

NGU Report

**Structural mapping of potential rockslide  
sites in the Storfjorden area, western  
Norway: the influence of bedrock geology  
on hazard analysis**

# REPORT

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| <p>Title:<br/><b>Structural mapping of potential rockslide sites in the Storfjorden area, western Norway: the influence of bedrock geology on hazard analysis</b></p>   |  |                    |  |               |                     |
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| <p>Summary:</p> <p>The western coast of Norway is particularly vulnerable to active rockslide development due to the recent post-glacial uplift and the deep incision of the fjords created by glacial activity, leading to extremely steep fjord sides. The purpose of this work was to determine the influence of structural geology on the hazard analysis related to large rock avalanches in the Storfjorden area. This is an area where several historical rock avalanches and related tsunamis have led to disasters with many people killed. Geological studies in the fjords have also shown that such large-scale events are relatively frequent in the region. The investigated area is 360 km<sup>2</sup> and comprises Sunnylvsfjorden, Geirangerfjorden, Norddalsfjorden, Tafjorden and the southern part of Storfjorden. We have examined over 40 potential landslide sites within this area. The objective was to determine if a series of particular geological factors were important for landslide evolution in order to construct a predictive geometrical model for the development of landslides within the area. Regional foliation mapping has shown a series of complex recumbent isoclinal folds in the host granodioritic to dioritic gneisses, where the average dip of the foliation is between 20-40°. The fjord system in Storfjorden consists of several east-west and several north-south trending fjords. At many sites, we have observed basal planes of possible rockslides developed parallel to foliation. Therefore, the orientation of the foliation with respect to the fjord can result in geometrically different types of landslide geometry and related hazard. The potentially active areas can be divided into two geometrical groups. These are i) toppling and ii) sliding. Detailed structural fieldwork has demonstrated that the toppling geometry make up the smallest volumes of potential landslides and in particular in specific areas where the foliation dips in the opposite direction to the fjord. Rockslides display the largest potential landslide volumes and occur specifically where the pre-existing structural geometries are favourable. i.e. rock slides occur where the foliation dips between 20-35° <i>towards the fjord</i>. This allows for the construction of a predictive spatial-geometrical model for the development of large rockslides in the Storfjorden area. Several critical factors must be present for the development of large potential rockslides. These are: 1) the orientation of the foliation with respect to the fjord. 2) The presence of a Basal Shear Plane (BSP) at the base of the potentially moving block. This can be a relatively planar structure but more often displays a complex step geometry due to the complexity of the fjord-dipping foliation. 3) The presence of a fault breccia on the BSP. These non-cohesive fault rocks demonstrate that the detached block is actually moving and at the same time provides a lubricating base for the block movement. 4) The presence of exfoliation which weakens the BSP. 5) The presence of a steep extensional fracture at the back of the moving block – a 'back crack'- which is necessary to detach the block. This also includes the sign of active postglacial movements leading to open tension cracks on top of the potential failure block. Where these factors are not present, there is generally no evidence for activity in the hangingwall block (hangingwall disintegration by fracturing, kinematic indicators, breccia development). 6) The presence of transfer faults with strikes parallel to the movement direction of the block in order to detach the block from the mountainside. We find that many back cracks are localised on and reactivate pre-existing geological lineaments. Small-fold development within the foliation also appears to have a large affect on the development and movement of rock-slope failures. We present a geometrical model for the development and predicted location of the largest potential rockslides in the Storfjorden area. The pre-fieldwork analysis of aerial photos allowed the identification of 49 different sites in the Storfjorden area which required field investigation, based on the presence of observed strong lineaments, obvious block detachments or the presence of active talus slopes. From the 49 sites identified, extensive fieldwork determined that 35 of these may have evidence for recent movement. Among the sites studied in 2005, 15 should be visited again in 2006 to collect more data and improve the knowledge of structures involved in the rockslides and to collect new GPS measurements to determine the magnitude and direction of displacement. This work will be integrated with two international groups focusing on hazard analysis in Storfjorden</p> |  |                    |  |               |                     |
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| Susceptibility  |  |                    |  |               |                     |
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## ABSTRACT

The western coast of Norway is particularly vulnerable to active rockslide development due to the recent post-glacial uplift and the deep incision of the fjords created by glacial activity, leading to extremely steep fjord sides. The purpose of this work was to determine the influence of structural geology on the hazard analysis related to large rock avalanches in the Storfjorden area. This is an area where several historical rock avalanches and related tsunamis have led to disasters with many people killed. Geological studies in the fjords have also shown that such large-scale events are relatively frequent in the region. The investigated area is 360 km<sup>2</sup> and comprises Sunnylvsfjorden, Geirangerfjorden, Norddalsfjorden, Tafjorden and the southern part of Storfjorden. We have examined over 40 potential landslide sites within this area. The objective was to determine if a series of particular geological factors were important for landslide evolution in order to construct a predictive geometrical model for the development of landslides within the area. Regional foliation mapping has shown a series of complex recumbent isoclinal folds in the host granodioritic to dioritic gneisses, where the average dip of the foliation is between 20-40°. The fjord system in Storfjorden consists of several east-west and several north-south trending fjords. At many sites, we have observed basal planes of possible rockslides developed parallel to foliation. Therefore, the orientation of the foliation with respect to the fjord can result in geometrically different types of landslide geometry and related hazard. The potentially active areas can be divided into two geometrical groups. These are i) toppling and ii) sliding. Detailed structural fieldwork has demonstrated that the toppling geometry make up the smallest volumes of potential landslides and in particular in specific areas where the foliation dips in the opposite direction to the fjord. Rockslides display the largest potential landslide volumes and occur specifically where the pre-existing structural geometries are favourable. i.e. rock slides occur where the foliation dips between 20-35° *towards the fjord*. This allows for the construction of a predictive spatial-geometrical model for the development of large rockslides in the Storfjorden area. Several critical factors must be present for the development of large potential rockslides. These are: 1) the orientation of the foliation with respect to the fjord. 2) The presence of a Basal Shear Plane (BSP) at the base of the potentially moving block. This can be a relatively planar structure but more often displays a complex step geometry due to the complexity of the fjord-dipping foliation. 3) The presence of a fault breccia on the BSP. These non-cohesive fault rocks demonstrate that the detached block is actually moving and at the same time provides a lubricating base for the block movement. 4) The presence of exfoliation which weakens the BSP. 5) The presence of a steep extensional fracture at the back of the moving block – a 'back crack'- which is necessary to detach the block. This also includes the sign of active postglacial movements leading to open tension cracks on top of the potential failure block. Where these factors are not present, there is generally no evidence for activity in the hangingwall block (hangingwall disintegration by fracturing, kinematic indicators, breccia development). 6) The presence of transfer faults with strikes parallel to the movement direction of the block in order to detach the block from the mountainside. We find that many back cracks are localised on and reactivate pre-existing geological lineaments. Small-fold development within the foliation also appears to have a large affect on the development and movement of rock-slope failures. We present a geometrical model for the development and predicted location of the largest potential rockslides in the Storfjorden area.

The pre-fieldwork analysis of aerial photos allowed the identification of 49 different sites in the Storfjorden area which required field investigation, based on the presence of observed strong lineaments, obvious block detachments or the presence of active talus slopes. From the 49 sites identified, extensive fieldwork determined that 35 of these may have evidence for recent movement. Among the sites studied in 2005, 15 should be visited again in 2006 to collect more data and improve the knowledge of structures involved in the rockslides and to collect new GPS measurements to determine the magnitude and direction of displacement. This work will be integrated with two international groups focusing on hazard analysis in Storfjorden.

## SAMMENDRAG

Vestkysten av Norge er spesielt utsatt for fjellskred på grunn av nylig oppheving av landmassene etter istiden som har ført til svært bratte fjord og fjellsider. Det er dokumentert flere historiske katastrofer knyttet til store fjellskred og flodbølger i Storfjorden, med Skaffjellet i 1731 og Tafjordskredet i 1934 som de verste. Formålet med dette arbeidet har i hovedsak vært å undersøke hvordan geologiske strukturer og fenomener influerer og kontrollerer utviklingen av store fjellskred i Storfjorden. Dette har stor betydning for de videre fareanalysene som skal utføres i indre Storfjorden. Områdene som er med i kartleggingen omfatter 360km<sup>2</sup> og består av Sunnylvsfjorden, Geirangerfjorden, Norddalsfjorden, Tafjorden and den sørlige delen av Storfjorden. Over 40 potensielle fjellskred objekter er undersøkt innenfor det prioriterte området Regional kartlegging av foliasjon (lagdeling) har vist at det opptrer en rekke komplekse isoclinal folder i den gneiser med lavvinklede akseplan (foliasjonen stuper mellom 20-40°). Fjordsystemet i Storfjorden består av flere øst-vest og flere nord-sør gående fjorder. Flere steder er det observert mulige basale glideplan for mulige store utglidninger som er utviklet parallelt med foliasjonen. Derfor kan retninger på foliasjonen i forhold til de ulike fjordsystemene resultere i ulike typer fjellskred og geometrier som har stor betydning for fareanalysene. De potensielle fjellskred områdene kan deles inn i to grupper. De er i) "toppling" eller "Velt" og ii) "utglidning". En må imidlertid være klar over at i en del sammenhenger kan de ulike typene opptre i samme område. Detaljert kartlegging av strukturer viser at toppling utgjør de minste volumene og er ofte begrenset til enkelte områder der foliasjonen heller innover fjellsida, altså bort fra fjorden. Områder med utglidninger har oftest større volum og oppstår hvor pre-eksisterende strukturer og geometrier ligger til rette for fjellskred. Dette vil for eksempel være der hvor foliasjonen stuper mellom 20-35° ned fjellsida og ut *mot fjorden*. Observasjonene fra hele fjordsystemet danner grunnlag for å bygge opp en kombinert struktur-geografisk modell som kan forutsi potensialet for utvikling av store utglidninger i indre deler av Storfjorden. Flere kritiske faktorer må være tilstede for å få utvikling av store utglidninger i fjell. Disse er 1) Fjordstupende foliasjon, altså ned fjellsida og ut mot fjorden; 2) Utvikling av et skjærplan eller en glideflate i bunn, ofte parallelt med foliasjonen (BSP). Denne kan være en relativt plan struktur men er oftere mer kompleks med en trappetrinn geometri pga kompleksitet i den fjordstupende foliasjonen; 3) Utvikling av en nedknusningszone (forkastningsbrekksje) langs potensielle glideplan (BSP) er også et kritisk forhold. Disse ikke-kohesive forkastningsbergartene indikerer at utglidningen kan være aktiv og i bevegelse, og vil tilføre "smøremiddel" til glidesonen; 4) Utvikling av overflateparallele oppsprekninger (eksfoliasjon) som opptrer pga heving av landoverflaten og fjerning av isstøtten etter siste istid. Denne kan være en viktig faktor for å gjøre potensielle glidesoner svakere og mindre stabil; 5) Utvikling av en steilstående ekstensjonssprekker i bakkanten av utglidningen er nødvendig for å frigjøre blokken. Dette inkluderer også spor etter aktiv bevegelse etter siste istid som kan være åpne sprekker på toppen av et potensielt fjellskred. Dersom disse forholdene ikke er observert er det generelt ikke noe bevis for en bevegelse av større volum. 6) Utvikling av en sideveis forkastning (transfer fault), parallelt med bevegelsesretningen for utglidningen, er ofte avgjørende for å få utglidninger frigjort fra resten av fjellsida. Mange steder er ekstensjonssprekker i bakkant av potensielle store utglidninger lokalisert til og mulige reaktiverte pre-eksisterende geologiske strukturer eller lineamenter. Små folder, utviklet i foliasjonen, ser også ut til å påvirke bevegelsesretning for noen utglidninger. Det blir presentert en geometrisk-geografisk modell som vil være et viktig utgangspunkt for å forklare og til en viss grad forutsi i hvilke områder en kan forvente store fjellskred i hele Storfjorden.

På grunnlag av studier av flybilder og generell geologisk informasjon ble det på forhånd identifisert 49 ulike lokaliteter i Storfjorden som hadde behov for feltundersøkelser. Dette var basert på markerte lineamenter og strukturer, utglidningsfenomener og skredavsetninger i fjellsidene. På bakgrunn av feltundersøkelser ble det konkludert med at det var indikasjoner på mulig bevegelse ved 35 av disse objektene. Det blir anbefalt at 15 av disse blir fulgt opp i 2006 for flere undersøkelser og for å eventuelt kunne påvise bevegelse ved bruk av GPS. Dette arbeidet vil bli gjort i samarbeid med to internasjonale grupper som skal arbeide med farevurderinger i Storfjorden.

## **1 INTRODUCTION**

The western coast of Norway is particularly vulnerable to active rockslide development due to the recent post-glacial uplift and the deep incision of the fjords created by glacial activity, leading to extremely steep fjord sides. The purpose of this study was to better define how the structural geology interacts with the hazard analysis related to large rock avalanches in the Storfjorden area. This area comprises Sunnlvsfjorden, Geirangerfjorden, Norddalsfjorden, Tafjorden and the southern part of Storfjorden. Several historical rock avalanches and related tsunamis have occurred in this area with subsequent human disasters. Geological studies in the fjords have also shown that such large-scale events are relatively frequent in the region. This study presents the preliminary results of structural fieldwork carried out in the summer of 2005. The purpose of this fieldwork was to investigate lineaments identified from aerial photos as potential failure surfaces in order to determine if there is active movement and therefore the possibility of a large rock avalanche and to determine if a series of particular factors were important for rock-slide development in this area. An important goal is to construct a predictive spatial and geometric model for the development of rock-slope failures within the Storfjorden area.

### **1.1 Regional Setting**

Autochthonous rock types from the Precambrian period were deformed and altered during the development of the Caledonian orogeny. These autochthonous rocks cover the whole of the mapped area of Storfjorden (Figure 1). The rock types mapped at 1:250 000 scale are for the most part undifferentiated gneisses, mostly quartz-dioritic to granitic with some migmatitic gneisses. The rock types have a large variation in mineral content and in most cases are grey-white or grey in colour and have a layered appearance, alternating light and dark based on feldspar and hornblende/biotite content (defining the metamorphic foliation). These layers can vary from several millimetres to several metres thick. Regional data shows that recumbent isoclinal folds were developed in the gneissic foliation. The axial planes of these folds are generally shallow dipping and have been refolded on extremely open fold hinges in such a way that the foliation is generally shallow dipping over the whole of the Storfjorden area but displays a changing attitude relative to the orientation of the fjord

and relative to the down dip gravitational direction in terms of landslide development. Therefore the orientation of the foliation with respect to fjord orientation and the orientating of foliation with respect to the fall-line towards sea-level are seen from the outset as important factors in potential landslide development sites.

Variation in the host rock is such that some of the more hornblende-biotite rich layers are extremely mafic in composition and consist of almost 100% biotite and/or hornblende. These zones form planar structures within the host rock which may be a zone of localisation for landslide shear planes, depending on their location and orientation relative to the gravitational fall-line.

## **1.2 Methodology**

Structural geology is used as tool to determine i) the geometry necessary for failure, i.e. the presence of a low-angle slip plane, a large extensional fracture detaching the block and a transfer structure, parallel to the line of down slope movement in order to detach the block, ii) kinematic evidence for movement activity and iii) an attempt of quantification of the stresses acting on the sliding plane. Figure 2 shows some of the classical types of structures associated with rockslides and which are expected to develop in the Storfjorden area if some critical objects are observed. On Figure 2A the block is considered to have free borders if not the case, transfer faults should develop to allow the movement of the block, they are vertical and slips along such transfer structures are highly oblique and parallel to the movement direction. In the course of this report some other types of structures will be described: conjugate system of joints which developed perpendicular to the basal shear plane, joints in the failure block parallel to transfer faults. Figure 2B shows a column failure/toppling process. Figure 2C shows the classical geometry of a wedge that is based on the presence of two basal shear planes with the intersection line corresponding to the direction of motion. However, other major structures can complicate this simple wedge geometry.



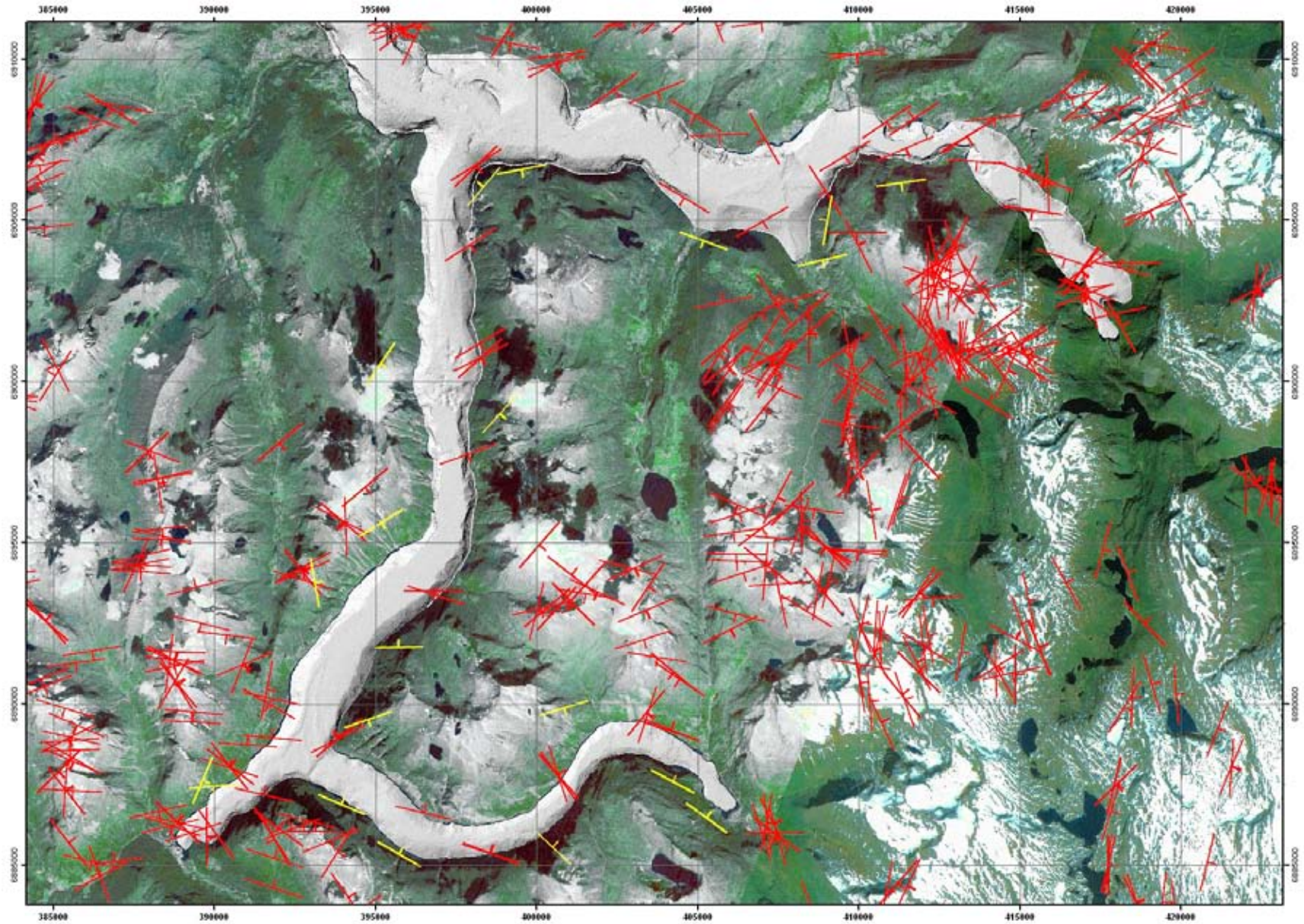
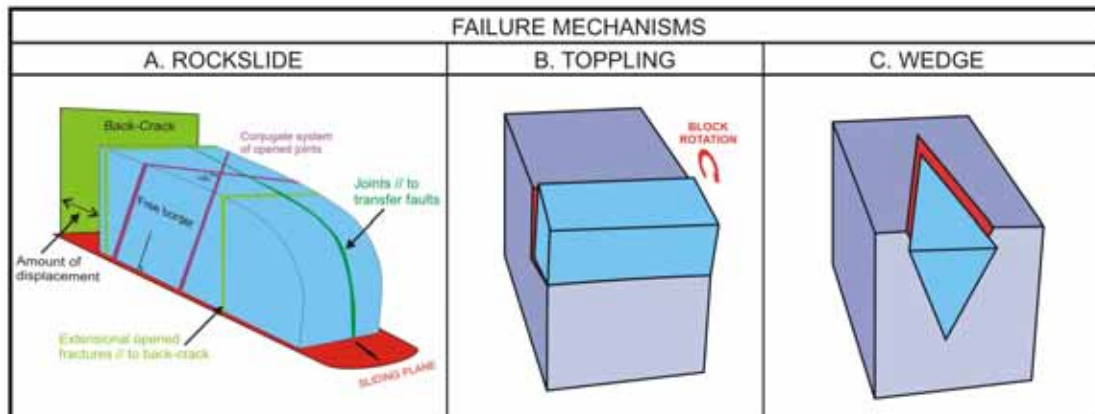


Figure 1: Bedrock geology map showing the different rock types and the variation in foliation and mineral stretching lineation across the Storfjorden area. Previously collected NGU data is in red, whereas our new data (averaged for each site) is shown in yellow.



**Figure 2: Examples of typical structures of rockslope failures: A-Structures associated with a rockslide geometry. B-Toppling. C-Typical wedge geometry.**

## 2 POTENTIAL LANDSLIDE SITES

### 2.1 Introduction

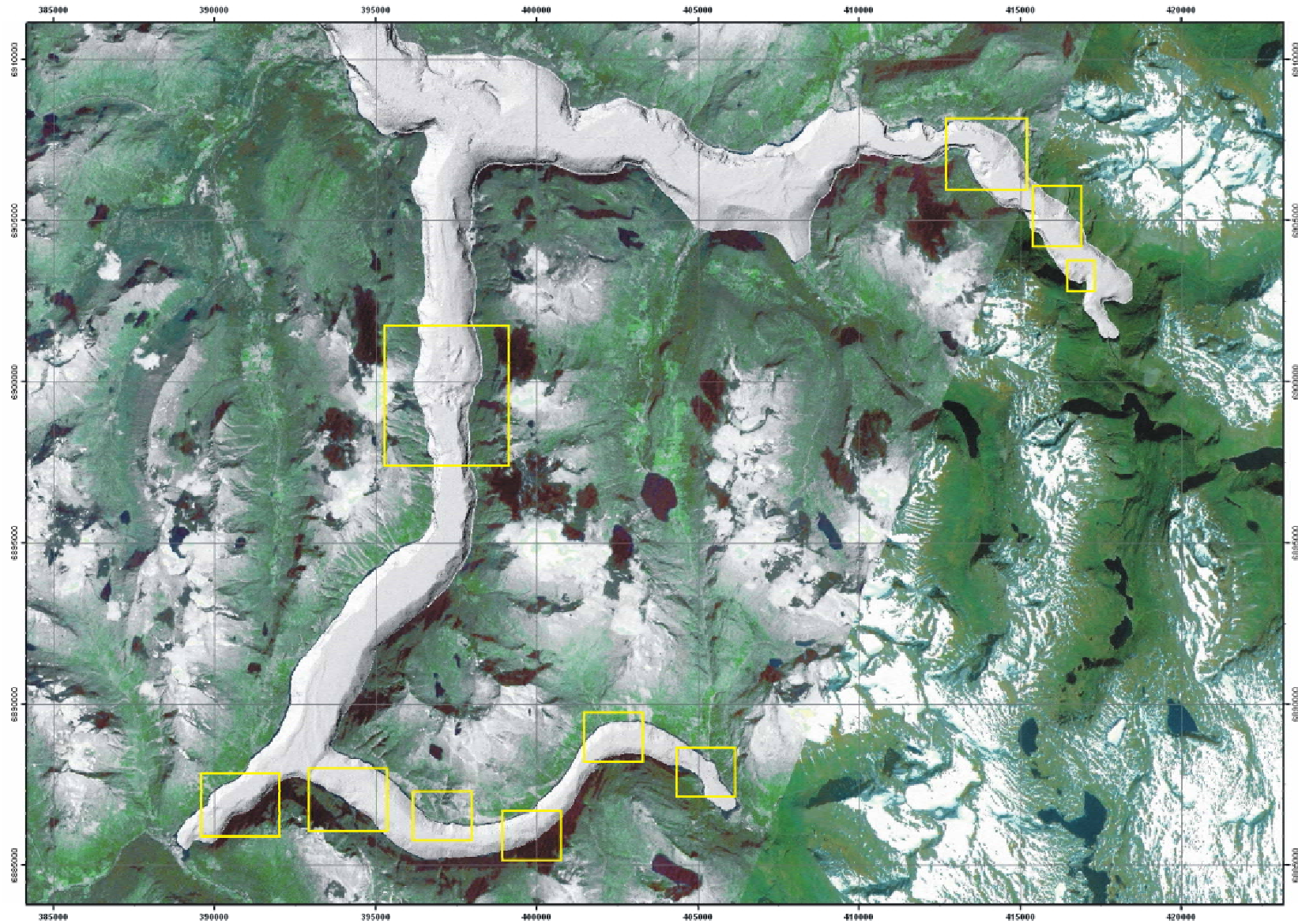
Prior to the fieldwork season, aerial photos were analysed to demarcate potentially important sites. It was also important to determine the localisation of previous landslide events within the fjord based on bathymetry data. The bathymetric map (Figure 3) shows that there have been a series of previous landslide events in specific areas in the Storfjorden area. These sites are in particular located in one area in Sunnylvsfjorden, several on the southern side of Geirangerfjorden, and at three sites in Tafjorden. From this preparatory analysis of aerial photography, 49 sites were identified showing significant lineaments, detached blocks or significant talus slopes (See Figure 4). These target areas are spread out over Sunnylvsfjorden, Geirangerfjorden, Norddalsfjorden and the South side of Tafjorden. Several sites are also present in Eidsdalen and Nordalen. The results of this pre-fieldwork study are shown in Appendix 1 (Table 1) and forms the basis for the fieldwork carried out in 2005. Table 1 also shows the list of priority sites based on the size and complexity of

the lineaments observed from the aerial photos. Those sites marked with an asterisk and labelled with 'b' on Figure 4 are those which were not identified from the pre-fieldwork study from the aerial photos but were rather identified in the field from helicopter observation.

