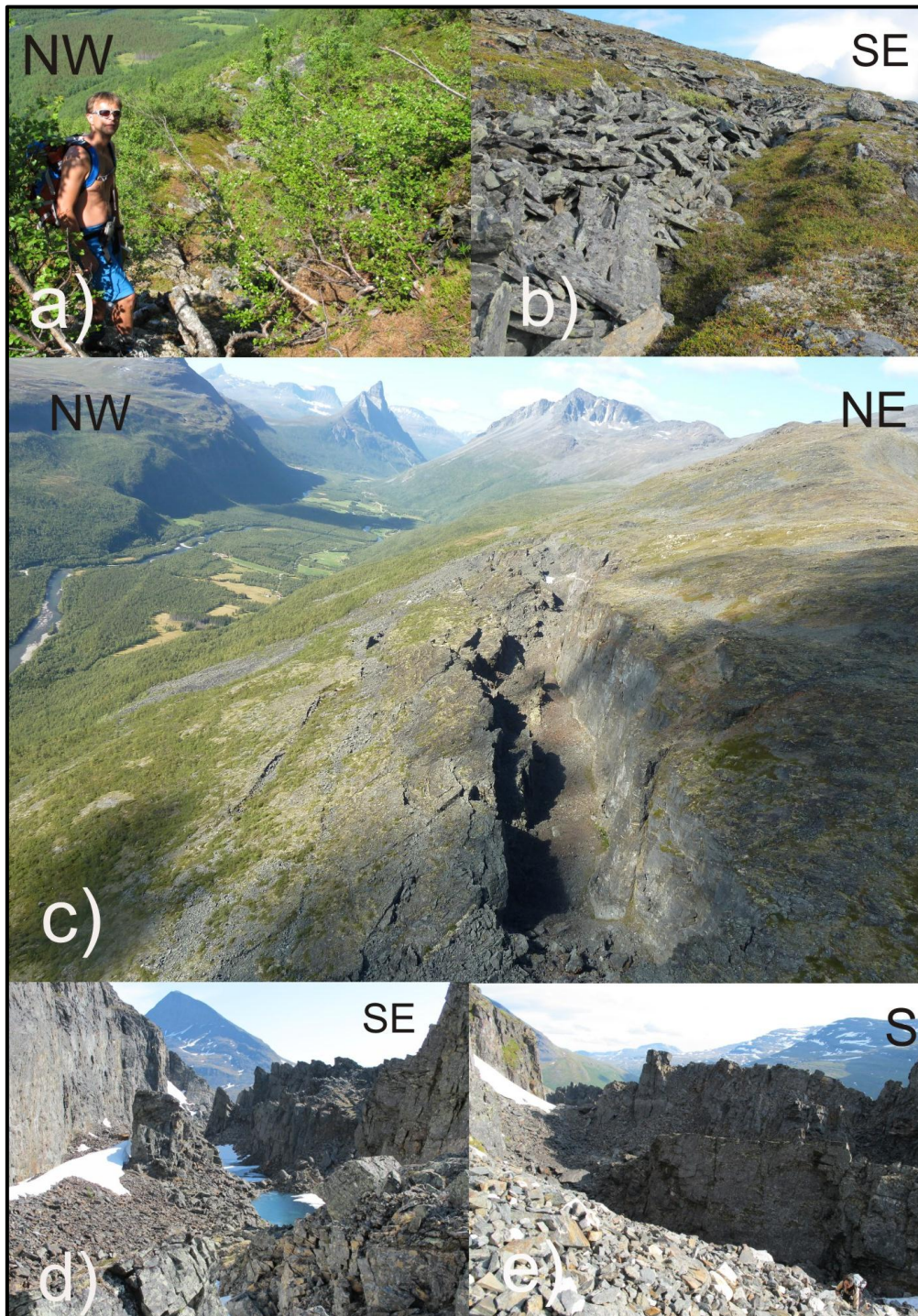
**Figure 4.29:** In the pronounced and biggest trench “Central Graben” is a tower which looks like a Structural Horst when seen from the north. a) When seen from the south it has a ridge-like shape with foliation dipping in SW down slope. b) From an aerial view we see it has the ridge shape, collapsed in parts. c) Looking from the north you get the impression that it’s a structural horst, standing in the middle as a horst ridge, the foliation which is dipping both inward and down slope can make the picture confusing. The structure is most likely a collapsed counter scarp.

#### 4.4.3.3 Trench (depressions)

In the RSF (Domain I) several topographic depressions exist, and they can be classified as clefts or trenches (Table 1) (Agliardi et al., 2001). The largest cleft is located in connection to and parallel with the back-scarp forming a huge depression or graben-like structure (Fig 4.30c; Table 1). Other subsidiary topographic depressions vary in width from a few meters to as much as 30 meters. The main graben-like structure is located just below the back-scarp, and can be traced more or less along the entire length of the back- scarp for about 900 meters (Fig. 4.6, Fig. 4.30c,d,e). The graben which is the biggest basin can in springtime be associated with having small water ponds located in it. The water drains out rapidly in early summer. There are also smaller trenches (Fig. 4.30a,b,d) mostly in connection with either subsidiary scarps or parallel to counter scarps. Apparent, but smaller trenches occur in the birch terrain in the terrace area, forming like elongated depressions with lengths of 10 to 100 meters (Fig. 4.30a). These are found close to the tree line in the middle part of the RSF area.



A trench goes oblique above the back scarp (Fig. 4.30b), developing in SE direction from the back scarp. The trench is filled with loose edgy rocks, milling its own infill. Developing from the depth connects with fractures above scarp and a scar in the back scarp (Fig. 4.6, Fig. 4.24a,b, Fig. 4.30b).



**Figure 4.30:** a) Smaller trench/cleft down in the birch trees. b) The trench is filled with edgy rocks on top of the back scarp; it joins with a scar in the back scarp view figure 23a. c) View of the whole central graben, a very pronounced trench/ scar in the slope as seen from this aerial photo looking north.(photo by Bunkholt, 2011) d) The big trench gets filled with snow in winter time. e) The trench consists of enormous amounts of talus rocks; view person for scale.

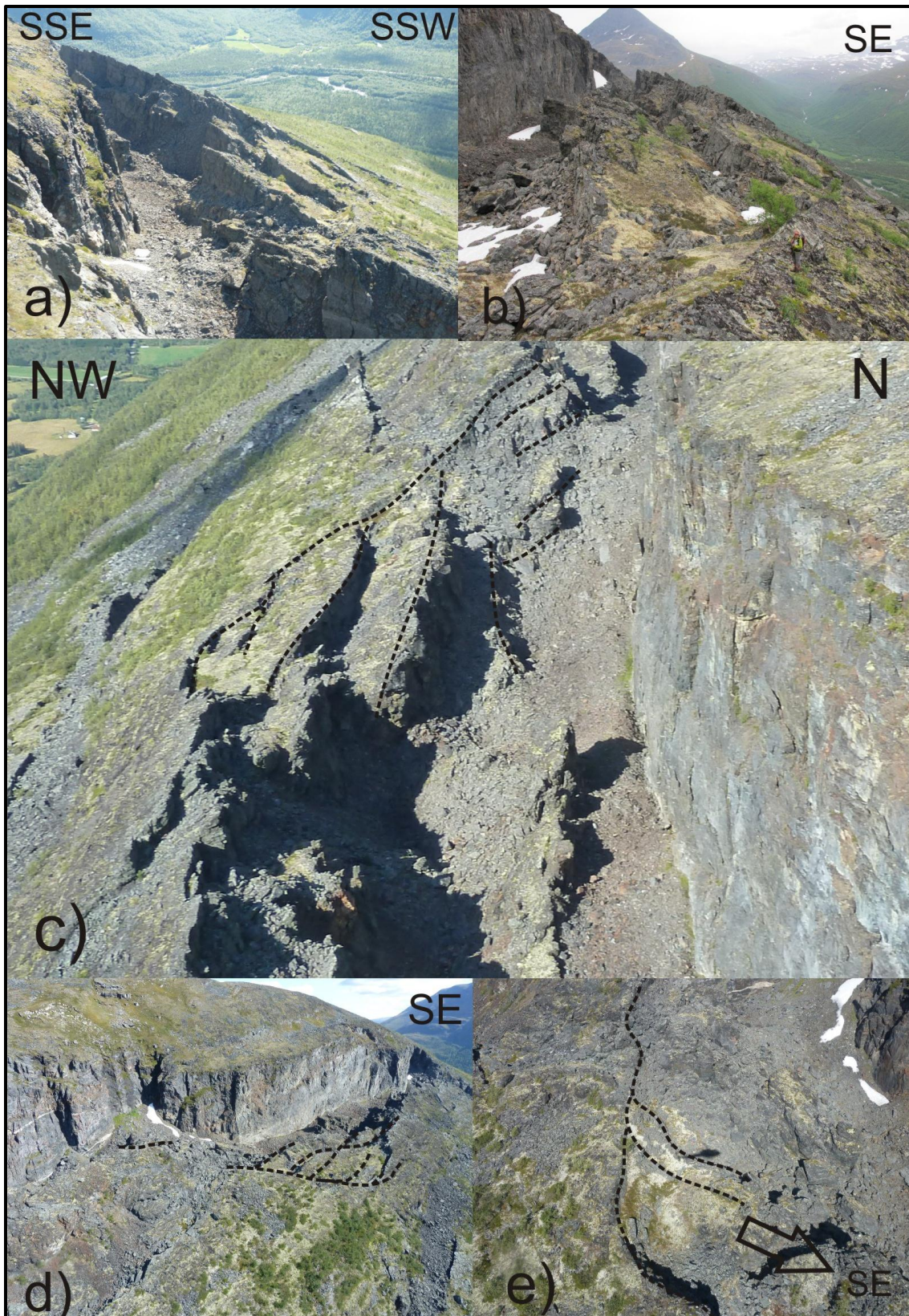
#### **4.4.3.4 Oblique structures**

Structures that are obliquely influenced or modified the structural and morpho-tectonic elements described above, are here termed oblique structures (Gibbs, 1990; Rosendahl, 1987) (Table 1).

The main area of the RSF (Domain1, areas W, Q, T and Y) that comprises oblique structures is along the huge depression and associated back-scarp described above (Chapter 4.4.3.3). In the central part of this depression the geometry of the depression and the back-scarp is very complex, with a number of fractures, subsidiary scarps, trenches and ridges with variable orientation, it reminds of a collapsed relay ramp. The NNW-SSE striking counter scarps are bound together with a NE-SW striking transfer scarp in north. The upper most part displays a collapsed ramp with NE-SW striking fractures (Fig. 4.31c). In meso-scale, we can see smaller oblique structures in the form of bent counter-scarps with a step-wise geometry down-slope (Fig. 4.31c).

In the far north, area W, subsidiary scarp display a curved geometry where the lower scarp continues as a fracture (Fig. 4.6). In area Q we can see a similar curvature between two anti-scarps (Fig. 4.6). In area T, which represents the dominant area for the location of oblique structures, an obvious curving of the back-scarp and formation of the bent counter-scarp system, from NW-SE strike to an oblique NNE-SSW strike is apparent over a distance of about 150 meters (Fig. 4.31c,d,e). These oblique structures seem to connect with a counter-scarp system with a ramp-like geometry of oblique fractures merging up from the main trench just below the back-scarp (Fig. 4.31c). The local counter scarp system displays a systematic stepwise geometry in connection to the curved and oblique fracture scarp (Fig. 4.31a-e).





**Figure 4.31:** This illustrates an accommodation structure; a transfer scarp oblique to the back scarp. The transfer scarp has strike SSW-NNE dip to SE, bending into several anti- scarps with strike parallel to the back scarp NW-SE. a-b) photos show the bending fracture plane into the counter scarp system view person for scale in b. c-d) Coming up from the central graben into a collapsed relay ramp, entering the bending fracture plan striking NNE-SSW and bends into the counter scarp system striking NW-SE. e) From a birds view the bending structure are very clear; for scale see shadow of helicopter and persons standing in the northern-most junction. (Modified aerial photos Bunkholt, 2011)

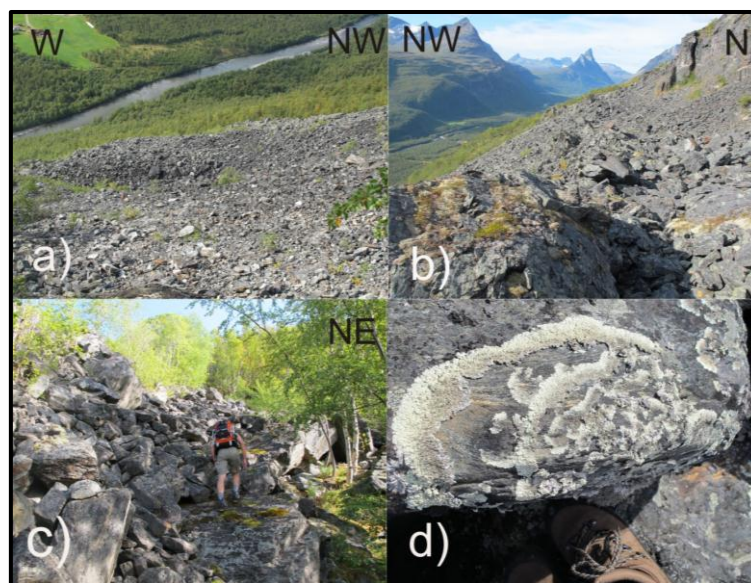


## 4.5 Geomorphologic elements of the rock slope failure area

In this chapter, apparent geomorphologic elements in the RSF area are described, and such elements are defined that are not directly related to morpho-tectonic elements where there is not a clear relation to structures and/or structurally-controlled elements. The origin, however, may still be considered as indirectly tectonically induced (see Chapter 5). Relevant structures of this category include: talus material, terraces, sinkholes and glacial deposits/elements (see Fig. 4.6).

### 4.5.1 Talus material

There are several talus areas inside Domain I, but also beneath the rock slope failure area. The material under are more like talus material from toppled bedrock. The talus field first described is the ones that have a structural pattern. The biggest one located in the far north of the study area, this is of a bigger size (250x585m) 0.15 km<sup>2</sup> (Fig. 4.6). The talus field area is showing on a lobe structure in the lower part, with the bigger size of boulders to the sides (Fig. 4.32c). Above the lobes it has a peak point. Above this peak there is a small trench (Fig. 4.32a), from here and up the slope show a steeper character (>30°) and with much smaller rock material almost sand and gravel, this area is very loose. Above this it flattens out and gets back into the talus field character. The field ends with a boulder covered counter scarp (Fig. 4.32b), 10 meters from a big subsidiary scarp. This scarp is the one showing a possible unconformity in the lithology (Fig. 4.27a).



**Figure 4.32:** The photo series are showing the talus field in the northern part of the rock slope failure area. a) The lower part of the field displaying a lobe character. b) The upper part is ending in a ridge shape covered by boulders, interpreted as a counterscarp to the scarp seen in the photo. c) On the way up in the talus field the material is sorted the way that the biggest material is on the sides. d) Radial growth of lichen can help to give a relative age to the talus field.

Many of the rocks in the area have big communities of radial growth of lichens (Fig. 4.32d). The lichen is known to have a slow growth rate 12 mm per century or 0.2 mm/year under optimum conditions (Hansen, 2008). The lichen may give a relative age to when the rocks were deposited.

The talus slope which is in connection to the southern scarp (Fig. 4.33a) display a much looser and lots of the material have a fresh origin. The mean inclination is here around 35 degrees; the rock has no lichen in this area.

The smaller talus scree slopes in the lower part of Domain I and beneath it (Fig. 4.33b), consist of stable rock material. This rock material has well developed lichen growth on it. These talus slopes do continue in the lower part of the slope but gets vegetated, with lots of smaller trees and even big pine trees.



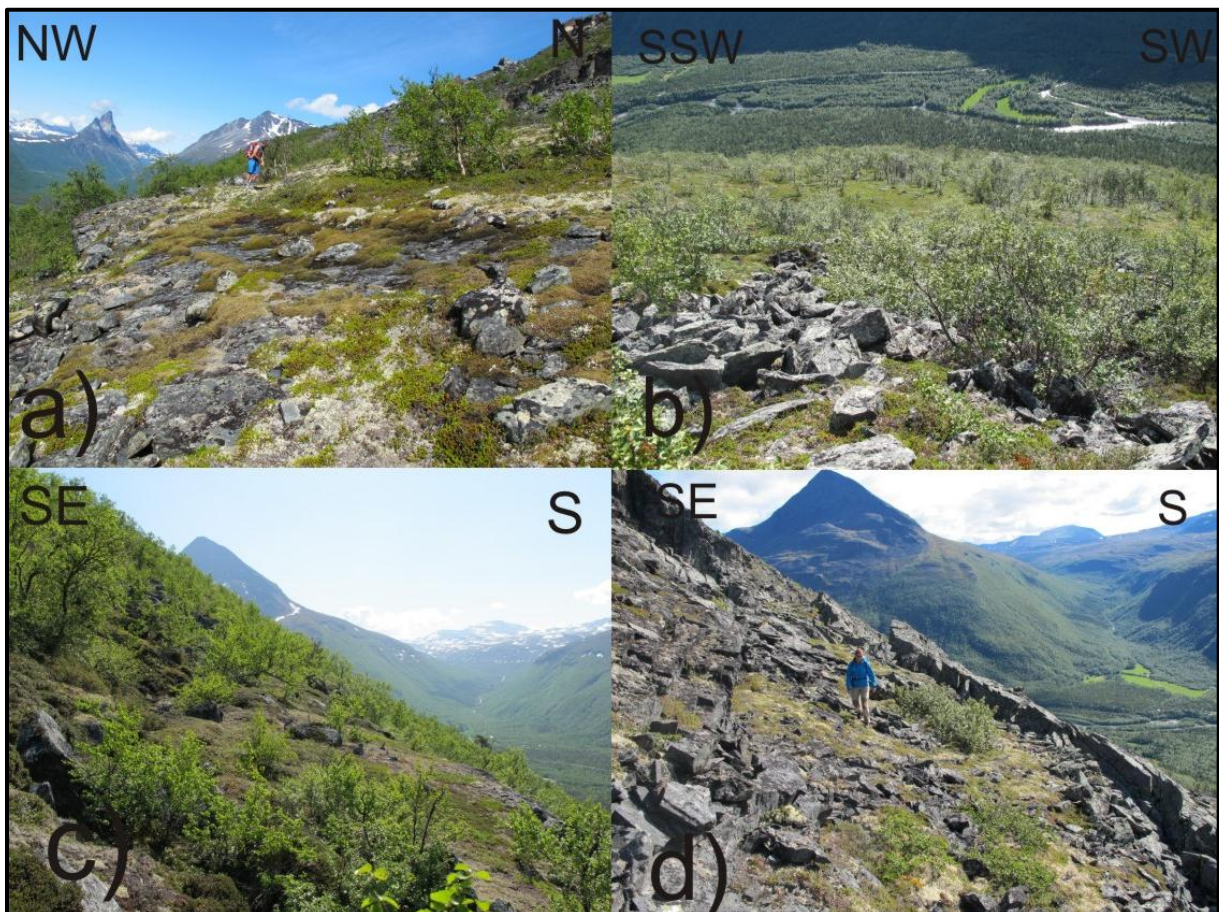
**Figure 4.33:** a) Talus slope in connection to the southern scarp, the rock is unstable. b) Smaller areas with talus scree in the lower part of the rock slope failure area and beneath it looking down into the valley.

The following genesis may be suitable for the different locations of the talus material. I) Rock-fall talus, normal talus material and boulders located below steep scarps, which origin may be due to frost shattering. II) rock-avalanche talus, areas where RSF have disintegrated during fall (Fig. 4.32 b, Fig. 4.33b), and III) RSF disintegration produced talus derived from rock slide in moderate slopes (Fig. 4.32a).



## 4.5.2 Terraces

The size of the terraces in the rock slope failure area varies from just a few meters in width to more landform size (Fig. 4.34). The definition that has been used is that the area is more or less horizontal to slightly dipping either towards the hill side, or outward but then not defined as a ridge. It's a step-like landform; a narrower terrace can be called a structural bench (Table 1). The genesis of these benches may be from differential erosion on rocks of different lithology as pre-slide erosion. Smaller areas as in Y-area where the counter scarps have a ridge form. Here slightly down dipping terraces are seen between the counter scarps (Fig. 4.34d). Bench like terraces can be followed for several tens of meters (Fig. 4.34a,c). In the northern area just south from the talus field (Fig. 4.6), there can be seen several smaller terraces as seen in (Fig. 4.34b). Looking on a bigger scale, the whole middle part of the rock slope failure area may be seen as a NW-SE striking terrace in the hill side (Fig. 4.5). There is not as clear visual terrace on the north side, but on the south side of the RSF area it is clear (Fig. 4.3).

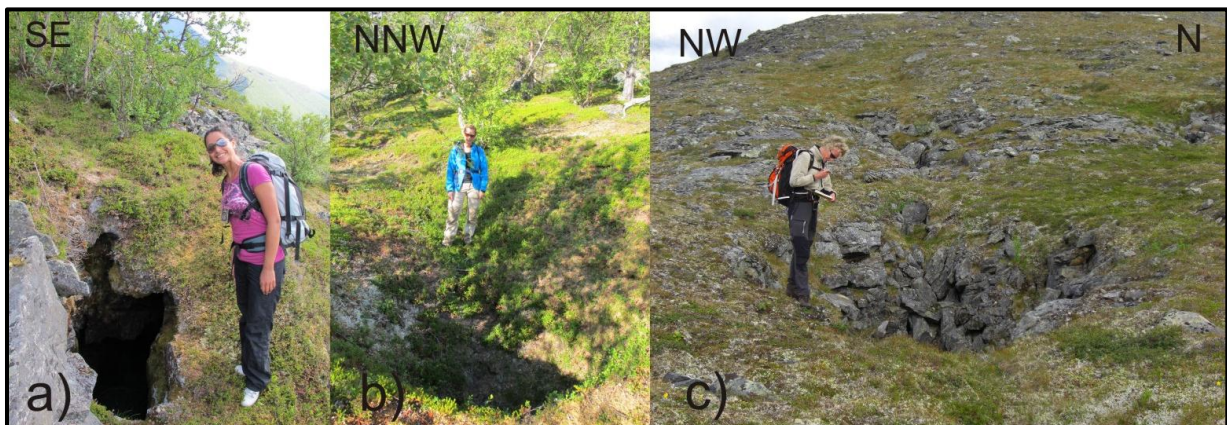


**Figure 4.34:** a) Looking north there are several gently down valley dipping terraces, formed in the polished bedrock. b) Terraces are easiest seen when looking down into the valley as here. c) Same as in a, but here the terrace are more vegetated. d) In the higher part of the rock slope failure there are smaller terraces partly filled with rock or vegetated as on this photo, these are located between counter scarps.

### 4.5.3 Sinkholes

Sinkholes are often seen in areas where the bedrock consist of Limestone. The rock slope failure area have documentet areas of limestone see (Fig. 3.3) but these observed sinkholes are located in other lithologies and may therefore be related to the RSF.. Here the defenition also include the shape and somewhat evolution of the sinkholes se definition (Table 1) as depressions in the terrain and disrupted vegetation cover (Henderson et al., 2011).

The sinkholes observed are located in the lower part of domain I (Fig. 4.6), were the vegetation has been clearly ruptured and it's a several meter deep cleft under (Fig. 4.35a). System of sinkholes are observed in Domain II, south from the crevasses in subdomain X (Fig. 4.6). These sinkholes are on average 4 meters in diameter and on a line striking N-S (Fig. 4.35b). In Domain II above the back scarp on the plateau, ther are sinkholes which have clear signs of humid conditions and vegetated with ferns, these are between 4-5 meters in diameter (Fig. 4.35c).



**Figure 4.35:** a) Sinkholes SW of the main rock slope failure area. b) Active sinkhole when the vegetation have been disturbed and ruptured the hole went several meters down and is interpreted as a fracture. This is located in the lower part of domain I. c) Aligned sinkholes at the plateau in Domain II.

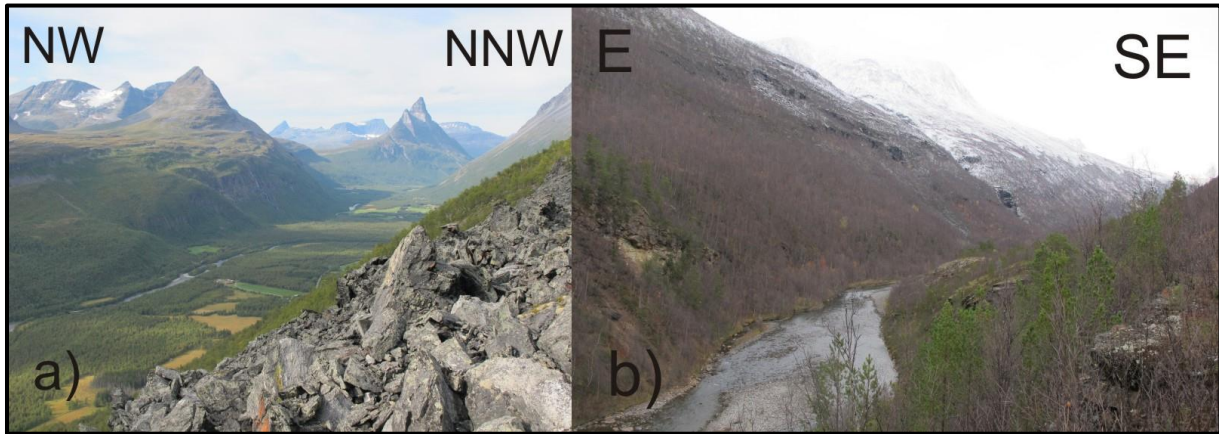
### 4.5.4 Glacial form elements

Here under forms as U-valley, (V-valley), chatter marks as crescentic scars and roche's moutonnees will be described, under the collective name glacial form elements. The U-valley "Signaldalen" is 17 kilometer long and on the widest about 2000 meters, orientation of the valley is NW-SE. The valley has a U-shaped geometry, with relatively steep sides and an almost horizontal bottom with a river meandering down valley (Fig. 4.36a). The upper part of the U-valley continues in southern direction into the Paras valley.