The fieldwork in 2005 focused on examining as many of these sites as possible in the field to:

- Determine if the structures on the aerial photos equated with real structures observed on the ground.
- Determine if there was recent evidence for active movement on the structures.
- Determine the relationships between the different structures observed.
- To define an area that is under active movement.
- Collect samples from breccia zones in rockslide sites to allow the determination of shear strength of the fault rocks.





**Figure 3: Map of the Storfjorden area showing bathymetry. A large, significant area of submarine talus is seen in Sunnylyvsfjorden north of Åkneset, at several sites in Tafjorden and in the whole length of Geirangerfjorden.**



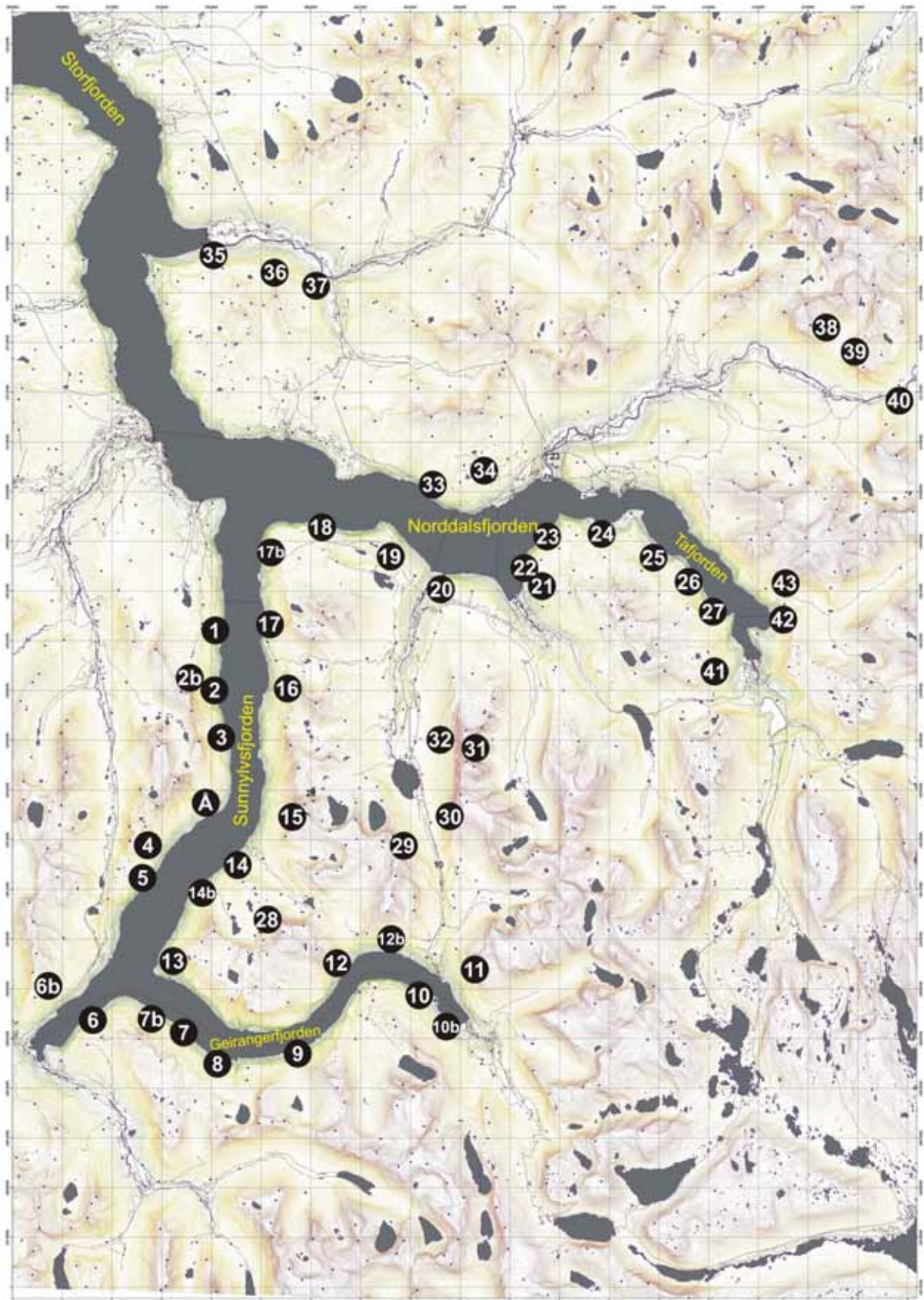


Figure 4: Map of the Storfjorden area showing the 49 potential landslide sites identified from aerial photos. Those with the suffix 'b' were not originally identified from the aerial photos but were identified following initial helicopter fieldwork. "Å" denotes Åkneset.

## 2.2 Site 2

### 2.2.1 Structures

This site is on the west side of Sunnylvsfjorden approximately 9km south of Stranda and 5km north of Åkneset (see Figure 4). This site has been observed by helicopter only. No landing was possible. An approximately 80 metres high block is detached from the slope by a set of roughly N-S steep, open fractures and its base lies on a plane parallel to foliation and dipping some 40 degrees towards the fjord (Figure 5).



**Figure 5: Structures observed from helicopter at Site 2. It was not possible to land at this site.**

This low-angle plane is most probably a sliding plane. The extensional fractures, which separate the mountainside up into several large blocks, have obvious displacements up to several tens of centimetres or more. These extensional fractures detach onto the potential low-angle sliding plane, suggesting that movements on this structure has caused the extensional fractures in the hangingwall. Just to the north of the detached blocks is a low-angle slab, which probably represents an old sliding plane which has since been overgrown with trees. Extensive previous landslide

activity occurred in this area as it is reflected in the bathymetry of the fjord downslope which displays extensive submarine talus deposits (see Figure 3).

### 2.2.2 Summary

- *Several extensional fractures with inferred fjord-directed movement are observed. These delineate several large blocks with over 80m vertical height.*
- *A low-angle sliding plane is postulated at the base of these blocks, although was not observed due to the inaccessibility of the site.*
- *Because of the height of the involved mass, we consider a high priority to gain access to the site in the next field season.*

## 2.3 Site 2b

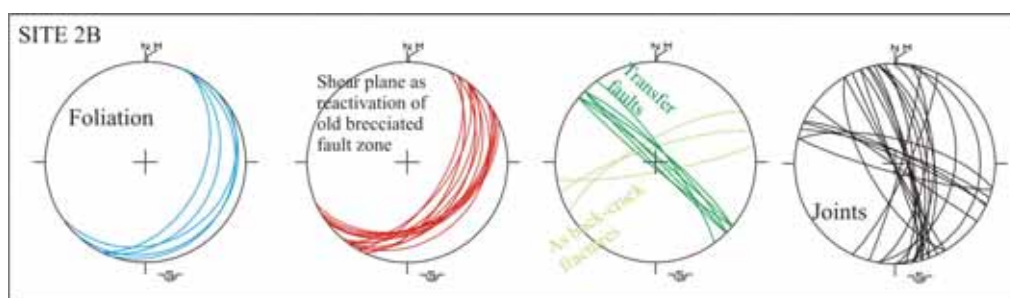
### 2.3.1 Structures

This site is close to Site 2 (see Figure 4) and lies on a prominent ridge approximately 900m above sea level. The foliation dips at approximately 37-50° to the east, towards the fjord (see stereonet data in Figure 6). Characteristic of this site is that very few steep extensional fractures are observed. For example, no extensional back-fracture was observed but potentially pre-existing joints that can play the role of such exist (they have trend of back-crack fractures; see Figure 6 and Figure 7). This site was therefore not identified as a potential rockslope failure site from the aerial photos. However, examination from the helicopter and on site showed an active movement on a large block. This movement appears to be occurring along a single, low-angle sliding plane at the base of the block. This is sub-parallel to foliation but cuts through the foliation and is slightly steeper than it (see Figure 8A). Examination of the fault plane has shown that it was indeed a pre-existing N-S striking brecciated plane (probably of Devonian age) which has been reactivated as a recent sliding plane, creating a new fault breccia. The low-angle detachment plane displays a very undulating surface and this is probably due to the localisation of the fault plane along an open anticline-syncline pair. This fault undulation has led to the development of several different types of secondary structures along the fault plane. Where there is an

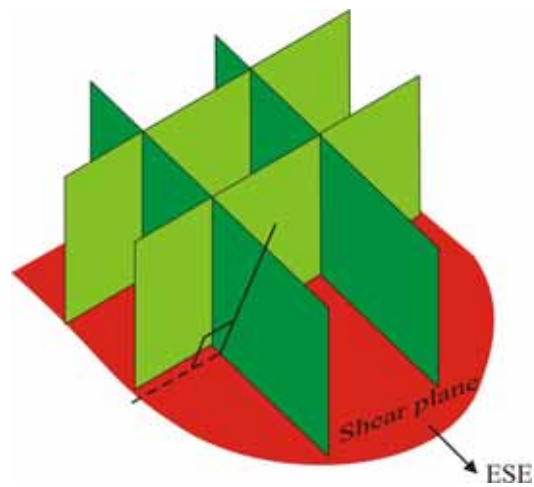


undulation along the fault plane, multiple faults are developed to form duplex-like structures (Figure 8B and Figure 9A). These develop as the irregular fault plane attempts to remove fault irregularities and produce a planar fault. Extensional fractures in the hangingwall are rare. However, they do occur as space accommodation structures where the low-angle sliding plane passes over a footwall ramp (Figure 8B and Figure 9B). However, these structures are extremely localised and do not affect the integrity of the hangingwall failure block. Indeed, the hanging wall block is not dissected by through-going extensional fractures, which suggests it consists of one contiguous block. Therefore, if the block was to fall, then it is likely that it would likely cause a larger tsunami as it would be less broken up under failure. Several observations suggest that this block is undergoing active movement:

- (1) the downslope kinematics of the duplex-like and ramp-related localised extensional structures in the hanging wall to the low-angle sliding plane.
- (2) The presence of a 15cm non-cohesive breccia on the low-angle sliding plane (Figure 9C). This breccia has been sampled and the strength of the slip-plane relative to the overburden of rockmass will be evaluated.
- (3) The 15 cm displacement of the block as a whole relative to the footwall, which is evidenced by movement relative to a recent talus slope (Figure 9D).

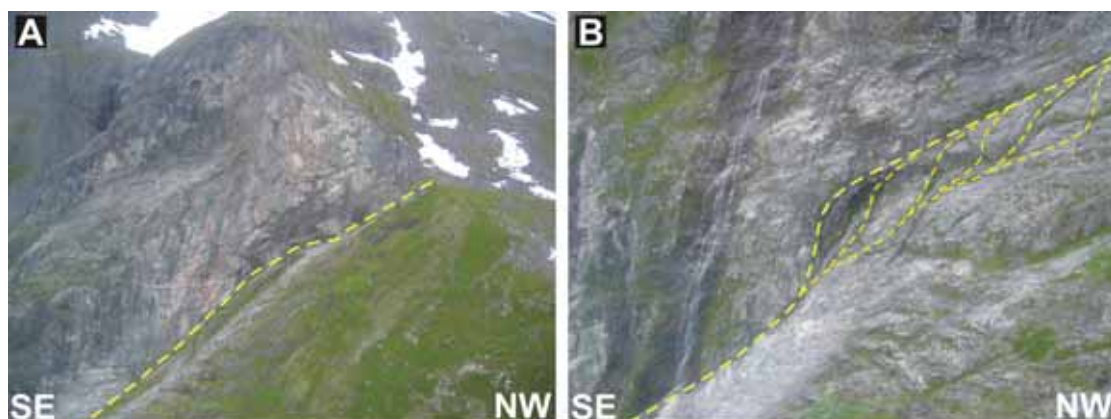


**Figure 6: Stereonet data for Site 2b. Foliation dips SE towards the fjord at 20-40°. The Basal Shear Plane including other shear planes are parallel to foliation. Two sets of extensional joints are observed in the hangingwall.**

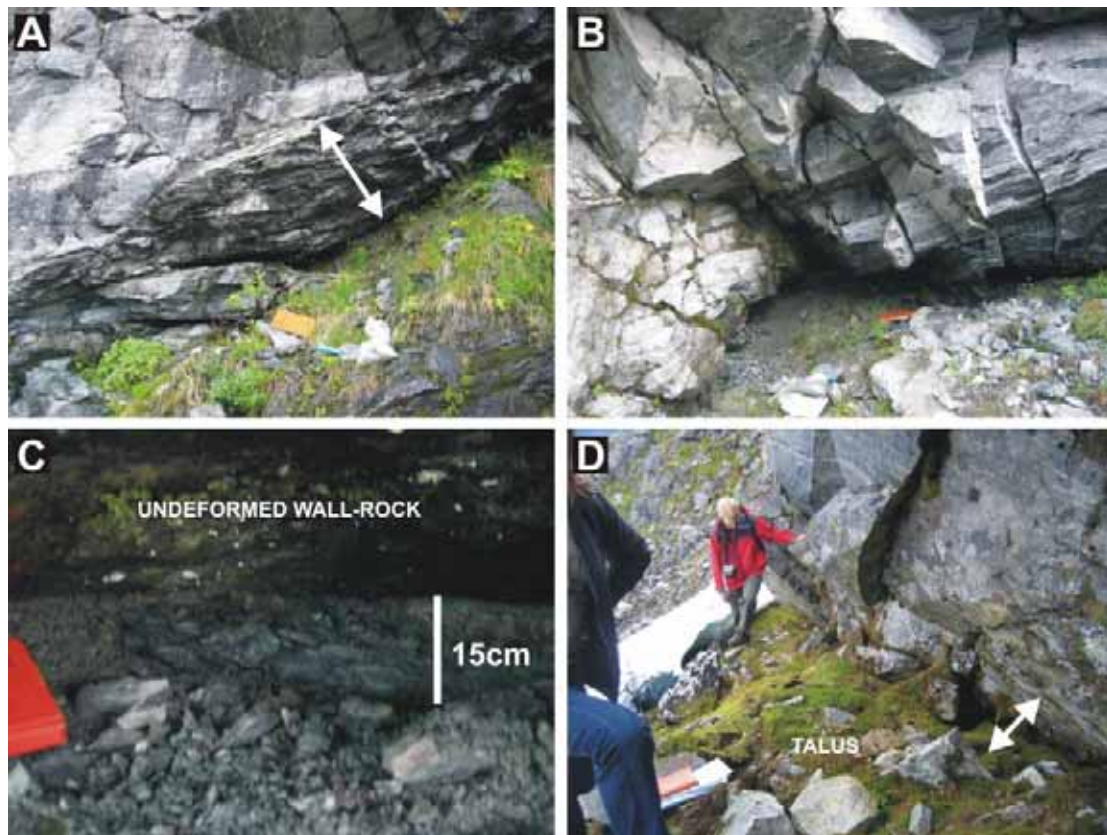


**Figure 7: Joints into the hanging wall to the Basal Shear Zone at Site 2b.**

A simple measurement of the volume based on the delimiting structures and an estimate of the height of the column of rock above the basal shear plane allows an estimate of the potential rockslide volume. This is tentatively approximated to  $1\text{Mm}^3$ . However, a much better estimate of the rockslide volume will be achieved after the analysis of the LIDAR data in conjunction with the mapped structures.



**Figure 8: Large-scale structures observed from air at Site 2b. A-Large scale picture of the whole of Site 2b. The low-angle detachment (dashed yellow line) dips down towards the fjord and reaches the surface at the top. B,-Locally developed duplex-like structures where the fault plane is undulating.**



**Figure 9: Structures observed at Site 2b. A-Duplex-like structure in hangingwall of the low-angle sliding plane. B,-Localised extensional structures in the hangingwall to a low-angle sliding plane ramp structure. C-Detail of the discontinuous fault breccia developed along the low-angle sliding plane. D-Where the low-angle sliding plane reaches the surface, it is detached from the underlying talus slope. The displacement is 15 cm.**

This site was therefore considered as experiencing active movement and it was therefore decided that in the first instance GPS measurement point should be set out to determine the magnitude of this displacement. Figure 10 shows the layout of these points relative to the main structures and the topography. These points will be measured again in the summer of 2006 and will assist in determining if further detailed work is required on this site.

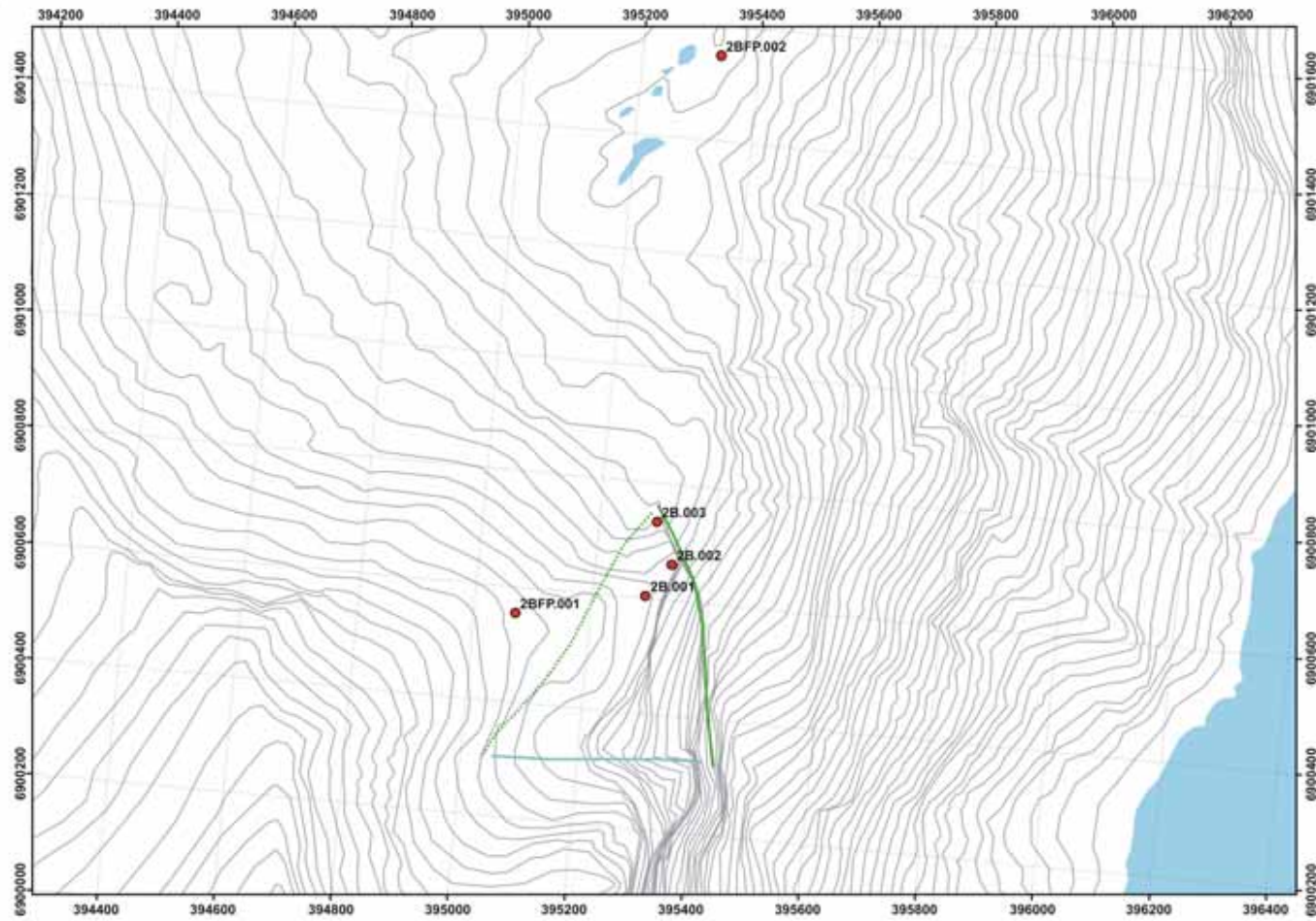


Figure 10: Topographic map showing location of GPS measurement points relative to the important structures. The solid green line is the basal shear zone. The dotted green line is its continuation intersecting the surface topography. The blue line is a postulated transfer fault which may detach the block.

### 2.3.2 Summary

- *A large, laterally continuous basal sliding plane is present at this site lying at the base of a large, apparently unstable block of  $1\text{Mm}^3$  estimated volume.*
- *Several lines of evidence suggest that movement on the basal sliding plane is recent and that the block is undergoing movement towards the fjord.*
- *There is no apparent back-crack at this site. This may suggest that this is a relatively new movement and a back crack has not yet had time to develop.*
- *5 GPS points have been set out on this block and will be measured again in 2006 to determine magnitude and pattern of movement.*

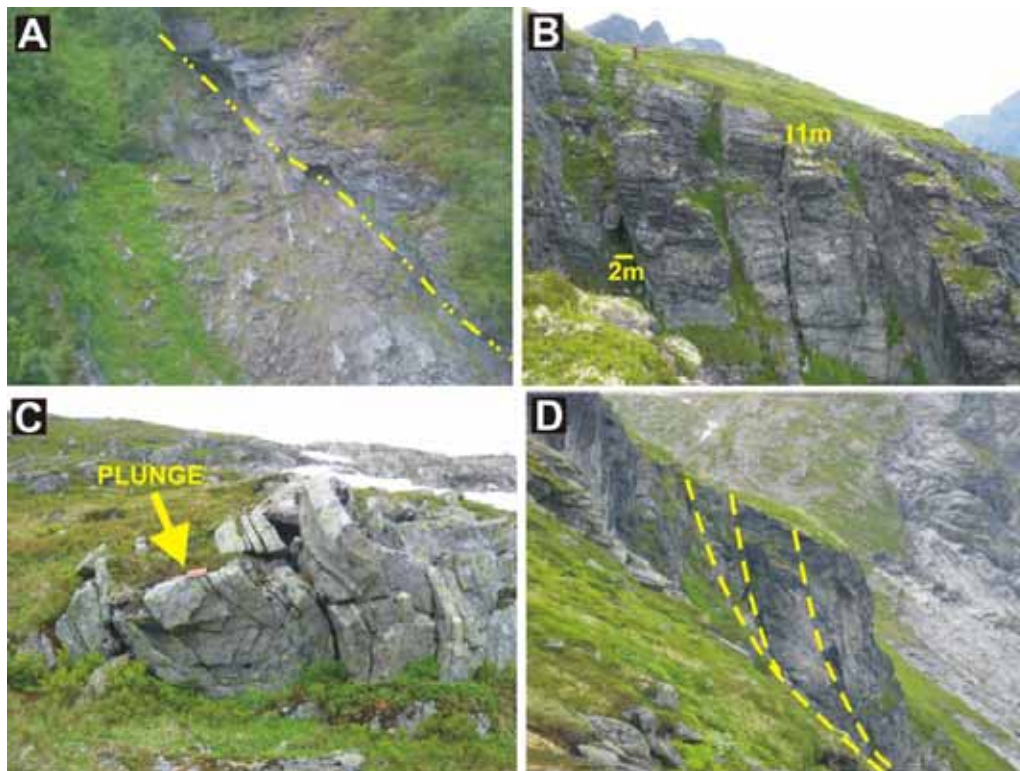
## 2.4 Site 4

### 2.4.1 Structures

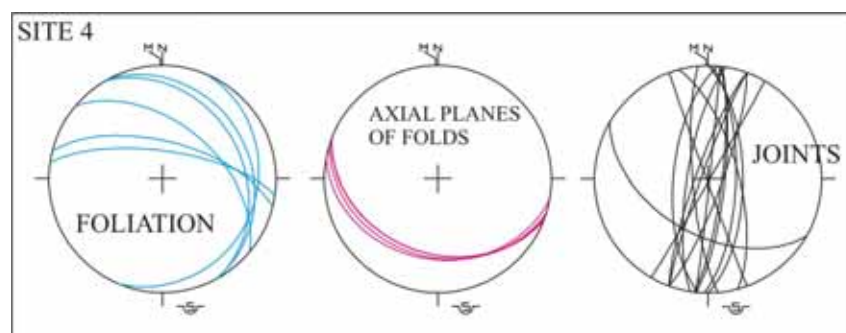
This site lies 1,5 km to the south of Åkneset on the same side of Sunnylvsfjorden, approximately 1000m above sea level. This site lies in a similar topographic position to Åkneset and displays remarkably very similar structures. A low-angle, fjord-dipping breccia zone is postulated at the base of the potential failure block although this has not been observed directly as the site was highly inaccessible. However, evidence suggests that an active sliding plane is present at the base of the block (Figure 11A). The potential failure block consists of at least seven column-shaped blocks. These are up to 50m wide and up to 80m high (Figure 11). These are separated by extensional fractures, which appear to have up to several metres of horizontal displacement. However, these are clearly inherited north-south striking structures, possibly of Devonian age (see Section 2.5.1) and may have been somewhat 'eroded-out' prior to displacement. Therefore several metres would be an upper limit to the horizontal displacement. Several metres of vertical displacement are also seen on some of the blocks (Figure 11B). A possible contributing factor to failure here is the presence of fjord-plunging small-folds in the granitic gneiss (see stereonet data in Figure 12). These have a trend of approximately  $100^\circ\text{N}$ , exactly parallel to the extensional direction of the column failure (i.e. perpendicular to the main set of



opened joints on Figure 12). They also have a plunge of 30-35° ESE, which is parallel to the supposed maximum dip and dip-direction of the low-angle sliding plane. The structural grain in this area therefore would promote a slippage of material at a moderate to shallow angle eastwards towards the fjord.



**Figure 11: Structures observed at Site 4. A-Potential low-angle sliding plane as observed from the air. It was not possible to land at this site but the broken nature of the rock and the development of a noticeable exfoliation 'shelf' strongly suggests the presence of a fault breccia. This zone appears to be the detachment zone for the extending blocks in the hangingwall seen in B. The supposed breccia zone dips at 25-35° towards the fjord. B-Extension of the mountainside along column failures. At least seven different columns with associated steep extensional fractures have been observed. C-Small-folds with a trend parallel to the extensional direction of the failure blocks and a plunge parallel to the maximum dip-direction of the postulated basal shear zone. These structures probably aid the development of a failure surface. D-Potential listric failure surfaces approximately 1km to the north of Site 4. This area has been named Site 4b and will be examined in the summer of 2006.**



**Figure 12: Stereonet data for Site 4.**

However, at present no GPS measurement points have been set out on this site. This is because we have only circumstantial evidence that a basal breccia is present. Further work here should focus on gaining access to the basal fault zone. The presence of a basal breccia would be direct evidence that the mountainside here is undergoing movement.

#### 2.4.2 Summary

- *This site displays structural types and geometries with similarities to those at Åkneset (Low-angle fjord-dipping shear plane, extensional fractures perpendicular to the movement direction).*
- *The site has a potential volume of 2-5 Mm<sup>3</sup>.*
- *A basal shear plane is not observed but is postulated from helicopter observations.*
- *No GPS points have been set out until a confirmation of a basal sliding plane has been made. This should be a priority for investigation during 2006, due to the large potential volume.*

### 2.5 Site 6b

#### 2.5.1 Structures

This site lies on the west side of Sunnylvsfjorden (UTM: 0389208, 6887980), approximately 5km south of Åkneset (see Figure 4), and lies approximately 700m metres above the fjord. Aerial photos were not available for this area; it was therefore not identified as a potential landslide area until fieldwork had begun. From the air several obvious critical structures can be observed (see Figure 13A). The key structure is a low-angle (25-40°) east-dipping plane. This structure dips towards Sunnylvsfjorden (Figure 13B). Above this basal plane, several large north-south striking extension fractures are present. Detailed field analyses were possible along the base of the identified block. Here a basal shear plane (BSP) with evidence of movement activity was identified (Figure 14). It partly follows the foliation that dips

25-30° towards the fjord. However, in general the BSP cuts through the foliation at a shallow angle and a well developed 15cm thick fault breccia is observed (Figure 14B). It lies sub-parallel to the foliation (see stereonets Figure 15). NW-SE trending joints act as transfer faults (Figure 15). Two other systems of joints opened in the failure block (Figure 15); one trends NE-SW and the other trends N-S. The newly extensional structures are NE-SW (Y and Z on Figure 13A) with a trend perpendicular to the main slip direction (Figure 16). With the set of NW-SE fractures they form a system of joints geometrically consistent with the motion of the block (Figure 16). The main back-crack of 3 meters width (Figure 17) is an inherited extensional fracture, which trends N-S, similar to ultra-cataclastic fractures of Devonian age observed frequently in Vestlandet. Figure 17A shows one of these N-S epidotised faults reactivated as an extensional fracture. The extensional fractures detach onto the low-angle sliding plane suggesting their generation is related to movement on the plane (Figure 17C). Figure 18 is an example of newly formed NE-SW extensional shear structures in the failure block. To summarise, two trends of extensional fractures exist on site 6b (1) the first is a reactivation of old N-S trending structures and the main back-crack (X on Figure 13A) developed along such a trend and (2) the newly developed extensional structures trend NE-SW (Y and Z on Figure 13A) which is perpendicular to the movement. All of these extensional fractures within the hangingwall block detach onto the basal sliding plane and are not present in the footwall, suggesting that the hangingwall block is extending due to the movement on the basal shear plane.

It was decided due to the apparent unstable nature of this block and the evidence for recent movement activity, that GPS monitoring equipment would be used. Figure 19 shows the location of the GPS points set out on this site. Mapping shows that the block is divided into three sub-blocks. Block B is the largest block and displays the most amount of movement activity, disintegration of the block by fracturing and gouge development. A single GPS point was set out on each block at the localities shown in Figure 19 and a single fixed point was set out approximately 100m west of the most westerly back-crack.

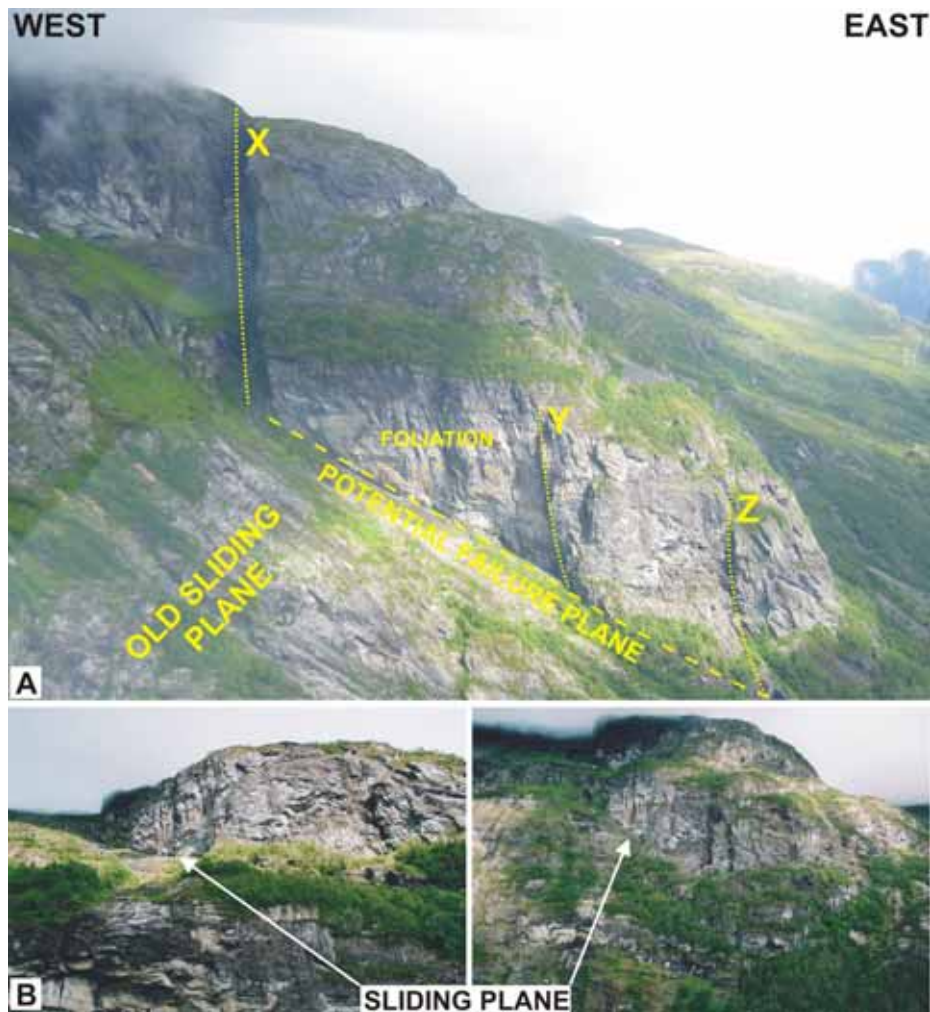


Figure 13: Photos of structures seen from the air at Site 6b. A-The large back-extensional fracture, suggesting several metres cumulative displacement is seen at X. Several smaller NE-SW trending extensional fractures are seen at Y and Z. The major transfer fault is in the plane of the photo. For scale, the height of the back-extensional fracture is approximately 100m. B-Two views of the sliding/shear plane from the foot of the structure.

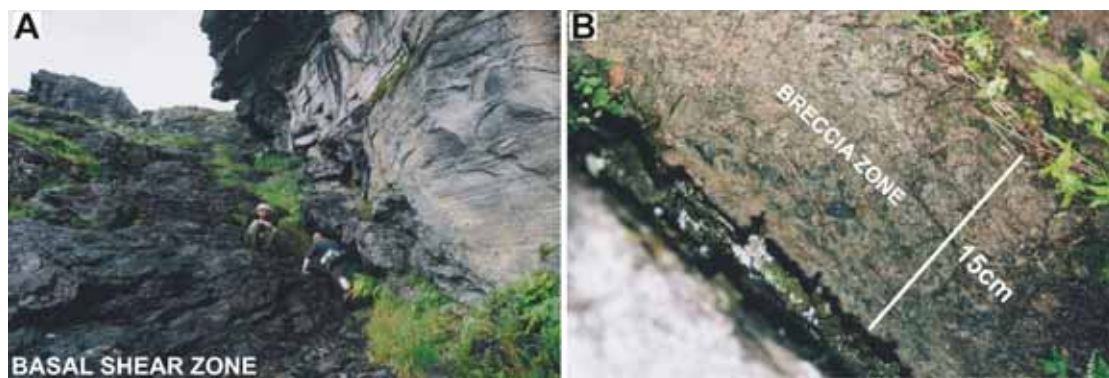


Figure 14. Structures observed at Site 6b. A-Two views of the sliding plane. B-15cm thick breccia on the low-angle, east-dipping shear zone.



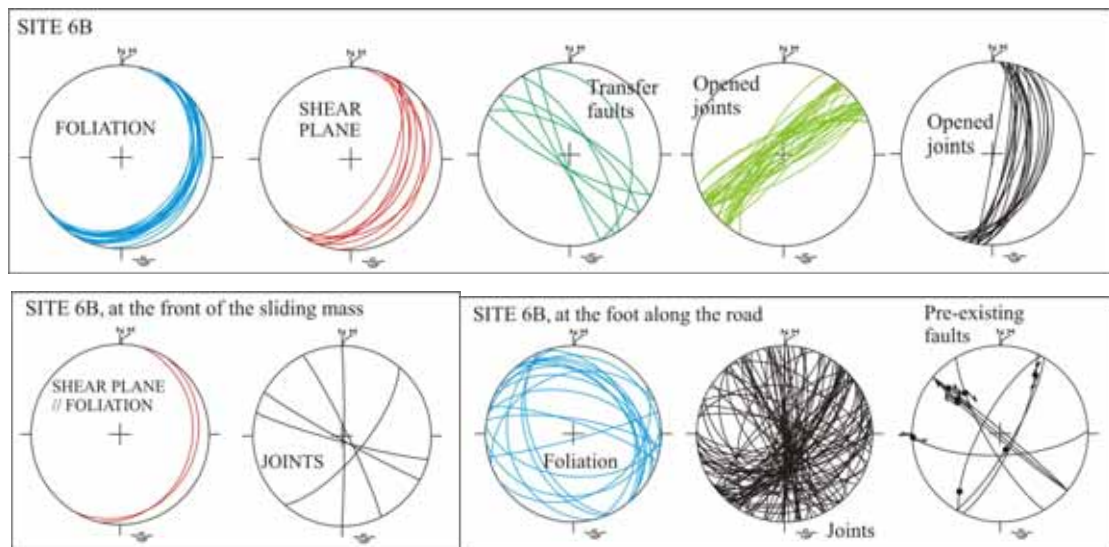


Figure 15: Top-Stereonet data for Site 6B in the main potential failure block. Bottom-Stereonet data for Site 6B in the toe zone and at sea level directly in the fall-line to the main block.

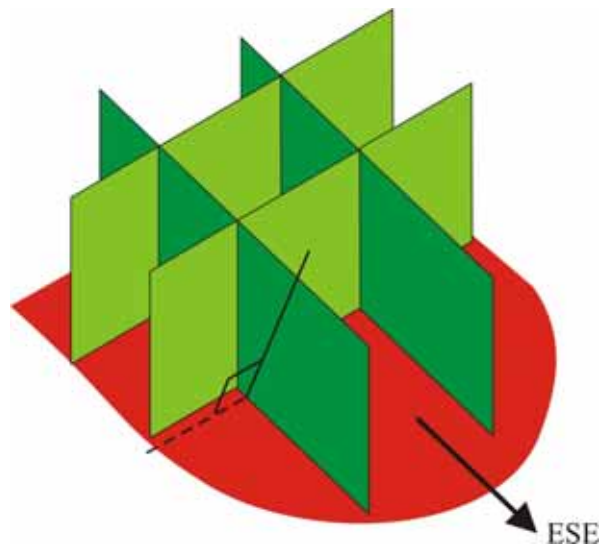


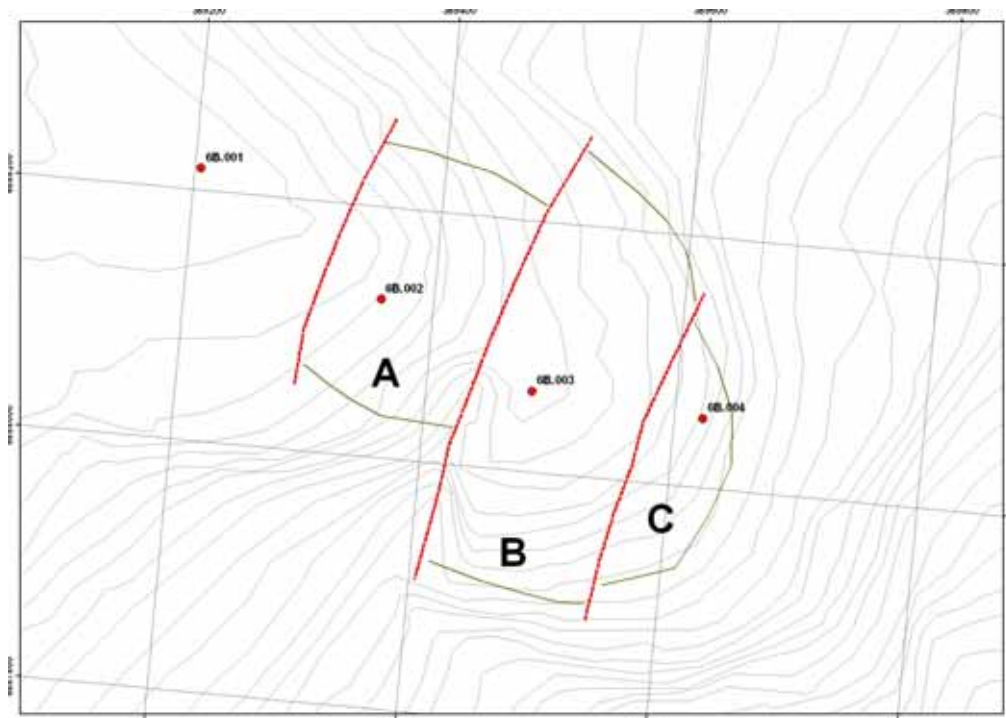
Figure 16: Scheme of the system of joints opened in the failure block at Site 6b.



Figure 17: A-Extensional fractures are a reactivation of north-south trending epidotised cataclastic faults. B- View of the back-crack fracture. C-Extensional fractures in the potential failure block in the hanging wall to the low-angle sliding plane (in dashed yellow line).



**Figure 18:** Example of the geometry and kinematics of relay zones on extensional shear structures from Site 6b. The movement direction of the segmented fractures is down towards the fjord (towards the left).



**Figure 19:** Map showing the position of GPS points at Site 6b relative to the different blocks. The UTM grid is 200m. The red lines represent extensional fractures which split the block up into three sub-blocks. The green lines mark the approximate limits of the blocks. Block B is considered the most dangerous as the back-crack on its western side is the biggest.

## 2.5.2 Summary

- *This site has developed identical structures to those observed at Åkneset (back-crack, opened fractures in the block, thick breccia along a low angle basal shear plane).*
- *A rough estimate of potential failure volume is  $4Mm^3$ . This volume will be refined after analysis of the LIDAR data in 2006.*
- *4 GPS points have been set out during summer 2005 and will be measured again in summer 2006 to determine the magnitude and kinematics of movement.*

## 2.6 Site 7b

### 2.6.1 Structures

This site lies on the southern face of Geiranger Fjord, 5 km east of Hellesylt (Figure 4). The shear plane developed along the foliation dipping 20-30 degrees towards the fjord (Figure 20). A 20cm thick discontinuous gouge is developed along the shear plane, separating the unstable block from the stable rock underneath. A sample has been taken from this gouge to test for fault-rock strength. Two trends of joints are developed in the failure block (pale green and dark green on Figure 21). If the movement of the block is dip-slip on the shear plane then these two trends are those of transfer faults, parallel to the movement, and of back-crack fractures, with strikes perpendicular to the movement. Such newly formed system of joints in the failure block have also been observed at site 6B (Figure 16).



Figure 20: Fault gouge developed at Site 7b. The gouge is up to 20cm thick but is discontinuous along the fault plane. The contacts with the intact wall-rock are very sharp.

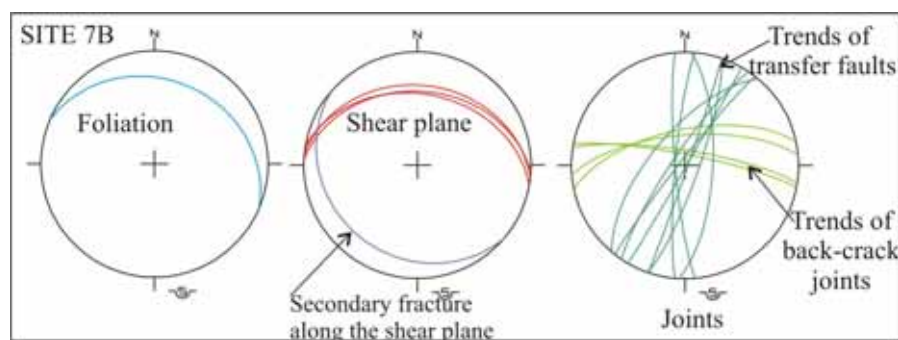


Figure 21: Stereonet data of structures observed at site 7b.

## 2.6.2 Summary

- *This site displays a foliation dipping towards the fjord and parallel shear planes which display extensive gouge material.*
- *This site is clearly actively undergoing movement but no mapping was possible at higher elevations (all work was done on geographically limited areas at sea-level).*
- *A gouge sample was collected from the shear plane which will be examined for shear strength to determine the fault rock properties.*

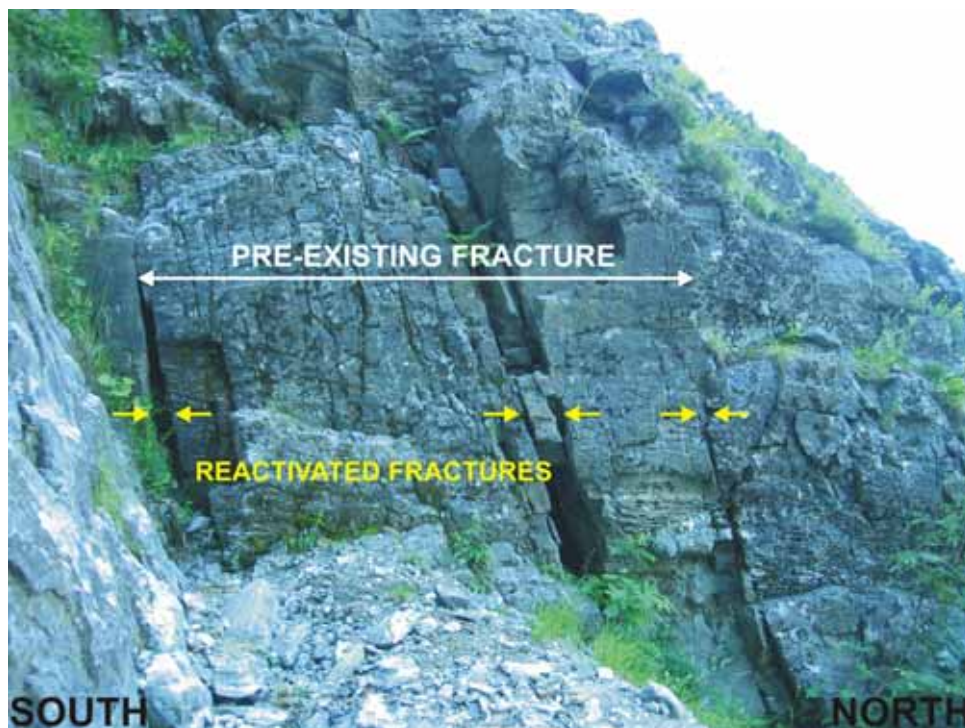


- *Further field work should try and determine the nature of the mountainside at higher elevations and to determine if a detached block is present.*

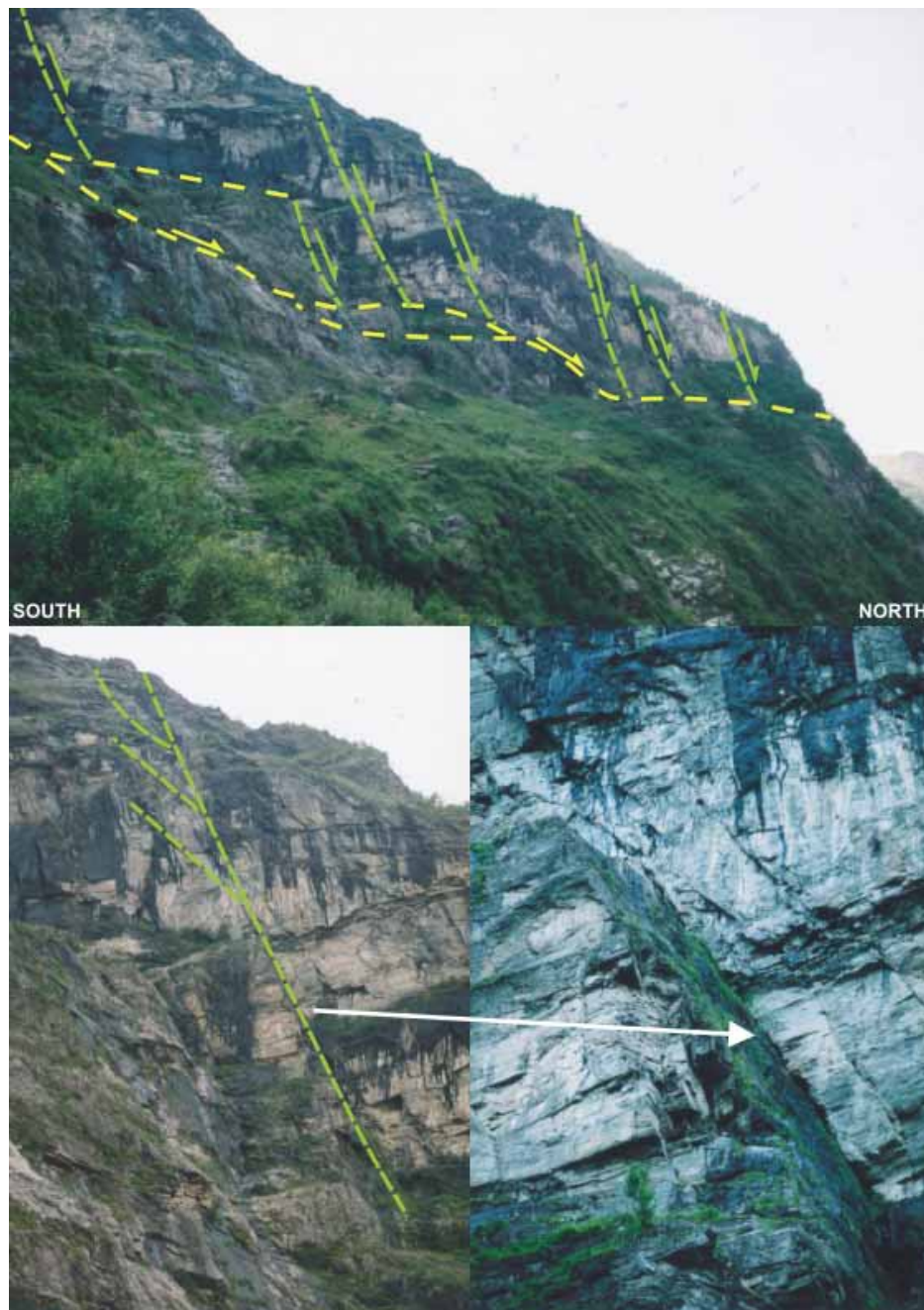
## 2.7 Site 9

### 2.7.1 Structures

Site 9 is on the southern face of Geiranger Fjord, 10 km east of Hellesylt village. Several large E-W lineaments were observed from the aerial photos. Fieldwork demonstrates that these consist of large (several kilometres length, several hundred metres fault length and several metres wide) pre-existing fractures (Figure 22). The foliation at this site dips towards the fjord and extensional structures are developed in the sliding mass (Figure 23) guided by transfer faults parallel to the motion of the block (stereonet on Figure 24).