The V-valley "Stordalen" is a tributary valley to Signaldalen, joining from E-SE. This V-valley is a fluvial and narrow, c. 6 km long and formed as a V, the water flow is rapid in the

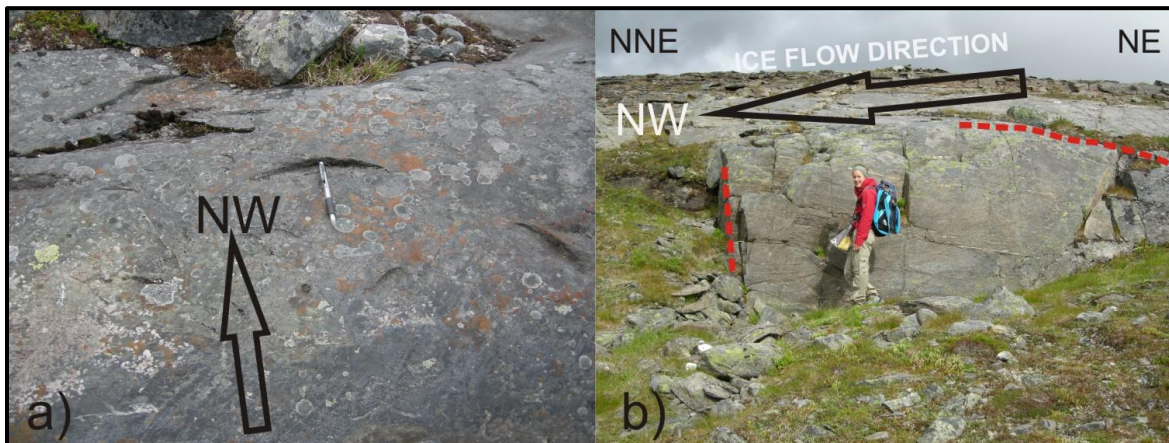


Stordalen river (Fig.4.36b). The Stordalen valley have bench like terraces and bedrock above these benches show on clear glacial erosion on the bedrock (Fig. 4.36b). The terrace may be seen as erosional glacial terraces which continues into the RSF area (Fig.4.3) (Agliardi et al., 2001).



**Figure 4.36:** a) U-valley-Signalaldalen; Signalaldalen river is meandering its way towards the sea in North West. b) V-Valley of Stordalen, the river is eroding its way deeper into the bedrock.

On the plateau in Domain II, there are several areas with chatter marks in the bedrock (Fig.4.37a) and the exposed bedrock in form of a roche's moutonnees (Benn & Evans, 1998) (Fig. 4.37b) gives us an ice movement towards the northwest. The glacial elements can be an indication of the direction to the ice movement of the ice sheet and what kind (cold/temperate) of ice formed these features. In the area below the Markus Mountain in connection to Domain II, it is observed polygenetic features which are built up with loose rock material.

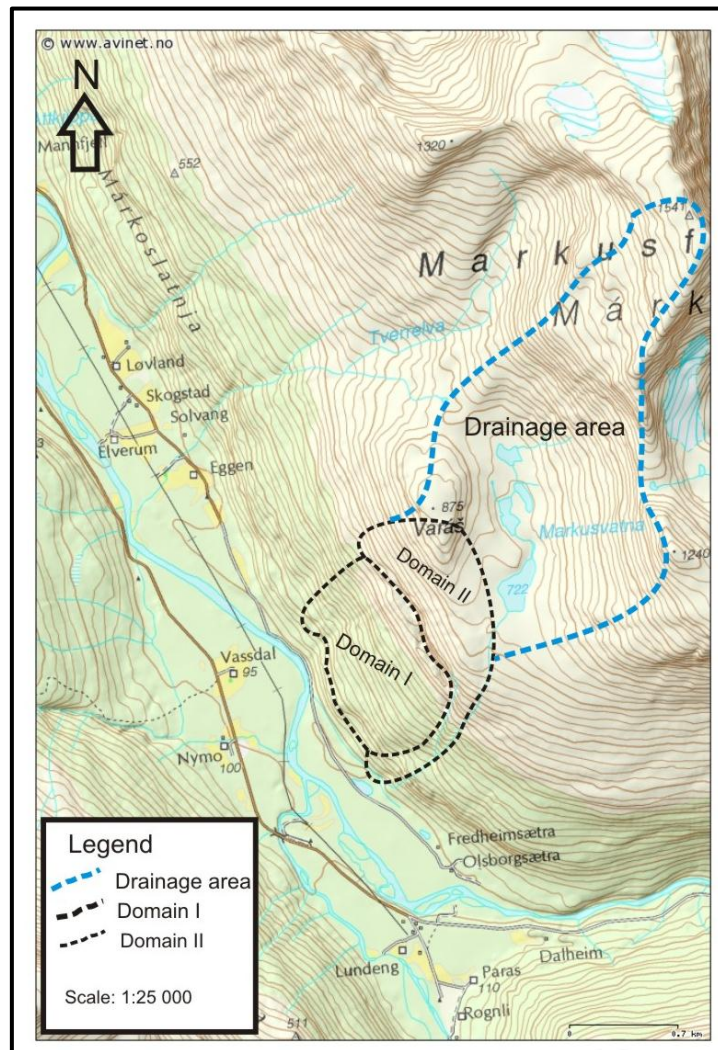


**Figure 4.37:** a) Chatter marks as crescentic scars showing on an ice movement in direction towards NW. b) The illustration show a roche's moutonnees, Ice flow from right to left. Note the lee face which has been quarried out and the abraded stoss side.

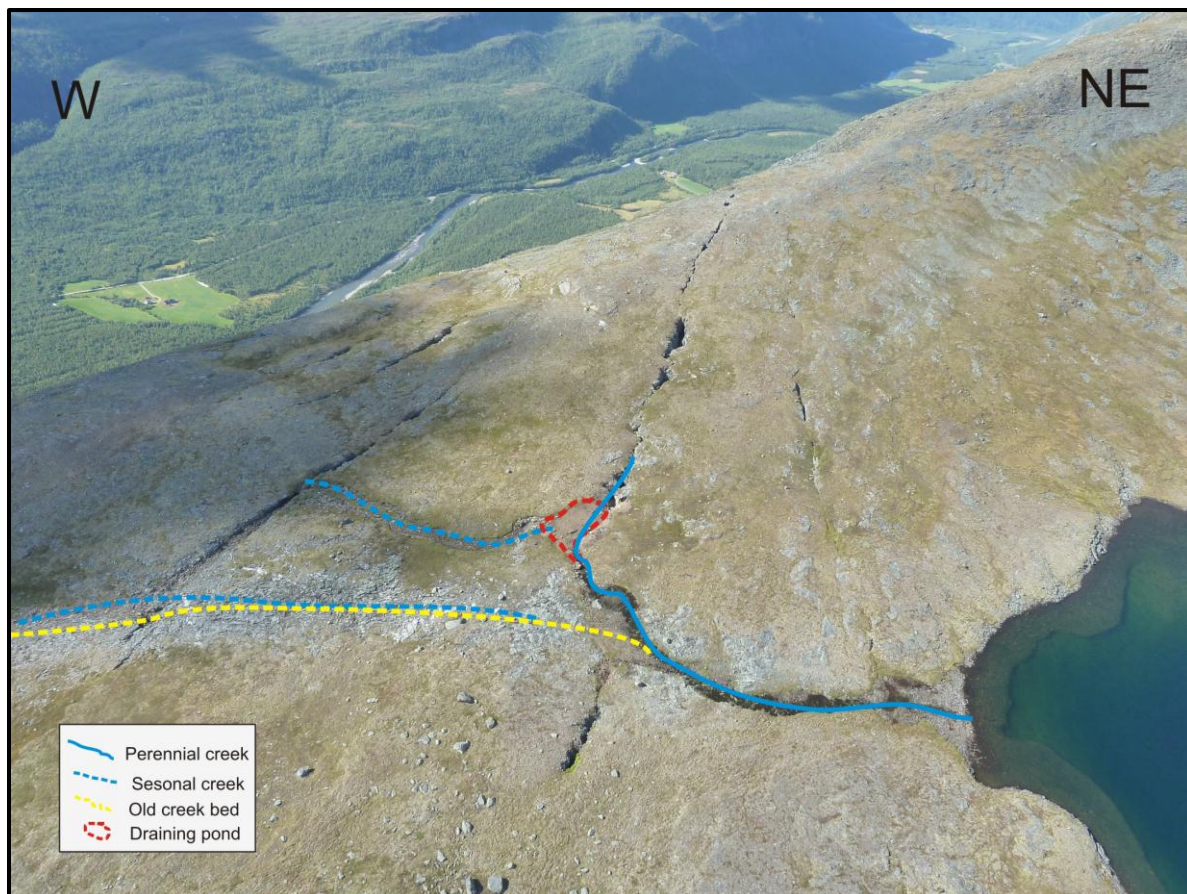


## 4.6 Drainage systems of the study rock slope failure area

The size, orientation and character of rivers, lakes and water supply to the valley that lies above the RSF area may be of importance for the understanding the processes of formation of the RSF (see chapter 5). The dominant drainage area is to the east of the RSF on the southern side of Markusfjellet within a glacial valley (Fig. 4.38). This mountain has peaks that reach around 1500 m.a.s.l., and smaller glaciers are located on its northern slopes. At the foot of these higher peaks, strings of small lakes are aligned in connection to a river. The lakes have an overflow of water into a pond that is clearly linked to an open fracture system just above the main back-scarp of the RSF area (Fig. 4.39) this is in Domain II (Fig. 4.38). This small pond seems to flush water directly into the fracture system, since the pond disappears from the surface at the end of summer; a feature observed two summers in a row, and this is probably a yearly event (Fig. 4.40a-b).



**Figure 4.38:** Map showing the drainage area; above the unstable mountain side in Domain I and II. (Modified map Statkart, 2012)



**Figure 4.39:** Overview photo above the RSF area showing the fracture system which is working like drainage for the small pond in photo. (Modified photo Bunkholt, 2011)

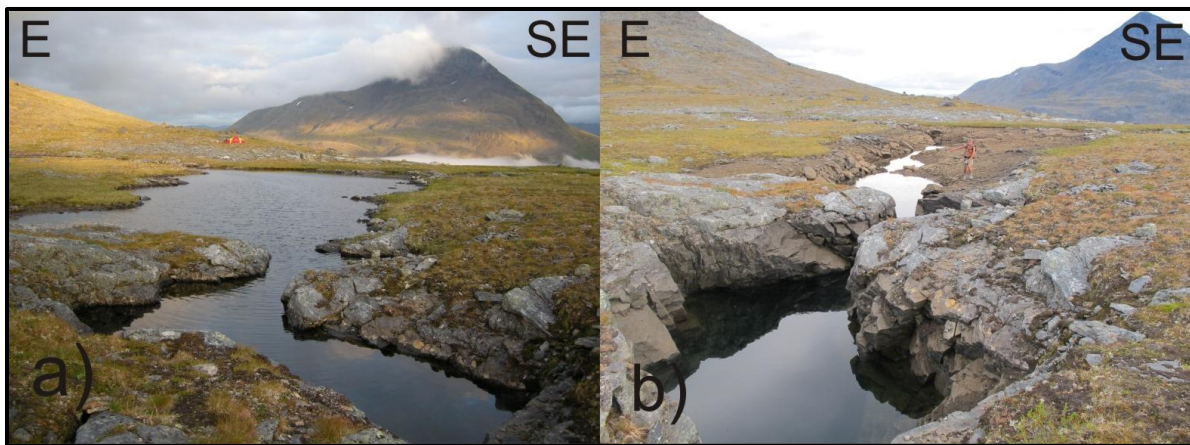
The RSF area was investigated for signs of water draining through crevasses and fractures by visual inspection. The area overall, contain some smaller lakes in Domain II, and during spring there is a heavy flow of water in a stream down the mountain side just south of the RSF area (Fig. 4.41a), the rest of the year it is totally dry. This area was also the location for a slush slide the 16<sup>th</sup> of May in 2010 (T. Figenschau, personal communication, 2011), which cleared the stream area for debris all the way down to the bedrock (see Fig. 1.7a, Fig. 4.6). A small pond in domain II; similarly, empties yearly (Fig. 4.39, Fig. 4.40a,b), and clearly is draining down into the fracture system in the area. In 2010 this emptying event happened the 11<sup>th</sup> of August, in 2011 the pond was emptied the 23<sup>th</sup> of august. After being emptied, running water from the mountain peaks and higher elevated lakes drained fully into this fracture system (Fig. 4.39).

The RSF area itself does not comprise any major streams or wet mark during the late summer. There was a big water pond present inside the main depression/trench in early June 2011 (Fig. 4.41b), but this pond had drained a week later. In the beginning of August 2011 a clear sound of running water from probably a few meters down below the loose talus material was

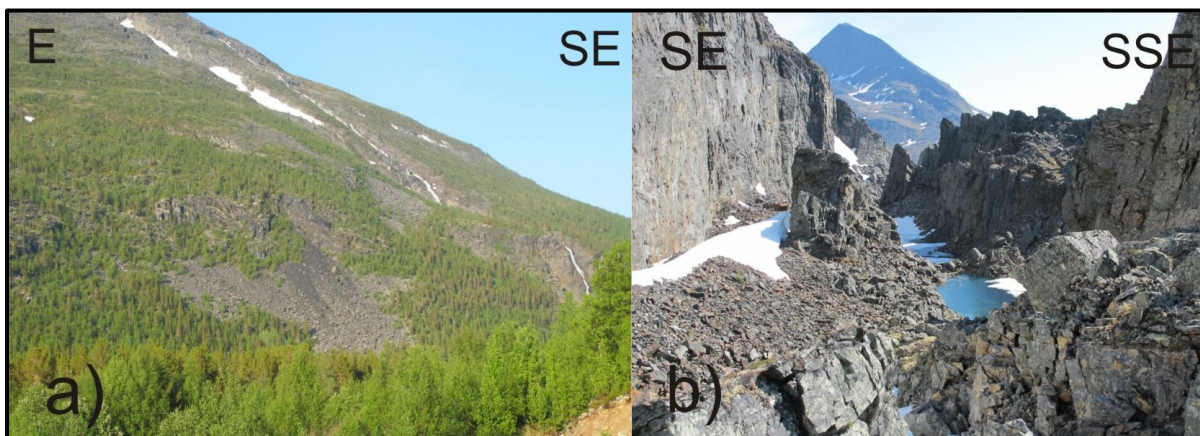


recorded in the more northern part of the major depression. This sound was obviously more than just melt water from the valley above, but rather, likely water shed into the fracture system. Finally, a small pond 1x1 m<sup>2</sup> has been observed in the southern end of the major depression (Fig. 4.6).

The area below the talus toe zone has also been investigated with the purpose of identifying water drainage systems. This was done in the beginning of June, and during heavy rain fall at the end of summer 2010 there was a small stream of water in the bottom of the RSF area. In July-August in 2011 this area was totally dry and there were no signs of water in this area (Fig. 4.6). During the field work, local people in the area told about late winter periods with ice-free conditions of the main river in Signaldalen, just below the RSF area (Fig. 4.38). The unstable ice or lack of ice can mean that there is water drainage up in the river from the internal part of the RSF area at this place (T. Figenschau, personal communication, 2011).



**Figure 4.40:** a) The small pond just before the emptying event in 2010. b) The drainage of the small pond in Domain II, has happened in 2011. The drainage is a rapid (one day) yearly drainage event, happening in late summer.



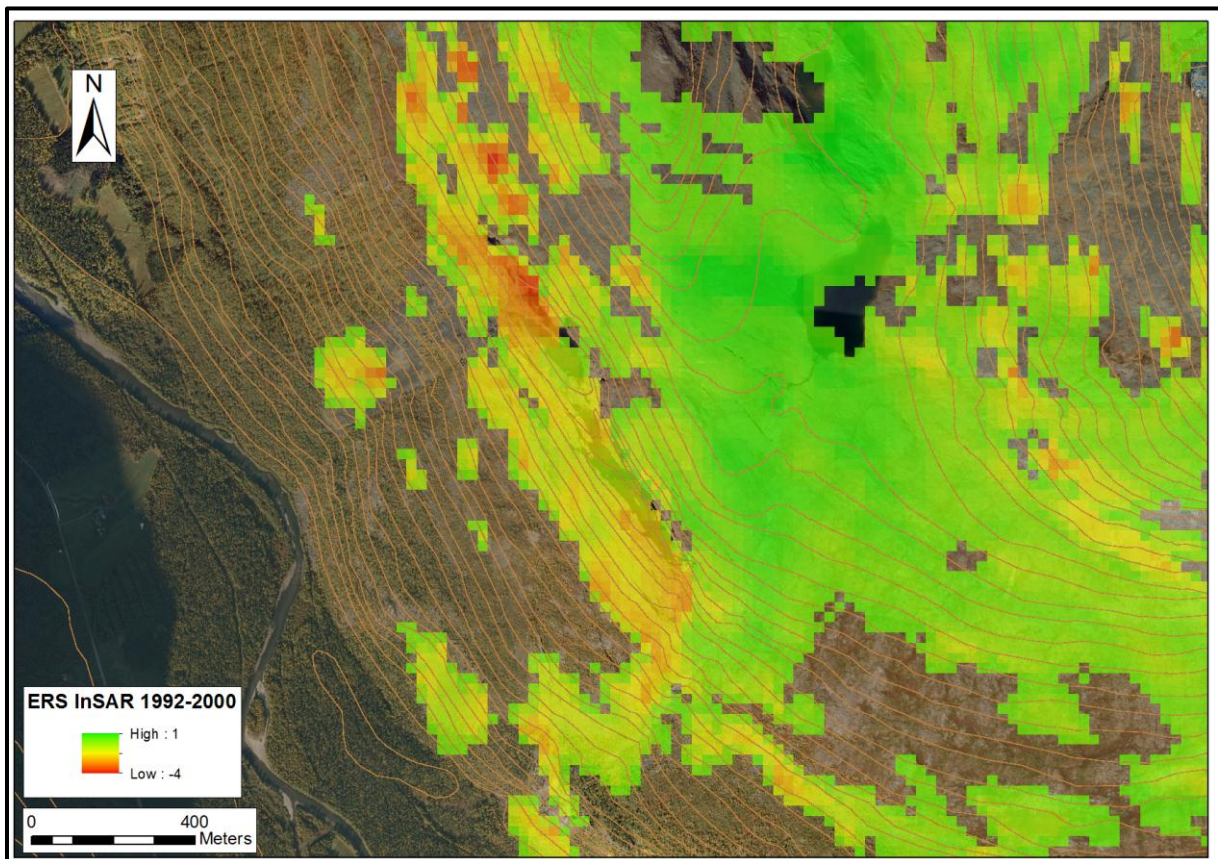
**Figure 4.41:** a) Panorama view the lower slope of the RSF area showing a river (to the right) that flushes water downwards close to the southern lateral scarp. This river on heavy snowmelt in the area, springs are over flowing, but later in the summer it dries out. b) The graben next to the back scarp has a small lake, a weak later it had drained away.



## 4.7 Description of In-SAR data

InSAR data may be used to record and/or monitor movement of the surface ground e.g. along fractures, geomorphologic surfaces, slopes, etc. (Lauknes, 2010; Hilley et al., 2004; Colesanti & Wasowski, 2006). Several sets of In-SAR data (from NGU) are available for the studied RSF area. Such data however, can only be a proof of the relative movement of the bedrock within the RSF area, because the satellite only measure movement straight up or down in respect to the satellite (Bunholt et al., 2011; Lauknes, 2010).

In an earlier report by NGU (Henderson et al. 2009) an In-SAR photograph was taken from ERS-1 Satellite (Fig. 4.42), showing that the area displayed a relative away from the satellite movement of as much as 10 mm/year during the period of 1992-2000. This largest relative subsidence is clearly confined to the RSF area and thus, likely controlled by the morpho-structures seen in the area (Henderson et al., 2009).



**Figure 4.42:** InSAR photo of the RSF area showing that the mountain slope underlain by the RSF area moved up to 10mm/year downwards in the time period 1992-2000. The InSAR documented subsidence is likely controlled by morpho-structures of the RSF area. (Photo is from Henderson et al., (2009), modified by Bunholt, 2012).

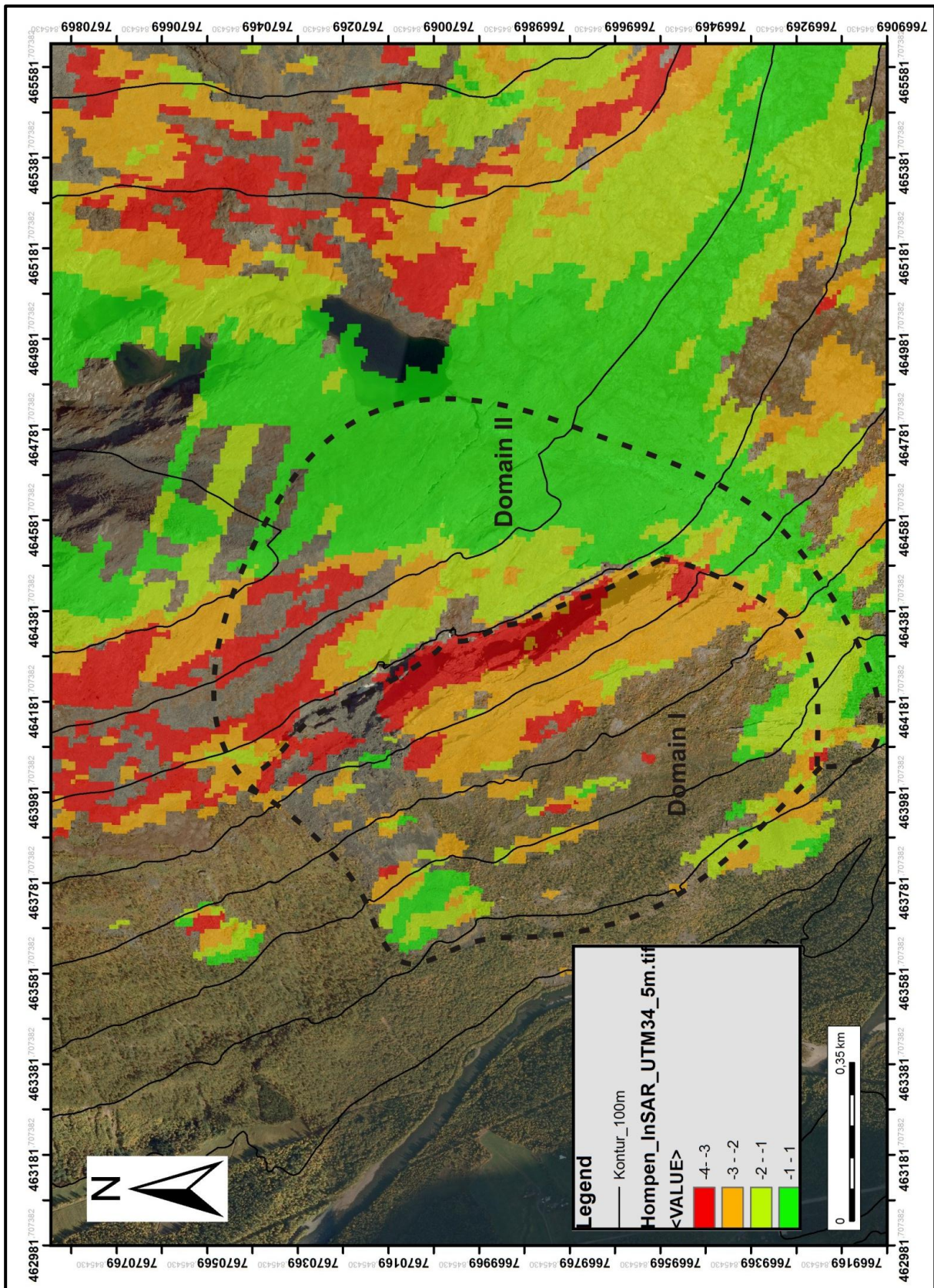
Recent In-SAR data, and those used in the present study, are from ENVISAT (from NORUT) (Fig. 4.43), a satellite which register movement in the terrain every 35 days in a descending route. The images are taken from a 21° angle (almost vertical) looking towards the west (290°), with a wave length of 5.6 cm. The data are from 2002-2010 (T.R. Lauknes, personal communication, 2011).

In the studied images, areas shown in red color move relatively away from the satellite and areas in green moves towards the satellite or are considered as relatively stable (Fig. 4.43). Areas with no color indicate that there is vegetation or other disturbances and no image data is available. The values are in vertical subsidence (mm/year) along line of sight (LOS) (Lauknes, 2010).

The green area (Fig. 4.43) is the plateau area above the main RSF area (Domain II), here the data shows a small amount of uplift and therefore may be stable. The same green color defines a belt that can be traced in a southern direction, still in the more or less stable, domain II area (Fig. 4.43). The red color in the middle of the photo (Fig. 4.43), indicating relative movement away from the satellite, overlaps well with the major depression of domain I just below the main escarpment or back-scarp, whereas stable domains indicated by yellow/green color represent the area above the back-scarp (Domain II). The red color becomes more intense when moving northward in the same elevation, and thus, clearly documenting that this is the area with the most evident subsidence away from the satellite (Fig. 4.43). The red colored areas farther north of the RSF area also display evidence of pronounced subsidence, but no field work have been done in this area. These domains, however, may reflect the continuation of the RSF and thus should be considered e.g. in later studies.

Among the more stable areas, small patches of yellow/green color areas suggest weak subsidence there as well, for example in the lower part of the RSF area (Fig. 4.43).





**Figure 4.43:** In-SAR photo over the Hompen area. The illustration shows on relative down subsidence in the middle part of the central graben, this is confirmed of structures in the field. The relative movement, in the northern part of the photo shows that there is subsidence in areas which were thought as stable areas. More fieldwork should be done in this area to make conclusions regarding visual morpho-structures. The map are made in Arc GIS with data from NORUT.



## 4.8 Description of dGPS data

In order to monitor potential downward movement of surfaces in the RSF area, a number of dGPS (differential Global Position System) points were installed in the field season 2008 by the Geological survey of Norway and the University of Oslo. The points were installed (drilled) into presumably stable rock as a fixed point (HO-6\_FP) and in blocks that were assumed to move as *rover points*, i.e. at two main cises in Domain I (points HO-1, HO-2 and HO-3) and in domain II (points HO-4, HO-5; see Fig. 4.44) (Henderson et al., 2009).

The method works such that a network of vectors is measured between points and change in position of these is calculated. If there is a change in coordinate position of the rover points, this is interpreted as slope deformation. A confidence level, which is based on the estimated coordinate standard deviations from the first and second measurements, is used to test if the points are moving or not. The points were measured in 2008, 2009, 2010 and 2011 (Eiken, 2012).