**Figure 22:** Steep pre-existing E-W trending fault zone at Site 9. The fault zone is 3m wide and consists of a 'damage zone' of many smaller fractures. These are partly cemented by quartz. This weak zone has been the focus for recent movement, producing three smaller fractures with both extensional and down-dip (fjord-directed) movement.



**Figure 23:** Several images and interpretation of Site 9. Extensional fractures are seen which are steeply-dipping towards the fjord. The foliation dips at shallow to moderate angles towards the fjord. We postulate shearing along the foliation to accommodate the extensional movement on the steep structures.

No direct evidence of the low-angle shearing planes at the base of the unstable block have been recognised. These were not observed in the field due to the inaccessibility of the area and the severity of the topography but such structures are postulated on

Figure 23. Further work should focus on defining the presence of a low-angle basal shear plane.

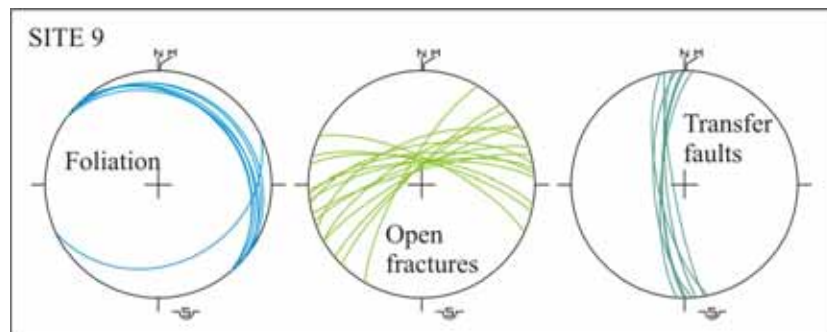


Figure 24: Stereonet for structures observed at Site 9.

### 2.7.2 Summary

- *Several large E-W trending pre-existing brittle faults have been reactivated by recent extensional and down-dip movement towards the fjord.*
- *Foliation dips towards the fjord in this area and it is postulated that the extensional and down-dip displacement on the steep structures is taken up on shearing along some basal structures, parallel to foliation.*
- *Further fieldwork should concentrate on gathering evidence for the presence of these basal shear zones.*

## 2.8 Site 10

### 2.8.1 Structures

This site lies on the south side of Geirangerfjorden at a height of approximately 3-400m, 4km NE of Geiranger village. This is an extremely steep but densely forested part of the fjord and it was not possible to land with the helicopter or otherwise visit this site. However, several critical observations were made from the aerial photos and from helicopter observation. Figure 25 shows the aerial photo for this area and depicts an arcuate depression in the topography which is most likely a back escarpment detaching a block in front of it. This was not particularly obvious from the helicopter visit but several critical pieces of evidence suggest active movement at this site.



Firstly, the foliation appears to dip gently or at a moderate angle towards the fjord (Figure 26A). Indeed pronounced exfoliation is seen on some surfaces. This is cut through by a steeply dipping (towards the fjord) extensional fracture on the SW side of the block. Figure 26B shows the same fracture from the NE side and shows that this fracture flattens out towards its base and appears to be parallel to the foliation at the foot of the slope. At this locality it appears that there is a fjord-directed extension on this fracture which would result in a shearing displacement at the base of the structure sub-parallel to the foliation.

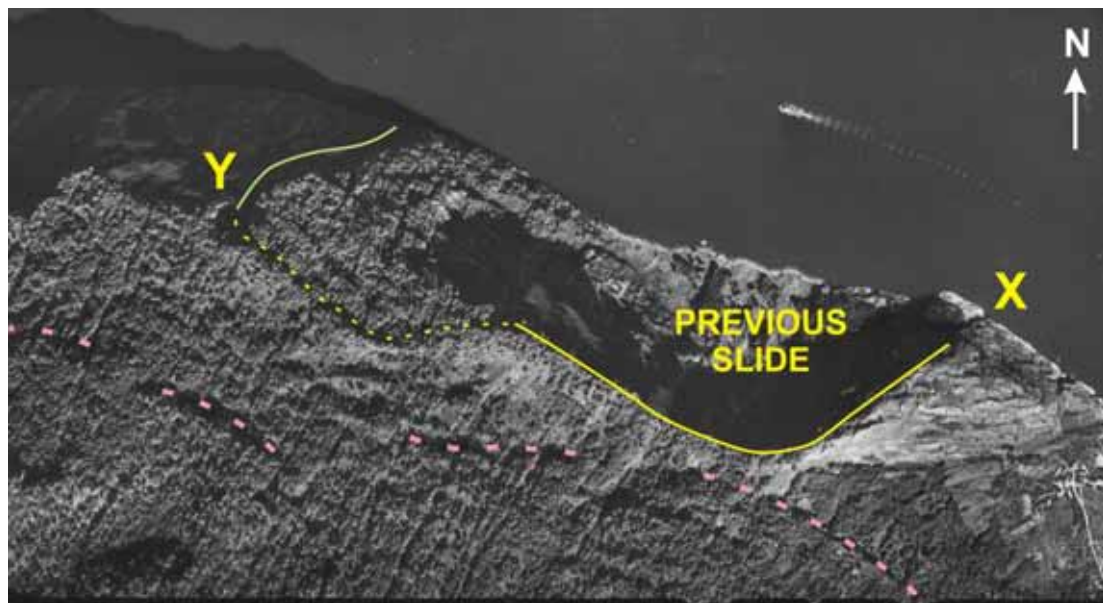


Figure 25: Aerial photo showing the presence of a partially obscured back escarpment at locality 10 (dotted yellow line). A previous slide has developed on the same structure (solid yellow line). The extension of this structure into a low-angle foliation parallel sliding plane is shown by the solid green line. Additional scarp structures are marked in red.

### 2.8.2 Summary

- *This area displays a potentially unstable block (with a tentatively estimated approximate volume of  $2Mm^3$ ) with the presence of a back escarpment produced by apparent extensional displacement along a steep fracture. Foliation dips  $20-35^\circ$  towards the fjord, providing ideal conditions for a rock-slide to occur. Extensive exfoliation planes are observed.*
- *This extensional structure becomes listric at its base and is parallel to the fjord-dipping foliation, which may cause or have caused shear sliding along the base of the valley side.*

- *Active sliding may be occurring here but more detailed fieldwork is required. It may be possible to walk into this area from Humlunggård to get a better idea of the movement activity or to set out GPS equipment. However, this would require a significant removal of forest in this area.*



Figure 26: Structures observed at Site 10 from the air. A-Extensional structure (dashed line) seen from the east. The low-angle planes are exfoliation along the foliation. This is Point X on Figure 25. B-The same structure seen from the west. The extensional structure (dashed line) shallows with depth and is parallel to the foliation near sea-level. The solid line represents the back escarpment seen on Figure 25. This is point Y on Figure 25. It was not possible to land with the helicopter at this site.

## 2.9 Site 10b

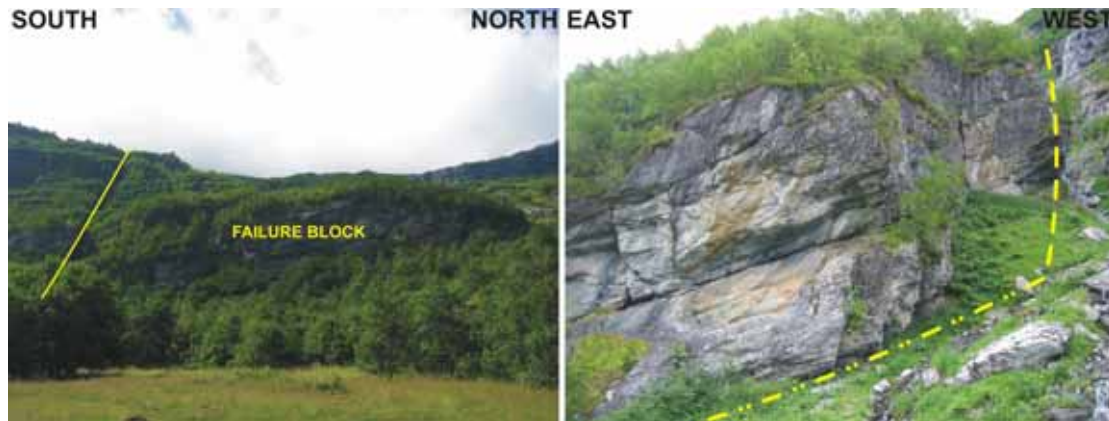
### 2.9.1 Structures

This site lies on the south side of Geirangerfjorden less than 1km directly west from the village of Geiranger and approximately 350m above sea level. The main characteristics of this site are a shallow (20-30°) east-dipping foliation towards the village of Geiranger. Several low-angle shear planes are developed sub-parallel to the foliation (Figure 27, Figure 28 and Figure 29). A steep, extensional fracture is developed at the western (back) margin of the potentially unstable block. This extensional back fracture appears to reactivate a long-lived regional N-S lineament

(Figure 27). It is difficult to determine the amount of displacement on this structure as the fracture has been further utilised as a river course and is partially 'eroded-out' (Figure 28B). However, the presence of a discontinuous fault-rock gouge along the main basal shear zone suggests that movement of the block has been recent. Several SW-NE pre-existing structures are apparent from the aerial photo interpretation and were observed in the field (Figure 28A and Figure 29) which delimit the potentially unstable block.



**Figure 27: Site 10b seen from the air. Clearly visible are the foliation gently dipping towards the fjord and the back extensional fracture (dashed line on right), which appears to be an inherited north-south lineament (solid line).**



**Figure 28:** Structures observed at Site 10b. A-View uphill up the fall-line. A large open transfer fault is observed on the left (solid line). B-Large, steep extensional fracture to the right (dashed line) and a low-angle basal shear at the bottom (dot-dash line) parallel to foliation. Detailed examination revealed a discontinuous 5-10cm fault breccia along this structure. This has been sampled for analysis.

A set of steep, open joints developed in the failure block. The joint systems display a conjugate geometry. (purple on stereonet Figure 29). Their geometrical relationships with the shear plane are consistent with a newly-opened array of joints as a result of dip-slip sliding occurring on the basal shear plane (Figure 28B and Figure 30).

## 2.9.2 Summary

- *An unstable block has been developed at this site where foliation dips shallowly towards the fjord.*
- *Low-angle basal shear planes are developed sub-parallel to the foliation and recent movement along the shear structures is evidenced by the development of a fault-rock gouge and the presence of an extensional back-crack.*
- *Further work should be carried out to set out GPS points to determine the magnitude and direction of displacement.*



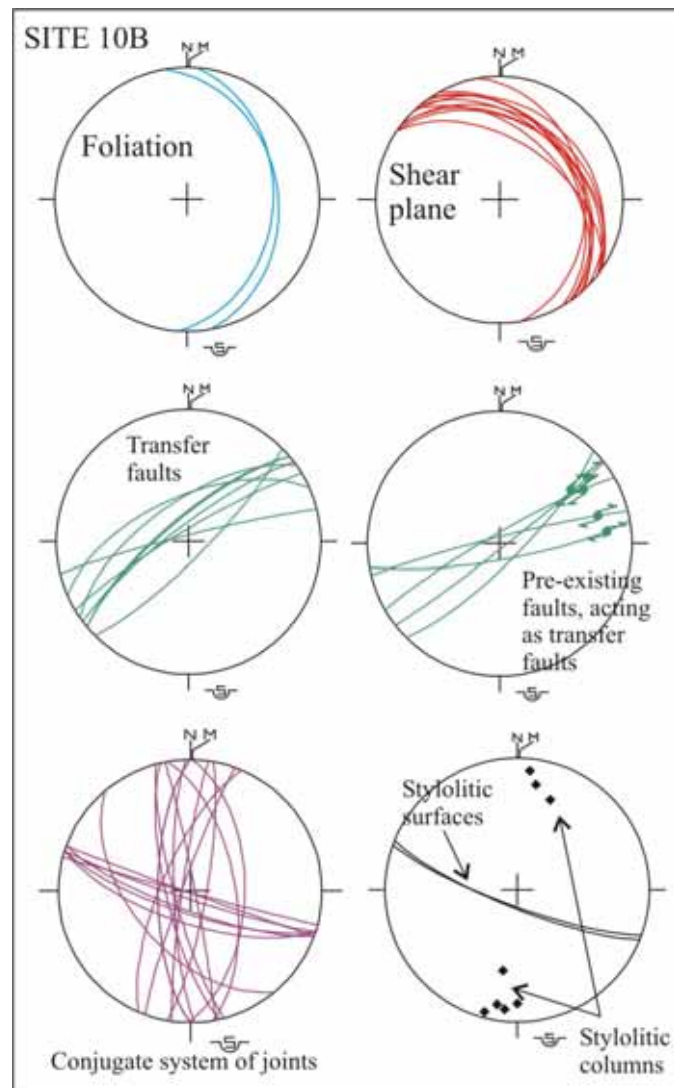


Figure 29: Stereonet data for structures observed at Site 10b.

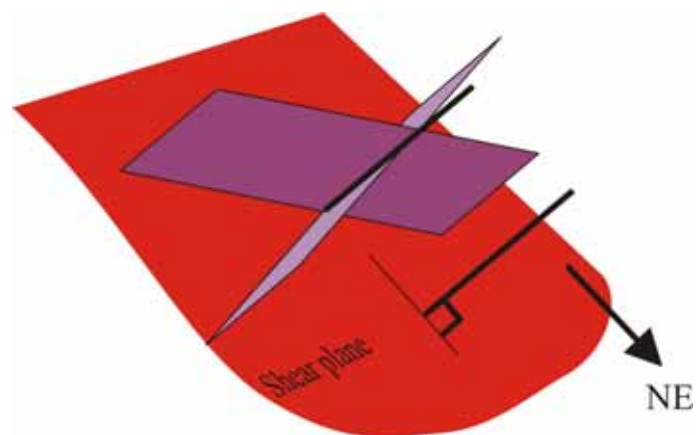


Figure 30: Scheme of conjugate system of joints which developed in the failure block at site 10b.



## 2.10 Site 11

### 2.10.1 Structures

This site lies on the east side of Geirangerfjorden directly to the north-east of the settlement of Geiranger. It was not possible to land at this site, therefore all observations have been made from the helicopter. The pictures from the helicopter (Figure 31) are significant and warrant more study in the field if it is possible to land at this site. Otherwise it is inaccessible. Both photos show listric structures dipping towards the fjord. It is clear that some previous slides have occurred along these structures (Figure 31A). An important feature is the role of the pre-existing fold guiding the formation of listric faulting (Figure 31B). From this site, we emphasised the importance of making a detailed mapping of pre-existing structures in further analysis.



**Figure 31: Structural observations made from the helicopter at Site 11. A-Low-angle structures steepening up into listric structures. This location shows the position of a previous slide. These structures dip towards the fjord. B-Listric structures reactivating recumbent folds (extensional fracture at left in the core of an isoclinal fold).**

### 2.10.2 Summary

- *Listric faults are observed which dip obliquely towards the fjord. These are reactivating pre-existing fold structures with shearing parallel to the shallow-dipping foliation and extensional fractures opening in the fold hinges.*
- *It was not possible to land on this steep slope. A further attempt should be made to get a closer look at this site in 2006 and to set out GPS points.*

## 2.11 Site 12

### 2.11.1 Structures

This site is 5 km NW of Geiranger Village approximately 1000 m above sea-level. It is along one of the steepest rock-faces in the fjord and therefore field observations were made difficult. Several N-S pre-existing lineaments act as transfer faults, delineating the eastern and western margin of several unstable blocks (Figure 32B). Foliation in this part of the fjord system is dipping moderately towards the fjord (Figure 32A, Figure 33 and Figure 34). Several well-developed exfoliation planes are developed parallel to foliation. These appear to facilitate the development of a basal shear plane (Figure 32A and Figure 33). This structure was not observed closely in the field due to its inaccessibility but appears to be similar in nature to those observed in other localities with breccia zones in a basal shear zone.

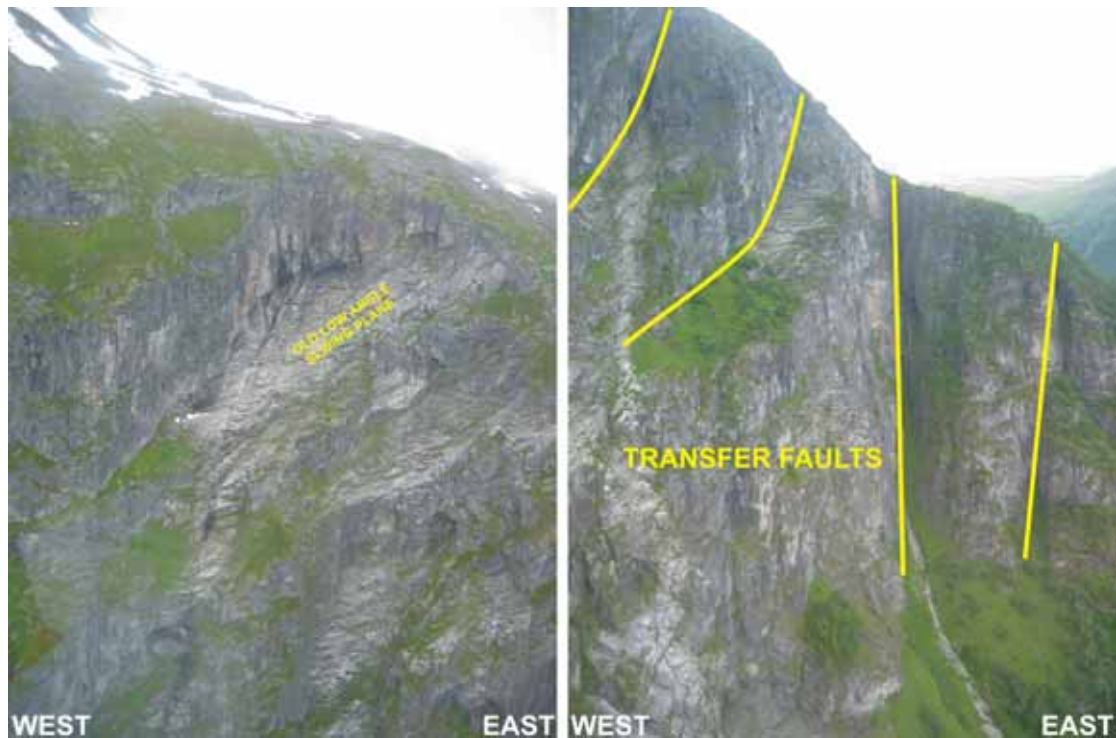
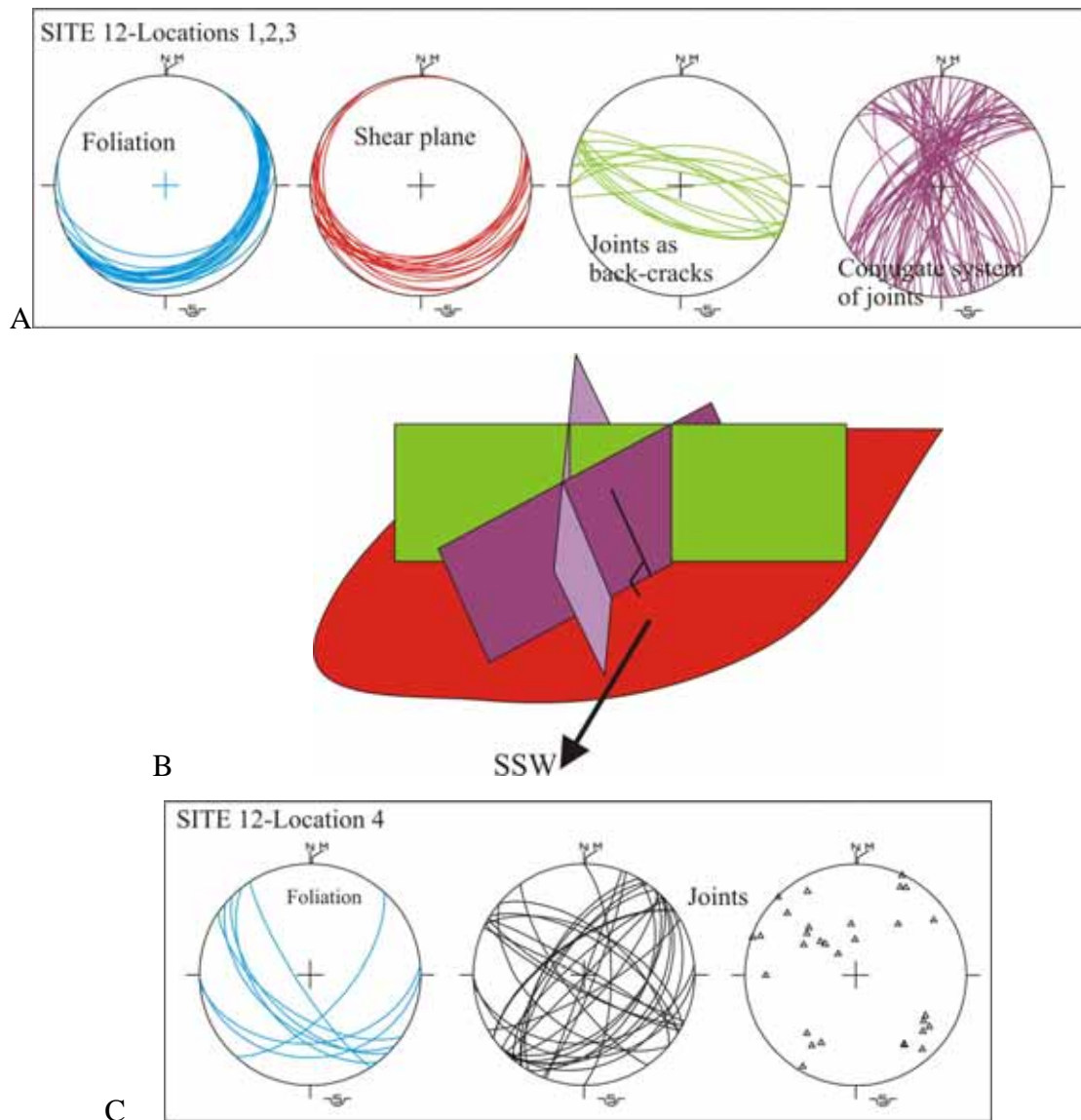


Figure 32: Structures observed at Site 12. A-Low-angle basal shear plane. It was not possible to visit this structure and therefore not possible to determine if a breccia is present on the structure. B-Steep transfer fault structures with a N-S strike which appear to be controlling structures for slope failure. These are most likely pre-existing structures.