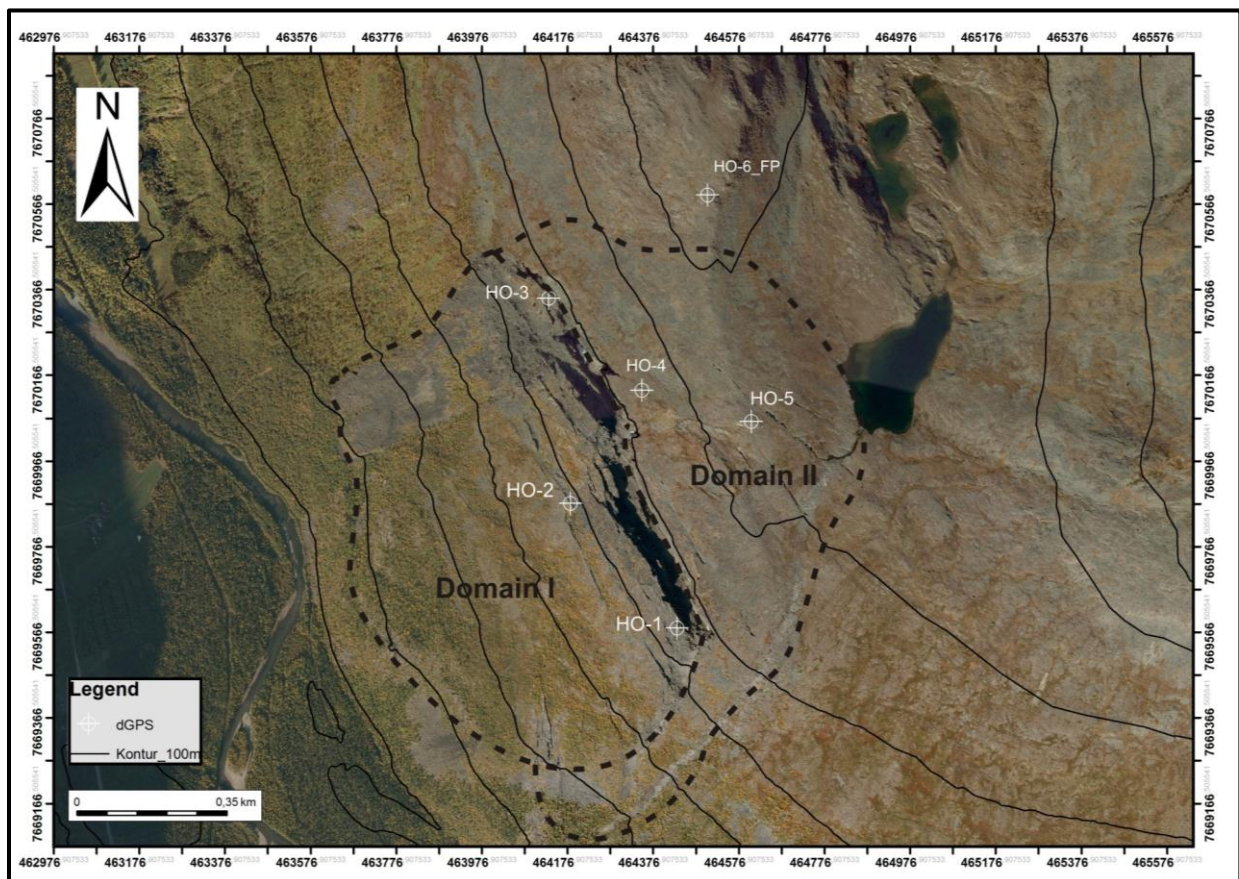


Figure 4.44: Installed dGPS points as a fixed point (HO-6\_FP) and rover points (HO-1, HO-2, HO-3, HO-4, HO-5).

The obtained results from individual point measurements are given as a change in the coordinates over time, and as direction and amount (distance) of the change. The data are shown in Table 2 and in graphic form (Fig. 4.45, Fig. 4.46); a more comprehensive presentation of the data is given by Eiken (2012).

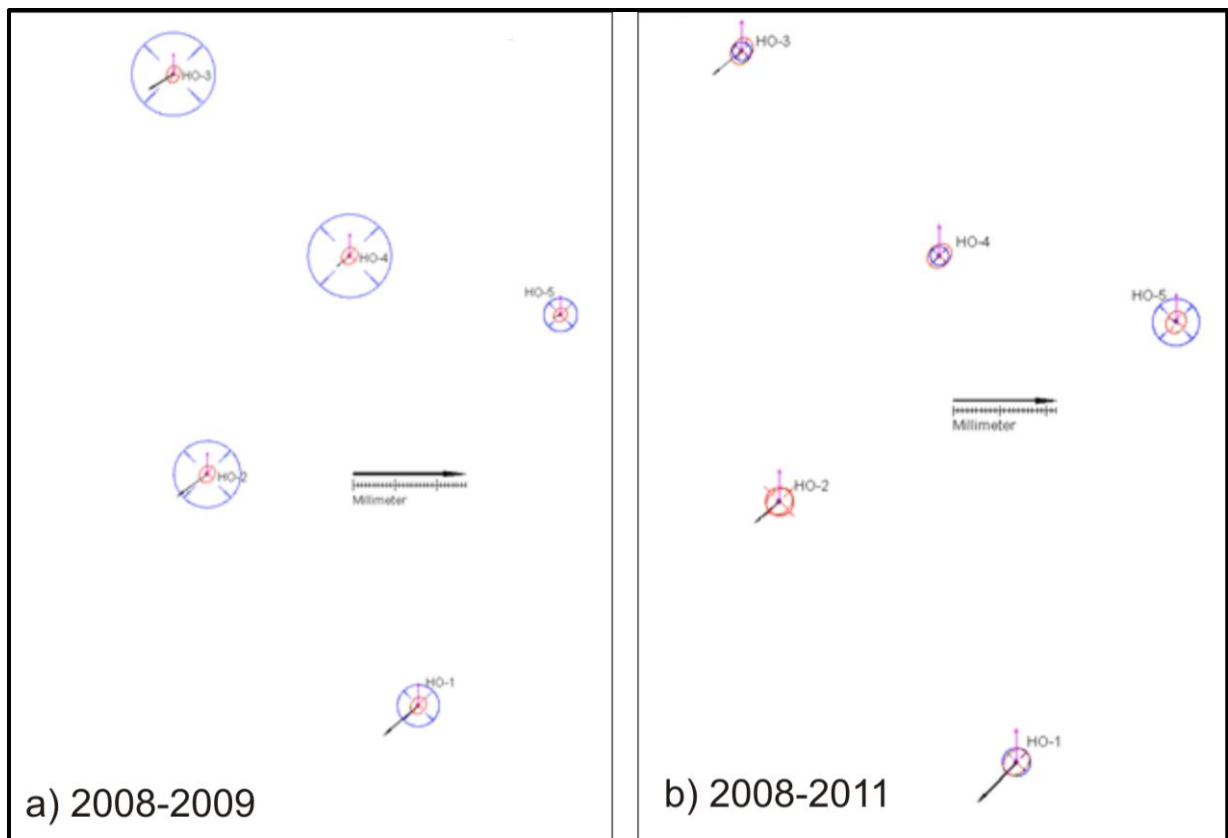
From Table 2 it seems clear that the measurements for the year 2010 do not correspond with the values obtained in earlier and later years. The reason for this presumed data error, can be e.g. that the weather during the summer of 2010 was very humid, and that heavy fog in the area affected the measurements (Eiken, 2012). Therefore, data from 2010 will not be taken account in this study.

When considering movements from the years 2008-2009 and 2011, the first year of results 2008-2009 show that the lower points, HO-1, HO-2 and HO-3 in Domain I, had a subsidence (Fig.4.45a) of 5-10 mm and a 7-11 mm horizontal change in southwestward direction (Table 2). Point HO-4 in Domain II, had a subsidence of 10 mm, but no significant horizontal change (Fig.4.45a). The HO-5 point in Domain II shows no significant changes (Fig.4.45a) (Eiken, 2012).

Morpho structures seen in association with these points (Fig. 4.44) are: point HO-1 is located on top of one of the highest counter scarps in the southern area. Point HO-2 is located on a smaller counter scarp in connection to a transfer structure. Point HO-3 is located in the north on a counter scarp area with smaller transfer structures. The counter scarp system is well developed in this northern area and located just above on of the major subsidiary scarps (Fig. 4.27a).

The total change in elevation of all points for the period 2008-2011 can be visualized through a confidence figure (Fig. 4.45b). The different confidence figures show that there is a pronounced horizontal change in the points HO-1, HO-2 and in HO-3 (Fig. 4.45b). But in a vertical sense, there is no significant change to refer from these data (Fig. 4.45b). The results, however, may include errors, such as weather conditions in 2010, additional calculating errors, etc., that can make the data uncertain (Eiken, 2012)

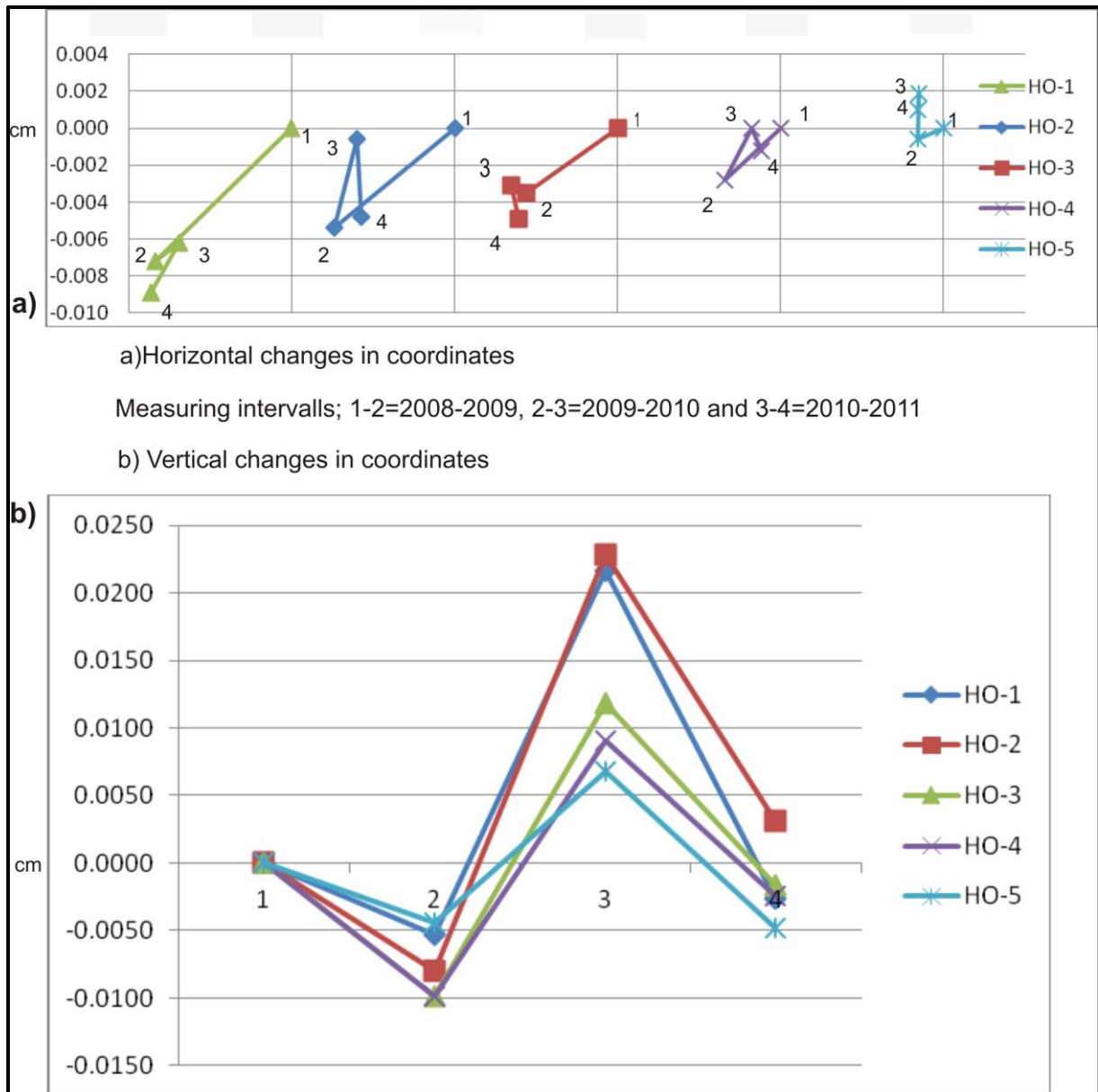
The measurements for year 2011 correspond with the first year results, but with less change horizontally (Fig. 4.45 a, b). The movement is a little more to the south (Table 2). (Eiken, 2012)



**Figure 4.45:** Illustration of confidence Figures over the change of the GPS points. For interval a) 2008-2009, the measurements show significant subsidence on all the points and horizontal movement with significance in HO-1. b) 2008-2011. Show that there is a horizontal movement to the south, with a clear significance of point HO-1, HO-2 and HO-3 and an almost significant subsidence at HO-5. Modified Eiken (2012).

The annual changes of plane and vertical movements can be visualized by graphic plots in which the horizontal change is plotted against the years on each (Fig. 4.46a). The other graph shows the vertical changes (Fig. 4.46b). In this plot both graphs for the year 2009-2010 (the second measuring interval) reveal deviating values, indicating opposite movement direction relative to the other measurements (Eiken, 2012).





**Figure 4.46:** Figure showing on change a) horizontally and b) vertically, note that the second measuring interval is deviating from the others. The second interval is interpreted as an error. Modified Eiken (2012).

The direction of movement of measured rover points is given as “goner” (400 degree). The first year interval, 2008-2009 of measurements show a southwest direction (a mean direction of 260 goner) of the moving points as seen in the Table 2. The year interval 2010-2011 shows a more southern direction (mean direction of 254 goner) as seen in Table 2 (Eiken, 2012).

**Table. 2**

PUNKT	År	N (UTM)	E (UTM)	H (ell.)	$\sigma_N$ [m]	$\sigma_E$ [m]	$\sigma_H$ [m]	dN [m]	dE [m]	Avst. [m]	Retning [° gon]	dH [m]
HO-6_FP	2009	7670576.6330	464508.4820	881.0360								
HO-1	2008	7669592.9045	464433.7783	577.6581	0.0006	0.0006	0.0016					
HO-1	2009	7669592.8973	464433.7699	577.6528	0.0003	0.0002	0.0008	-0.007	-0.008	0.011	254.89	-0.005
HO-1	2010	7669592.898	464433.7714	577.6797	0.0005	0.0006	0.0011	-0.006	-0.007	0.009	253.40	0.022
HO-1	2011	7669592.8956	464433.7697	577.6555	0.0007	0.0007	0.0017	-0.009	-0.009	0.012	248.91	-0.003
HO-2	2008	7669871.5361	464179.8936	517.1770	0.0006	0.0006	0.0015					
HO-2	2009	7669871.5307	464179.8862	517.1690	0.0003	0.0002	0.0008	-0.005	-0.007	0.009	259.87	-0.008
HO-2	2010	7669871.536	464179.8876	517.1998	0.0004	0.0006	0.001	-0.001	-0.006	0.006	293.65	0.023
HO-2	2011	7669871.5313	464179.8879	517.1801	0.0007	0.0007	0.0017	-0.005	-0.006	0.007	255.44	0.003
HO-3	2008	7670353.2941	464139.2371	613.9578	0.0006	0.0005	0.0015					
HO-3	2009	7670353.2906	464139.2315	613.9479	0.0003	0.0002	0.0007	-0.003	-0.006	0.007	264.44	-0.010
HO-3	2010	7670353.291	464139.2306	613.9696	0.0004	0.0005	0.0009	-0.003	-0.007	0.007	271.67	0.012
HO-3	2011	7670353.2892	464139.2310	613.9562	0.0007	0.0006	0.0016	-0.005	-0.006	0.008	256.92	-0.002
HO-4	2008	7670134.4314	464351.1542	683.5129	0.0006	0.0006	0.0016					
HO-4	2009	7670134.4286	464351.1508	683.5030	0.0003	0.0002	0.0007	-0.003	-0.003	0.004	256.14	-0.010
HO-4	2010	7670134.431	464351.1524	683.522	0.0004	0.0005	0.0009	0.000	-0.002	0.002	300.00	0.009
HO-4	2011	7670134.4302	464351.1530	683.5105	0.0006	0.0006	0.0015	-0.001	-0.001	0.002	250.00	-0.002
HO-5	2008	7670063.4433	464604.7617	763.6608	0.0005	0.0005	0.0014					
HO-5	2009	7670063.4427	464604.7601	763.6564	0.0002	0.0002	0.0006	-0.001	-0.002	0.002	277.16	-0.004
HO-5	2010	7670063.445	464604.7602	763.6676	0.0004	0.0005	0.0008	0.002	-0.001	0.002	357.46	0.007
HO-5	2011	7670063.4443	464604.7601	763.6560	0.0006	0.0005	0.0014	0.001	-0.002	0.002	335.56	-0.005

Table 2: Results for coordinates and changes for the DGPS points at Hompen ( $\sigma_E$ ,  $\sigma_N$  and  $\sigma_H$  are the uncertainties in the measurements; dN, dE and dH are changes in North-South, East-west and elevation direction, respectively; Avst. is true movement, meaning the hypotenuse between dN and dE). Retning is the value for the local movement direction (marked with yellow color). The data are modified from Eiken (2012)

# 5. Discussion

## 5.1 Introduction

In this chapter I discuss the origin and processes that may have operated during the formation of the RSF in the study area. The discussion is based on the data presented in chapter 4 and will be focused on (i) the relationships between structural and morpho-tectonic elements, (ii) the relation between morpho-tectonic data and InSAR and dGPS measurements (iii) kinematics and mechanisms of formation, classification, (iv) initiation, controlling factors and driving forces, (v) regional implications of the study, and finally, (vi) a short hazard evaluation for further avalanching.

The RSF study area was divided into two domains. The division of the RSF area into Domain I and Domain II, was based on observed morphological structures in the different areas and the dominating scarps on ortho photos over the area. The division can now be supported with data and observations from the field. Domain I is structurally confined to the area below the back-scarp zone (Fig. 5.7), whereas Domain II represents the area which seems to be stable, but still has the potential to develop into a RSF since it contains internal structures similar to those of Domain I (e.g. tensile fractures).

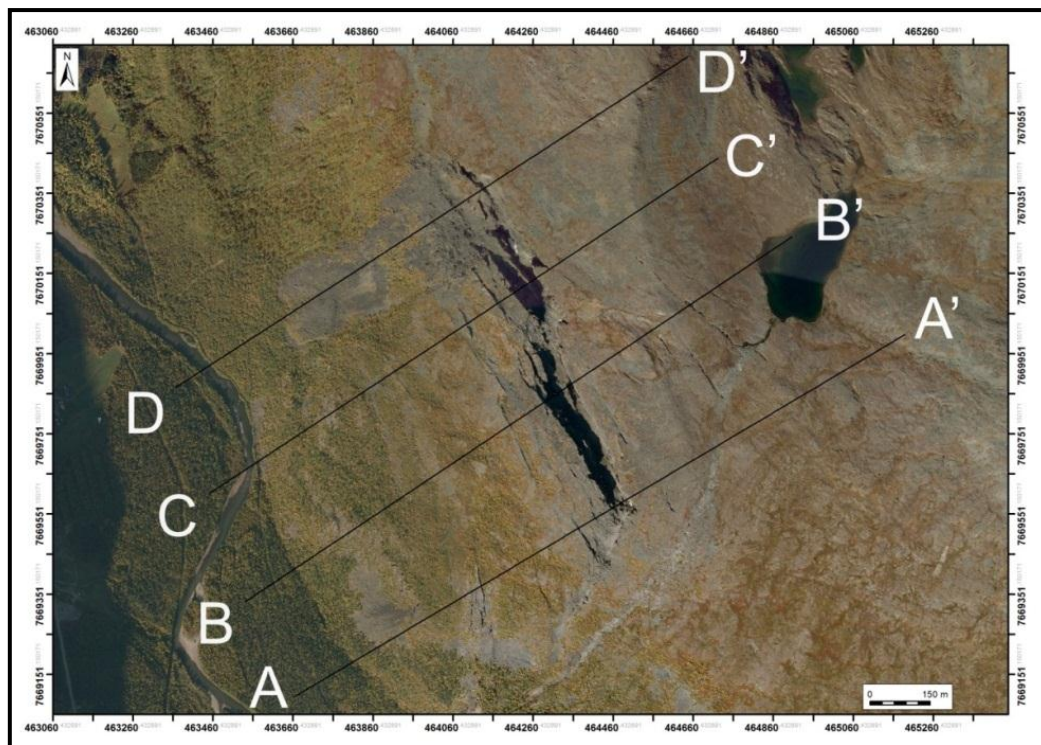
In Domain I, the back-scarp defines a NW-SE striking major fracture or “normal fault” that forms the upper and eastern boundary of the domain. The southern boundary is a NNE-SSW striking, steep lateral scarp relative to the back-scarp that displays internal foliation striking c. SW-NE  $30^\circ$  dip to NW, meaning that the dip direction is into Domain I. This lateral scarp seems to terminate in the valley to the south, but may continue further south (Fig. 4.7). The foliation in the back scarp strikes NW-SE with moderate dip to SW; thus dipping downslope into Domain I (Fig. 4.7). The northwestern boundary of the RSF is defined by the talus from the landslide situated there. These observations support the hypotheses that Domain I represent the main RSF area displaying the most movement and comprise movement-related morpho-structures, while Domain II is an area which seems to be stable but may potentially develop into a larger RSF area.



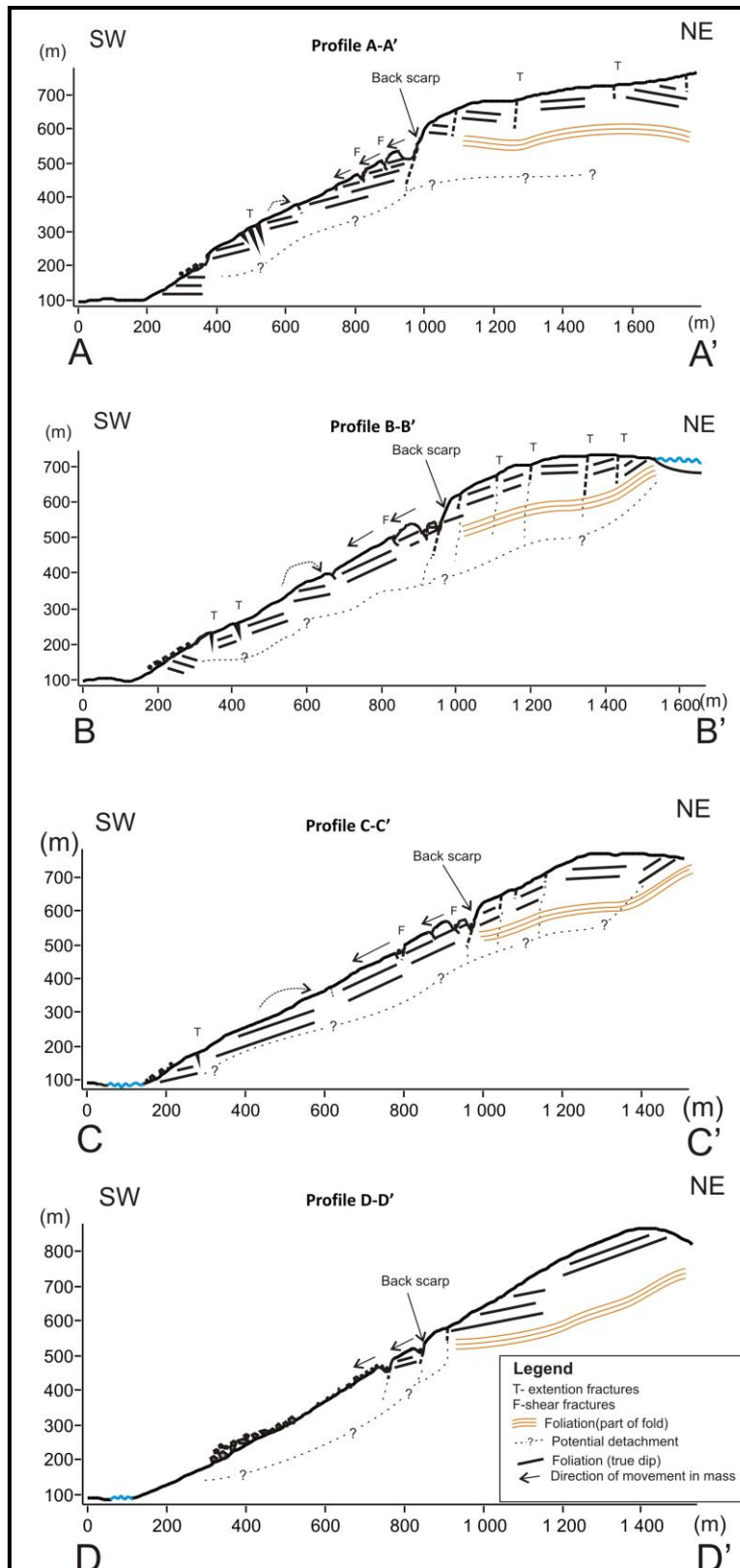
## 5.2 Discussion and interpretation of the structural and morpho-tectonic elements

The orientation of the structural and morpho-tectonic features in the RSF is fundamental when trying to evaluate the movement history and evolution of a major RSF system (Agliardi et al., 2001). In this subchapter there will be a discussion of the different structures and fabrics (ductile and brittle) observed in the bedrocks as well as the morphological elements in the RSF area, and the character and kinematic interpretation of these fabrics will be used to suggest processes of formation.

The discussion is based on data descriptions from Chapters 3 and 4, and on an interpretation of four main cross-sections through the RSF (Figs. 5.1 and 5.2) and supplementary enlarged profiles (Fig. 5.4). The most important aspect is to compare the orientation of foliation and fractures within the RSF, with corresponding orientation data outside the RSF, may help to sort out e.g. movement processes of the RSF (see Chapter 5).



**Figure 5.1:** Location of the four main cross-sections through the study RSF area shown in Figs. 5.2 and 5.4.



**Figure 5.2:** Profiles (1:1) across the RSF area in various domains (see Fig. 5.1 for location of cross-section lines), illustrating the variation in dip of the foliation according to location in the RSF area. The dip angle is apparent dip calculated with respect to the profile lines. Foliation data are shown in Fig. 4.7 and Fig. 4.10. Note a major, apparent fold structure (labeled with orange line) in the upper part of the RSF area. Potential detachments may occur in the bedrock in the RSF area as drawn by stippled lines view (Fig. 5.4b) for explanation of detachment plane. Major morpho-structures as scarps and counterscarps and major fractures are slightly exaggerated. Profiles are made in ArcGIS, and modified with drawings in Corel Draw4.

## 5.2.1 Discussion of bedrock structures in the RSF

### 5.2.1.1 Foliation

The interpreted profiles (Fig. 5.2) show that there is a significant variation in the orientation of the foliation, from the valley through the RSF area. The foliation strikes may help us to find the extent of the potential RSF area and to restrict the area.

The foliation strikes NE-SW with steep dip to NW in the southern part of Domain II, and in the most southwestern part of Domain I the foliation turns more NW-SE with a gentle dip to NNE, into the RSF area (Fig. 4.7, Fig. 4.9). This change in attitude can be interpreted as due to the presence of a lateral boundary structure to the south and southwest that controlled the outline of Domain I in RSF area, with the southern scarp as the oblique boundary of the RSF to the south. This structure however may have included parts of Domain II. The foliation in this southwestern part of Domain II has a dip direction toward NNW into Domain I, which may be favorable in respect of propagation of lateral scarp into Domain II (Fig. 4.7).

In Domain II (above the back scarp); the average foliation strikes NW-SE with a moderate dip to SW, which is similar to the average foliation inside the RSF (Fig. 4.9). The back scarp (Fig.4.9) cuts steeply through the average foliation, and thus unlikely controlled the establishment of the scarp as the upper boundary and extent of the Domain I in the RSF. The low angle of dip of the foliation in the back scarp does not by itself make a potential risk of propagation in NE direction, but the area show several tensile fractures above the back scarp (Fig. 4.39, Fig. 5.2), which may be a sign on that more movement are under development.