Figure 33: Structures observed in outcrop at Site 12. The dashed line is at the base of the postulated unstable block is interpreted as a low-angle sliding plane. The complex and dense suite of fractures and joints within the unstable block appears to stop at the base of the block, suggesting that their formation is related to the movement on the basal shear plane.



**Figure 34: A-Stereonet data for the structures present at Site 12, locations 1,2,3. B,-Scheme of joints developed into the block at locations 1,2,3. C,-Stereonet for the structures present at Site 12, locations 4.**

The basal shear zone appears to have an angular discordance with the foliation planes. In addition to the transfer faults which are the free borders of the block and the development of a basal shear plane (Figure 32 and Figure 33), spectacular systems of joints are developed at this site (Figure 34). First, we can recognise a conjugate system of joints (in purple on Figure 34B) with an intersection normal to the shear plane and vertical joints acting as 'back-crack' type fractures (in green on Figure 34B). These sets of joints are particularly consistent with newly-developed structures related

to movement of the unstable block down-dip with a dip-slip motion under gravitational forces towards the fjord.

### 2.11.2 Summary

- *This site displays fjord-dipping foliation, steep extensional fractures at the back margin of the unstable block and what appears to be a low-angle basal shearing plane at the base of the unstable block.*
- *A spectacular suite of joints is developed in the unstable block which have a lower limit at the proposed basal shearing plane. The geometry of these structures and their delimitation to the base of the unstable block suggests that they formed in response to movement on the basal shear plane, thereby suggesting evidence for block movement.*
- *This site should be a target for GPS monitoring in summer 2006.*

## 2.12 Site 12b

### 2.12.1 Structures

This site was not initially selected from observations made on the aerial photos. However, during the examination of Site 12, this site was observed at a distance of several kilometres to the east of Site 12, on the same side of the fjord. This site displays a single, listric fault, with an angle of between 20-35°. This structure steepens up as it reaches the surface and forms an extensional fracture, which appears to be several metres wide. The area in front of the listric fault in Figure 35 appears to be the basal structure to a previously failed block on the same structure. This site should be examined in more detail in the field during 2006.





Figure 35: Structures observed at Site 12b. This site was only observed from a distance but a long, listric fault was observed (dashed line) steepening up into an extensional fracture on the left. This is accompanied by several extensional fractures detaching down onto the listric fault (dotted lines).

### 2.12.2 Summary

- *This site has not been visited but remote observation suggests the presence of an extensional back fracture with a listric geometry, lying parallel with the fjord-dipping foliation at depth.*
- *Several extensional fractures are seen above the postulated basal shear zone.*
- *The area to the west of the site is a planar surface dipping towards the fjord. This has the appearance of a pre-existing failure surface. Therefore, there appears to have been some rockslope failure activity here in the past.*
- *Fieldwork should be carried out on this site in summer 2006.*

## 2.13 Site 13

### 2.13.1 Structures

Site 13 lies at the corner of Geirangerfjorden and Sunnlyvsfjorden (Figure 4 and Figure 36A). The foliation dips towards Geirangerfjorden and is in an ideal orientation to be reactivated as shear planes (Figure 36B and stereonet on Figure 37). Two sets of pre-existing lineaments are present with NW-SE and N-S trends (Figure 36A). Both sets of lineaments are potential transfer faults. However, unlike many of the other sites where the foliation is dipping towards the fjord (Figure 36B), there is a back-crack present, which is evidence of the extension of the block, there is no evidence for the development of a fault-rock gouge. Large E-W striking opened vertical joints are among the main characteristic structures of the site (Figure 36B and C and Figure 37). Despite the fact that there is evidence for some minor disintegration of the block (with the development of extensional fractures), there is limited evidence for major, unstable movement. This agrees with observation that no fault-rock gouge or basal sliding plane is developed along the foliation. However, there is some evidence for fault-locking or 'buttressing' against steep reverse fault planes in the unstable block (Figure 36C) where extension in the block is stopped against structures which are not able to move. These type of 'buttressing' structures tend to work against gravity, thereby stabilising the instable block to some extent. On the plateau at the rear of the site, a back-crack parallel to the E-W trend of opened joints is developed (Figure 38). This back extensional fracture is evidenced by the presence of a 3m wide depression in the landscape at the back margin of the unstable block. This shows a 50cm depression in the landscape which has a different vegetation which is a response to the different local hydrology along the fracture. It is not clear how much movement there has been on this structure. GPs points should therefore be placed on this structure in 2006.

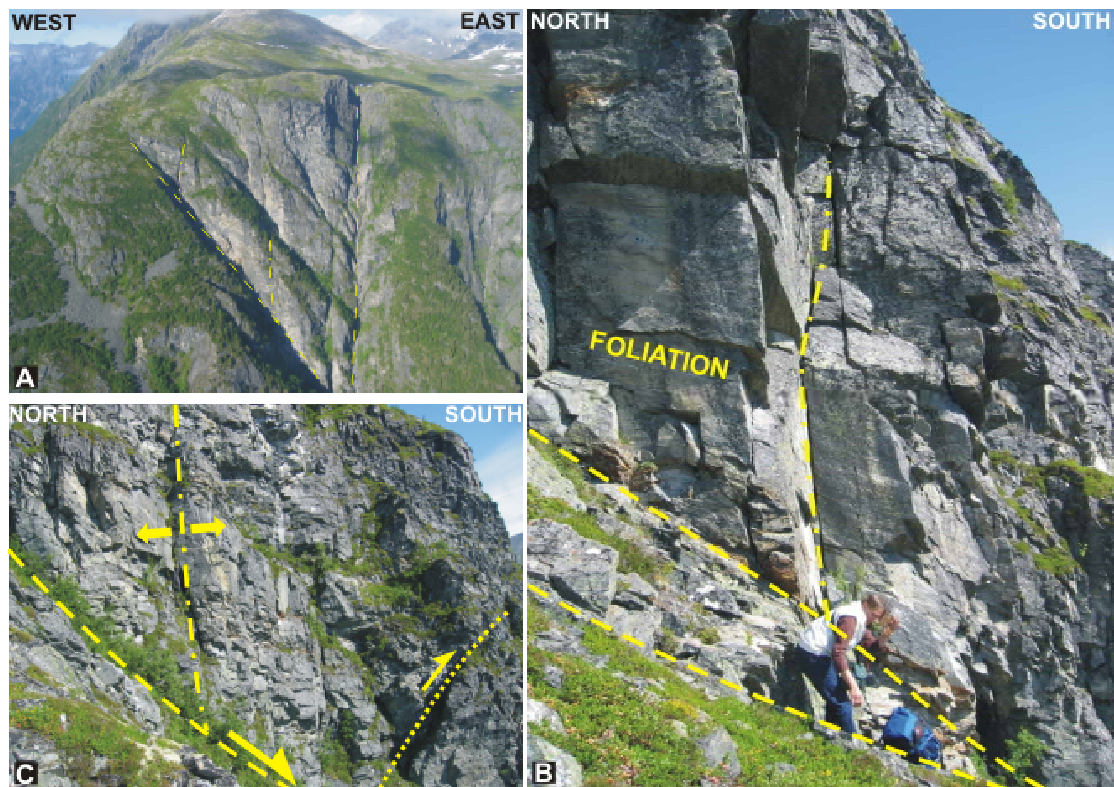


Figure 36: Structures observed at Site 13 along the scarp towards the fjord. A-NW-SE and N-S large sets of fractures seen from the helicopter. B-Foliation dipping towards the fjord and E-W large opened fractures. C-Reverse fault development against the downward motion of the block.

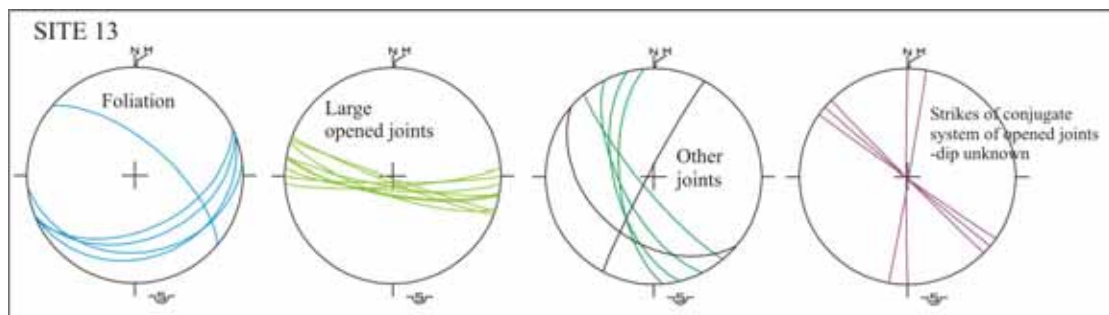
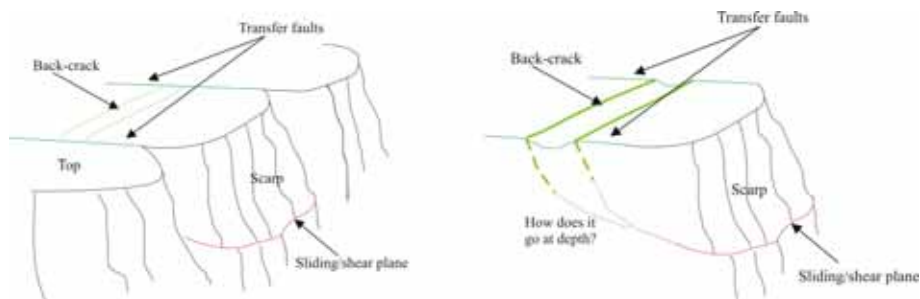


Figure 37: Stereonet data for structures observed at Site 13.



A



B

Figure 38: The observation of a 'back-crack' on the landscape at site 13 onto the plateau. A-An E-W depression is marked by the changing of vegetation. It is interpreted as an incipient back-crack. B-The back-crack is likely to develop if motion occurs along the sliding plane.

### 2.13.2 Summary

- *This site shows transfer faults and some disintegration of an unstable block by the development of a limited number of extensional fractures.*
- *However, there is no basal shear plane developed at the base of the block and no development of a fault-rock gouge. These factors suggest that the block is not particularly unstable.*
- *The presence of 'buttressing' structures in the unstable mass may have 'locked' the movement.*
- *The presence of a depression in the back-margin of the unstable block suggests movement but it is not clear that this movement is in any way significant.*

- *GPS points should be set out on this site in 2006 to determine if there is displacement to account for the development of the significant depression seen in the topography.*

## **2.14 Site 14b**

### **2.14.1 Structures**

Site 14b lies on the eastern face of Sunnylvsfjorden, 12 km south of Stranda village (Figure 4). The presence of a 'back-crack' is suggested by the occurrence of a depression filled by water at the rear of the flat area and against the steep scarp (dashed white line on Figure 39). The foliation does not dip straight towards the fjord (the strike of foliation is ENE-WSW) but slightly oblique relative to it (see Figure 40). Observation from the helicopter suggests that this structure at the back of the block, forming the depression, is listric in nature and therefore become flatter at depth and appears to intersect the topography at depth and thereby defines a detached block. However, it is not clear if there has been recent movement activity on this structure (solid yellow line on Figure 39). The front face of the block displays very fresh rock, suggesting at least that there has been extensive rock-fall in this area. We recommend that in the summer of 2006 GPS points be set out here prior to more detailed mapping.

As with sites 10b and 12, a conjugate system of open joints developed into the sliding mass (purple on stereonet Figure 40). However, the outcrop is poor on this block and due the severe topography only the top surface of the block was accessible.





Figure 39: View of site 14b from the helicopter. The dashed white line represents the back extensional fracture. The solid yellow line marks the approximate position of the extension of this structure at depth. This structure appears to have a listric geometry and is therefore flattening out at depth. Clearly there has been some recent landslide activity in this area due to the presence of fresh rock surfaces.

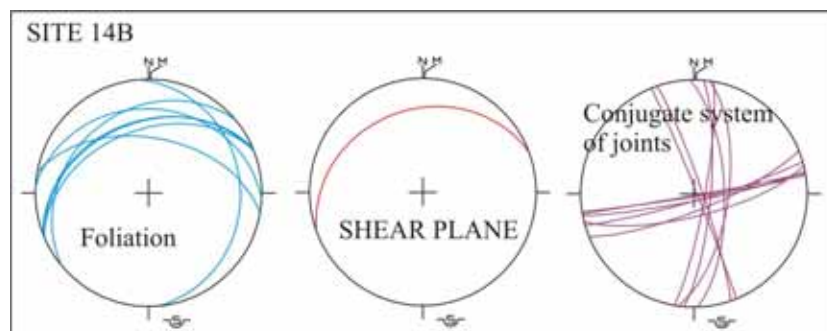


Figure 40: Stereonet data for Site 14b

#### 2.14.2 Summary

- *This site displays a wide depression at the back of the postulated slide block. This is a listric structure which appears parallel to foliation at depth and therefore may possibly act as a sliding surface. However, there is limited evidence for recent movement.*

- *Open joints are developed in the potential failure block but it is not clear how significant these are in terms of block disintegration; the outcrop observed was limited.*
- *We recommend the setting out of several GPs points in summer 2006 to determine if there is movement as a pre-requisite to further detailed fieldwork.*

## **2.15 Site 16**

### **2.15.1 Structures**

Site 16 lies on the eastern side of Sunnylvsfjorden (see Figure 4). We could not get access to this site and only took some pictures from the helicopter of an unstable part of the slope (Figure 41). The block is detached from the slope at the back by a largely open fracture of unknown displacement. At the base of the block is a discontinuity along which the steep, open fractures are rooted (Figure 41). The basal structure is probably an inherited discontinuity intrinsic to the structural geology of the area. This site shows a very interesting criterion for instability. The detached block clearly shows a dense network of fractures, which are not developed as such in the surroundings. This could be an indicator of the instability of the mass: more fractures developed and more the mass becomes unstable up to a critical value of fracture density (value which remains unknown). A tool to get the maturity of unstable mass could be a systematic determination of the density of fractures in the unstable mass and to evaluate the increase of density through time.



Figure 41: Development of a dense network of joints in a potentially unstable block at site 16. The steep, open fractures (a major one shown in green) appear to detach onto a shallow, fjord-dipping discontinuity (yellow).

### 2.15.2 Summary

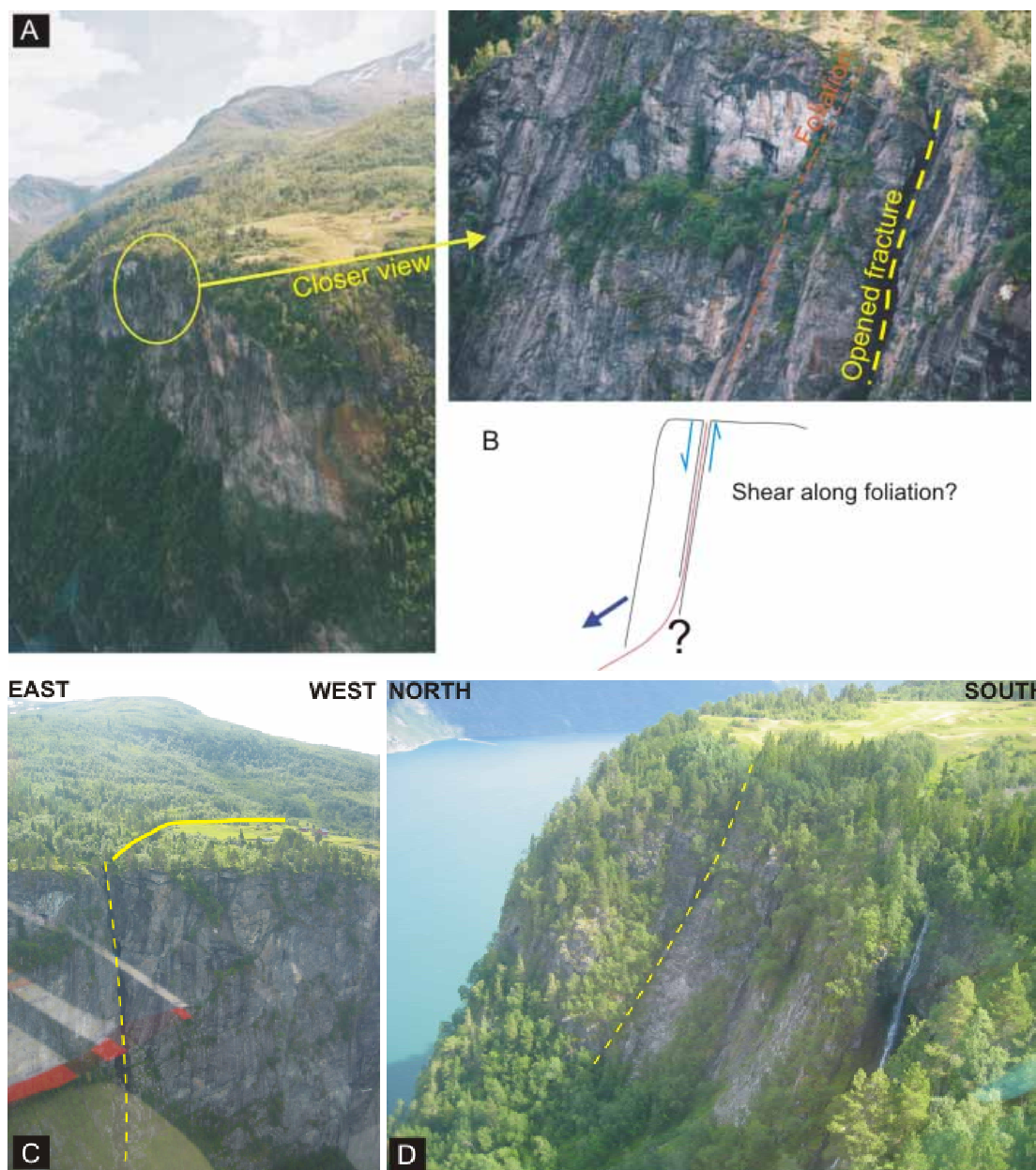
- *This site shows a remarkably high density of fractures in the unstable block. We assume that such a high density of joints demonstrates a process of advanced disintegration of the unstable block.*
- *However, it is likely, with such a disintegration of the block that falling volumes will be low but falling events will be high.*
- *This area requires further field examination in 2006.*

## 2.16 Site 18

### 2.16.1 Structures

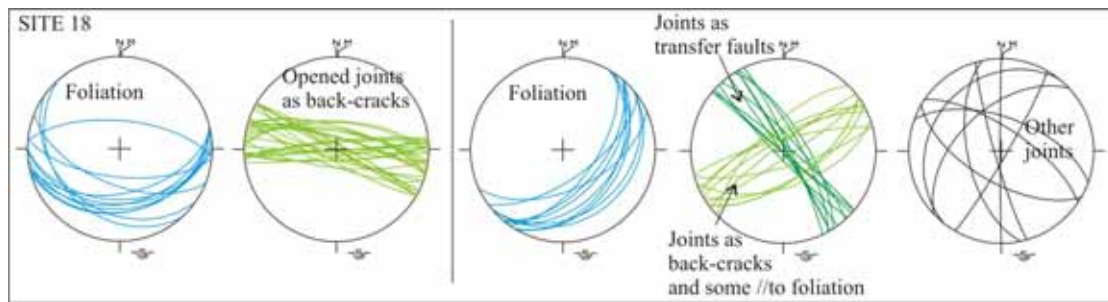
This site is located on the south side of Norddalsfjorden in the western part of the fjord (Figure 4). The foliation surface here is changing in strike but steeply-dipping towards the fjord (Figure 42A and Figure 43) and is therefore also a good candidate for the developing of a shear plane (Figure 42B). The joint sets are also consistent

with the characteristic trends, which usually form in a failure block (Figure 42C and D and Figure 43) when there is evidence of recent movement activity. If a shear plane parallel to the foliation were to develop, then a reactivation of these joints as transfer faults and a back-crack extensional fracture would be expected.



**Figure 42: Structures observed at Site 18. A-Steep foliation (orange) and fractures opened along the foliation. B- Hypothetical view of the rock failure process. C- Major E-W back fracture (solid yellow line) and foliation parallel extensional structure seen from the NE, D, major E-W extensional fracture seen from the west.**





**Figure 43: Stereonet data for Site 18. Two different trends of foliation are associated with different trends of joints (as 'back-cracks' in both cases).**

Several ridges are observed in the topography on top of the block. These are up to 1m high and step down towards the fjord. They may represent down-dip extension of the block along several steep, extensional fractures. The main back-crack displays a 2m high down-stepping depression in the topography of the block. When this depression is followed to the extremities of the block it is clear that this is the result of several tens of centimetres of extensional displacement. Therefore, there is evidence that there has been significant movement on the detached block, but it is not clear how recent this extension has been. In addition it is not clear what the mechanism of displacement is at the base of the unstable block. For example, it is not clear if the displacement is occurring by a toppling or slide mechanism (as shown on Figure 42B) or if the displacement is 'pinned' (hinging) at the base of the block near to sea level. We therefore recommend the setting out of GPS points in the summer 2006 to determine the nature of displacement and therefore the likely mechanism of displacement and the magnitude of displacement.

### 2.16.2 Summary

- *This site has steeply-dipping foliation which dips towards the fjord. Large extensional structures have developed parallel to the foliation, which have down-dip displacement resulting in the formation of several metre-high terraces on the topography on the top of the unstable block.*
- *Several tens of centimetres extensional displacement towards the fjord is noticed on the main structure. However, it is not clear when this movement took place or what is controlling the sliding out of the block at its base.*



- *We recommend the setting out of several GPS points on this site to determine the nature and magnitude of displacement (if any) prior to more detailed fieldwork.*

## 2.17 Site 20

### 2.17.1 Structures

Site 20 lies on the southern side of Norddalsfjorden, just on the east of Eidsdalen on the western flank of the Storåsnakken mountain. At this site, the foliation is generally steeply SSE dipping and open joints are developed along the foliation (Figure 44 and stereonet on Figure 45). A large, 45° dipping sliding plane can be well observed on Figure 46B. This shows a folded gneiss at the base of the unstable mass. It appears that the shear plane has localised along this pre-existing ductile discontinuity. The folds are characterised by axial planes dipping 40 degrees to the south and by large opened planes that formed parallel to the fold axis and that may act as sliding planes (stereonet on Figure 45). Other joints cut the failure block and may be consistent with transfer faults (stereonet on Figure 45).



Figure 44: Structures observed from the air at Site 20.

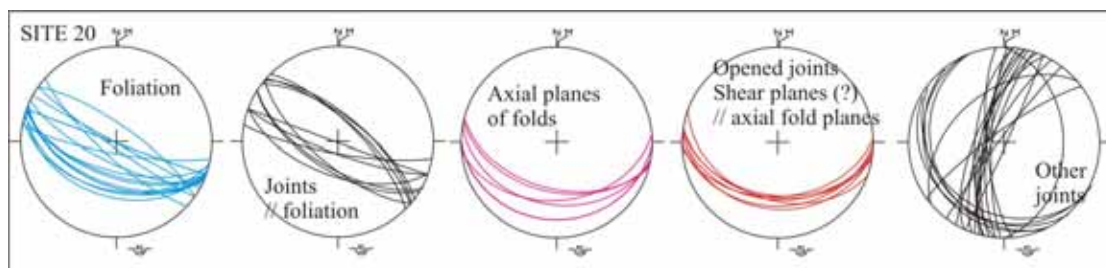
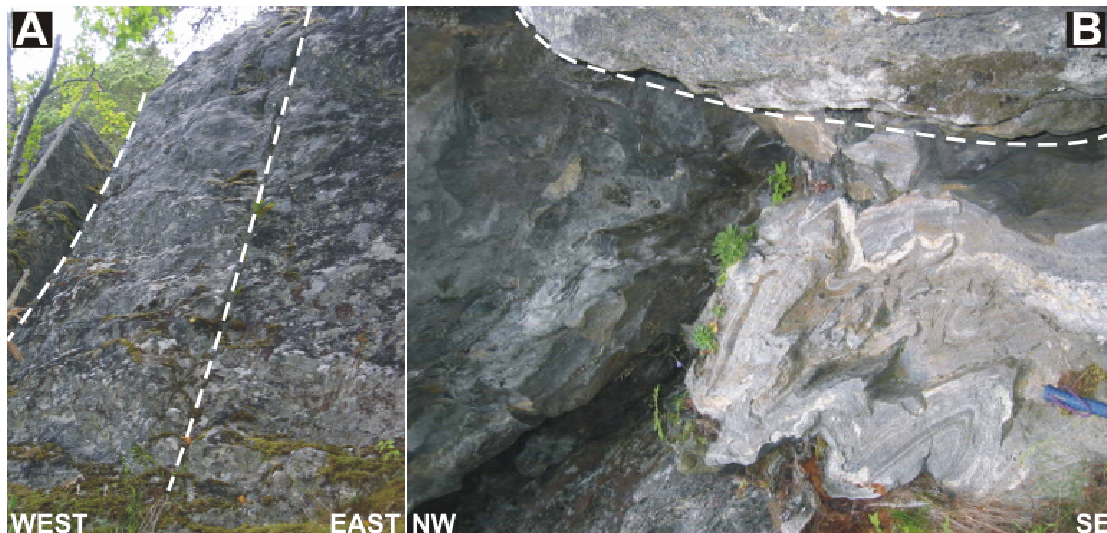


Figure 45: Stereonet data for Site 20.



**Figure 46: Structures observed on the ground at Site 20. A-N-S extensional fractures which are most obvious from the helicopter (see Figure 44). These are pre-existing fractures which have been reactivated and now produce active rock-fall. B-Sliding plane dipping towards the SW. No fault-rock gouge is developed here but the rock-fall occurs along these low-angle planes and are detached on the extensional structures observed in A. The sliding plane is localised along a series of ductile small –folds.**

### 2.17.2 Summary

- *Steep foliation is combined with a low-angle discontinuity which may be a sliding plane to detach large blocks up to several tens of m<sup>3</sup>. There is no evidence for large scale instability here*
- *As the village of is located directly downslope of the unstable slope, we propose to make this site a priority for next year in terms of GPS monitoring because of the threat of rock-fall and to determine the full extent of the unstable block.*

## 2.18 Site 21

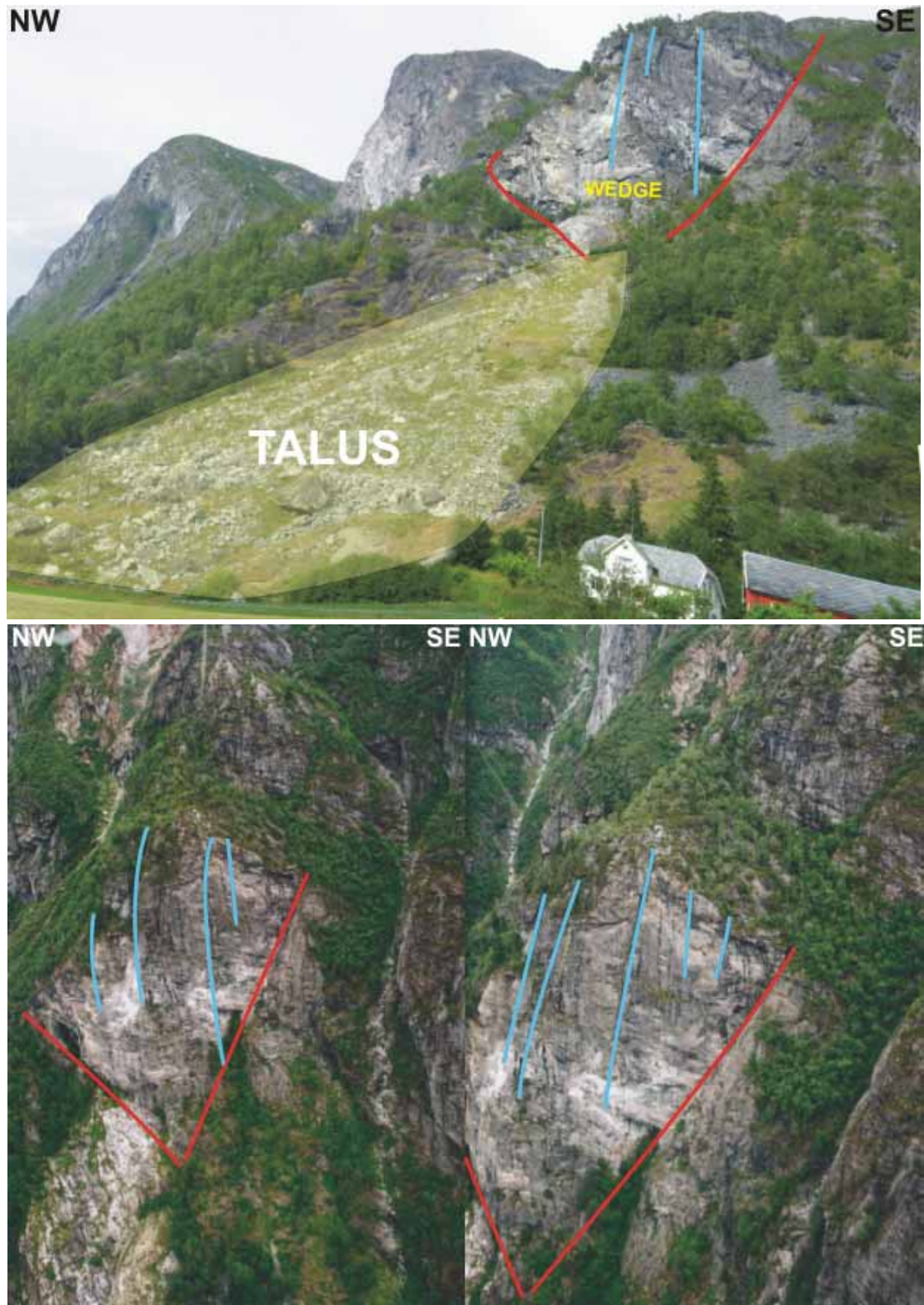
### 2.18.1 Structures

This site is a west-facing slope in Norddalen approximately 300m above sea level. This site displays an impressive, recent talus fan, which has threatened the small community of Norddal (Figure 47). Preliminary examination of the mountainside shows that several unstable blocks still remain present. Two basal surfaces limits the unstable mass and define a wedge geometry (Figure 48 and Cf section 1.2). However, the classical wedge is only defined with these two basal shear planes (Figure 2C)

whereas at this site, one or two secondary fractures developed at the back of the block. Two possible geometries are possible for this site as illustrated on Figure 48. The north-western basal limit of the mass is a 45 degrees SE dipping shear plane and the southeastern limit is a 45 degrees NW dipping shear plane (respectively in red on the stereonets on Figure 49). They formed together the basal structures along which the displacement of the block may occur. The slip along these planes is oblique (not dip-slip) parallel to the intersection line of the two basal shear planes (Figure 48 and Figure 50). The basal shear plane we have reached and analysed is the north-western one. This 45° SE-dipping shear plane is sub-parallel to the amphibolitic foliation. This structure is not dipping out towards the valley but is rather orientated 45° to the valley sides (see Figure 47). This shear plane lies on the lithological contact between an amphibolite at the base and a grey coloured dioritic gneiss above. The grey gneiss is relatively competent but displays steep joint structures (Figure 50). These form a steep conjugate extensional set, probably related to movement on the low-angle shear plane (Figure 50). Some of these conjugate structures are larger and appear to have formed a hangingwall wedge structure, which are detaching downwards on to the basal shear plane (see Figure 47). The basal shear plane between amphibolite and the grey gneiss is a very chemically weathered zone with abundant white mica. However, it also appears that the micas here have been brecciated due to recent movement activity. Samples of the fault material were taken to determine this with microscope examination.

This site was deemed reasonably inaccessible due to very steep valley sides, therefore, only a cursory evaluation of the structures could be undertaken. A further attempt will be taken in 2006. However, the presence of a low-angle shear zone where at least some movement activity is noticed and the presence of extensional fractures in the hangingwall to the basal shear zone suggests that movement is occurring along the basal shear plane and the hanging wall is responding by gradually disintegrating.





**Figure 47: (TOP) Photo montage image of Site 21. In this montage the image is foreshortened. (LEFT) Frontal view from the air (red lines as the two shear planes, blue lines as extensional fractures). (RIGHT) View of the southeastern shear plane (solid red line) of the wedge (in blue extensional fractures in the wedge).**



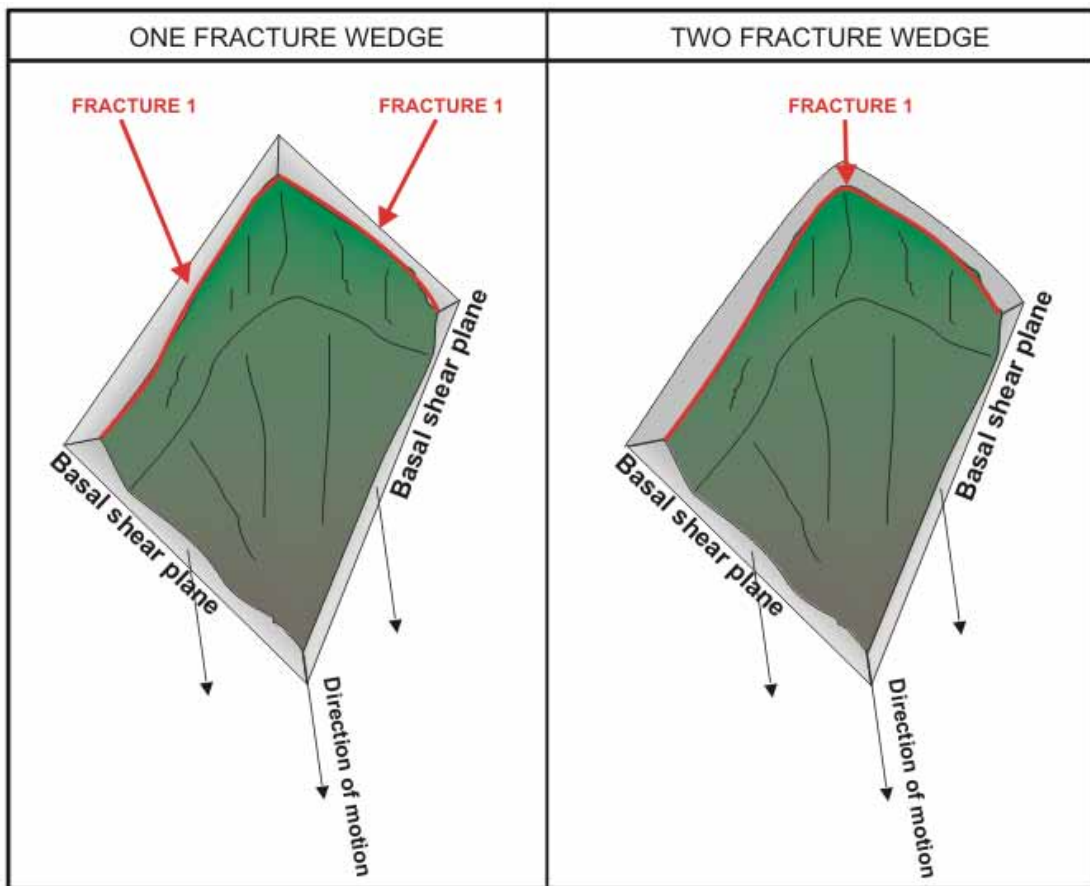


Figure 48: The geometry of the wedge at site 21. Two possible models: (LEFT) With two steeply dipping back-crack structures. (RIGHT) With only one steeply dipping back-crack.

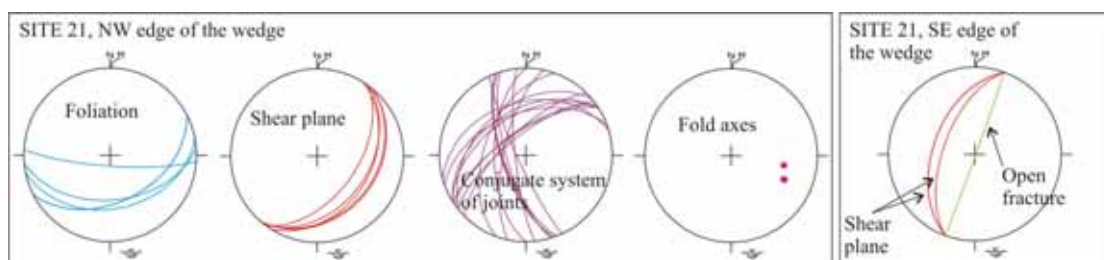
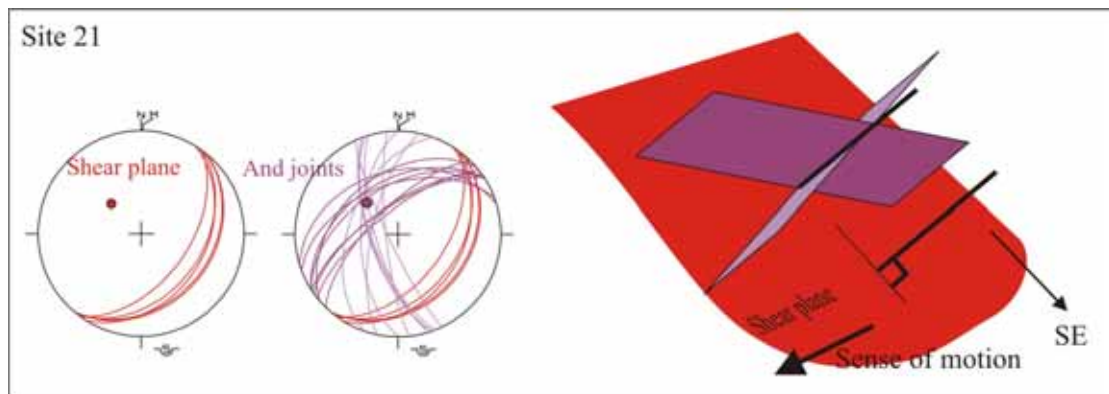


Figure 49: Stereonet data for Site 21.



**Figure 50:** Joints developed in the hangingwall of the north-western part of the wedge. Note that the displacement is not dip-slip along the basal shear plane (the motion is accommodated by the two basal planes and is parallel to their intersection line; see Figure 48).

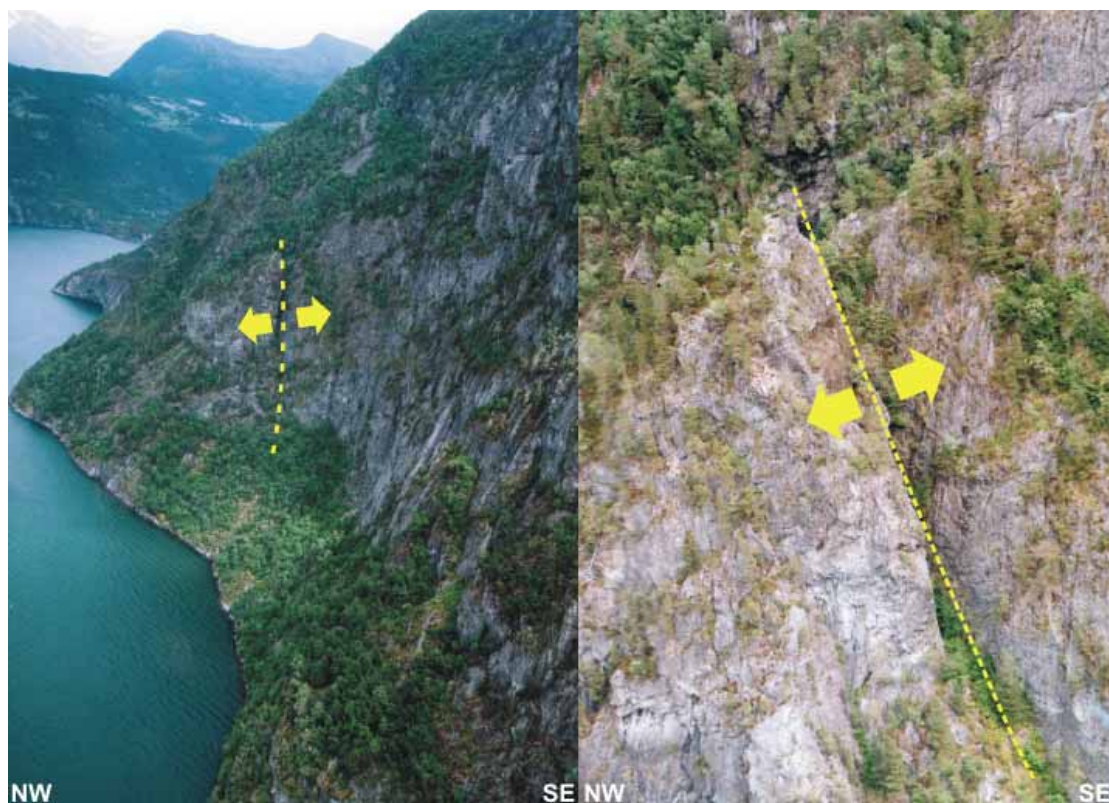
### 2.18.2 Summary

- *This is a known site for frequent rock fall and several recent rock avalanches.*
- *The wedge structure is well-developed, sitting on top of two differently oriented basal shearing planes.*
- *Some evidence exists for the active movement on the weakened layer of micas at the base of the unstable block on the basal shear plane.*
- *2 GPS points were set out in summer 2005. Measurements should be performed on these again in 2006 to determine the magnitude of movement on the unstable block.*
- *More mapping of this site should be done in 2006 to better define the poorly-constrained geometry of the failure block*

## 2.19 Site 22

### 2.19.1 Structures

Site 22 near Norddal village is affected by toppling (Figure 51). The foliation is vertical and trending NW-SE (stereonet in Figure 52). Open joints are developed along the foliation. Both pre-existing, breccia-filled vertical fault zones and vertical joints form a conjugate system of open joints (in purple on Figure 52A and B). The combination of structures here favours a toppling process of failure directed to the E or ENE (Figure 52B). Other gently dipping, pre-existing fault zones are re-opened and can act as a detachment fault zone (in red on Figure 52A and B) at the bottom of the failure block. Figure 52B summarises the structure of site 22.



**Figure 51: Pictures from helicopter showing the toppling of rock masses. (LEFT) General view to the north of Site 22 near Norddal village. (RIGHT) Detail of a mass detached from the slope at site 22 (seen on A).**

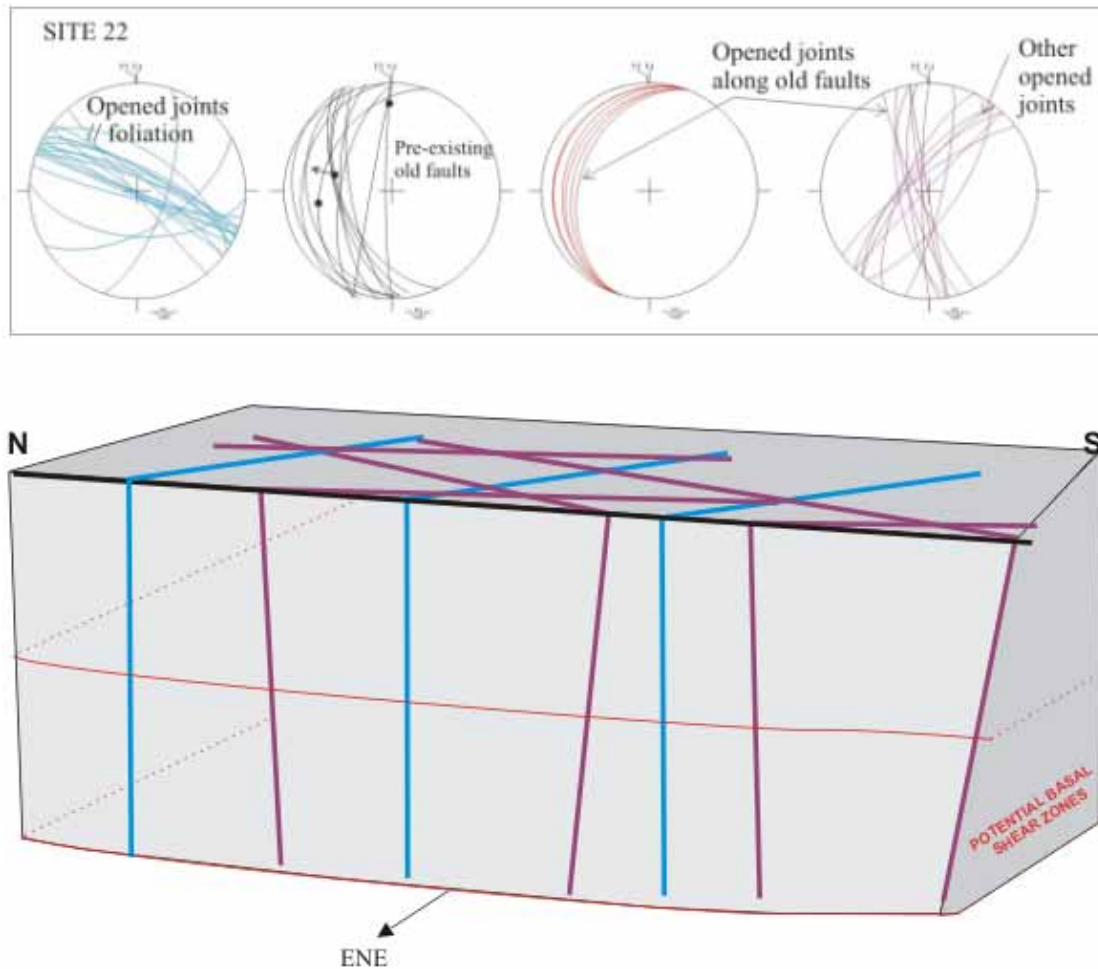


Figure 52: (TOP) Stereonet of data collected at site 22. (BOTTOM) Schematic drawing of the brittle structures developed at site 22. The scarp is trending N-S.

### 2.19.2 Summary

- *A vertical foliation is accompanied by a set of conjugate near vertical fractures along pre-existing lineaments and the development of some new joints, testament to movement activity.*
- *Some minor evidence exists for the development of minor fjord-directed sliding planes but the main failure mechanism here is likely to be toppling, thereby reducing the likelihood of a large volume of unstable material.*



## 2.20 Site 27

### 2.20.1 Structures

Site 27 is found on the southwestern side of Tafjorden. The structures identified at this site have been only observed from the helicopter. It was not possible to land here because of the extremely steep terrain. Several high and large opened fractures cut the slope of this side of the fjord (sites 25, 26, 27, see locations on Figure 4). At site 27, such fractures are nearly 100 m high is associated with a plane dipping towards the fjord along which shearing and displacement may be occurring (Figure 53).

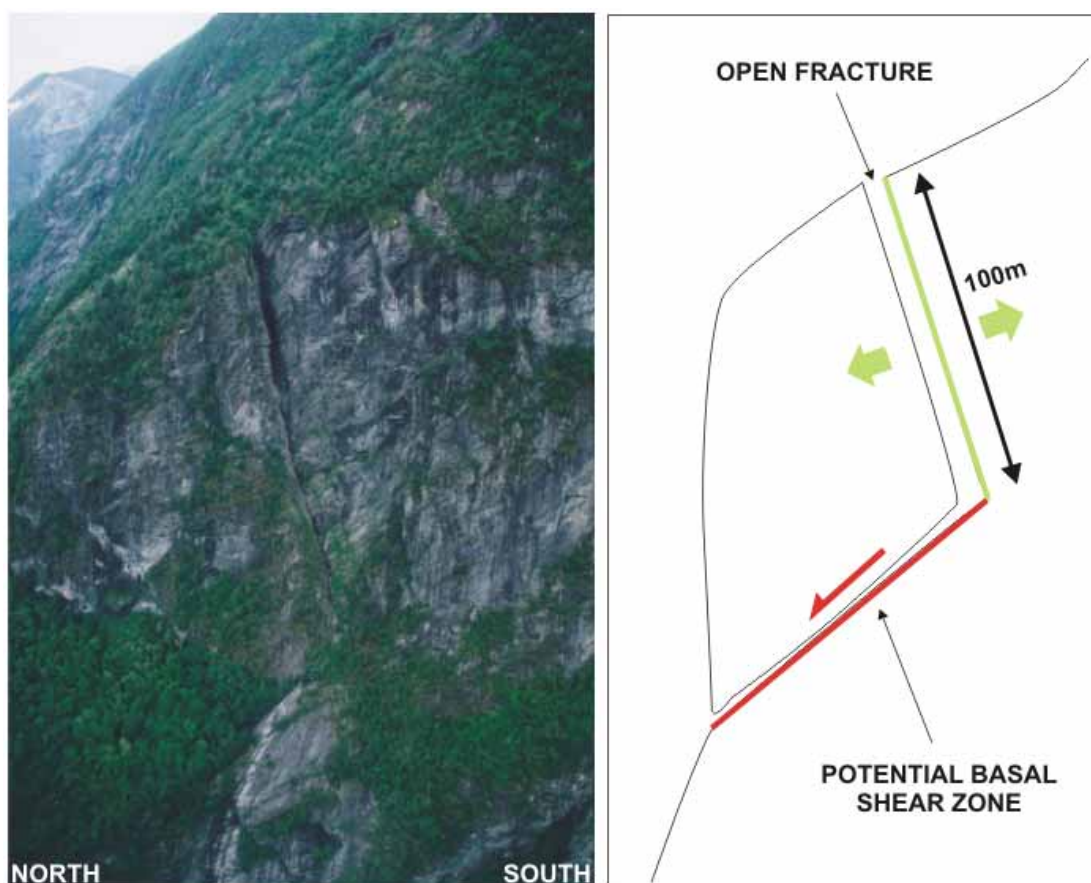


Figure 53. Structures observed from the helicopter at Site 27. It was not possible to land here. A large extensional 'back crack' (in green) was observed and possibly a low angle sliding plane (in red).