In some places along and above the back scarp the foliation dips gently inward toward the scarp (Fig. 5.2A), suggesting that this upper area of the RSF may represent an anticlinal fold structure, formed due to inward rotation against a normal fault producing a roll-over structure (Fig. 5.2A) (Gibbs, 1984), or alternatively, the back-scarp formed on the downslope attitude of a Caledonian fold (cf. Binns 1967). The area above the back scarp may be a mesoscale major antiformal fold, and this may be a major flanks of an open anti fold with axial plane striking NW-SE with dip to the NW (Fig. 3.6, Fig. 5.2). Such interpretations would help to explain the variation of foliation above the back scarp and corresponds largely with Binns (1967) structure map (see Ch. 3.3.1).

The variation in orientation of the foliation may also be related to other structures e.g. mega boudins, amphibolite lenses or pre-existing fractures in the bedrock, however, not observed



here but abundant elsewhere in Domain I (see Chapter 4). It should be kept in mind that there may be fold structures which may have been overlooked and now can give misleading data.

If the rotation of the foliation toward the back scarp is due to movement of the RSF on a normal fault below, the degree of rotation can be estimated and similarly, variations of the foliation relative to other internal escarpments (e.g. counter scarps) in the RSF (Fig. 5.2) can help to estimate the local internal rotations.

The variation in attitude of the foliation observed in the profiles (Fig. 5.2) in the areas below the back scarp are interpreted to be due to internal movement in the RSF and rotation against potential sliding surfaces at depth (see Ch. 5.4.4). The data and profiles show only a slight variation in dip direction of the foliation between the upper and lower area of Domain I. These slight variations are interpreted to be because of down valley rotation or tilt of smaller, internal blocks in the upper part of Domain I, where the dominant morpho-structures are counter scarps (Fig. 4.10, Fig. 5.4). The down dipping surface of the counter scarps is the foliation plane (Fig. 4.10, Fig. 4.28A), and one possible interpretation would be that the foliation was a sliding surface at depth (Fig. 5.2A, see further discussion in Ch. 5.2.2).

In the middle portion of the RSF (Fig. 4.10, Fig. 5.2A, B, C) the foliation dips more gently outward, i.e. toward the slope. This slight dip toward the slope may be interpreted as rotation due to the RSF getting stacked or imbricated, as in a forward propagating thrust stack (Mahr et al., 1977). The lowest part of the profiles (Fig. 5.2A,B) shows a sub horizontal to inclined, towards the mountain rotated foliation, and the foliation is in a mica schist horizon (Fig. 3.4a). This mica schist unit is not exposed in the more northern part of the RSF. An interpretation is that in the southern part of the RSF, this mica schist layer and its foliation may have worked as a sliding plane for parts of the RSF (see Ch. 5.4.4).

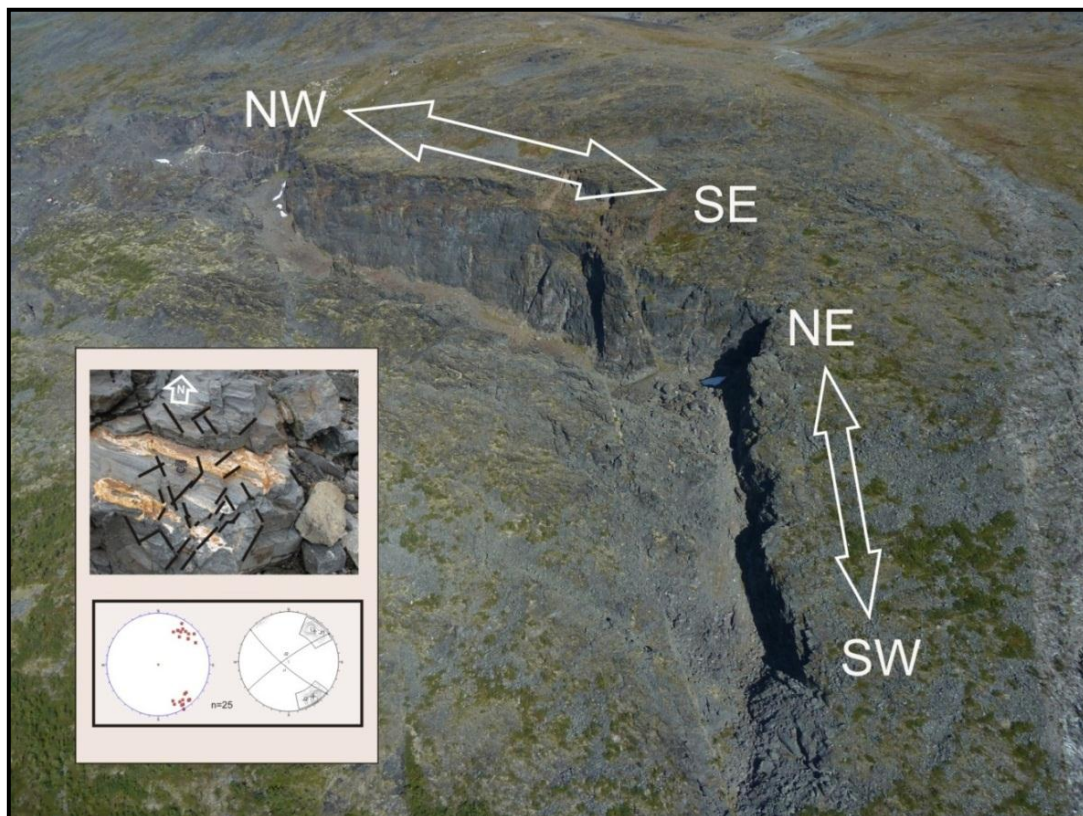
### **5.2.1.2 Fractures**

The lineament map of the study RSF area (Fig. 4.1), Domain I, shows a dominance of lineaments striking NW-SE, with subordinate lineaments striking NE-SW. These two main directions also seem to correspond with the boundary escarpments that enclose the RSF area (Fig. 5.3).

Fractures seen in Domain II, display a main strike NW-SE with steep to sub vertical dip (Fig. 4.12), and these fractures are common above the back scarp. On a smaller scale, fractures in unaffected bed rocks of Domain II (Fig. 4.14, Fig. 5.3) include obvious sets striking both

NW-SE and SW-NE, which are the same directions as the back scarp (NW-SE) and the lateral southern scarp (NE-SW) (Fig. 5.3), respectively. This suggests that the presence of fractures with favorable NW-SE and NE-SW trends may have controlled the extent of the RSF area, the back scarp defines the crown of Domain I and the lateral southern scarp represents the lateral boundary to Domain I today.

There may be a propagation of both the back scarp and the southern lateral scarp into the more stable areas in Domain II (Fig. 5.7) supported by InSAR movement. The fractures above the back scarp (Fig. 4.39) may be interpreted as gravitational fractures, resulting from tensile fractures that opened when the back scarp developed (Fig. 5.11) (see Ch. 5.4.1). Alternatively they may be due to some kind of back propagation of Domain I, against a deeper located detachment (see Ch. 5.4.4).



**Figure 5.3:** The southern lateral scarp striking NE-SW and the Back scarp striking NW-SE, showing the similar directions as seen on the small scale analyses inserted photo. (Modified background photo Bunkholt, 2011)

In Domain I, which is the area displaying most morpho-structures such as scarps, counter scarps and trenches, fractures have a dominant strike NW-SE (see Ch. 4, Fig. 4.16). Fractures striking NNE-SSW occur in the upper part, where it also has been registered W-E striking fractures (Fig.4.15). It seems clear that fractures striking NW-SE are the dominant in the upper part of the area (sub areas W, Q, T, X). In the most northern area (W) fracture sets

striking NW-SE and NNE-SSW dominate, this area having experienced a smaller landslide (Fig. 5.2D). One reason for this landslide in the northern part of Domain I may be that the lithology here was more susceptible to fracturing and weathering processes (Fig. 3.5), leading to a potential zone of weakness and hence sliding.

There is still a dense pattern of brittle structures such as fractures in area W (Fig. 4.16), and this pattern may have indirectly controlled the evolution of an RSF area. An interpretation is that such a high density of fractures in different directions demonstrates a process of disintegration of the unstable area. It is likely that the area will experience frequent failure events such as toppling (see Ch. 5.4.3) but the volumes may be low (Fig. 4.27) (Ambrosi & Crosta, 2006; Agliardi et al., 2001, 2009; Saintot et al., 2011; Blikra et al., 2006a).

In the south eastern area (Y) (Fig. 4.16); most fractures strike WNW-ESE and NNE-SSW but also NW-SE are represented. This area consists of high frequency of counterscarps striking c.NW-SE which have been truncated of several fractures (see Ch. 4.4.3.2).

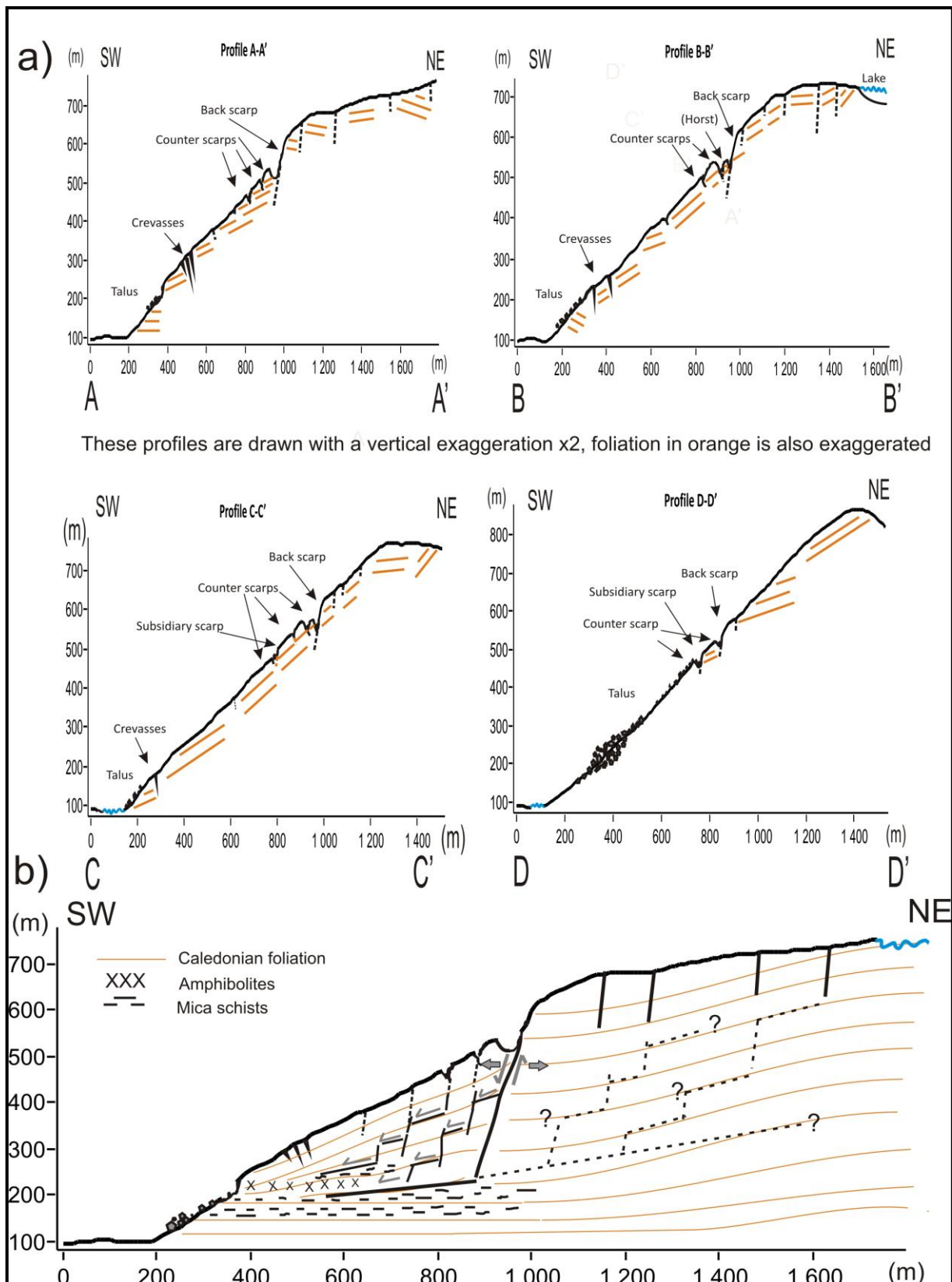
Crevasses occur frequently in area X (Fig. 4.16). The strike direction here is dominantly NNW-SSE but also more NW-SE striking sets occur. The bedrock sampling reveals that in this area competent bedrock such as granite occurs at the surface (Fig. 3.3) that may fracture when deformed. Below this crevasse zone there is a more amphibolitic rock resting on top of a mica schist. Here an interpretation is that the bedrock on top of the mica schist may have slid on the underlying substrata. A similar movement pattern is seen with crevasses on glaciers (Benn & Evans, 1998). An interpretation as to why this area is experiencing this form of fractures may be lithological differences under the bedrock at the surface (Fig. 3.4), and the total movement pattern for the RSF area (Fig. 5.4b, see Ch.5.4.4).

From this discussion it can be concluded that the development of the study RSF may to some extent have been structurally controlled. Notably, it seems clear that the pre-existing fractures and joints in Domain II and their orientation relative to fractures within the RSF (Domain I) may have been critical in the development of the RSF area (cf. Agliardi et al., 2001). The origin, significance and regional correlation of the fracture sets will be discussed further in sections 5.5.3 and 5.5.7.



### **5.2.2 Discussion of the relationship between morphological element and foliation-fractures in the RSF area**

In this section, morphological elements in the RSF that may have an obvious relation to bedrock foliation and fractures will be discussed, as these elements may tell us something about the initiation and movement history of the RSF. In particular, the strike orientations and dip of these structures relative to the inferred movement planes are important in order to sort out RSF mechanisms and controlling factors. The data and relationships will be discussed using the cross-section interpretations (Fig. 5.2) and selected enlargements (Fig. 5.4).



**Figure 5.4:** a) Illustration showing four profiles (1:2) over the whole potential RSF area; major morpho structures are labeled. Major fractures observed in the area are marked with vertical dashed lines. b) An geological model over Hompen RSF, and potential detachments. I) listric planar II) a listric step-wise geometry, vertical fractures connecting weakness structures into a step-wise geometry (Blikra et al., 2006a).

### 5.2.2.1 Escarpments

The most obvious and pronounced escarpment is the overall NW-SE striking, steep **back scarp** (Fig. 4.6, Fig. 4.21, Fig. 5.4). This scarp is not continuous along strike in its upper part, but makes a step or transition to form two en-echelon scarps, with change to more NNW-SSE direction in northeast. The back-scarp and its accompanying major graben-like feature resemble that of an extensional graben system (e.g. Gibbs, 1984) and thus, likely were driven by combined extension and gravity (Fig. 5.11). As a consequence, the area where the back scarp makes the step, is interpreted as an oblique transitional zone or transfer zone (Gibbs, 1984; Lister et al. 1986) (Fig. 4.21, Fig. 4.31, Fig. 5.6). The area where the back scarp makes the step may be considered as a collapsed ramp structure or relay ramp (Trudgill & Cartwright, 1994), developed in connection with an oblique transfer structure (Fig. 4.31c, see Ch. 5.2.2.4). This may be an effect of the step the back scarp takes.

Regarding the depth of the back scarp in the RSF area (Fig. 5.4b) the interpretation shows how potential breaks in the bedrock foliation at deeper levels may occur along steep fractures parallel to the back scarp (Fig. 5.2, Fig. 5.4b). In such places the steep fractures may link to the foliation at deeper levels in the bedrock and form step like or listric detachment, it is speculated how deep the back scarp may proceed downwards into the bedrock (Fig. 5.4b). Back scarps may work as a crown (Fig. 5.6, Fig. 5.7) to the RSF area and are common structures seen in large-scale RSF areas elsewhere (e.g. Agliardi et al., 2001; Ambrosi & Crosta, 2006; Blikra et al., 2006a; Braathen et al., 2004; Jarman, 2006; McCalpin, 1999; Osmundsen, 2009; Saintot et al., 2011).

The other major scarp is a **lateral southern scarp**. The rock mass in this location seems to collapse along the scarp after movement; talus and rock materials are just beneath the scarp, the dip direction of the foliation supports a small sliding mechanism (see Ch. 5.4.3), and toppling (see Ch. 5.4.3) may still be active locally in this part of the area. In connection to the southern scarp there is a lineament seen in the aerial photo (Fig. 5.3), which is interpreted to be a parallel lateral anti scarp to the lateral southern scarp, striking NE-SW.

In the most northern area, there is a high density of fractures displayed in area W (Fig. 4.16, Fig. 4.27). The effect of these fractures may be one reason why the big talus field developed just under the big **subsidiary scarp** in the area. The bed rock here seems to be in a contact zone of the upper hornblende schist and the lower more massive amphibolite (Fig. 3.5). As clearly seen in the photos (Fig. 4.27), the upper zone with hornblende schist is much more



exposed for fractures both laterally and transvers cutting the foliation. The mafic rock is less flexible for adjustments; this again can lead to the mafic rock experiencing more erosion. This may be enhanced by fluid flowing through the cracks (Blatt et al., 2006).

There is a “toe zone scarp” (Fig. 4.6, Fig. 5.7) which can be seen as subsidiary scarps. This scarp is situated in the lowest part of Domain I. The scarps are several meters high and vertical or overhanging. These scarps may have been formed by different processes, e.g. glacial erosion (see Ch. 5.5.1) and may be the exposure of the lower part of the moving RSF.

### **5.2.2.2 Counter scarps**

Counter scarps occur throughout in Domain I (Fig. 4.28), but the map shows that the counter scarps dominate the upper part (Fig. 4.6, Fig. 5.7, Fig. 5.4). The counter scarps are linear to sub linear features in connection to either the back scarp or subsidiary scarps. The counter scarps is highest in the south (c.10 m); towards the north the height gets lower (c.4 m) and a more swarm-like ensemble of counter scarps are present (Fig. 4.28A). In the swarm area of counter scarps, there is also a transfer scarp (Fig. 4.31, see Ch. 5.2.2.4) which bends into the counter scarps. Further north the counter scarps get higher (c.8 m) again. In the very far north the counter scarp is connected to the subsidiary scarp in the area that has experienced failure as a landslide (Fig. 5.6, see Ch. 5.4.5). From these observations, it may be inferred that during the initial failure of the RSF, strain that caused failure (extension and gravity) was laterally segmented or moved along-strike from one area to another (see Ch. 5.2.2.4), creating different types of counter-scarps.

By comparison, similar morpo-structures such as ridges, anti-scarps or counter scarps are common features in RSF areas elsewhere (Agliardi et al., 2001; Ambrosi & Crosta, 2006; Blikra et al., 2006b; Braathen et al., 2004; Jarman, 2006; McCaIpin, 1999; Osmundsen, 2009; Saintot et al., 2011). These structures are the result of the development of the scarp itself, i.e. they form in connection to the scarp. In extensional systems it is common to see antithetical structures like fractures or faults in the hanging wall (Lister et al., 1986; Davis & Reynolds, 1996; Bergh et al., 2007). Counter scarps are often seen as linear features alone or in swarms (Agliardi et al., 2001), and the displacement is usually vertical/horizontal and perpendicular to the back wall (Kinakin & Stead, 2005). Many small movements on different sliding planes (Fig. 5.4b) in the bedrock may give the result of major movement at the surface, as seen with the counterscarps in the upper area of Domain II and may explain why most morpo structures are seen in this area and registered movement (Blikra et al., 2006a).

### 5.2.2.3 Depressions and Trenches

The major topographic depression seen in the area is located just below and parallel to the main NW-SE striking back scarp and bounded to the southwest by the counter scarps (Fig. 4.6, Fig. 4.30c, d, e, Fig. 5.7). It can be classified as a major graben/trench (Table 1) (termed central graben), or alternatively a half graben, located between the back scarp and the first counter scarp (Fig. 4.6). The area has a major down-drop of c.20 meters and horizontal offset of 60-80 meters. Further north in the depression there is a collapsed counter scarp which can be interpreted as a horst when viewed from the north, but with closer observations it is interpreted as a collapsed counter scarp (Fig. 4.29). The entire depression has a massive infill of block material that may have formed by mechanical toppling (see Ch. 5.4.3).

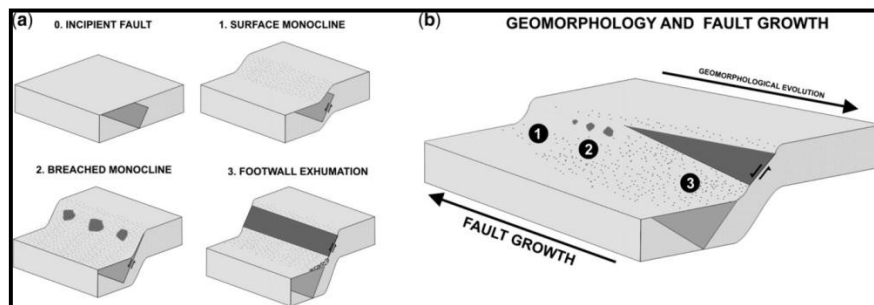
The main depression is interpreted as due to dip-slip (normal) movement of the entire RSF from the back-scarp, and may have formed below active faults/fractures that propagated out from the scarp and into the footwall behind the back-scarp. This backward propagation of fractures into the footwall may have formed the depression in a similar way as graben-structures form in extensional regimes; as half grabens or central grabens, the latter occurs when a depressed area is bordered by parallel scarps (Agliardi, 2001; Lister et al., 1986). It also resembles well the mechanism of in-sequence development of normal faults in a graben-forming event (cf. Lister et al. 1986).

The origin of the central graben in Domain I is probably a result of subsidence and extension of the rock mass at the same time. The orientation of the structure is parallel to the observed back scarp and the counterscarps, indicating extension and normal dip-slip movement down-to the southwest. In many RSF areas, grabens of this type are common structures in combination with a back scarp, and form the upper limit for the RSF area (Agliardi et al., 2001). At Hompen this major graben may not be the upper limit of RSF area, since major fractures also occur above the back scarp, which may in the future propagate and develop the Domain II area into a potential failure area (Fig. 4.39).

In addition to the main graben, the studied RSF area shows several smaller half grabens which may better be called trenches because they are smaller in size. Most of them are in connection with a boundary scarp (Fig. 4.30a, b). A trench just above the main back scarp (Fig. 4.30b) can be traced well into Domain II (Fig. 4.24a, b), and this development may be interpreted as a backward propagation of the RSF area. The trench has a steep, monoclinallike upper edge and consists of edgy rock material that may be a result of frost weathering

processes such as frost shattering (see chapter 5.5.6). However, to achieve such a large amount of rocky material from frost weathering, there is need for a large number of frost thaw cycles and the angle of the slope where the trench is located should be more gentle than observed. The current steep attitude of bounding fractures would drain water too fast from the area (French, 1996).

The most likely interpretation of this particular trench (Fig. 4.30b) is that it formed along a progressively developing fracture/fault (Fig. 5.5) (Henderson et al., 2011). It is common that graben and trenches can range from tens of meters to less than a meter, and the movements may be both vertical and horizontal. This fits well with the observations at Hompen (Kinakin & Stead, 2005).



**Figure 5.5:** Illustration showing how a fault may evolve. Starting with a monocline in the surface, the fault may be active but is not visible because of rubble on surface (Fig. 5.9a), with time the scarp may be fully exposed. (Henderson et al., 2011).

#### 5.2.2.4 Oblique structures

In this section, structures that have an oblique appearance are discussed. The two most important occurrences are (i) in the central part of the main depression (central graben) described above, and (ii) along the southern boundary of the RSF (Fig. 5.7). Regarding the former, the oblique structure splits the central graben into two parts and includes as well a collapsed relay ramp (Fig. 4.31c) and, thus the structure may represent a transfer zone (King, 1978; Larsen, 1988; Morley et al., 1990) The other main oblique structure is the southern lateral scarp that may also be considered as a transfer structure in the studied RSF area. Transfer structures are common in extensional regimes and may work as accommodation zones between the scarps, and/or they form along the geographic (or structural) margins of a moving block (e.g. King, 1978; Larsen, 1988).

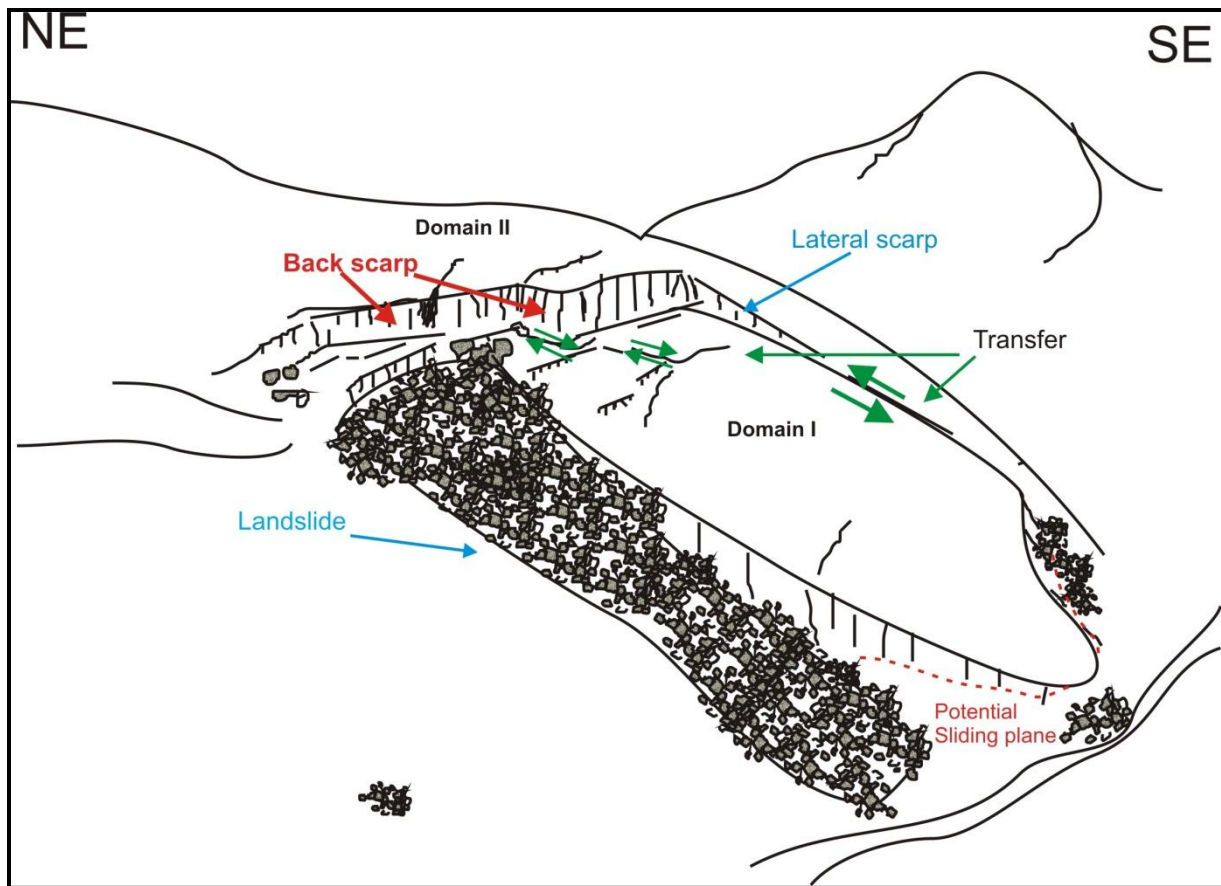
There are several smaller transfer structures (Fig. 4.6 and 5.6) in the RSF area Domain I, connecting counter scarps with each other. The transfer structures observed may have formed



when rock masses on either sides of a moving rock body accommodated for different speeds. For example, the southeastern part of the RSF may have moved faster than the northern part (see Ch. 4.8), therefore the structures will display a shear component inside the Domain I area (Fig. 5.6) as oblique scarps and the oblique counter scarp in the south (Fig. 5.3). One way to achieve differential movements is when the RSF can be linked to a detachment surface at depth (e.g. along foliation surfaces). In this case there may be lithological differences in the detachment that would create, for example, ramps and flats when the hanging wall moves across the detachment. Transfer zones may develop as an effect of the presence of such ramps and flats, when affected as a linked system of different slip surfaces (Gibbs, 1990).

If the oblique structure of the central graben of the studied RSF (Fig. 5.6) is a transfer zone (see chapter 1.6) there should be an oblique fracture surface between two fracture surfaces or main scarps. Furthermore, in order to classify as a transfer structure, the oblique fracture should have been active at the same time as when the movement appeared; when the movement is transferred from one place to the next (Morley et al., 1990). The area is accommodating to its new situation and zones develop in response to mechanical interaction between half grabens. These zones can be interpreted as releasing overlap zones where the arrangement and displacement of the rock cause stretching/extension within the overlap zones (King, 1978; Gibbs, 1984; Lister et al., 1986; Rosendahl 1987; Morley et al., 1990; Fossen, 2010).

Where the transfer structures are oriented perpendicular to or oblique/transvers to the back scarp or subsidiary scarps, it is possible to use the direction of the structure as an indication of transportation direction (if the transfer structure does not show a throw more than in the roll-over) (Gibbs, 1990). The structure will be parallel with the motion of the block (Fig. 5.6) (Gibbs, 1984; Henderson et al., 2006).



**Figure 5.6:** Schematic “sketch” diagram showing the overall structure of the RSF area and interpretation of the oblique structures and transfer zones, and presumed movement directions along the oblique structures. Some of the structures are exaggerated, e.g. potential sliding plane.

### 5.2.2.5 Talus

Talus material is seen all over the rock slope failure area, but there is a bigger field of talus material in the central graben and in the northern part, in connection with a subsidiary scarp (Fig. 4.6, 5.2, 5.6). The talus material in the central graben is formed by disintegration and fall of rock into the graben through toppling processes (see Ch. 5.4.3).

The area that comprises talus material in the northern area has experienced total failure and is interpreted as a rock avalanche (landslide), of what is a counter scarp to the back scarp (Fig. 5.7); the rock material has been estimated to have been deposited several thousand years ago, through lichometry dating (see Ch. 4.5.1). A rock avalanche is defined as large mass of rock debris that slides, flows or falls rapidly by gravitational movement (Hutchinson, 1988; Keller, 1992; Hungr et al., 2001), and may be repetitive deposits are seen as boulder fans or lobes on fjord bottoms (Braathen et al., 2004). Further investigation is needed to determine if this area has experienced repeated rock avalanches. The subsidiary scarp where the talus material originated displays a high frequency of fracture systems striking NW-SE and NE-SW (Fig.

4.27). This may explain why the whole slope has disintegrated into talus material that moved downslope as a rock avalanche. The ridge-like element in the upper part of the talus field in connection to the scarp is interpreted as a collapsed counterscarp that has been covered with talus.

The big talus field in the north is still moving, as evidenced by the InSAR image (Fig. 5.7), in the upper part the movement may be related to a interpreted buried counter scarp or just frost heave (Fig. 4.32b, Fig. 5.7), the movement in the lower lobe is most likely related to seasonal frost heave processes. Talus scree in the southern area may be of more recent age and active today. When looking at the InSAR image (Fig. 5.7), this talus is most likely formed from processes along the whole southern lateral scarp derived from rock toppling (see Chapter 5.4.3). The talus material seen in the lowest part of the RSF area (Fig. 5.7) is surrounded by talus material covered with some kind of vegetation with a sparse earth cover. This talus material has its origin from the toe zone scarp (Fig. 5.7), which is most obvious in the lower southern part of the RSF.

#### **5.2.2.6 Terraces**

Many of the terraces in the RSF area are seen as benches between the counter scarps in the upper part of Domain I, dipping down slope (Fig. 4.34d). These terraces seem to have a surface of loose bedrock material. There are several down-slope dipping terraces in Domain I, these terraces are mostly seen as morphological dip slip areas (Fig. 4.34a), many are not vegetated, and others are sparsely vegetated (Fig. 4.34). If these areas reflect the surface of the bed rock foliation, it supports that they may show a slight down-slope rotation, interpreted from foliation change (Fig. 5.2) located in the upper part of the Domain I area below the counter scarps but above the crevasses (Fig.5.4). Through the profiles (Fig. 5.2) a slight upward rotational area may be interpreted in three of the profiles just above the crevasse areas. This upward rotational area may be connected to the major terraces seen more from a distance in the field (Fig. 4.34b). A similar kind of rotation is commonly seen in extensional regimes (Lister et al., 1986).

#### **5.2.2.7 Sinkholes**

Sinkholes appear to be associated specifically with three different locations in the RSF area. There are sinkholes (Fig. 5.7) in the lower part of Domain I, in the southern part of Domain II and above the back scarp in Domain II. Sinkholes seem to be present in areas that correspond to the orientation of internal fractures of the RSF area, e.g. striking NW-SE and NNW-SSE.



There is a clear connection to the different fracture systems and the sinkholes; they are all found in connection with or close to fractures (Fig. 5.7). The disturbed vegetation is evidence that there have been small movements or actions of other gravity forces (Henderson et al., 2011). This movement is supported by InSAR data from the area, which shows a significant movement at the sinkhole location in the middle of Domain I (Fig. 5.7). The areas in Domain II which have sinkholes do not show much movement today; thus we can conclude that is more or less stable today. There is no evidence that the sinkholes have a connection to karst formation, even if limestone exists in the bedrock (Fig. 3.3), which may affect formation of sinkholes. The observed sinkholes can be linked to fracture systems, which may be seen as pre rock slope structures. These sinkholes can now be seen as developing rock slope failure structures in Domain II. Sinkholes in Domain I can be interpreted as active, either from gravitational forces or tectonics.

### **5.2.3 Observed morpho-structures in relation to InSAR image**

When analyzing the most recent InSAR image of the area (Fig. 4.43, Fig. 5.7), it is clear that the majority of morpho structures, e.g. counter scarps and transfer structures, are seen in areas that show some kind of continuing movement, in this case away from the satellite (Fig. 5.7). This kind of movement is a relative movement with respect to the other colored areas, and therefore this discussion will be based on that.

As seen on the map (Fig. 5.7) the green areas are interpreted to be more or less vertically stable, compared to the others. The green area covers mainly the plateau in Domain II, consisting of several deep and open fractures. This area may have active movement, but the movement can be masked by the uncertainties associated with the InSAR measuring methods, e.g. the angle the satellite is recording from. The opening of the fractures may not be recent, and if there is movement it may be masked by different reasons e.g. the angle from which the satellite is recording signals. Looking north in Domain II, there is more red color, meaning that this area shows the largest downward movement with respect to the other colored areas. An interpretation of this is that the topography in this area consists of loose talus material, its origin may be just weathered rock material, or the foliation (Fig. 5.2) in this area may favor sheeting as weathering mechanism (Fig. 5.2). The bedrock in this area consists of biotite schists, a rock that weathers and cracks very easily and remains as flakes of rock. So the reason that this area shows high down movement may just be that the area is exposed through seasonal erosional variations as frost thaw processes moving the loose material on top of the

bedrock. It may also be that the back scarp is propagating in the northern direction and enlarging the whole RSF area.

The morpho-structure map shows that there is a good accordance between InSAR data and observed and mapped structures in the field. Counter scarps, transfer structures and trenches are morpho structures which are all seen in the upper part of Domain I, i.e. the area displaying the most movement with respect to the assumed more stable area in Domain II, above the back scarp. The InSAR data from ERS-1 satellite works well as a complement and to support other interpretations made for the RSF area.

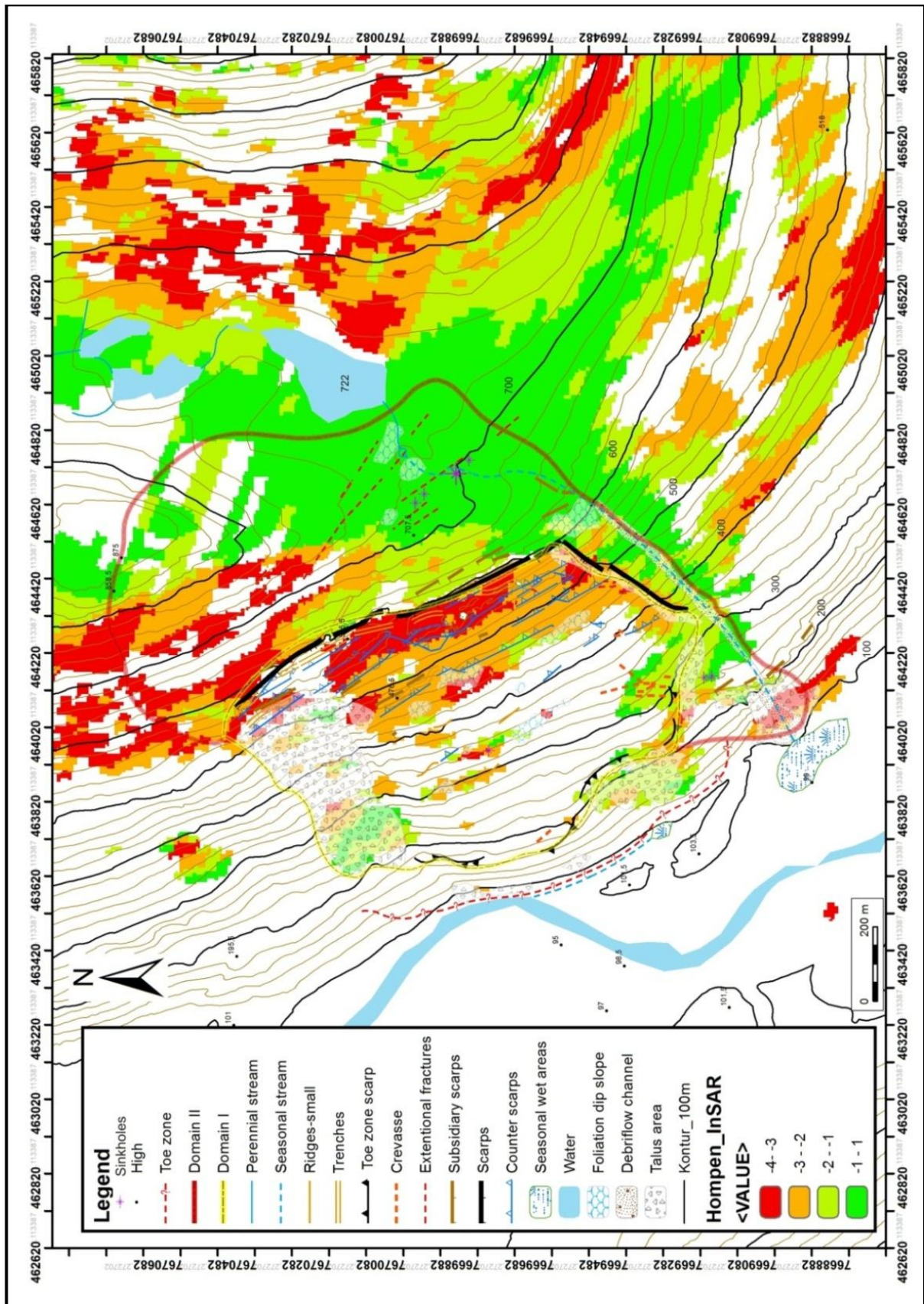


Figure 5.7: Morpho structure map with an overlay of InSAR image, showing the observed structures in the RSF area. The areas which show on most InSAR movement coincides well with areas with most developed morpho structures as counter scarps and scarp in the most eastern part of domain I. Maps are made in Arc GIS with InSAR-data (2002-2010) from NORUT.



### 5.2.4 Observed dGPS movement in combination with InSAR and observed morpo structures

An InSAR/dGPS analysis has been made in order to compare the observed morpo-structures in some areas with InSar data, as described below. Combining the InSAR data and data from dGPS points (Fig. 5.8), there is a clear connection at point HO-1. Observed structures at that point (HO-1) are counter scarps going parallel to the back scarp. At this point it measured the greatest (10 mm/year) south west movement in dGPS but no significant vertical movement (Fig. 4.45b). The area shows slight relative movement down on the InSAR image (Fig.5.8).

The time interval 2008-2011 (including one year of errors) is a too short for validating potential active movement of RSF's which may display creep, so the discussion is based fully on a short time period. During the total time interval the studied RSF shows no significant vertical movement on the dGPS data over the area. Regarding horizontal movement there is significant movement in all the points in Domain I (Fig. 4.45b) but most in HO-1 as described above. The other dGPS points do not show any significant movement.

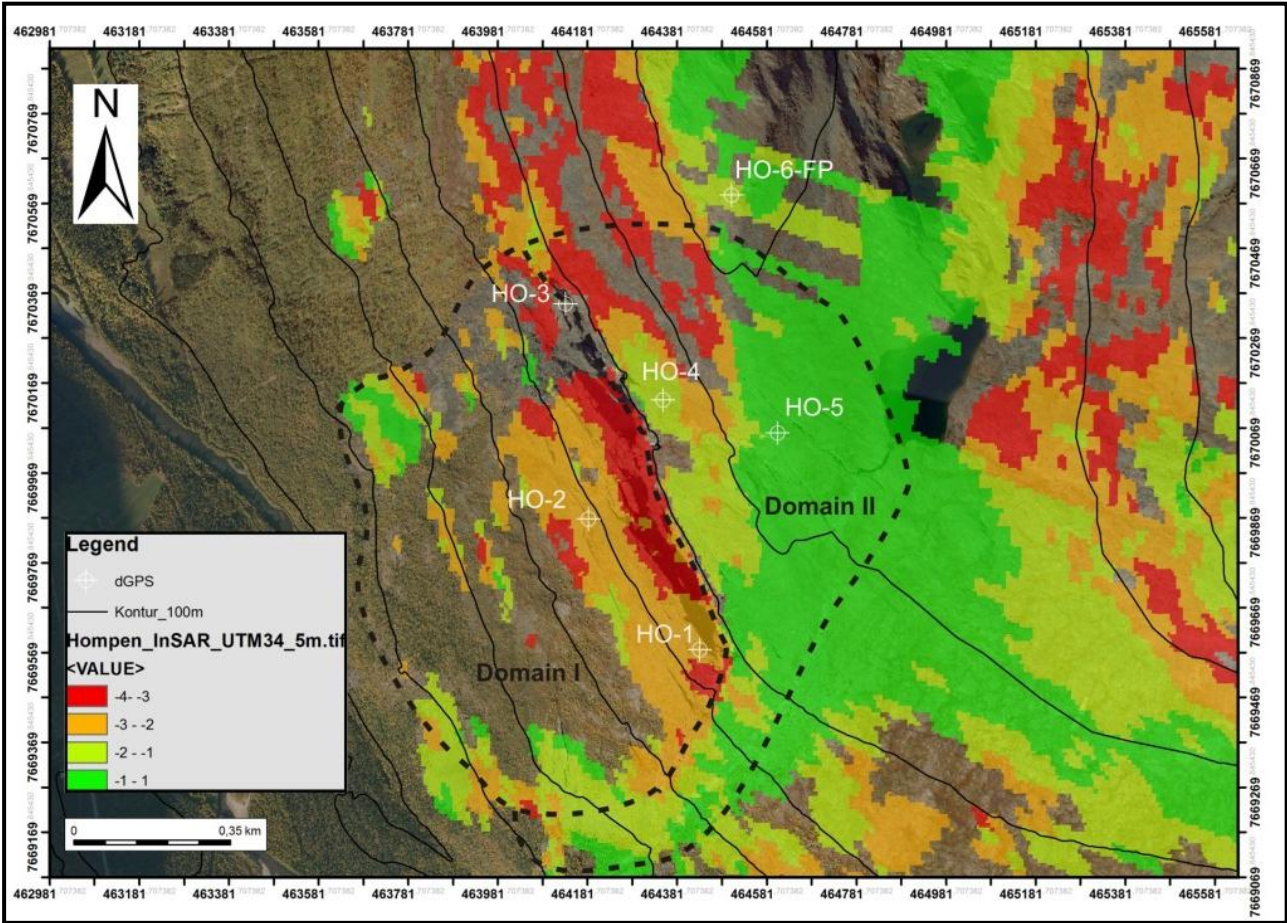


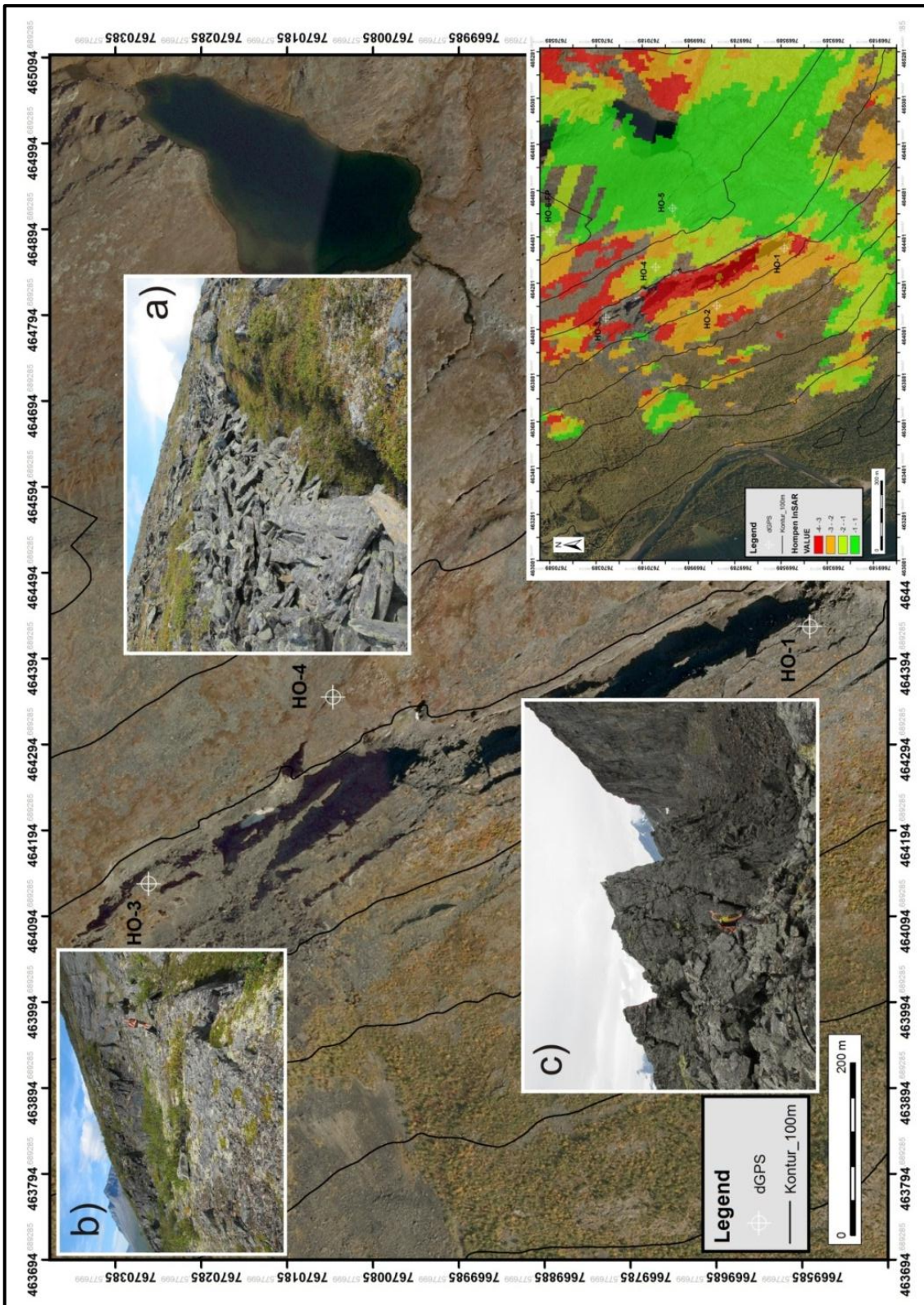
Figure 5.8: InSAR image (2002-2010) data from NORUT, with labeled dGPS points data from (Eiken, 2012) in the RSF area.

#### **5.2.4.1 The dGPS points position in connection to some observed morpho structures**

HO-4 is located close to a trench in Domain II, which may be a potential developing fault (see Ch. 5.2.2.3) above the back scarp (Fig. 5.9a). On InSAR data the same area shows that there is surface movement. The dGPS data does not show any significant movement at that point (HO-4). Interpretation of the seen movement on InSAR in that point today is most likely from surface processes. Point HO-3 (Fig. 5.9b) is placed in an area which is a counter scarp system with small transfer which also is the top of a major subsidiary scarp. This area does not show any InSAR movement, while the area west and south west of the point shows high negative values, meaning that there is registered movement away from the satellite. The area consists of only loose rocky material so the interpretation is that the movements are seasonal variations at the surface. The area which shows the highest horizontal significant dGPS movement is the HO-1 point (Fig. 5.9c) which is also the area which is showing InSAR movement. This point is located on top of one of the highest counter scarps in the RSF area. From the interpretation it seems clear that it is movement in this area. This may be the area which has developed a basal sliding plane and is slowly creeping downslope toward the exposed zone (Fig. 5.7) below the toe zone scarp in the south.

To conclude, when combining InSAR data, dGPS data and field observations (Fig. 5.9) it seems clear that the current and potential future activity in the RSF area may be linked up with specific morpho-structures of the area. There may be errors with both InSAR and dGPS data, but when combining this with field observations, the analyses may be supported by each other.





**Figure 5.9:** Ortho photo over the RSF area with both the InSAR data and labeled dGPS points. Inserted photos show morpho structures at the points a) point HO-4, trench above the back scarp b) point HO-3, transfer area in counterscarp system c) point HO-1, top of the biggest counterscarps



### **5.3 Discussion of movement directions in the rock slope failure area**

The movement pattern of the study RSF might be able to be resolved by using slip linear data if present along the main back scarp or other internal movement surfaces. Such fabrics, however, are hard to find, and there are not found any clear lineation on bedrock or foliation surfaces that can help to solve a kinematic history. Therefore other approaches have to be considered, such as: the orientation of structural and morphological features observed in the area, including: oblique/transfer scarps, counterscarps and trenches. Fractures and their behavior in the area can also help kinematic interpretations, as well as attitude of local foliation when it appears to have been rotated or tilted due to internal movements. In-SAR and dGPS data, aerial photo interpretation, geological and geomorphological field surveys and other potential movement indicators (see Agliardi et al., 2001), may help to verify an overall movement character of the RSF area.

A kinematic map has been constructed that shows the main orientation of observed structural and geomorphological elements in the RSF area (Fig. 5.10) and the arrows indicate local movement directions within the RSF. The movement is considered to be normal to or away from major scarps and counter scarps (Gibbs, 1984; Kinakin & Stead, 2005; Henderson et al., 2006), whereas it is parallel to oblique structures such as transfer scarps (Gibbs, 1990). The map shows that there is a dominantly SSW movement direction in the upper part of RSF area, changing to a more SW and west direction in the lower part (Fig. 5.10).

The maximum displacement of the RSF area can be estimated from the e.g. amount of opening of the major striking NW-SE back scarp, counter scarps and open, presumed extensional fractures. This value is a cumulative surface value taken from the back scarp and counter scarps, there is uncertainties of how deep the planes of the back scarp and counter scarps proceed downward into the loose rock material filling the graben. (Henderson et al., 2006)

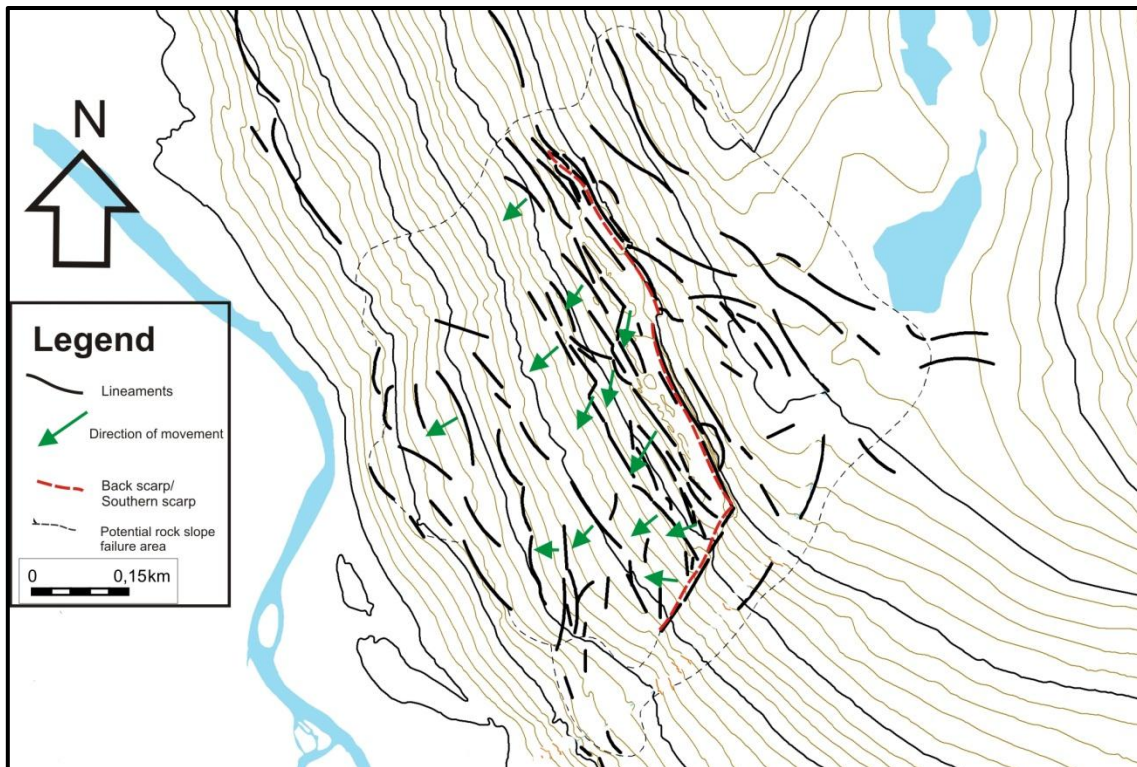
The total horizontal displacement is from the back-scarp and surface of associated counterscarps calculated to be between 60-80 meters (most in south and less in the north). The total vertical displacement is estimated to be c. 20 meters in the back scarp. These are values measured through DEM models and ortho-photos in Arc GIS and should be considered as interpretative values.