### 2.20.2 Summary

- *This site displays both steep, extensional fractures, with significant extension towards the fjord, and a low angle plane, which may be a shear plane.*

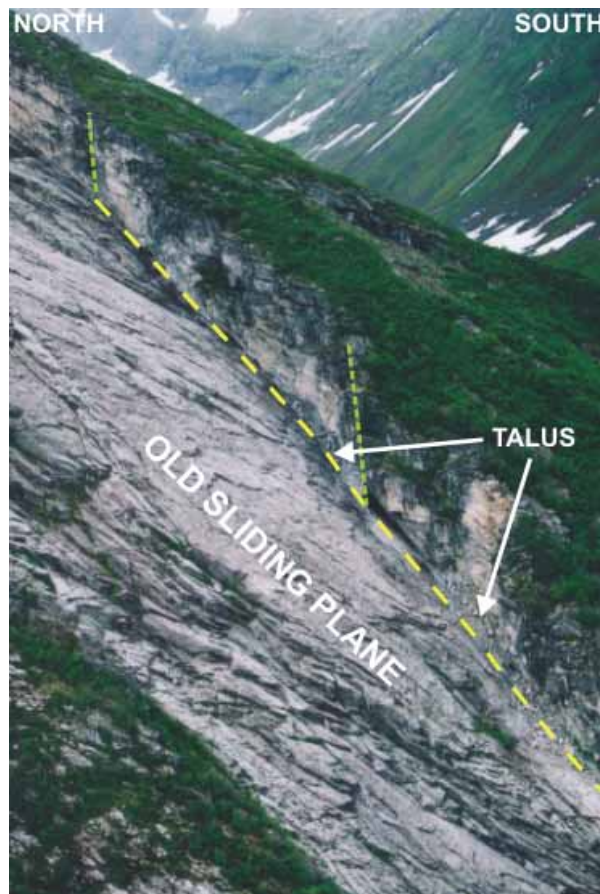


- *This site was not visited in the field due to inaccessibility due to the steep terrain but deserves more attention in summer 2006. It is especially critical to focus on the low angle plane to determine if a fault rock is present, which is testament to movement on the low-angle plane. This would explain the displacement seen on the steep extensional structure.*

## 2.21 Site 38

### 2.21.1 Structures

Site 38 lies on the northern side of Valldalen (Figure 54) and belongs to the southern scarp of Høgstolen mountain (see Figure 4).



**Figure 54:** Structures observed from the helicopter at Site 38. The foliation dips moderately towards the valley along which sliding planes may have developed (yellow). Along the potential shearing plane a blocky talus can be observed and can be the result of rock disintegration subsequent to movement along the shear plane. There is some evidence for steep, extensional fractures (green) and the presence of an old sliding plane

This has only been observed from the helicopter. However, some critical structural relationships have been identified and will deserve further investigations in summer fieldwork 2006. The foliation dips moderately towards the valley and sliding planes may have developed along the foliation as shown in Figure 54. In the footwall of the slope (directly above the red line) on Figure 54 talus is present and may be the result of the rock disintegration as a result of movement. Also, the fresh, unvegetated rock surfaces below the postulated shear plane on Figure 54, and the 'stepped' geometry of this surface, appear to represent a past sliding plane, suggesting there have been previous rockslides here.

### 2.21.2 Summary

- *Foliation dips moderately towards the valley. Basal shear planes may have developed along the foliation.*
- *Some evidence of disintegration occurs along planes dipping towards the valley by the presence of talus at the base of the scarp slope. This may suggest recent unstable activity.*
- *The fresh, unvegetated plane structurally below the scarp may be a past failure surface and therefore the large block above the proposed low-angle sliding plane lies along the same failure surface.*
- *Sites 38 (and 39) should be investigated in summer 2006.*

### **3 DISCUSSION**

This section examines the common geological, geometrical and topographic factors seen within the whole of the Storfjorden area and attempts to pinpoint the present critical structures or group of structures, which appear to be necessary for the production of potential large landslide volumes.

#### **3.1 Controlling factors for potential rockslope failure**

##### **3.1.1 Pre-existing lineaments**

The pre-existing lineaments, which are mainly fault zones, are common in the Storfjorden area. When they are close to, or intersect the slope of the fjords, they are potentially influential structures for rockslide development. They can often be traced over large distances, across fjords and from the fjord to the surrounding high plateaus. A typical example of such a structure is displayed on Figure 55, showing the southern face of Geiranger Fjord between Homlung and Geiranger villages. This large vertical lineament is re-opened and may enhance the development of failure blocks. Some good examples have been already mentioned in this report and we reiterate some of them below.

At Site 2b, the shear plane is developed along a pre-existing brecciated fault zone dipping towards the fjord. N-S trending large vertical fractures are also very well developed all along the western slope of Sunnylvsfjorden and up to the high plateau. These are largely re-opened or reactivated and therefore contribute to rock-slide formation as observed at sites 2, 2b, 4 and 6b. At site 10b, the most distinct lineament set corresponds to a system of inherited faults with clearly well-developed strike-slip slickensides, enhanced with chlorites on the fault planes. These structures are obviously reactivated in the sliding process and play the role of transfer faults to accommodate the downslope motion. Finally one of the best examples has been observed at site 22 where two different types of faults, both characterised by pre-existing, chlorite-rich fault rocks contribute to the development of an unstable rockmass. The first set is vertical and together with the vertical foliation and another set of vertical, potentially newly-developed joints favour a toppling process with the cutting of the slope in a columnar fabric. The second set corresponds to old fault

zones gently dipping towards the fjord. They intersect the columns and may form the structures required to detach the rock mass at the foot of the columns. These examples evidenced the need to systematically map the pre-existing lineaments (as joints and faults), which previously developed during geological time in the Storffjorden area. This should be done systemically on a regional scale in further study.

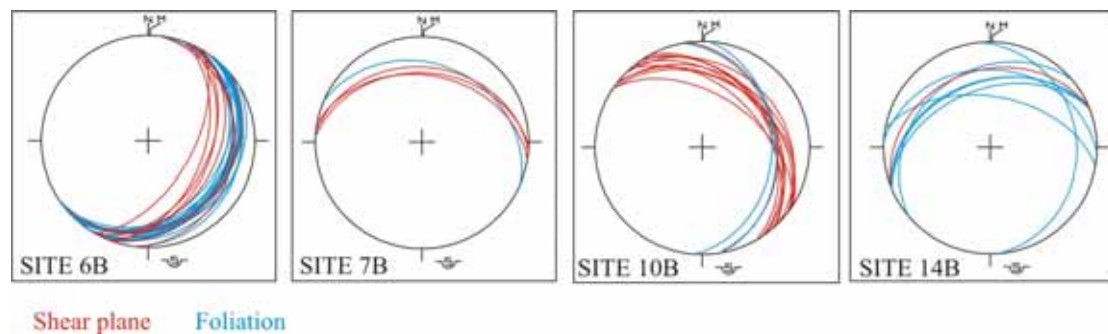


**Figure 55: Helicopter view between Homlung and Geiranger villages on the southern face of Geiranger Fjord, showing examples of major lineaments which are reopened and could be one of the controlling factors in the origin and development of a failure blocks.**

### **3.1.2 Foliation dipping towards fjord**

In many sites of Storffjorden area, we have noticed the importance of the orientation of foliation in regards to rockslide development. When the foliation dips towards the fjord (sites 2, 2b, 4, 5, 6b, 7b, 10b, 14b, 27) or towards the valley (site 38), we have commonly observed the development of the basal shear plane parallel to foliation (as shown by stereonets of measurements at sites 6b, 7b, 10b, 14b on Figure 56). In the gneissic rock mass of the Storffjorden area, foliation comprises alternating layers of feldspars, quartz and micas, each of various thicknesses. The mica-rich layers are

potential sites of enhanced basal shear plane development as the cohesion of micas is less than that of other minerals, such as feldspars and quartz.



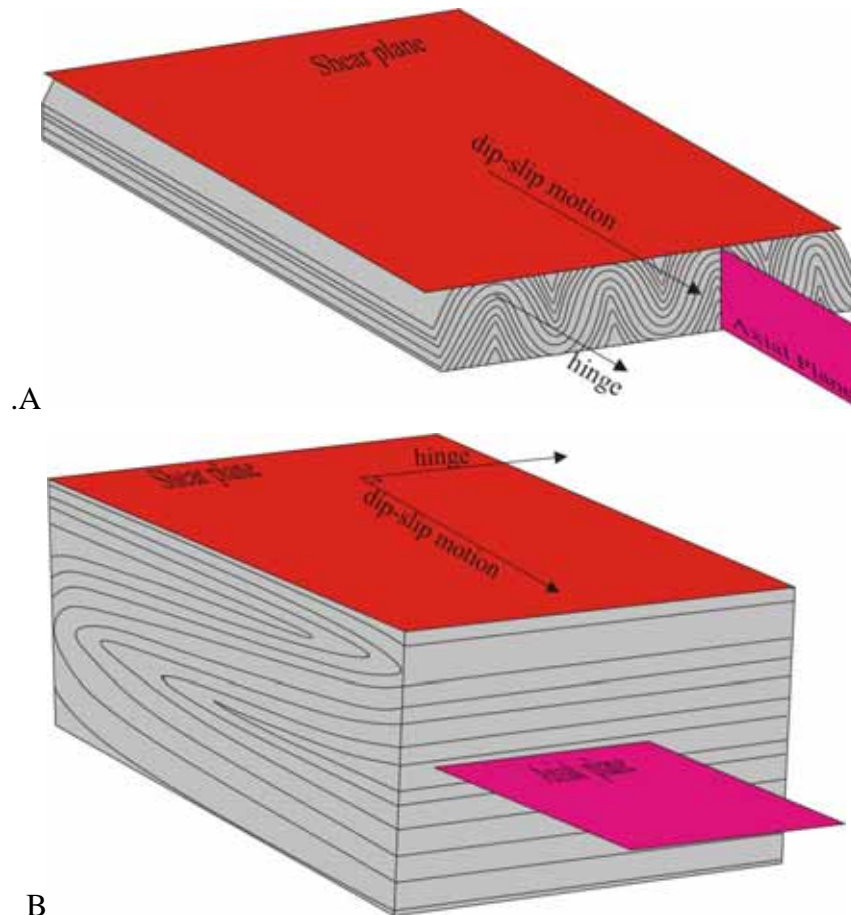
**Figure 56: Examples of potential failure sites in the Storfjorden area where the basal shear planes are parallel to the foliation.**

In section 4.3.1, we will go further in the relationships between pre-existing foliation and the development of a shear plane at the base of failure blocks. We will demonstrate how the value of the dip-angle of the foliation is an important factor to take into account for the probable occurrence of basal sliding planes.

### 3.1.3 Small fold development

At several sites, shear planes developed according to the geometrical constraints of the pre-existing fold geometry. Several examples are shown in Figure 57. Figure 57a shows how the sliding mass movement direction is constrained to the trend and plunge of pre-existing ductile small-fold hinges. Figure 57b shows how shear planes are developed parallel to shallowly-dipping small-fold axial planes. These examples highlight the importance to systematically map the pre-existing geological structures in order to predict the complexity of the geometry of the basal shearing planes which ultimately define the volume of the block and the nature in which it is moving.





**Figure 57: A-Shear plane developed perpendicular to the axial planes of folds (as at Sites 2B, 4B, 21). B- Shear plane developed parallel to small-fold axial planes (as at Site 20).**

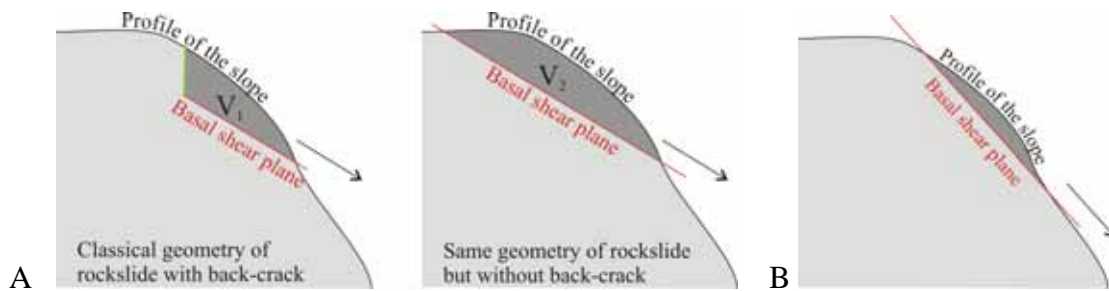
### 3.1.4 Development of basal shear zone with breccia

At all of the active sites studied (where the process is not toppling) a basal shear zone is developed (at sites 2, 2b, 4, 6b, 7b, 9, 10, 10b, 11, 12, 13, 14b, 20, 21, 27, 38). Such basal shear planes can be considered as a primary structure along which the sliding has occurred. The extensional back-crack and transfer faults could therefore be considered as secondary structures accommodating the motion of block along the sliding plane. In addition, it is the stresses acting on the basal shear plane that are critical to be taken into account for a mechanical study of rockslides (see section 4.3.1). If there is active movement a breccia almost always forms along the basal shear zone. The breccia formation is a dynamic process indicating shearing and friction along the plane, the breccia being derived from the disintegration of the host rock. The thickness of the fault rocks in active visited sites can be from millimetres up

to tens of centimetres. These breccia zones also display a wide variation in continuity along the fault plane. For example, some display continuous planar coverage of the fault zone whereas others form isolated lenses leaving some of the fault plane as rock-rock contacts. Samples have been collected (at Sites 2b, 6b, 10b, 21) to examine how the process of breccia formation evolves. The grain characteristics (size and shape) will be taken into account to determine how 'mature' the fault rock has become and this will ultimately be related to shear strength tests of the variously evolved fault-rock materials (see section 4.3.3 for more detailed explanations).

### **3.1.5 Development of extensional back fracture**

Irrespective of whether the landslide process involves toppling or sliding, large, open and steeply-dipping to vertical fractures usually form at the back of the unstable rockmass under tension (Figure 2A and B in section 1.2). However, there are some cases where back-crack structures are not observed. These exceptions are where the basal shear planes emerge at the surface and intersect the mountainside topography (Figure 58; and as on site 2b). This often involves much larger rockslides (compare the two volumes  $V_1$  and  $V_2$  on Figure 58). When the basal shear plane is steeply-dipping and roughly parallel to the slope surface, a 'thin' slice of the slope can easily detach and no back-crack forms in such a process (Figure 58B). A typical wedge structure is also without extensional back-cracks as the two basal planes emerge at the back of the block (Cf. Figure 2C in section 1.2). Note that the wedge we have observed at site 21, shows one or two back-crack plane(s) which render the geometry of the unstable block quite complex (Cf. Figure 48). In turn, when the process is toppling, such structures can be the primary structure involved in detaching the block from the slope.



**Figure 58:** A-The typical geometry of a rockslide along a basal shear plane: with the development of an extensional back-crack structure (left) and without a back-crack (right) (note the differences of involved volumes:  $V_1 < V_2$ ). B-No back-crack extensional structure develops when the basal shear plane is steep and close to the slope.

In the field we have been extensively searching for evidence of back-crack occurrence. Along some steep scarps, we have recognised basal shear planes or incipient basal shear planes. These are most often localised parallel or near parallel to foliation surfaces but this is not always the case. Scarp investigation is often difficult as they often occur on the steepest topography. However, it is possible to find evidence of scarp development on the flat plateau behind the unstable block. When back-cracks form, but before they are fully opened, they may be detected through a changing of ground vegetation, of topography (they are commonly form depressions in the topography) and are often more watered that the surroundings (such is exemplified in site 13, section 2.13).

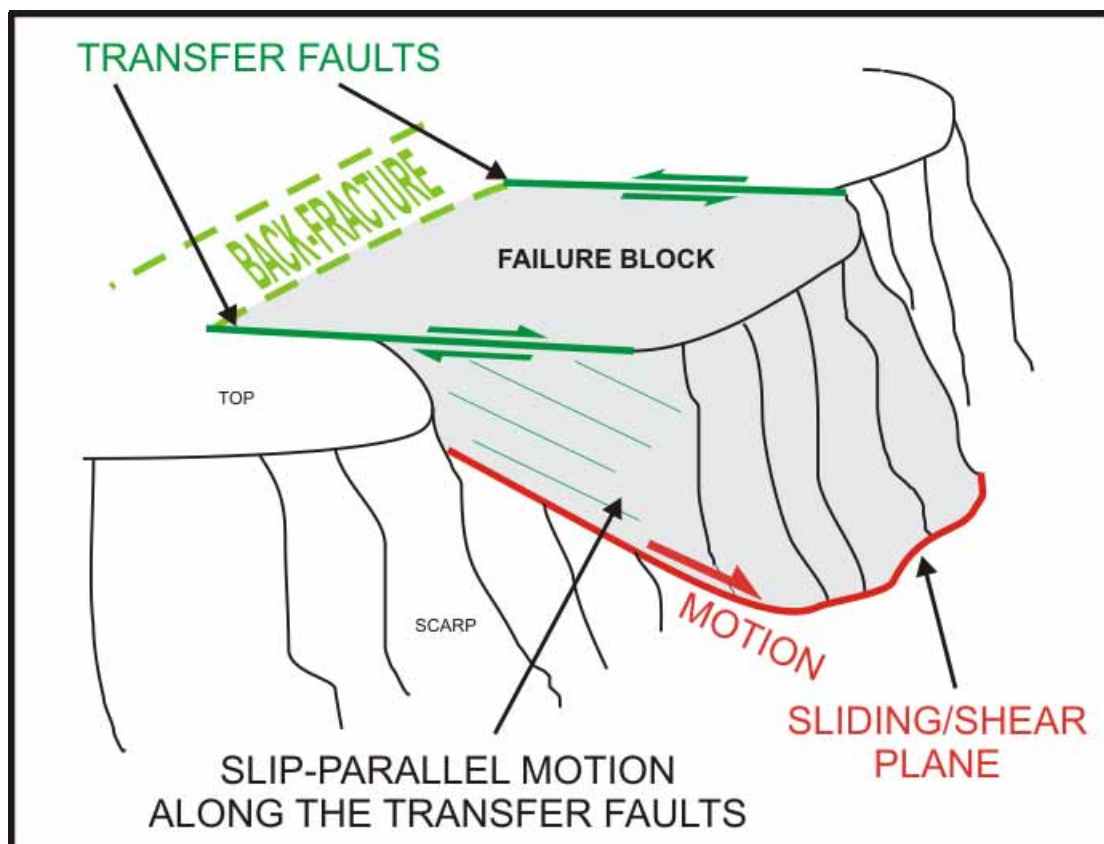
The amount of opening at the back-crack provides the amount of displacement of the block relatively to the slope. (as indicated on Figure 2A in section 1.2). This value is a minimum total displacement of the whole block as opening of other extensional fractures in the block should be taken into account to determine the total cumulative displacement of the block at its front. Steeply dipping pre-existing discontinuities such as foliation surfaces or joints and faults, are potential back-crack extensional structures, if their orientation is appropriate.

### 3.1.6 Transfer fault development

In order to fully detach a rockslide block three structures are fundamentally needed along a relatively planar slope:

1. the basal sliding plane.
2. the back extensional fracture.
3. the transfer faults (Figure 59).

Transfer faults are necessarily two major surfaces that develop in a vertical plane and parallel to the motion of the block thereby delineating the geographical margins of the block. The slip kinematics along them are often highly oblique and parallel to the displacement, and in an opposing sense of shear from one another (Figure 59). They have the role to 'transfer' the movement of the block downslope. Site 13 is a good example of an unstable rockmass with the three types of structures (Cf Figure 38 of section 2.13). However, in most of the visited sites, the limits of the blocks are free borders (for example at site 6b) as the slope is often irregular, which could be due to previous adjacent landslides which have removed significant parts of the slope.



**Figure 59:** The two main transfer faults of a rockslide. Note the opposite sense of movement along each of them and the slip-parallel motion on both of them.

Pre-existing vertical discontinuities such as joints and faults can take on the role of transfer faults, if their orientation is suitable. Such example has been seen on site 10b where old strike-slip faults have the trends of transfer structures (see stereonet of Figure 29 in section 2.9.1).

### **3.1.7 Vertical orthogonal system of joints and conjugate system of joints normal to shear plane.**

Our observations also provide the geometry of structures developed within the sliding mass. These joints and extensional structures form due to disintegration of the rockmass and are directly linked to the deformation or movement along the Basal Shear Zone. They can be perpendicular systems of joints but conjugate systems of joints are also observed with a  $60^\circ$  angle between the two conjugate planes (Figure 2A in section 1.2). In the perpendicular case, one trend of the joints is parallel to the displacement vector while the second set of joints is perpendicular to the movement direction (as observed on sites 2b, 6b, 7b, 9, 13, and 18 and illustrated on Figure 7, Figure 16, Figure 21, Figure 24 and Figure 37). In addition, both joint sets are often vertical joints and have the same structural geometry as the vertical main back-crack structure and of the transfer faults (Figure 2A in section 1.2). In the second case, the joints of the conjugate systems are not vertical but perpendicular to the basal shear plane lying below them at the base of the unstable block (Figure 2A of section 1.2). Another point of importance is that the bisectors of the conjugate systems are alternately parallel and perpendicular to the motion of the sliding block. For examples, at sites 10b and 14b the bisector of the obtuse angle between the conjugate joints is parallel to the motion direction (Cf. Figure 30 and Figure 40 respectively) and at sites 12 and 21, it is the bisector of the acute angle between the conjugate joints that is parallel to the motion direction (Cf. Figure 34B and Figure 50 respectively). The significance of this geometrical difference between joint sets is not yet understood. However, the geometries of such conjugate systems of joints are clearly strongly related to the attitude of the basal shear plane and to the motion along it.

We have observed at some places an association of these above described sets of joints. At site 12, in addition to the presence of a conjugate system of joints,



additional joint sets have the properties of vertical back cracks (Cf. Figure 34B, section 2.11). At site 10b, a set of joints which trends parallel to the transfer faults is present in addition to the conjugate system of joints (Cf. Figure 29 section 2.9.1).

As demonstrated above, the trends of vertical joints mimic the trends of the transfer faults and of the extensional back fractures. These may commonly be reactivated sets of old, pre-existing structures. In turn, the conjugate systems of joints are most probably new fractures formed only when rock sliding occurred as the geometry and spatial distribution of these fractures is clearly linked to the basal shear plane and the motion on it.

## **3.2 Predictive models and susceptibility maps**

### **3.2.1 Predictive spatial model of rockslide and toppling formation**

The Storfjorden area highly emphasises the active control by the structural-tectonic elements of the bedrock geology on failure block geometry and spatial distribution of failure blocks. With some certainties we are able to build a predictive model of landslide development based on the geological background of the area. The first factor to take into account is the steepness of the slope. A second important one is the attitude of metamorphic foliation relative to the slope. Figure 60 shows a schematic cross-section of the Storfjorden area but such a geometrical style can be applied to anywhere on the west coast of Norway. The foliation is shown as generally shallow-dipping either east or west, forming long-wavelength recumbent folds. Dependent on how the fjord topography intersects this regional foliation geometry, then there are fjord walls where the foliation dips towards the fjord and areas where the foliation dips into the mountainside. In the former case, the greatest instabilities are likely to be along the foliation planes and the development of rockslide geometries is most likely. In the areas where the foliation dips into the fjord walls then a toppling mechanism of failure is likely if pre-existing steep structures facilitate this. This conceptual model is limited to two dimensions and does not consider the possibility of the interlay between structures and topography in 3 dimensions. However, an important conclusion from this model is that, based on the interaction of changing foliation orientation and fjord trend, then there should be specific areas in which rockslides are

more likely and areas in which toppling is more likely. Given the assumption that rockslide geometries are likely to account for the larger failure block volumes relative to toppling events (which is seen from the historic record), then this strongly suggests that the largest failure events are likely to occur in specific areas of the Storfjorden system. This critical finding is discussed in Section 3.2.2.