The main movement direction of the RSF below the back scarp seems to have been normal to the strike of the back-scarp, since the graben and associated counterscarps are all parallel to the unbroken part of the back scarp (Fig. 4.30). By assuming a dip-slip/normal-slip component the hanging wall moved down-section by c. 20 meters relative to the footwall (Fig. 5.6).

The transfer structure is connected in a bending geometry from NE-SW turning into a counter scarp system striking NW-SE (Fig. 4.31c). In this same area the back scarp makes an eastern step and continues NNW. The overall geometry of the RSF area now indicates an oblique-slip (transverse) movement towards SSW.

A common feature along extensional normal-slip faults is that the hanging wall collapses and creates a secondary plane that dips into the main scarp, the down-dropped area in between is the graben, as seen in the Hompen RSF area (Fig. 4.29). When the area displays a dip-slip in connection with a strike-slip movement as with the transfer structure seen (Fig. 5.6), it can be mentioned as having a component of strike-slip, and the total movement may then be described as an oblique-slip. This movement is inferred from the observed transverses/transfer scarps and relay ramps in the area.

The kinematic map and movement directions are based on the orientation of observed lineaments (Fig. 5.10) and morpho-structures in the area. The movement is normal away from scarps and counter scarps (Kinakin & Stead, 2005) and parallel to transfer structures and transverses scarps (Gibbs, 1990; Henderson et al., 2006). The map (Fig. 5.10) shows that there is a SSW movement in the upper part of domain I, farther down-slope the direction turns more SW/W based on the criteria's mentioned above. Possible movement directions in Domain II is not labeled on the map, but this area consists of tensile fractures with varied width between 0.5-5 meters. A brief estimation of horizontal movement based on the fractures width is c. 9 meters, measured on DEM models in Arc GIS.



**Figure 5.10:** This map is illustrating the kinematics in Domain I, in respect of major observed lineaments. Note the SSW direction of movement close to the back scarp (dotted red line) the movement pattern changes to more West lower on the slope.

Morph- structures as counter scarps in the southernmost and lower part of the RSF support that the movement there was normal to the back scarp. The major southern scarp, which is oblique to the back scarp may have worked as a transfer scarp to the entire RSF (Fig. 5.6). Along this lateral southern scarp, the rock mass seem too collapsed along the scarp, there are talus and boulders along the entire scarp. The dip direction of the foliation supports a small sliding mechanism (see Ch. 5.4.3) in same dip as the foliation, and a sort of toppling mechanism (see Ch. 5.4.3) in this part of the area may be active. There are fractures cutting the foliation and newly toppled material below the southern lateral scarp. The initial movement in this area may have been sliding, because of the linear anti-scarp (Fig. 5.3) which is parallel to the southern lateral scarp.

The movement directions obtained from the data and discussed above, are largely supported by the dGPS measurements of the area during the time period 2008-2011. Measurement shows a significant movement in the southern part of Domain I at point HO-1, it is moving (10 mm/year). There was a south west direction during first measuring period (Fig. 4.45a) in all points located in Domain I (HO-1, HO-2, (HO-3)) now the movement is slightly more to the south (Fig.4.45b, Table 2). (Eiken, 2012)



## **5.4 Mechanisms and classification of the Rock slope failure**

This chapter discusses possible mechanisms of initiation and further development of the RSF area, and includes an attempt to classify the RSF. From the literature, a number of different classification efforts of RSF have been applied (e.g. Cruden & Varnes 1996; Hutchison 1988), most, however focused on morphological aspects of slope movements and few with regards to structural aspects alone. In particular, the initial failure mechanism of a RSF is strongly influenced by the geology/topography and structure of the area. This is because an RSF's may start either as an extremely rapid or a slow movement mass. There can also be secondary processes operating with the RSF which can be direct or delayed in time. (Evans, 2006)

The two most used classification systems so far include an American taxonomic classification system (Cruden & Varnes, 1996), and a British classification (Hutchison, 1988) that pays attention to the observed morphology of the RSF. The classification by Braathen (2004) is a used classification in Norway and focuses on what kind of mechanisms that are active and the source area. My attempt to classify the studied RSF will be based primarily on Braathen et al., (2004), but it will be complimented with aspects from the other classification systems when relevant. Three main types of structurally induced RSF are classified by Braathen a) rock fall b) rock slide/translational slide and c) complex fields, all are controlled by deformation style, slope gradient and size of the RSF (Fig. 5.13) (Braathen et al., 2004).

RSF in general moves in different ways, rapid movement can be as rockslide, rock avalanches and catastrophic spreads and rock falls. Debris flows can be extremely rapid and devastating and may be triggered by just smaller rock falls e.g. the one in Signaldalen in 2008 (Fig. 1.7). The slower movements can be considered as creep (see Ch. 5.4.2); there are some uncertainties and a need for identification of their transition to a catastrophic failure. Rapid movement and sliding are the most common ways a massive RSF may be transported (Malgot & Baliak, 2002).

### **5.4.1 Initiation mechanisms of the RSF and their relation to topographic stress distribution**

In order to discuss the possible initiation mechanism of the RSF, several aspects are important, e.g. rock type, slope profile and stress distribution of the slope.

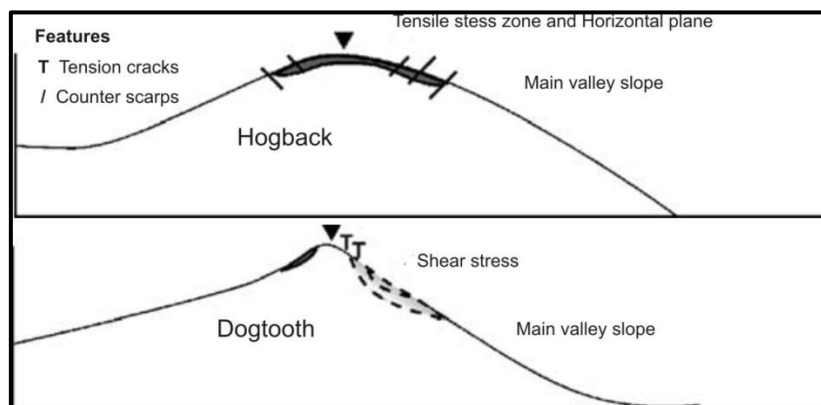
The studied RSF in Hompen is made up of various metamorphic bedrock with a well-developed ductile foliation. It is bounded by a back scarp, counterscarps and transfer structures and located in a steep hillside with an average of c. 35° surface dip to the SW, situated just below a flat plateau at c.700 m.a.s.l. (Domain II). This in combination topographically defines the Hompen area as an asymmetric ridge. This ridge may be comparable with other asymmetric slope profiles (Fig. 5.11). RSF in asymmetric ridges may form when the asymmetric ridge collapses due to gravity loading and or a combination of gravity and tectonic loading.

In the Hompen RSF area the NW-SE striking back scarp is a steep wall with a vertical displacement of c. 20 meters, indicating that there has been a major movement of the RSF, likely involving both displacement and gravity. The total lengthening of domain I area may be up to 10%, indicating that there has been at least some extension in the area, giving the domain I area a horizontal movement between c.60-80 meters of opening. In Domain II mainly the area above the knick-point of the convex slope moved outwards, here several deep vertical tensional fractures have developed on the plateau (Fig. 4.39). This combined lengthening of Domain I and the presence of tensile fractures in Domain II suggest that both vertical and horizontal forces acted during the initiation of the RSF (Fig. 5.11).

The distribution of stress in asymmetric ridge forms (Fig. 5.11) are dependent on gravity loading and a combination of gravity-tectonic loading. Through elasto-plastic constitutive models discussed by Kinakin & Stead (2005), the response of stresses in the rock mass can be discussed, but for considering erosion and weathering processes on the rock mass, the zone of elasto-plasticity should only encompass the surface zone of the model. The Hompen RSF area (Fig. 5.15) may be classified as the ridge class termed “Hogback” or “Dogtooth” (Fig. 5.11), these are asymmetric ridge types which are modeled under elasto-plastic behavior (Kinakin & Stead, 2005). The Hogback model suggests that horizontal stress on the ridge will be higher on the down-dip side of the valley, and that gravitational loading will not greatly affect the material properties inside the rock mass, while tensile stresses are highest on either sides of the ridge top. When tectonic stress is implied on the ridge, the vertical stress at the ridge top

may increase. If the tectonic stress exceeds the gravitational stability of the rock mass, failure may occur at the toe of the slope and a potential RSF may begin to develop. The typical morpho-structural features of a RSF, e.g. back-scarp, counter scarps, etc. postulated from this model fit well with those of the Hompen RSF area (Fig. 4.6, Fig. 5.11) and the “Dogtooth” model thus may be valid even today. (Kinakin & Stead, 2005)

Structurally controlled morpho-structures of a RSF formed mainly as a result of gravitation are generally termed “slope tectonics” (Jaboydoff et al., 2011), and this concept may well be considered relevant for the Hompen RSF. In order to classify as a tectonic-induced RSF, the internal structures normally may be linked to an episode of crustal deformation, or if the RSF is controlled by e.g. inherited regional-scale structural or deformational features. It can be concluded that for the Hompen RSF the effect of stress distributions and a topography similar to a asymmetric ridge may have allowed slope tectonics to operate as the main initiation process, that later became an important controlling factor for slope instabilities and further failure (cf. Jaboydoff et al., 2011).



**Figure 5.11:** Illustration showing vertical «tensile stress» and stress in the horizontal plane in the Hogback asymmetric slope profile, and shear stress field in the Dogtooth profile in an elasto-plastic model. (Modified Kinakin & Stead, 2005)

## 5.4.2 Creep as a movement mechanism

Analysis of InSAR and dGPS data (see Ch. 5.2.4) clearly indicates that the studied RSF are actively moving downwards with approximately 7-10mm/year (Fig. 4.45b). If this movement is due to gravity settings or creep in the surface layers such a movement may proceed for many years before anything dramatic happens in the RSF area. Such a slow movement may include a variety of deformation mechanisms, referred to as e.g. “deep creep”, “deep-seated creep” and ”sackungen” (McCalpin, 1999; Agliardi et al., 2001,2009; Braathen et al., 2004).



With this type of creep the sliding may be very slow; this is common as a slow pre-avalanche deformation or pre-failure movement (Crosta & Agliardi, 2003; Blikra et al., 2006b).

### 5.4.3 Discussion of failure mechanisms

To be able to discuss what failure mechanisms which have been active at Hompen RSF a small introduction to the two most common mechanisms observed for generation of RSF in general from literature will be presented before it will be discussed own data.

A short presentation of the theory of the two mechanisms which are observed at Hompen RSF: Toppling and Sliding (Fig. 5.12)

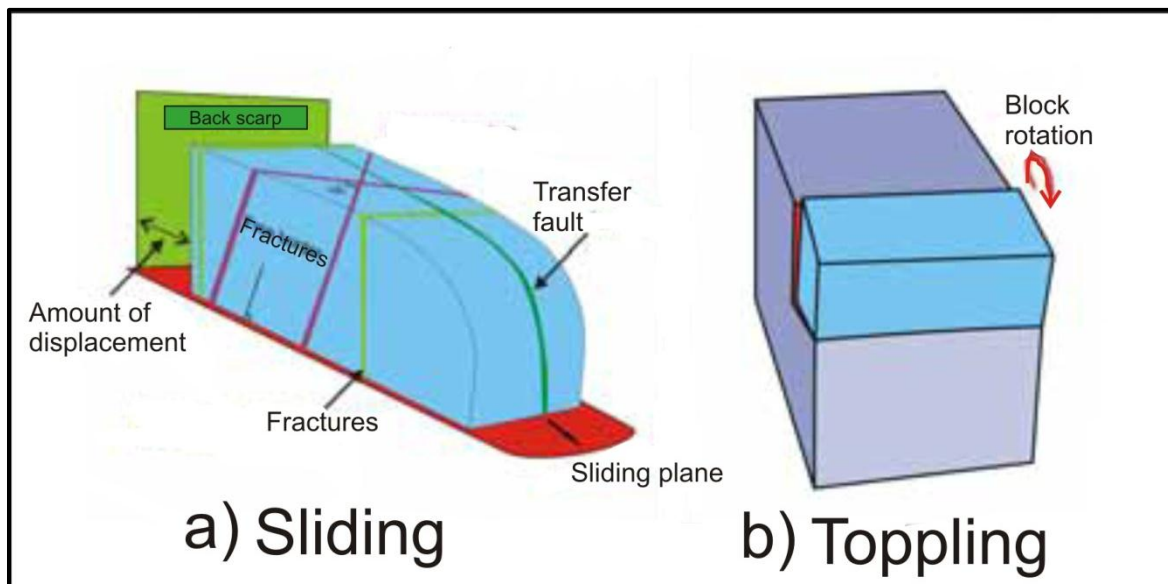


Figure 5.12: Typical RSF structures a) Slide geometry and b) Toppling geometry (Modified Henderson et al., 2006)

**Sliding:** Planar sliding occurs along a geological structure e.g. foliation plane, detachment or fault (Fig. 5.12). The plane should dip downslope, but should be less steep than the slope, the plane should “daylight” intersect the slope. There are some conditions which should be satisfied to give sliding along a plan defined by Hoek and Bray (1981).

- Strike (The strike to sliding plane should not differ more than  $20^\circ$  in orientation to the slope strike)
- Dip (There should be a daylight of plane)
- Friction angle (The dip to failure plane must be greater than angle of friction, but this may get affected by e.g. fluids (see Ch. 5.5.5))

- Lateral release (There should be a release surface to define boundaries). (Hoek and Bray, 1981)

Sliding is commonly seen in moderate slope gradients ( $<45^\circ$ ) (Braathen et al., 2004).

**Toppling:** Toppling involves a forward rotation, of blocks or columns of rock (Fig. 5.12).

There are three kinds of toppling defined by Goodman and Bray (1976).

- Block toppling, occurs where fractures/joints are widely spaced and that there exist cross fractures. The cross fractures provides a release surface.
- Flexural toppling is observed where fractures/joints are closely spaced and that there is no cross fractures and therefore no release surface. The rock columns bend under gravity influence.
- Block-flexure is a combination of the two above mentioned, where columns of rock may move along cross fractures. (Goodman and Bray, 1976)

The toppling mechanism may be seen in areas which have a steep slope gradients ( $>60-75^\circ$ ) (Braathen et al., 2004).

These are the two most common mechanisms working in RSF, in different ways. Sometimes one of the mechanisms may be dominant, in many cases there may be a complex combination of the two mechanisms then the RSF are referred to complex mechanisms (see Ch. 5.4.3.3)

#### **5.4.3.1 Toppling mechanisms**

In the Hompen RSF the major central graben, bounded by the back-scarp and associated counter-scarps, has a massive infill of talus blocks with angular shape, fresh bed rocks and a bed rock composition that characterizes the upper part of the back-scarp (Fig. 4.30c, d, e). This would support a mechanism of local active rock fall (i.e. toppling) of blocks from the back-scarp into the graben. The back scarp, however, is almost vertical and smooth, with only a few obstacles sticking out and that is mostly in the middle part (Fig. 4.24b). The middle part is the area which displays an en-echelon step in the back scarp and which is also connected to the transfer zone.

These observations suggest that some of the material in the graben may have its origin from the top portion of the back-scarp as down-dropped rock fall material. Toppling material may also have originated from the counter scarps into the graben (Fig. 4.28), then, the toppling process may be so-called flexural toppling which is mainly gravitational controlled block fall. Other types of toppling processes operating e.g. in subsidiary scarps may be classified as

block toppling (Fig. 4.27b), were the vertical plane at the back works as the release surface. On a larger scale, the entire upper part of the domain I may be considered as a huge rotated block of the foliated bedrock, which has been rotated out from the release surface the back scarp. If this is the case then the back scarp may be steep and continues downward into the bed rock. The alternative interpretation, i.e. that the major anti-formal structure there is a Caledonian fold, cannot be ruled out.

Along the southernmost RSF-bounding lateral scarp, toppling may be active on a local scale even today as indicated by abundant fresh talus blocks, and fresh-looking scars also occur in the wall face. In this area the foliation is dipping into the RSF area, here the toppling slides locally on a release surface which may be made up by a foliation plane or a weaker layer (Fig. 4.26).

#### **5.4.3.2 Slide mechanisms**

dGPS data have documented a slow movement of the RSF area of approximately 7-10 mm/year (see Chapter 4.8). The movement is so slow that it categories under the definition creep (see Ch. 5.4.2). To have this type of slow movement it requires a detachment or sliding surface at a deeper level. In the Hompen RSF area a sliding surface is not obvious, but well-developed foliation surfaces exist in mica schist's in the lowest part of the southern area of Domain I that may be interpreted as one or more potential sliding surfaces (see Ch. 5.4.4). This sliding surface may not be continuous below the entire RSF, the southern part of the RSF seems to have parts developed, here the potential detachment is exposed and the area shows the most continues movement (see Ch. 4). The whole Domain I area has experienced a total horizontal lengthening of c.10 %, and such an amount of lengthening requires a basal detachment (Braathen et al. 2004). An alternative interpretation is that there may be other weak planes e.g. fractures or foliation surfaces operating as sliding surfaces (Fig. 5.4b), and which may be linked to a step-wise sliding surface at depth (Braathen et al., 2004; Blikra et al., 2006a).

The northern boundary of the RSF area which is the landslide area (Fig. 5.6, see Ch. 5.2.2.5), can be seen as an internal translational slide were a sliding event appeared as a rock avalanche.



### **5.4.3.3 Complex field mechanisms**

A RSF complex field area is characterized by extent that exceeds  $\text{km}^2$  and depth from  $>20\text{m}$ , deformation mechanism can be a combination of rockslide, rock fall and block rotation as toppling, the area can show intricate deformation pattern above one or several detachment levels and requires a complex attitude of either a listric, step-wise or planar detachment (Braathen et al. 2004).

For the studied RSF at Hompen, surface expressions that may indicate a complex field mechanism include: anti-formal/roll-over foliation, a major back-scarp, counter scarps, oblique scarps, internal graben and horsts, and fractures with multiple dip directions.

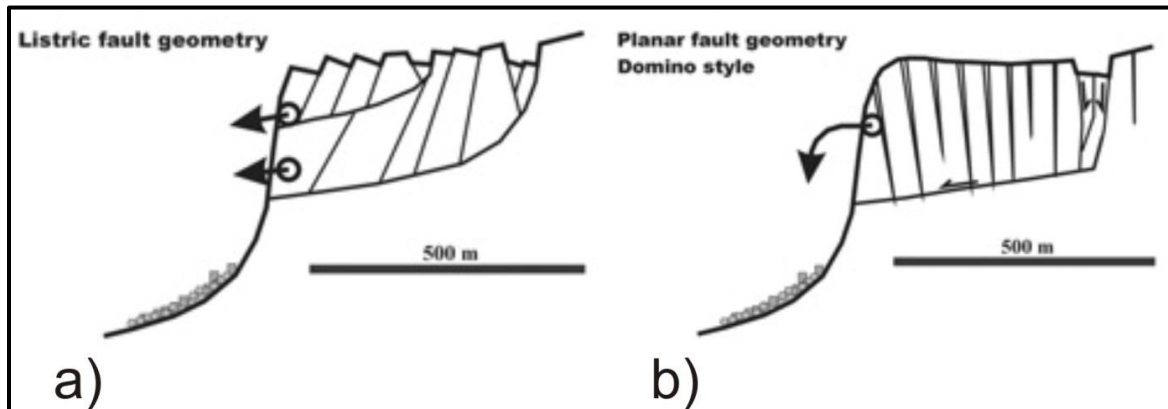
A possible indicator of a roll-over rotation of the foliation that may be linked to a deeper, listric detachment, is the major anti-form above the back-scarp, and the inward dip of the foliation below the back-scarp. If this is due to downward motion of the hanging wall, the back scarp must continue way down into the bed rock of the RSF (Fig. 5.2, Fig. 5.4b). The RSF area has a total horizontal displacement in Domain I of 10% and that should qualify for the presence of a detachment (Braathen et al. 2004). The area also displays evidence for creep as movement mechanism today (see Ch. 5.4.2), and there is also thought to be a sliding plane in the lower part of the southern area. Because of the steep and potentially deep back-scarp, the interpretation is that there is a partly developed sliding plane with a step-wise /listric or even more ramp flat detachment (Fig. 5.13c) the sliding plane may even exist well below Domain II (Fig. 5.2).

The existence of a deeper detachment below the entire RSF area is supported by the large area affected ( $\text{km}^2$ ) by deformation structures (see Chapter 4), the volumes of the unstable rock mass most likely exceeds 10 million  $\text{m}^3$ , depending on the depth to the sliding plane (Braathen et al., 2004).

### **5.4.4 Development of detachment**

A critical factor for the development of a huge RSF sliding rock mass is the presence of a basal sliding surface or detachment (Fig. 5.18, Fig. 5.4b). Such a detachment would represent the primary structure for development of a major sliding component, whereas the back-scarp and oblique transfer structures should be present as secondary structures reflecting the strike-slip/lateral component. This situation, however, differs if the RSF formed purely by the toppling mechanism. (Henderson et al., 2006)

In the Hompen RSF area (Domain I), there are no clear exposures of a basal sliding surface. But a possible small detachment surface is exposed in the southern portion of the lateral scarp (Fig. 4.26), as well as in the lower part of the RSF in the south, within the mica schist layer (Fig. 3.4a).



**Figure 5.18:** The dominating detachment styles in complex slide geometries. a) An listric fault geometry b) a planar geometry. (Modified Braathen et al., 2004)

There is a potential upper sliding plane going parallel with the foliation in the southern lateral scarp (Fig. 4.26), which may have worked as a sliding surface in this area (see Ch. 5.2.2.1). The origin and development of this possible basal sliding plane beneath the southern part of Domain I may have been controlled by tensile stress present throughout the RSF area, following rapid de-glaciation, and leaving an undercut de-glaciated valley open for major erosional processes. This stress situation may then have activated inherited weak areas such as main fractures trending NW-SE along the back-scarp and corresponding tensile fractures above (in Domain II), whereas the subsidiary NE-SW fractures became more favorable locations for oblique reactivations. In combination, these reactivations may have marked the onset of the Hompen RSF (see Ch. 5.4.1).

There may also be lithological differences in connection with foliation, which may help to develop shear planes (Fig. 5.2, Fig. 5.4b). The RSF area has several areas with mylonitic rock (Fig. 3.3), which is common to see in old shear zones, but nothing points on reactivation of these. The mica schist layer observed in the southern part of the RSF (Fig. 3.3) exist at several levels north of the RSF as seen on map (Fig. 3.2) which may have a connection to development of sliding planes. To see the propagation of fractures in Domain II, above the back scarp it's also adjacent to believe it exist a lower basal plane. The fractures in Domain II may propagate down towards a plane or they may be tensile fractures due to gravitation in connection with mass movement during opening of the back scarp. The foliation in the area

show on variation (Fig. 5.2), it may be evident that the foliation varies where there are observed structures in the bedrock or topography but it can also be folding in the bedrock which is not observed. The foliation can work as a sliding plane, in Hompen the average foliation in the RSF are almost sub horizontal (Fig. 4.7), which means that, most likely the foliation by itself will not work as a sliding plane. But, the foliation may work as a weakness zone and be affected by fractures and other processes and therefor develop into a sliding plane in parts of the RSF area, step wise geometry of the detachment may be the fact (Fig. 5.4b).

When the mafic rocks (amphibolite and hornblende gneiss) which the RSF area mainly consist of (see Ch. 3), gets fractured and fluids can penetrate down, minerals as typically clay minerals e.g. illite and chlorite may develop through weathering and grinding processes in the bedrock. These new minerals migrate down and may work as lubricates, the movement as creep can exist in even very low angle surfaces because of the low frictional strength of the clay minerals. In the lowest part of the RSF area there is layers of mica schist, this surface may be a potential layer which may work as a basal sliding surface going sub-parallel on top of the mica rich layer. This layer is sub horizontal, but because of the structural behavior of collapsed micas when reacting with fluids, it may work as a perfect sliding plane. (Morrow et al., 2000)

To support the argument that there should be a basal detachment is that when lengthening of the area is more than c. 5% (total lengthening at Hompen c. 10%) (see Ch. 4.4.3) the lengthening should be enough for fracturing the rock and through that generate a detachment. Also the yearly water drainage event (see Ch. 4.6) with the small pond in Domain II, support the hypothesis of a detachment and that water seeps into the groundwater (Braathen et al., 2004).

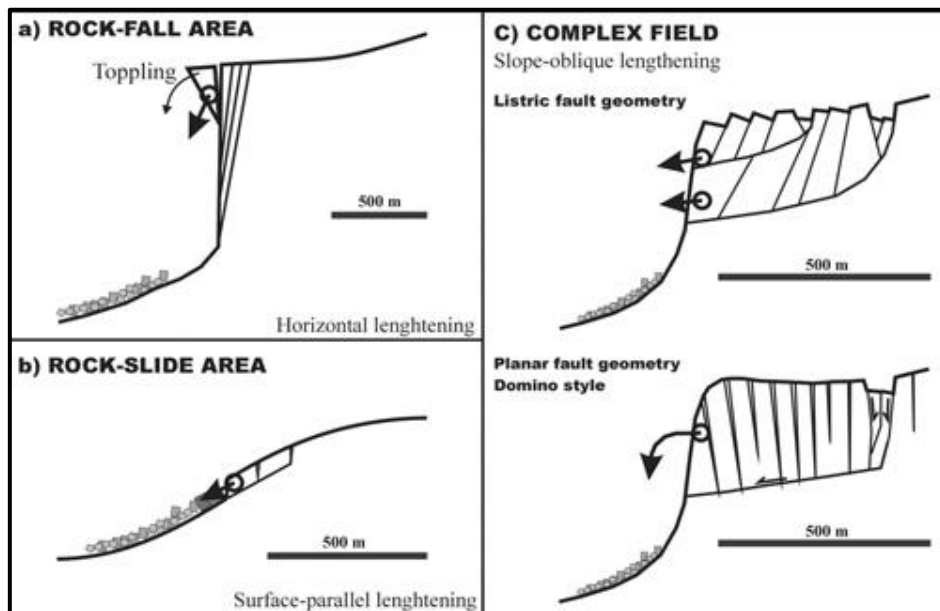
The structural style of the hypothetical detachment is interpreted to; the back scarp are a steep sliding surface with a unknown depth, fractures above the back scarp goes more or less parallel to the back scarp and may develop as deep as the back scarp and joins a detachment (Fig. 5.2). If there is a basal detachment under the whole or parts of the RSF area, this may go parallel to the mica rich layer, and then the area can be given a structural style as planar detachment (Fig. 5.18b). But it is more likely that there is a stepping geometry of the detachment in the RSF area, which is working its way step-wise down on different foliation planes which may work as sliding planes (Fig. 5.4b), or even a more listric detachment (Fig.



5.18a) in the area, that also fits better with observed morpho structures on the surface in Domain I.

### 5.4.5 Classification of the Hompen RSF area

In order to classify the RSF based on the discussions above, we need to keep in mind the mechanisms mentioned (see Ch. 5.4.3). Three main types of RSF areas can be formed during failure of large rock masses in mountain slopes (Braathen et al., 2004). These include: a) rock-fall areas, b) rock-slide areas and c) complex fields, their classification is based on the pre-avalanche deformation patterns that can be seen within the avalanche source areas, as well as on deformation patterns and internal movement mechanisms (Fig. 5.13) (Braathen et al. 2004).



**Figure 5.13:** Geometric model for RSF, a) rock-fall area b) rock-slide area and c) complex field (Braathen et al., 2004)

When considering the Hompen RSF area in view of geometrical observations (Chapter 4) as a framework for classification (Braathen et al. 2004), it may be classified as both as a rockslide area with transitional slide (the northern part of Domain I) and a complex field with one or more detachments (Fig. 5.13). This is based on the e.g. presence of possible planar (foliation-parallel) detachment surfaces (Fig. 5.4b), complex scarps and counter-scarps that indicate internal rotation. The RSF area in addition, may have been affected by local rock-fall and toppling of materials from the scarps. The size of the unstable rock mass (c. 60 or 120 million m<sup>3</sup>) also would attest for a very complex mechanism of formation (Henderson et al., 2009). The Hompen RSF is therefore considered as a complex field area based on the above mentioned components and characteristics (Braathen et al., 2004).

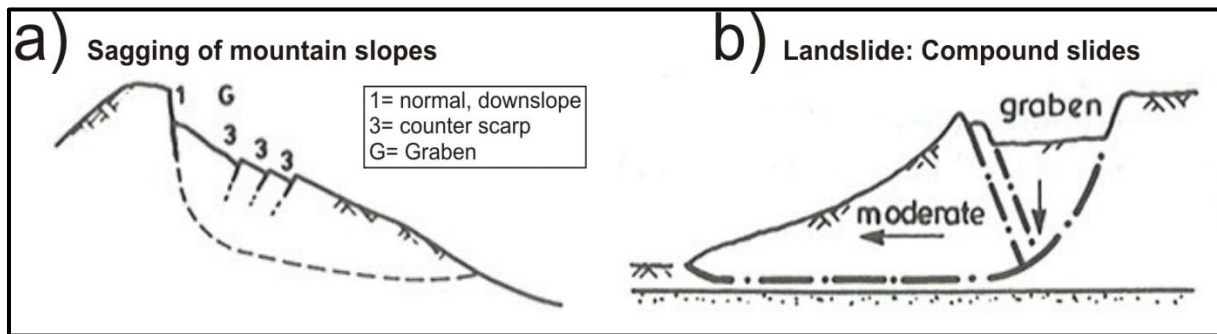
When comparing Braathen et al.'s (2004) classification, with another classification that focuses on slope morphology resulting from the movement of the slope itself, and not necessarily the internal structure (Hutchinson, 1988), an easier evolution can be displayed for the RSF area. In this context, the Hompen RSF may represent an immature RSF that potentially will develop into a sliding RSF sometime in the future. Using the different failure mechanisms of Hutchinson (1988), the RSF can be classified as formed by "Sagging of mountain slopes" (Fig. 5.14a), i.e. where the surface morphologies are complex and the upper part consists of fractured rock and multiple sliding surfaces. A well-established graben system may be formed, with or without internal horsts linked and breached against the transfer areas as relay ramps. The rock mass moves very slowly, and the largest amount of displacement occurs in the upper part of the slope (Hutchinson, 1988). These features, in combination match almost perfectly with those observed in the Hompen RSF area (see Chapter 4).

The development of the Hompen RSF area may also be referred to as an immature Landslide: Compound slide (Hutchinson, 1988) (Fig. 5.14b). Then the speed of the RSF area needs to accelerate from the one measured today (10 mm/year), by Eiken, (2012). A compound slide is characterized by a large coherent slide block which slide much faster than by sagging. For compound slides there is a need for a bi-planar or listric sliding surface. Such a gliding plane or detachment may be present in the Hompen RSF area, or it may potentially be under development.

Regarding the classification by Hutchinson's (1988) and the toppling component at Hompen, there is not registered much of vertical displacement in the area today (see Ch. 4.8) except local toppling. But within the graben which is developed from a major extension, there is a collapsed relay ramp (Fig. 4.31c), here frequently local toppling exist. Because of the major extensional forces a conclusion is that it cannot be pure toppling as failure mechanism (Hutchinson, 1988).

In advance of a total failure an RSF area often develops pre-avalanche deformations as seen at Hompen RSF (see Ch. 4), the movement can be seen as pre failure movement as creep (see Ch. 5.4.2). This type of slow movement may last for a long time before eventually, total failure occurs. This type of movement and deformation of the rock mass is often referred to as DSGSD (deep seated gravitational slope deformation) which is a mass movement with velocity up to 10 mm/year (e.g. Hutchinson, 1988; McCalpin, 1999; Agliardi et al., 2001, 2009; Ambrosi & Crosta, 2006).

From the above discussion it can be concluded that the Hompen RSF area may be classified as an initial stage of a sagging mountain slope, i.e. a morphologic landslide (Hutchinson, 1988), and that it potentially may evolve into a more advanced, compound slide in the future (Fig. 5.14).



**Figure 5.14:** Morphological classification by Hutchinson (1988). a) Classification based on observed surface morphology b) classification which assumes coherent bedrock and sliding planes. (Modified Hutchinson, 1988)

The definition DSGD (Deep-seated slope gravitational deformation), can from now on be used for the Hompen RSF area; it shows features as morpho-structures as scarps and counterscarps, the size of the phenomenon is comparable to the slope, it shows a low rate of displacement (mm/y) and it has minor landslides inside the deforming bedrock mass (see Ch.4) (Agliardi et al., 2001).

#### 5.4.5.1 Extent/volume estimation of the RSF area

The extent of the potential RSF area; i.e. Domain I, is estimated from the observed boundary scarps and internal and external characters of the structures and from detail study of ortho-photographs and InSAR data. When comparing these data with the InSAR photo (Fig. 5.7), the boundary of Domain I against Domain II to the south is supported by the InSAR photo showing a similar polygonal geometry. In the more northern part of the image the boundary of the RSF (Domain I and II) is supported by morpho-structural features in the field and aerial photographs. The area further north and north east, which shows active movement on the InSAR photos, may have undergone surface processes such as frost shattering and other erosional processes, but it can also be due to a further propagation of the RSF area in that northern direction.



Active movement within the Hompen RSF (Domain I) is clearly evident (see Ch. 4.8), and an estimate of the areal extent of Domain I reaches c. 0.63 km<sup>2</sup>. If Domain II is included, the calculated total area would be c. >1 km<sup>2</sup>, the boundary for this domain is uncertain when looking on the new InSAR image (Fig. 4.43) and more work has to be done regarding the propagation of that domain. The whole south west facing mountain slope of Signaldalen may be an area more exposed for RSF view further under chapter 5.5.

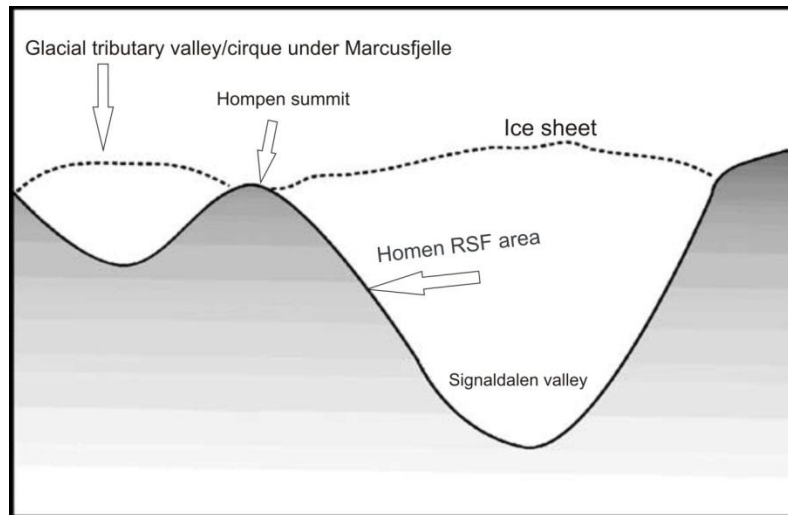
An attempt to estimate the volume of the Hompen RSF area was done by Hendersson (2009), yielding an approximate volume of between 60 and 120 m<sup>3</sup>. The calculation is based on a suggestion that the back scarp proceeds to a depth of c.100 meters, and that the RSF area is limited to the NW by the observed talus/rock avalanche (Hendersson et al., 2009). This estimate is however, uncertain, and more work is needed, e.g. Lidar data. Based on the hypothesis that the basal sliding plane may be within the mica schist layer in the lower part of the RSF, the total mass above this unit may exceed the current estimate considerably. Thus, the volume estimate of Henderson et al., (2009) should be regarded as tentative until better numerical data becomes available.

## **5.5 Controlling factors and driving forces for RSF**

Deformation of mountain slopes and their movement into becoming a RSF area is still not fully understood. It is certain that it is not only one factor which is affecting an area and there are several driving forces to enhance the development. In this part some of factors which Hompen RSF area are interpreted to be effected of, will be discussed e.g. glacial effects, inherited fractures, lithology, hydrogeological conditions and permafrost conditions in the area.

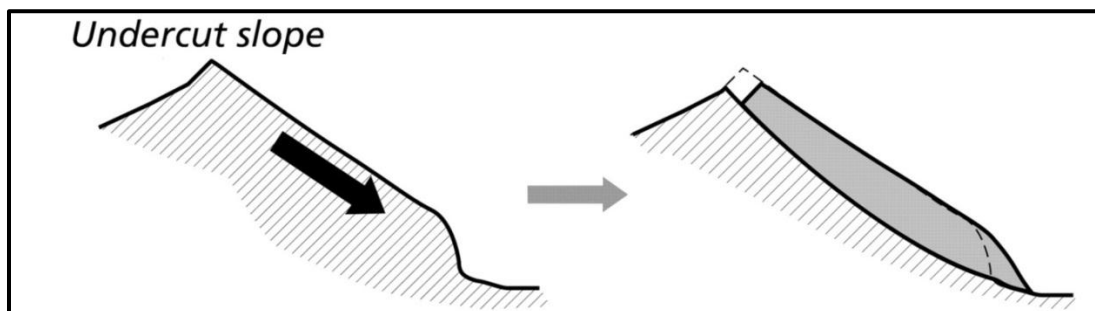
### **5.5.1 Glacial erosion**

From the description of glacial form elements in the RSF area (Chapter 4), it seems clear that the area has been strongly affected by glacial activity. In this perspective, Signaldalen can be classified as a U-valley, whereas the adjacent valley of Stordalen has a V-shape formed by water erosion, Stordalen is considered as a tributary valley. Similarly, the circular mouth of the mountain (Markustind) just above the studied RSF may be called a tributary valley or cirque (Fig. 5.15). These glacial features with steep hillside along the main U-shaped, glacially eroded valley may have exerted a pronounced hazard for later avalanches and/or RSF as discussed below.



**Figure 5.15:** Illustration showing the formation of asymmetric ridge, how the glacial erosion in a main valley «Signal dalen valley» and tributary/cirque areas form the topography. (Modified Kinakin & Stead, 2005)

The glacial erosion of the U-shaped Signaldalen valley by e.g. its main river in the valley bottom since the termination of the last glaciation may have caused pronounced under-cutting of the RSF area both by glacial erosion and by water (Fig. 5.16). The polished slabs in the RSF and surrounding areas, with chatter marks and roche's moutonees structures support the theory that the ice sheet has been relatively thick, and with an eroding temperate ice (Benn & Evans 1998). The structures seen make it possible to estimate the direction of the ice movement, which is dominantly to the NW. The mountain of Markustind and also the summit of Parastind were likely part of a larger nunatak area that suffered from severe permafrost. Several of the polished slabs in the RSF area are truncated by fractures which are interpreted as rock slope failure structures. These fractures may be due to the RSF movement or fractures in connection with relief after de-glaciation. Commonly, freshly exposed rock after a de-glaciation event will undergo expansion due to removal of the confining pressure (Bain, 1931), and thus, this is a phenomenon which critically may weaken a rock mass (Benn & Evans, 1998).



**Figure 5.16:** Illustration showing how a slope may be stressed by undercut, which may result in instability and deformation of the slope (Jaboyedoff et al., 2011).

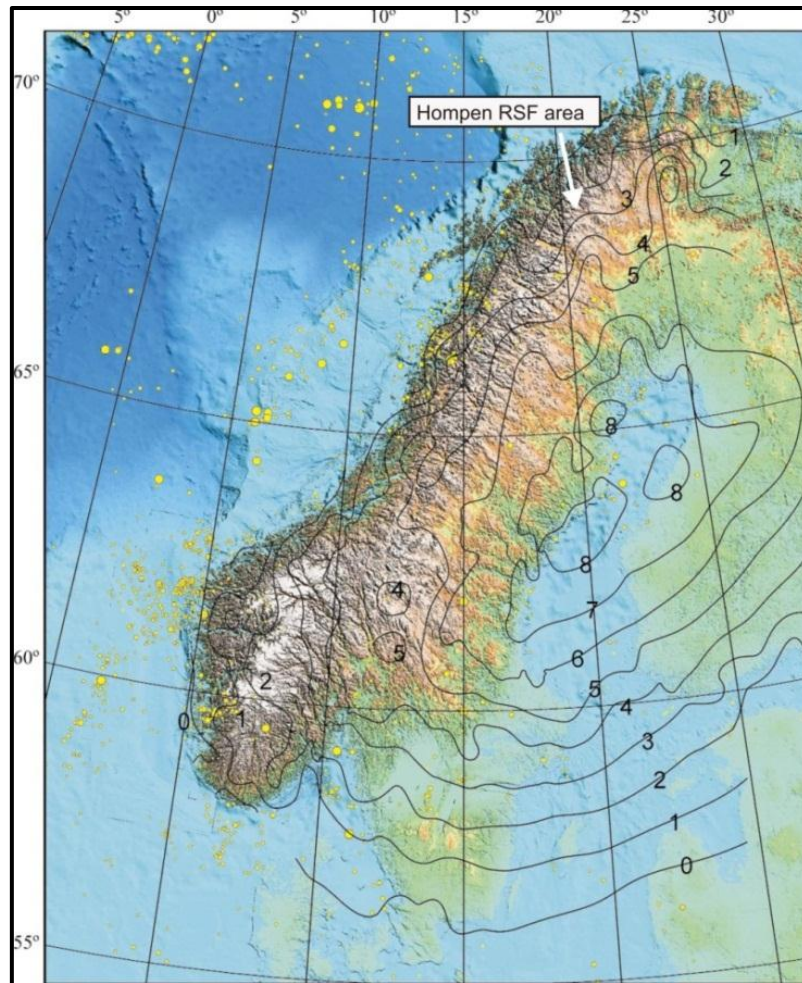
A previous interpretation of the Hompen RSF area, including the major central graben structure, was that of a glacier melt-water channel (see Corner, 1977). The reason for such an interpretation was that the direction of the graben NW-SE seemed to correspond well with the regional ice-movement direction towards NW (Fig. 4.37). From the orientation of the channel alone, it may be considered a lateral melt-water channel, but since the talus material in the graben is highly angular and does not show any sign of water erosion, another explanation must be found (see Ch.6).

### **5.5.2 Glacial rebound**

A major morphological factor that may have affected the stability of the Hompen RSF area is glacial rebound. Several authors (e.g Dehls et al., 2000; Dahl & Sveian, 2004; Jarman, 2006; Vorren et al., 2006) point out that the load of the glacier, produced high internal stresses on the slope and valley floor. During glacial rebound a release of elastic strain energy might give the result of propagation of network of joints and may later cause failure of large rock masses (Blikra et al. 2006b). Thus, regarding the Hompen RSF, glacial erosion of the Signaldalen valley bottom with undercutting of the slope, followed by a rapid retreat of the ice may have created a pressure relief and subsequent isostatic uplift of the area.

During the last glaciation the “Weichselian” ice sheet covered the entire RSF area, but the ice retreated in a really short time period (Corner, 1980). When a huge ice volume disappears so fast, it will lead to a huge weight release on the ground surface during a short time interval. Scandinavia are still experiencing crustal uplift due to removal of the last ice sheet 10000-8000 years ago. For example, in the Gulf of Bothnia in Sweden, near “Höga kusten”, the rate of uplift is c. 9 mm/year, whereas uplift along the coast in western Troms is approximately 1-1.5 mm/year and in the RSF area it may be as much as 3 mm/year (Fig. 5.17). (Dehls et al., 2000)





**Figure 5.17:** A shaded relief map of Scandinavia, showing current apparent uplift rates (mm/year), and yellow dots are earthquakes greater than 3.0 since 1965. (Modified map Dehls et al., 2000)

### 5.5.3 Inherited fracture systems

The description of regional and local lineament patterns in central Troms (Fig. 4.2, Fig. 4.1) combined with field observations (see Ch. 4.4.2) shows that a number of brittle fractures and faults exist in the bedrock of the studied RSF area. Such pre-existing systems may be traced for large distances (Henderson et al., 2006), and since they define zones of weakness in the bedrock and often are linked up with major escarpments and fjord-valley systems, they may provide a control on the location of RSF (cf. Osmundsen et al., 2009, 2010)

In the study RSF the majority of fractures seem to reflect such an inherited pre-existing system. In particular, the back-scarp and the oblique scarp that bound the RSF both seem to correspond with the orientation of regional NW-SE and NE-SSW fracture sets (Henderson et al., 2006; Hansen et al., 2011; Gabrielsen et al., 2002). The possible best evidence that a pre-existing fracture existed along the NE-SW oblique scarp, is that it contains widespread mineralization of epidote on adjacent fracture surfaces in several locations along the scarp.

Obvious Caledonian metamorphic minerals such as amphibole, garnet and epidot are general components of the bed rock in the area (see Chapter 3). Later in the Caledonian Orogeny, retrogression altered these minerals to e.g. chlorite, hematite and epidote (Binns, 1978). During Mesozoic and/or Cenozoic tectonic events linked to the opening of the North Atlantic (Chapter 1.5), a subsidiary low-grade metamorphic mineral assemblage (epidote + hematite + quartz) was locally formed and precipitated in the fracture sets, e.g. NE-SW striking fractures.

Previous workers suggested that the fjord and valleys in Norway were structurally controlled and arranged along regionally extensive fracture systems and that the fractures were pre-glacial in origin (Randall, 1961). In 1968 it was pointed out by Bjerrum & Jørstad that major fracture sets existed at different depths and along the valley sides. These fractures seemed to be nearly vertical in the upper part of the slope and became more gently dipping lower in the slope. The interpretation then was that the fractures may have been formed during different stages when the stress changed during the erosion of the valley profile (Bjerrum & Jørstad, 1968). More recent studies (Osmundsen et al., 2011) have discussed the influence of inherited fracture patterns from the more coastal areas and reactivated normal faults (see Ch. 5.5.7).

Fractures in general are zones of weakness, and during reactivation they may enforce sliding of rock masses and sliding planes to develop (see Ch. 5.5.4). The reactivation of the NW-SE and NE-SW striking, inherited fractures at Hompen may have been triggered by numerous processes, e.g. changing water pressure within the fractures, melting of permafrost, earthquakes, and gravitational forces or because of natural weathering processes. These almost vertical pre-existing fractures may be seen as perpendicular fractures against assumed sliding plane/planes (Fig. 5.4b).

#### **5.5.4 Lithology**

The type of lithology, lithological variations (see Ch. 3.3) and the attitude of bedrock foliation (Fig. 4.7) can be considered as potential controlling factors for the location of the studied RSF. For example, competent rocks may easier crack to form rock masses and rock falls, whereas schistose bedrocks, gneisses and marble may be more susceptible to sliding due to mechanical weakening and e.g. chemical weathering (Saintot et al., 2011). Mafic bedrocks are considered as hard rocks, more resistant to surficial deformation and will therefore crack when exposed to stress instead of deforming in a plastic way. If fluids then are present or added as meteoric water or from melting permafrost the rock is even more pronounced to erosional processes such as cracking and frost-shattering. Such processes may also operate

well along bed rock fabrics, such as lithological contacts, mega-boudins and mylonitic foliation zones in the RSF area (Saintot et al., 2011).

The observed bedrocks in the studied RSF area include a variety of different lithologies, quartz-feldspatic gneisses, amphibolite gneisses and mica-schists (see Chapter 3). Lithological variations do not alone control the initiation of a RSF in general, but softer schist's may give a distinct style of deformations with lower shear angles and creep (Crosta & Agliardi, 2003; Braathen et al., 2004). In the Hompen RSF the diverse lithology may at least locally, have controlled the internal style of deformation, and also helped to localize fractures and potential detachments. The abundance of fractures in some areas/lithologies, for example, may have enhanced fluid flow which can lead to (chemical) erosional weathering of mafic minerals and e.g. clay minerals with a low friction coefficient, thus causing movement as creep along a detachment (see Ch. 5.4.4).

The present work supports the hypothesis, that lithology and lithological variations may have had at least a subsidiary effect on the observed morpho-structures in the different areas (Saintot et al., 2011), through fractures and fluid flows which enhanced weathering of e.g. mafic minerals and clay minerals with a low friction coefficient and are prone to fail. The new minerals caused by such a crushing and grinding process produced very fine debris which may be called "gouge", these secondary minerals are typical in the clay family, those of sheeted crystal structures and these are characterized by low frictional strength (coefficient of friction) especially when saturated with water. A small sheet of water may lubricate the mineral grains, and makes it even easier for them to slip. The other effects in connection to the frictional strength of the minerals is the hydrostatic fluid pressure and if there is a low fault permeability or strain rate dependency (Morrow et al., 2000).

### **5.5.5 Hydrogeological effect on the RSF area**

One of the most important driving mechanisms for RSF area is thought to be that of water drainage into the area (see Ch. 4.6). The effect of increasing pore pressure because of e.g. rainfall, snow melting or lake drainage, (chemical) erosional weathering acting along discontinuities may result in long term reduction of shear strength and may enhance the movement of a RSF (Braathen et al., 2004).

Since there is no evidence of permanent surface water in the Hompen RSF area, the groundwater table must be at a lower level and water may have worked its way down into the RSF area. This suggestion is supported by good drainage of the area through numerous



fractures that may have systematically drained the water deeper into the RSF. There are observed seasonal water in the graben next to the back scarp in early summer (Fig. 4.30d), this water may have drained down into the RSF area as soon as the snow melted. The interpretation of this kind of drainage is that melt-water drained into a frozen crack system. The origin of this trapped water may be from winter snow and ice (Fig. 4.30d) (huge amounts of snow are trapped in the area during winter). The water drains down into the RSF area as soon as the ice is melted between the loose rock materials in the graben. There is no clear evidence on where the draining water emerges (see Ch. 4.6). The whole RSF area and the land area under the toe zone scarp (Fig. 5.7) show no sign of water during late summer month. The water may emerge into several deep open fractures and deeper down in the bedrock and drain all over the RSF, it is a big drainage area which may be able to store and transport a lot of water. The final drainage may be into the ground water table and into the river of Signaldalen (Braathen et al., 2004). That the river has areas which does not freeze properly during winter, may be a sign of that the groundwater seeps out with high pressure into the river from the RSF area. Those parts of the RSF area which might consist of high hydrostatic water pressure may influence and work in order to destabilize the rock mass.

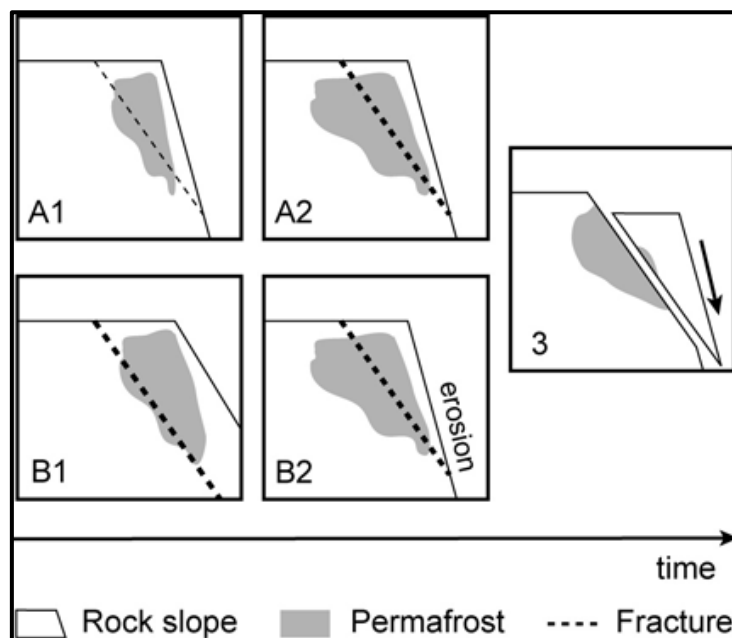
The effect water has on fault gouge minerals (see Ch. 5.4.4, Ch. 5.5.4), are also very important to take into account. When water is added if it as: rain, drainage events, melting of permafrost or from other source it induces as extra amounts or just as predicted amounts it will affect the RSF area and may make it destabilize. Many of the sheet minerals have shown to reduce their frictional strength to as much as 60%, when water is adsorbed by the mineral or interlayered in the sheet-structure (Morrow et al., 2000).

Another potential triggering factor for the studied RSF area is variation in hydrostatic fluid pressure. For example, a rapid increase in pore pressure may lead to reduction in effective normal stress and a reduction in shear resistance of the sliding surface, this variation of fluid flow is highly present at the Hompen RSF with seasonal drainage of water ponds (see Ch. 4.6). The weight of water can also act as a driving force by itself on the rock mass. To get a groundwater pressure to build up, the water should be trapped in the RSF area, this may be done by sealing of the area, by e.g. a low-permeable membrane either as an ice sole (in cold regions or if permafrost exist) or a gouge sole along a basal detachment this may also be what is happening in the RSF area with ice that blocks the fluid flow (Braathen et al., 2004).

## 5.5.6 Permafrost

There is no obvious sign of permafrost in the Hompen RSF area today, but most likely the area has been subjected to permafrost activity in the past and there can be local permafrost in favorable areas. This is supported by the observation of polygenetic features (see Ch. 4.5) in the area above the lakes in the Markus valley, these may be relict rock glaciers or slope failure deposits seen on satellite images (Wilson, 2004), and that there is perennial snow/ice in the fractures in the RSF area (Fig. 4.13c, Fig. 4.18, Fig. 4.20) may also support the hypothesis that there may be permafrost today in the area (H. Christiansen, personal communication, 2012).

The RSF area is experiencing a water drainage event (see Ch. 4.6) which is interpreted to be related to the snow/ice melt. This ice down in the fractures all over the RSF area may create wedging of fractures (Fig. 5.18), if water is available and many freezing processes exist. The ice will expand and further cracking of the rock is evolving. This process may be one working at the Nordnes unstable mountain slope, here the highest movement in the rock is during winter (that is when segregation of ice expands the rock mass) (Blikra & Kristensen, 2011). The same process can be active at Hompen during periods when permafrost has or are existing in the area.



**Figure 5.18:** Illustration showing the evolution of A) stable joint in permafrost, starting to widening by ice segregation in permafrost, failure is a fact when permafrost melts B) stable joint freezes, the slope is exposed for erosional processes, failure is a fact when permafrost melts or the fracture gets daylighted. (Gruber & Haerberli, 2007)

The RSF area have several fractures where the snow/ice does not melt during summer. The fractures behind the back scarp, melt very late in the summer, if they melt the temperature down in the fractures may never reach the surface temperatures (Fig. 4.39) (H. Christiansen, personal communication, 2012). As low as 200 m.a.s.l. (Fig. 4.20) and on the plateau at 700 m.a.s.l. this is observed (Fig. 4.39). Even if the RSF is a SW facing slope with lots of sun and last summer with warm and dry weather the snow does not melt, so there may be permafrost in the area today making the bedrock stay cold. Most likely the area did not have permafrost during the retreat of the Weichelian Ice sheet because that was a temperate ice sheet. Under temperate glaciers it is rare to find permafrost (Benn & Evans, 1998). The permafrost which may be in the area today and surrounding areas may also be from climate stable colder periods after the last ice sheet retreated e.g. the little ice age (c. year 1350-1850).

If there is permafrost, these processes will help to enforce the frost shattering, a mechanical disintegration of rock as splitting and break up. Freezing water in cracks and pores, or along bedding planes can be referred to frost shattering (Jackson, 1997) as long as the permafrost exist it will stabilize the rock, it is when climate conditions change and melting starts the rock may get unstable of enhanced water in the RSF system (Gruber & Haeberli, 2007) (Fig. 5.18). This may be why we see movement in slopes today, that there is a melting of unknown permafrost destabilizing areas which earlier have been stable or experienced earlier RSF's.

Permafrost may be a driving mechanism for movement in unstable mountains and may give stability problems in bedrock (Gruber & Haeberli, 2007; Blikra et al., 2009). First it may work as stabilization for the rock mass, segregation of ice and frost shattering processes makes the existing joint to fracture and when the permafrost melts the failure may be a fact. The mechanisms that link warming and destabilization is not well understood. There are especially three different surface conditions which effect bedrock consisting permafrost: How thick ice or snow cover the area have, the amounts of fractures in the bedrock and how much water is available and may drain into the fractures. (Gruber & Haeberli, 2007)

It is known that there is permafrost in the mountains in north Norway at elevations as low as 550 m a.s.l at Nordnes unstable mountain slope in Troms, it is monitored permanent ice down at 20 meters depth in one of the crackdown in a crevasse (R. Evenes, personal communication 2011; Brown et al., 2001; Christiansen et al., 2010; H. Christiansen, personal communication, 2012). There are an ongoing research project with boreholes and mini loggers just 25 km, north east (Skibotnvalley) from Hompen (Fig. 1.8), showing the distribution of the boreholes



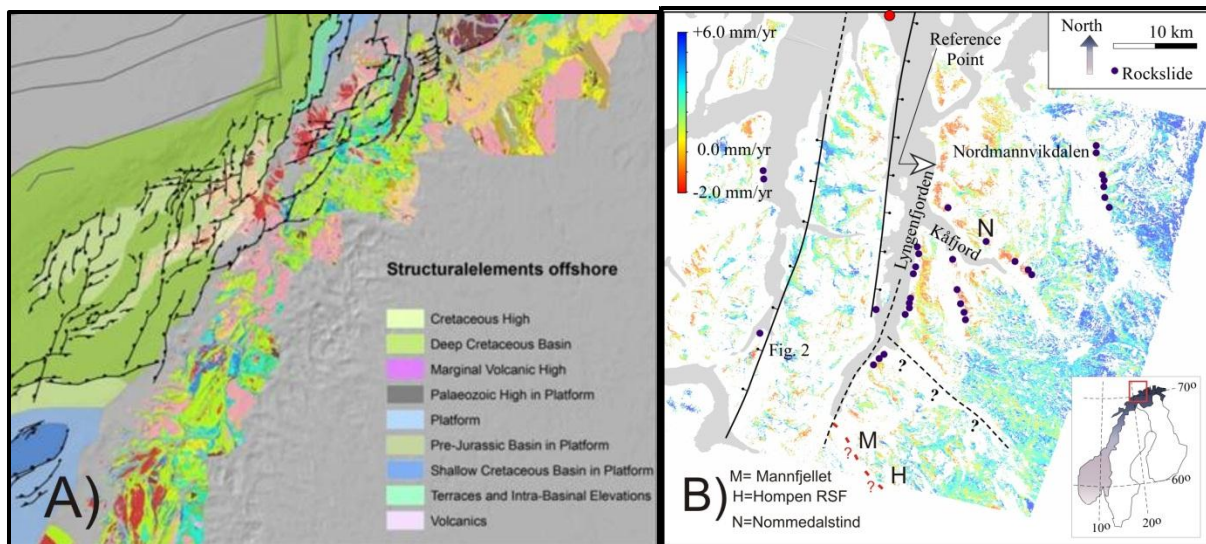
and mini loggers ([www.tspnorway.com](http://www.tspnorway.com)) (Tspnorway, 2012). The regional permafrost is located from about 800 m.a.s.l, but there can be topographical conditions favoring permafrost at much lower elevation (Christiansen et al., 2010; H. Christiansen, personal communication, 2012). In a report regarding the movement on Paras, a neighboring slope to Hompen (Fig. 1.2b), it is mentioned that the movement may be related to permafrost (Hendersson et al., 2009).

There is a high potential that the Hompen RSF area are experiencing several frost thaw cycles down in fractures, and that will enhance wedging and cracking of rock. These phenomena do not need permafrost, and are most likely phenomena happening in the areas experiencing toppling as a failure mechanism. Areas on the InSAR image (Fig. 5.7), have some areas which indicate a high (red) relative movement away from satellite, some of these red areas coincides with areas consisting of talus material e.g. northern landslide lobe and loose cracked bedrock north above back scarp. These areas are interpreted to be indicating movement because of frost thaw cycles.

### **5.5.7 Regional fracture systems and neotectonic activity**

Already in 1886 it was pointed out by a Gregory Peschel that there was a relation between fjord and valley directions and regional fracture pattern in the Lyngen area (see Ch. 3.4). Peschel (1886) further indicated that the fjords were arranged along fracture lines and that they were pre-glacial in origin (Randall, 1961). However, two additional regional fracture directions (NW-SE and NE-SW) did not fit into the fjord and valley system. But it was a clear connection to the NNE direction in regard of fjord and fractures (Fig. 3.14) (Randall, 1961).

Pre-existing regional fracture systems in the bed rocks and neotectonic activity are potential factors that may have controlled the initiation of the studied RSF (Braathen et al., 2004; Redfield et al., 2005; Blikra et al., 2006b; Osmundsen et al., 2009, 2010). Neotectonic activity in Norway has been reported and documented by earthquakes and InSAR interpretations (Fig. 5.19B) that appears to have a link to some of the main regional fractures and faults in e.g. northern Norway (Fig. 5.19A) (Hansen et al., 2011). However, just a few of the major earthquakes have been classified as due to certain neotectonic fault activity ‘Almost certainly neotectonics’ and some are ‘Probably neotectonics’, most of the claims were attributed to other effects than neotectonics (Lindholm et al., 2011).



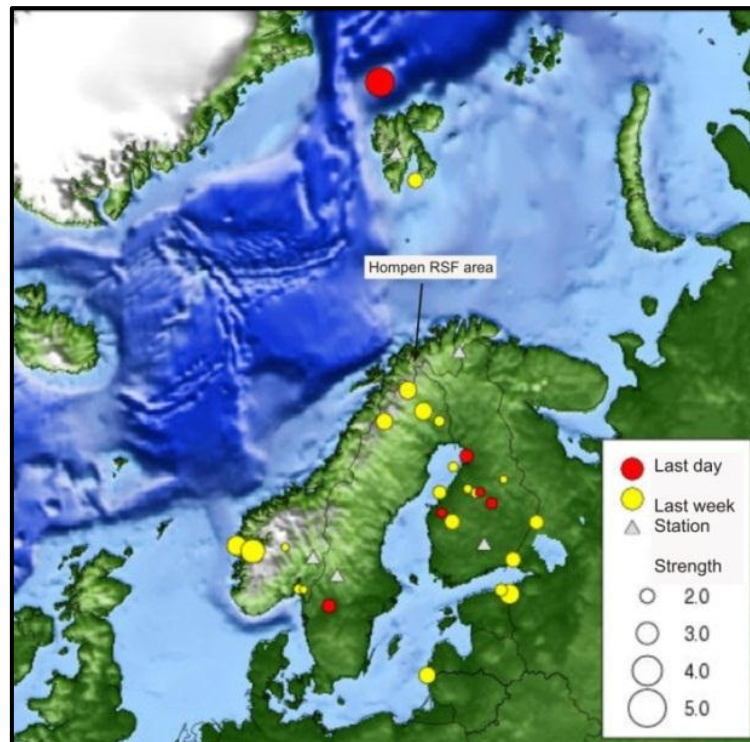
**Figure 5.19:** A) Regional map showing normal faults in the outer part of Troms and Nordland. Main trends are NNE-SSW, NE-SW and ENE-WSW which is similar to what is seen on land (Fig. 1.4 and Fig. 4.2) (Modified by Hansen (2011)). B) InSAR image over the Lyngen peninsula with assumed active normal fault, Signaldalen valley is the southern most valley turning east. Identified RSF are clustered around the presently active Lyngen Fault Complex (labeled with dashed red lines with the down throw indicated) (Modified from Osmundsen et al., 2009)

There is a ‘Almost certain neotectonic’ fault recognized in North Norway e.g. in Troms, Nordmannvikdalen just north of Kålfjord (Fig. 1.4), this is a NW-SE trending normal fault with dip to NE (Dehls et al., 2000), this is one of the ‘Almost certain neotectonics’. Many others faults are classified under ‘Probably neotectonics’ and may be seen as secondary effects of large-magnitude earthquakes. This may be seen as RSF structures and other collapsed structures (Lindholm et al., 2011). One of the criteria which are in generally in use for classification of neotectonic faults is that the fault has a offset/length ration of c. 1:10 000 (Dehls et al., 2000), there are no known neotectonic faults in the area of Hompen.

The Norwegian coast has been subjected to tectonic uplift of c. 0.1-0.3 mm/year during the Quaternary period (e.g Mangerud et al., 1981; Sejrup, 1987), in addition to postglacial rebound/uplift (see Ch. 5.5.2). Recent seismic activity in Scandinavia, however, shows much higher values (Fig. 5.17), and can be explained by continued tilting of Norway and Sweden due to ridge push from the Mid-Atlantic ridge (Pascal et al., 2005). This means that Quaternary tilting due to ridge push also can play a role in the neotectonic activity (Dehls et al., 2000).

Regarding recent earthquakes in Troms, there are quite frequent smaller magnitude earthquakes (Fig. 5.20) (NORSAR/jordskjelv.no). It is assumed that there were more earthquake activity and larger magnitude earthquakes in the time period just after the last de-

glaciation, but there is no clear evidence that earthquakes have triggered RSF in north Norway (Blikra et al. 2006; Gregersen, 2006).



**Figure 5.20:** A) B) Map over Scandinavia and the most recent seismic activities (down loaded 31.3.2012), as seen there have been several 3.0 (Rh), earthquakes in northern Scandinavia (NORSAR/Jordskjelv.no, 2012)

The connection of the Hompen RSF to regional faults is not well documented. However, and as interpreted from (Fig. 5.19b), most RSF in central Troms have occurred along the trace of Lyngenfjorden, on both sides, which is parallel to the presumed Mesozoic Lyngen fault (Osmundsen et al., 2009, 2010). This major lineament terminates in the inner part of the fjord, near the mouth of Signaldalen. Reactivation and later uplift of such regional Mesozoic faults in Central Troms (Fig. 5.19a, b), may have happened in the Cenozoic, after the main rifting and opening of the Norwegian-Greenland ocean (Redfield et al., 2005; Osmundsen et al., 2009, 2010; Bergh et al., 2007). In central Troms regional uplift and fault-fracture reactivation is still considered to be in progress as documented by InSAR data (Fig. 5.19) and the presence of morpho-tectonic elements that coincide with presumed Mesozoic faults (Osmundsen et al., 2009). In the Lyngen peninsula and the Kåfjord valley (Fig. 1.4, Fig. 5.19) InSAR data (Fig.5.19) show that the Lyngen peninsula is moving upward towards the satellite and areas to the east of Lyngenfjorden are moving away from the satellite (Osmundsen et al., 2009, 2010). This effect was interpreted by Osmundsen (2009) as due to the presence of a major normal



fault striking NNE-SSW and with steep dip to the ESE, with the Lyngen peninsula in the footwall and the Kåfjord area in the hanging wall. Interestingly, most recent RSF areas occur in the hanging wall of this normal fault (Fig. 5.19b; Osmundsen et al. 2009). In this perspective, the subsidiary valleys of the presumed Lyngen fault, i.e. the valleys of Kåfjord and Signaldalen, may be interpreted as normal faults striking oblique to the Lyngen peninsula (Fig. 5.19, 5.21A).

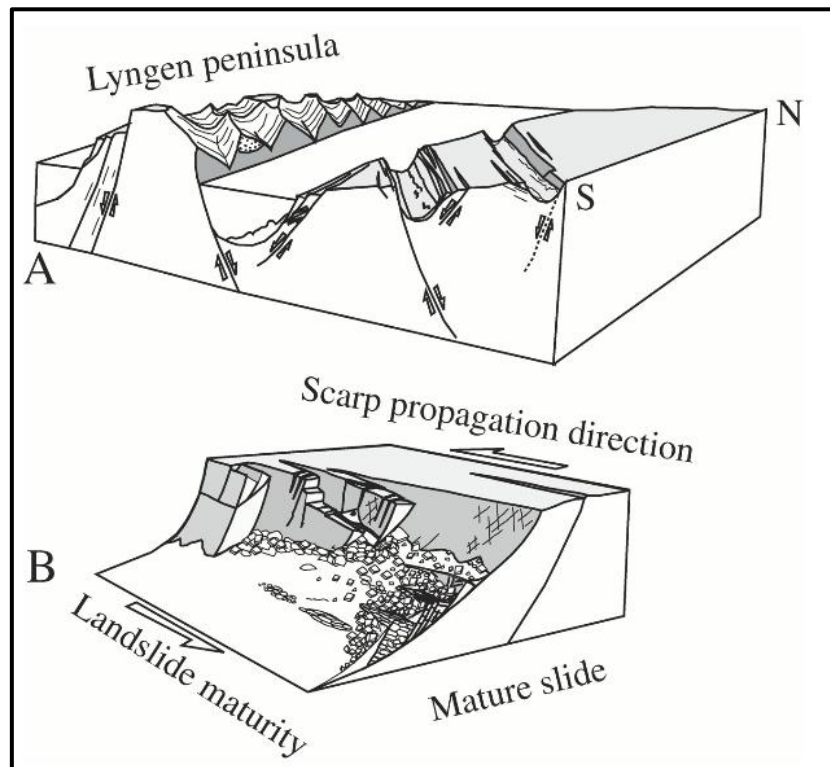


Figure 5.21: A) Illustration showing the relation between structures, landscape and RSF in connection to the Lyngen peninsula. B) Evolution of a RSF from initial stage with a surface, a steep propagating scarp and to a more mature stage where the glide plane is exhumed. (Osmundsen et al., 2009)

This oblique fault system seems to have more unstable escarpments on the SW facing slopes, e.g. corresponding with the hanging wall, and these hillsides could have been more pronounced for RSF (Fig. 5.21A,B). That a major NW-SE striking fault may exist in the study RSF area is inferred from meso-scale observations of high-frequency network of fractures and faults, as well as by the observed fractures in the bedrock in domain II, above the main back-scarp (see Ch. 5.5.3). This interpretation is also supported by InSAR data (Fig. 5.19b) and the observation that several RSF areas are clustered on the southwest facing slopes of other major valleys farther north, for example in Kåfjord-Nomedalstind, Signaldalen-Mannfjellet and Hompen (Fig. 5.19b).

More work should be done regarding this topic, in particular, in order to resolve and test the amount of movement on these regional scale faults (Osmundsen et al. 2009). The movement indicated from InSAR images (Fig. 5.19b) must be resolved, i.e. whether it represents recent movement or if it has been lasting for thousands of years. The validity of movement estimates from the InSAR data can also be tested. From a glacial point of view, how may the sea level rise match with the tectonic uplift history? This aspect is interesting since there is no report of a change in shoreline levels across Lyngenfjorden, compared to the mainland (G. Corner personal communication, 2012).

In summary, the regional scale fracture orientations in central Troms seem to correspond well with the more local trends observed in the area. The NW-SE and NE-SW striking fractures observed by Randall (1959) may have provided zones of weakness in the bedrock in the studied area. In particular, the NE-SW striking back-scarp and NNE-SSW striking oblique/transvers scarp that bound the RSF may have been reactivated regional normal faults which have formed the main valley directions in the area.

## **5.6 Evaluation of geo hazard**

The whole discussion may point out the importance of displaying more than one parameter supporting the hypotheses that an area is in movement. Therefore this type of multidisciplinary approach on RSF research is interesting and makes a relevant platform for discussion a RSF's areas further evolution.

Hompen RSF area may have potential for develop to a hazardous RSF area. It may have a developing major basal sliding plane or several smaller step-wise sliding planes developed in weakness zones in the bedrock e.g. mica schist layers. With right type of secondary factors e.g. fluids, gauge development, frost-thaw cycles etc. Even if there is just a sub horizontal daylighted sliding surface a huge mass of rock can be moved, first as creep and depending on conditions maybe accelerate (Willenberg (2004) in Blikra et al., 2006a). There is nothing that indicates that this process is active and would happen in next century, there are several factors which just seem to be initiated.

The Hompen RSF would not qualify to a risk area regarding RSF's, there is too little economic loss and potentially now human lives would get lost, it is to remote area. There would be secondary effects if a major slide event, as that the river of Signaldalen would get blocked. The Hompen RSF will experience several smaller rock falls or rock avalanches in

closer future, through sliding and toppling there are several favorable conditions in the area for that.

The 30° dip direction of the foliation in the southern lateral scarp may be favorable to developing a sliding surface, and there are also pre-existing fractures (Chap. 5.2.1.2) in the bedrock which may cut through the foliation and enhance propagation south. InSAR image (Fig.5.7) also shows that there may be movements in the bedrock south of the southern lateral scarp.

The back scarp truncates the foliation; the low angle (c.15°) of dip in the back scarp does not necessarily mean that the back scarp can propagate further east, as the case in the southern lateral scarp. But in contrast, the area above the back scarp consists of several major tensile fractures (Fig. 4.39), which may be a sign that there are or have been movements in the area. The whole area may develop a basal sliding plane under the whole unstable rock mass, with secondary effects of that.

The future evolution of the Hompen RSF will most likely be dependent on what hydrogeological conditions the area will have and get in the future.



## 6. Summary and conclusions

The Hompen rock slope failure area has been studied through extensive field work and investigations, including collecting the field data and mapping of observed bedrock and morpho-structures, studying aerial photos, DEM models, InSAR data and dGPS measurements. This multidisciplinary approach and use of techniques as InSAR data and dGPS measurements has proven to be very useful when interpretations and conclusions are made. Several maps have been constructed in Arc GIS which has shown to be useful for the interpretation of the RSF.

- The Hompen RSF area is divided into two domains: Domain I, the area where most morpho structures are seen, from c.200-600 m.a.s.l., area of c. 0.63 km<sup>2</sup> and a mean gradient of 35°. Domain II, the area which was thought to be stable, mostly defined above the back scarp. The total area of the whole RSF will exceed >1,5 km<sup>2</sup>. This division is supported by observations and measurements taken for this thesis, e.g. InSAR data. The Domain II area boundaries are uncertain and more work has to be done to define the outer boundaries.
- The Domain I RSF area is structurally confined by an upper back scarp zone striking NW-SE (900m long and c.100m high) as the eastern boundary of Domain I. The southern boundary is an oblique NE-SW striking lateral scarp, joining the back scarp in a 120° angle. The height of the scarp is c.30m, and it lowers as following topography downslope towards SW, diminish to the south. The toe zone scarp with talus zone beneath, form the toe zone as the lower limit. The northern boundary is confined by a major talus area defined as minor landslide area. Domain II is the area adjacent to Domain I, but defined to the east and south because of found pre-rock slope failure structures in these areas e.g. major tensile fractures. Domain I is separated from Domain II by the fact that the mass has a vertical displacement of c. 20m and a horizontal movement of c.60-80m.
- The Hompen RSF reveals gneissic bedrock with areas of amphibolite and mica schist. The area may be part of a major Caledonian anti-form fold. There are significant variations in the orientation of the foliation in the area from sub horizontal NW-SE striking to steep NNE-SSW striking in Domain II (above back scarp) to a more NW-SE striking sub horizontal and gently dipping in Domain I. The foliation and its strike

and dip directions will not itself be a reason for the development of the RSF in the area.

- Two distinct fracture sets are mapped within the both domains, steeply dipping features with approximately strike NW-SE to N-S strike and NE-SW. The NW-SE fracture set is present almost in all localities in the RSF; the trends of these steeply dipping fractures follow the main trends of lineament in the region.
- The area display structures as e.g. scarps and counter scarps which are typical pre-failure deformation structures, which can be seen in RSF areas worldwide. These morpho-structures can be comparable with structures seen in major extensional tectonic regimes, e.g. continental rift zones. Therefore the term “Slope tectonics” can be used when discussing RSF structures. The upper area of Domain I where most of the structures are observed, e.g. a major graben with belonging major escarpment “back scarp.” In connection to this there is a system of several or single counter scarps. There are also several transfer structures in connection to en-echelon stepping fractures or counter scarps such as e.g. collapsed relay ramp in the major graben.
- The movement direction of the RSF (Domain I) is mainly interpreted from observed morpho structures in the area. Movement is normal to scarps and counter scarps, transfer structures that show an oblique direction will most likely have a movement direction which goes parallel to the structure. There are major transfer scarp which can be seen as a counter scarp to the south lateral scarp. This indicates that there may be a shear component in this area, while the other smaller transfer scarps in Domain I indicate that the movement is parallel to the transfer scarps, moving SSW and a result from different speed of the sliding mass. This hypothesis is supported by dGPS data and InSAR data over the area which indicates a SSW direction of movement significantly highest in the southern part of the RSF.
- The interpreted movement mechanism today is creep, which occurs at present with a speed of (7-10 mm/year) as indicated by dGPS. The movement is interpreted to be due to movement along several smaller step-wise sliding planes developing in weakness zones in the bedrock. The steps may be linked together by vertical fractures. There is also clear evidence of toppling as failure mechanism, shown by the major graben which is filled with toppled rock material. Seasonal freeze thaw processes may be the most active process in the area today and are seen as local toppling.

- The interpretation of step-wise sliding planes in the RSF area can be supported by the fact that most morpho structures are observed in the upper area, which may be a result of several small sliding surfaces in the bedrock possibly causing higher movement on the slope surface in this area. The sliding planes have developed in a pre-existing weaker zone, e.g. mica schist's foliation in the bedrock, can be supported by that there may exist several layers of mica schist in the RSF area.
- Regarding classification of the RSF area, the area is defined under the complex field consisting of a sliding component, either as a planar detachment because of the steepness of the back scarp, or as several step-wise sliding planes. The total RSF area is of major size, according to Braathen (2004). There are several areas which show an active toppling. There is a minor landslide in the northern part. The conclusion is that it is a complex listric RSF (Braathen, 2004), which is hard to put just into one specific order. The Hompen Rock slope failure area can with this thesis is classified as a DSGSD (Deep Seated Gravitational Slope Deformation) with features scarps, counterscarps and internal minor landslide areas.
- A major reason why we find Hompen RSF area where it is located is: the topography of the slope, pre-existing weak zones in the bedrock and that there were stored stress regime in the slope.
- The effects of the de-glaciation in the area which may impact the RSF is;
  - rapid ice melt and fast retreat of ice from the valley
  - glacial unloading and uplift of the area
  - stress release from stored stresses in the bedrock
  - destabilizing of the slope by undercutting by glacial erosion and water
  - high pore fluid pressure, in the bedrock because e.g. melting of permafrost and a more humid climate with meteoric precipitation.
- The fracture distribution and their origin in the RSF area are interpreted to be pre-existing fractures. The RSF areas bedrock consists of inherited structures such as pre-existing joint sets striking NW-SE and NE-SW, which may have their origin in a tectonic setting during Mesozoic time and the extensional regimes during Norwegian/Greenland Ocean opening in Cenozoic. These directions correspond well with regional lineaments seen in the region and an early fjord-valley and fracture study made in the Lyngen area.



- Regarding further evolution and hazard of the RSF area, my interpretation is that the area will not suffer a major catastrophic event, meaning that the whole volume will not fall out at the same time. There can be smaller volumes which will fall out, depending on what future climatic and environmental conditions the area will experience. There is no direct infrastructure in the area today; there is a major river in the bottom of the valley, so there is no direct hazard for human life or infrastructure.

The area is still an interesting subject for further studies regarding fluid interaction in RSF areas, and more work should be done on that. There may also be more work done on what effect permafrost may have on the RSF areas. Further work should also be done on the movement pattern in the RSF area. A suggestion is to place several more dGPS points in the lower part of Domain I (one in the south near the crevasses and one further north) and one north of the minor landslide area, to measure if there is movement in the area, or just surface weathering processes. Little is known about the movement pattern in the lower part of the RSF. If there existed a better understanding of mass movement in this area it would also support or refuse the hypothesis from this thesis, regarding the existence of several sliding planes in the upper part of Domain I. There could also be done volume estimations, which also need more work especially regarding the depth to the assumed sliding plane/planes. When the volume is estimated it will also be possible to make a realistic hazard/risk evaluation, with potential run out distances.

To summarize my conclusion: The Hompen RSF area is a fracture induced failure (pre-existing brittle structures) striking NW-SE and NE-SW, activated through different processes e.g. glacial unloading, internal stresses, melting of permafrost etc. The start of the RSF was with both an extension and vertical drop of the mass, starting with toppling, but soon went over into a gravitational slide because of the horizontal lengthening of the RSF mass. The movement as creep today is due to several step-wise sliding planes which work their way down through fractures to a deeper detachment. The area may have been stable in periods when permafrost was present (stabilizing the mass), but during the last time period this potential stabilizing ice has disappeared or is disappearing. This may also lead to enhanced seasonal frost thaw cycles and change of pore fluid pressure in the bedrock affecting the RSF.

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