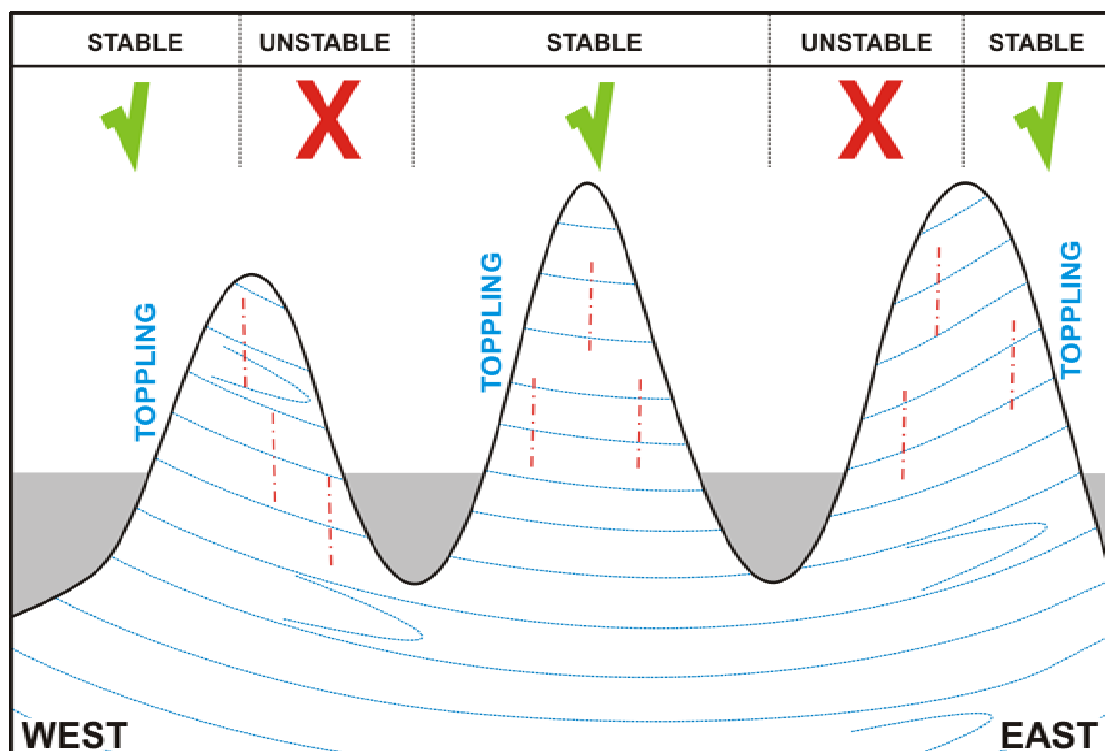


Figure 60: Schematic diagram showing the potential for large rockslide geometries as a result of a combination of attitude of metamorphic foliation (blue) and landscape factors. In the areas that are marked stable, there will also be the possibility of toppling, especially if pre-existing steeply-dipping lineaments are present (red).

### 3.2.2 Maps of susceptibility based on geological structures

Section 3.2.1 has demonstrated that different areas of the Storfjorden fjord system should display different types of failure mechanisms and thereby the largest volumes of potential failure blocks, which are most likely to be as a result of rockslide instabilities, should be more likely in specific areas of the fjord system. Analysis of the regional foliation variation relative to the difference in the trend of the different fjords on a regional scale shows that this is indeed the case. In the simplest case,

Figure 61 shows a map of the Storfjorden area and the areas in which the foliation is dipping towards the fjord between 20-40°. These areas are shown in yellow and the largest areas are located principally on the west side of Sunnylyvsfjorden, intermittently on both sides of Geirangerfjorden and on the north side of Tafjorden. The areas demarcated in red are those where the potential for large landslides with typical rockslide geometries may be possible based on our structural observations. We have qualitatively divided the potential failure blocks up dependent on volume into large and small volumes. Figure 61 clearly shows that there is a good correlation between sites that we have classified as potentially unstable and the relationship between fjord-dipping foliation and fjord trend, particularly where the largest volumes are concerned. Comparison of Figure 61 with the evidence for palaeo-instabilities from the bathymetry data in Figure 3 also shows a surprising correlation between the structural evidence from out field analyses of the location of instable fjord walls and the evidence for past events. Furthermore, it has been demonstrated in Section 3.1.3 that in at least 6 sites that the complex geometry of pre-existing small-fold structures has constrained the movement direction of unstable blocks. We therefore have attempted to further constrain those areas where foliation is fjord dipping by 20-40° with those areas in which small-fold hinges are lunging towards the fjord at a similar angle. The results of this are shown in Figure 62. These geometrical parameters appear to be constrained to the western side of Sunnylyvsfjorden and, with the exception of Tafjorden, contains all of the large potential rockslide failure sites (including Åkneset) we have identified from field analyses. This remarkable correlation suggests that the combination of structural features described in this report are essential to the development of large, potential unstable rockmasses in the Storfjorden fjord system. We therefore demonstrate the fundamental importance of incorporating structural analyses in the spatial and geometric delineation of susceptibility maps for Storfjorden.

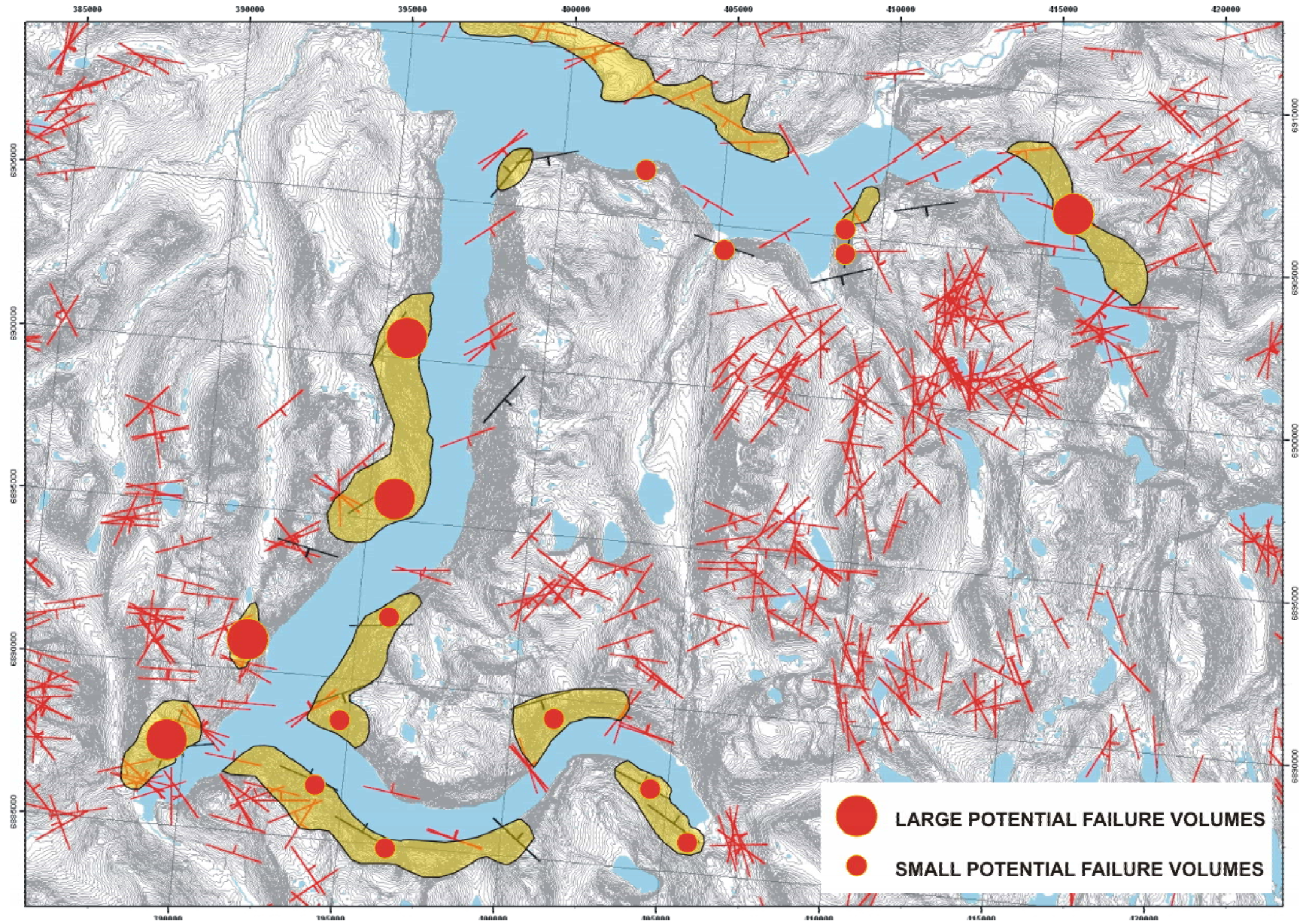


Figure 61: Map of susceptibility based on geological information. Foliation is in red (NGU data) and black (our data) The potential rockslide sites based on orientation of foliation with respect to the fjord orientation are shown in yellow. This prediction method agrees remarkably well with the selected potential hazard sites in Figure 4.



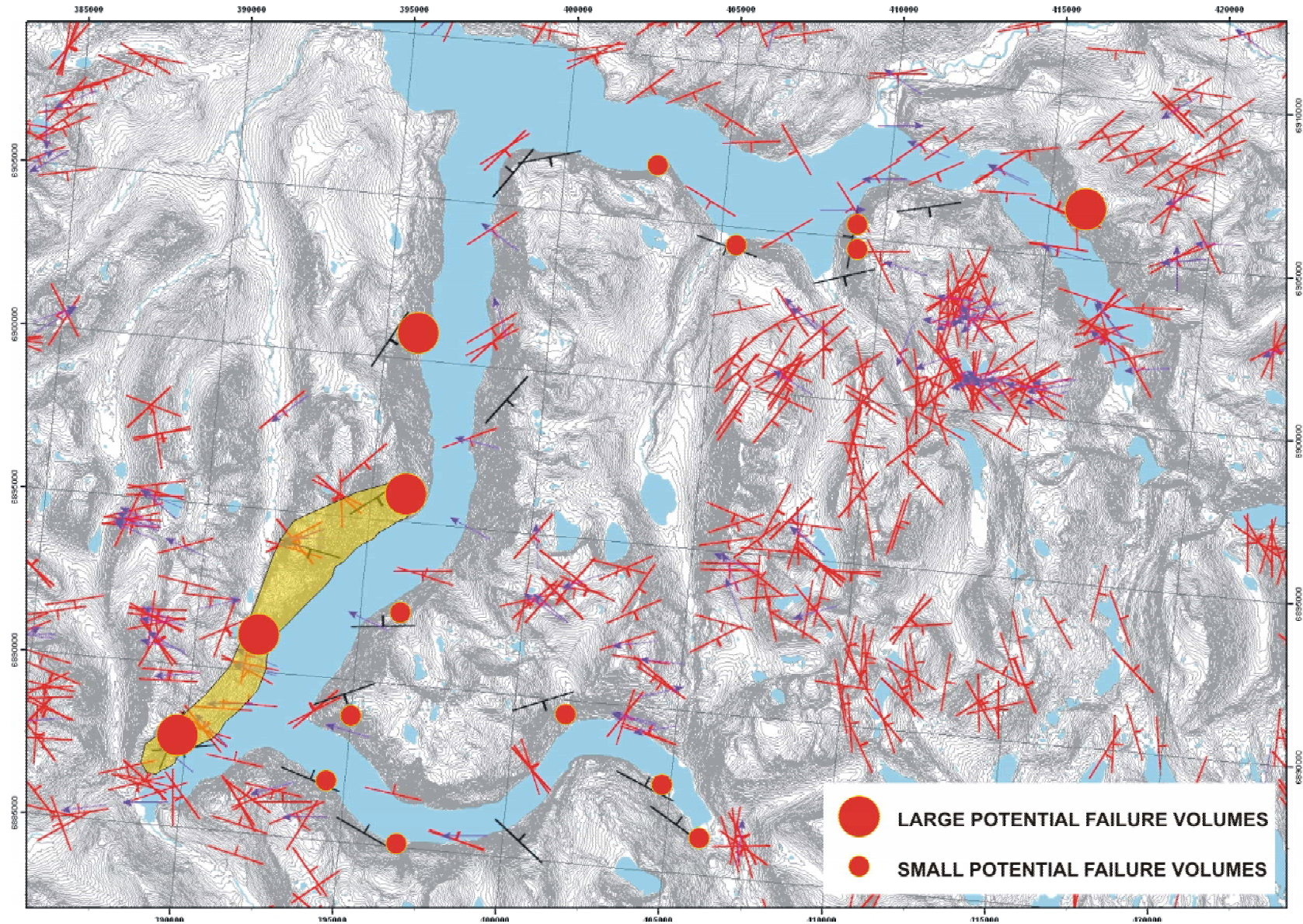


Figure 62: Map of susceptibility based on geological information. This is the same as Figure 61 but also includes small folds and lineation (in purple). The yellow areas show where the lineation-small fold plunges along the fall-line towards the fjord. It is interesting to note that the most impressive back-cracks and the most evidence for active block movement coincides with this western side of Sunnylvsfjorden.

## 4 RECOMMENDATIONS FOR FURTHER WORK

### 4.1 Continuing field analyses

Section 3.2, which presented susceptibility maps based on the spatial variation in unstable slopes based on geometrical features relative to the regional foliation and variation in the fjord trend, defines a basis for further, more detailed regional fieldwork within the Storfjorden area. However, the results of the susceptibility maps presented are not based on all of the sites which were picked out from aerial photo analysis. Furthermore, many of the sites that we have discussed above have only been observed from the helicopter or have not been visited at all during the 2005 field season. Therefore, there remains much fieldwork to be done.

Figure 63 shows the status of the 49 different sites that were initially picked out from the aerial photo analysis prior to the field season in 2005. This shows the sites divided up into three types dependent on their status relative to the 2005 field season. Those shown in red have been visited on the ground and display significantly interesting structures. At many of these sites, several things are required:

- Further detailed structural analysis.
- Re-measurement of GPS points already set out in 2005.
- Setting out of new GPS points in 2006.

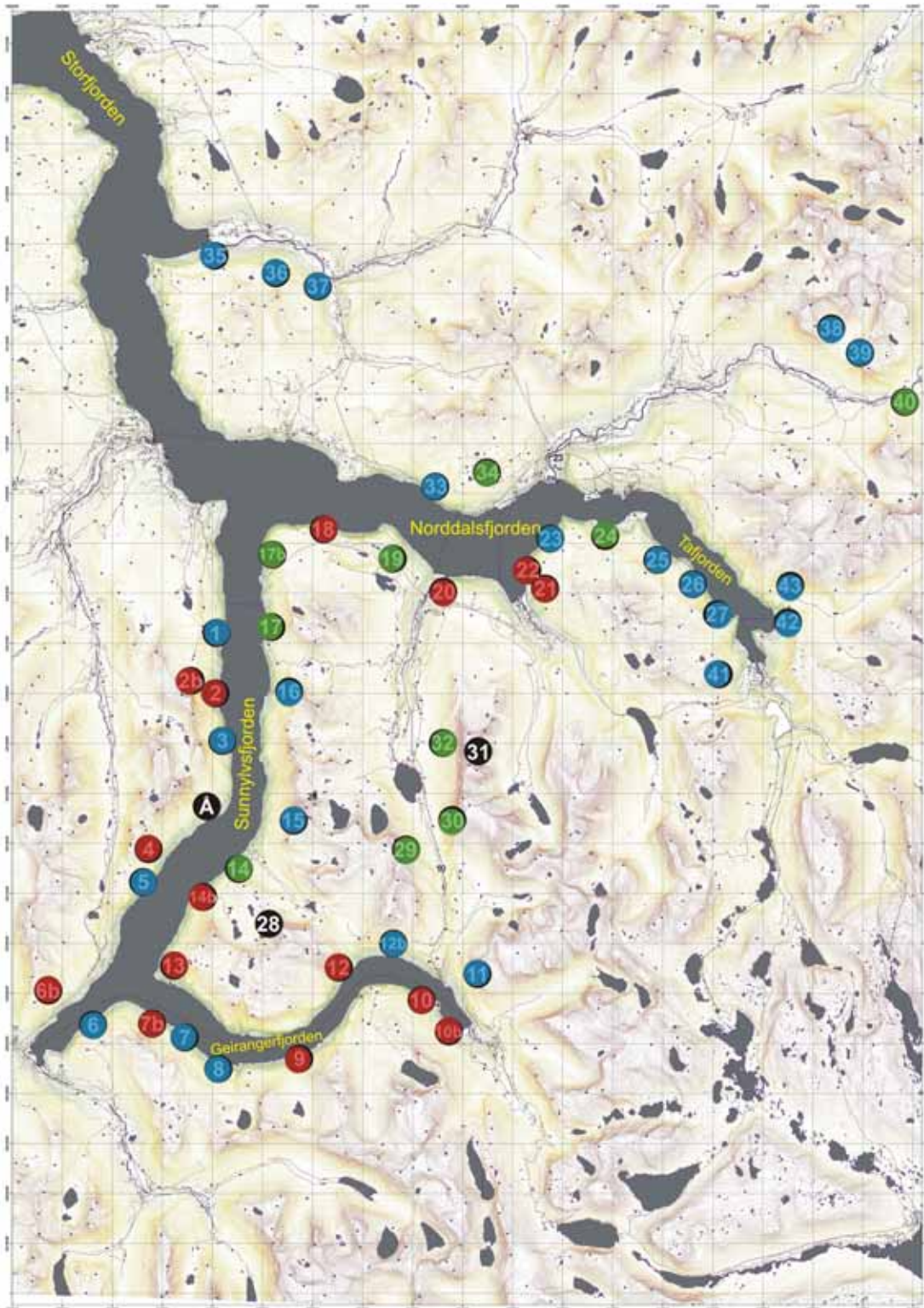
The sites marked in green have been examined, either on the ground or from the air and display no significant structures,

The sites marked blue are those in which no detailed work has been carried out or no helicopter landing was possible to carry out detailed structural analysis. An attempt should be made to visit as many of these sites as possible in the 2006 field season.

Therefore, to summarise, extensive fieldwork is required in the 2006 field season to determine the possibility for instability in many sites that have not yet been examined in detail, GPS measurements need to be carried out on sites to determine if there has



been displacement during the winter 2005/2006 and GPS points need to be set out on new sites.



**Figure 63: Summary of state of study for each sites. In red: field analyses is made and further studies are needed in the summer of 2006. In blue: field analyses should be in summer 2006, in green: the sites have been checked and do not display potential rock failures.**

## **4.2 Volume estimation**

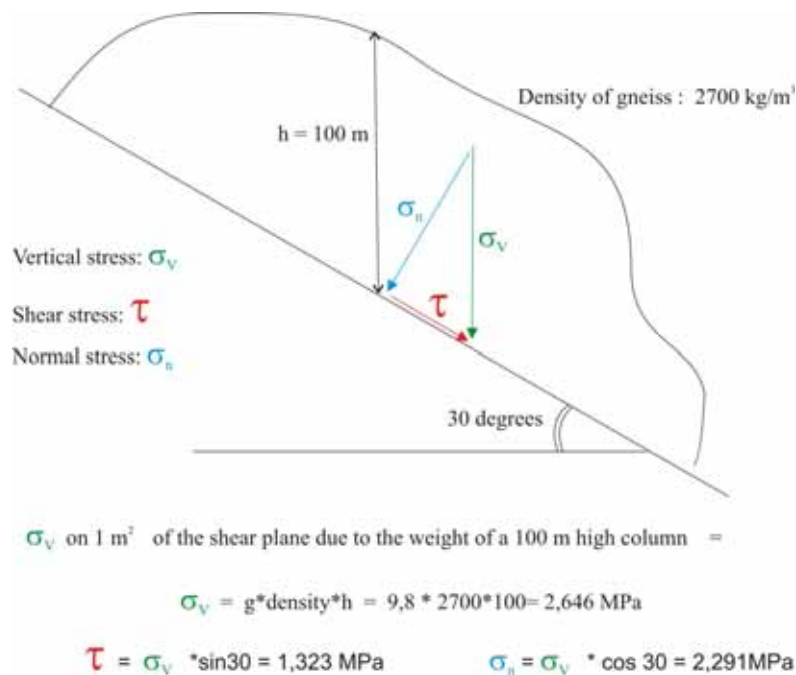
On the sites with clearest evidence for active movements and objects more likely evolved into a larger slide, we have attempted to calculate an approximate volume of the unstable rock. However, these volumes should be taken as tentative until some numerical data becomes available. LIDAR measurements of the whole of the Storfjorden area were carried out in the autumn of 2005. Based on this highly detailed numerical topographic data, we will be able to integrate our structural mapping with the LIDAR data to gain estimations of specific volume of rocks involved in the slides we have observed at all of the sites. With high precision topographic data (from the LIDAR measurements) new topographic DEM models will be available, thereby allowing the determination of the geometry and volume of the unstable blocks.

## **4.3 Quantitative studies**

### **4.3.1 The shear stress on the shear plane: defining the conditions for failure**

#### **4.3.1.1 Basic methodology**

A very simple approach can be used to elucidate the maximum shear stress acting on sliding planes (Figure 64). To do so, the highest column of rock above the unstable sliding block is measured. The angle of the sliding plane from the horizontal is also required (Figure 64). The only acting force on the fault plane is the weight of the unstable rockmass. The downward and upward limits of the unstable block are free surfaces without stresses acting on them. In the cases where the block is confined by closed transfer faults, the confining stresses can have a low but negligible value. The normal stress acts against the sliding of the unstable block and tends to close the sliding plane. In the following sections 4.3.1.2 and 4.3.2, 4.3.3 we highlight the necessity to do some simple calculations at different sites of acting stresses on shear plane and to compare the values with the strengths of the rocks (and of the breccia-gouge or mica-rich layers of the gneiss). This will provide more qualitative information on the likelihood of failure on each specific site.



**Figure 64: Stresses acting on a sliding plane (due to the weight of a column, 1m<sup>2</sup> diameter of rocks on the plane).**

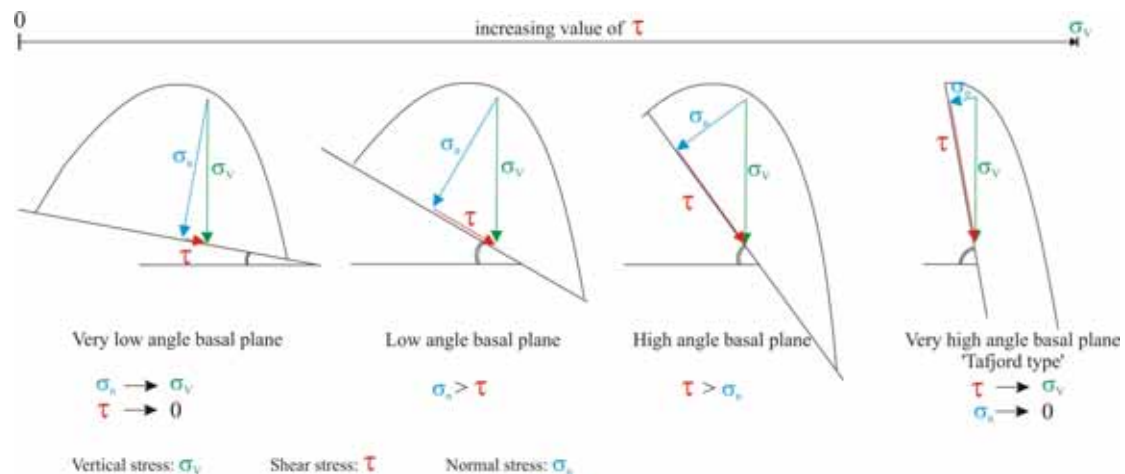
#### 4.3.1.2 The influence of foliation orientation relative to shear stresses: the Tafjord type model

In the hypothetical case where the dip-angle of the shear plane increases, the shear stress acting on the shear plane increases. This value approaches the value of the vertical stress when the shear plane tends towards vertical (Figure 65). Therefore, in a situation where the shear stress is acting on a steeply-dipping foliation surface, the shear stress can be considered as tending towards a maximum value approximating the vertical stress, due solely to the weight of the overlying unstable block. The normal stress is, in turn, reduced to a minimum value. The normal stresses generally acts against gravity and therefore the downhill motion of the unstable block along the sliding plane. The higher the value of shear stress on such a foliation plane, the higher the risk that the shear stress becomes higher than the failure criteria and that a sliding plane will develop. Particularly where the sliding plane is developed in soft micas or a fault-rock gouge which are inherently weak layers, the increase in shear stress subsequent to the increase of foliation dip angle is critical.

As such, the area of Tafjord and Nordallsfjorden is characterised by a foliation steeply dipping towards the fjord at 70 to 85°. The shear stress due to the weight of a column of rock tends to be maximal along such steep surfaces and the frequency of sliding planes development along the foliation (and mostly along the mica-rich layers) is with



certainty higher than in areas where foliation is less steep. In addition, such processes involve substantial volumes of rocks sliding down along a near vertical axis. This therefore makes the Tafjord area particularly vulnerable to landslides and it has already strongly suffered such a frequency of large events in the past.



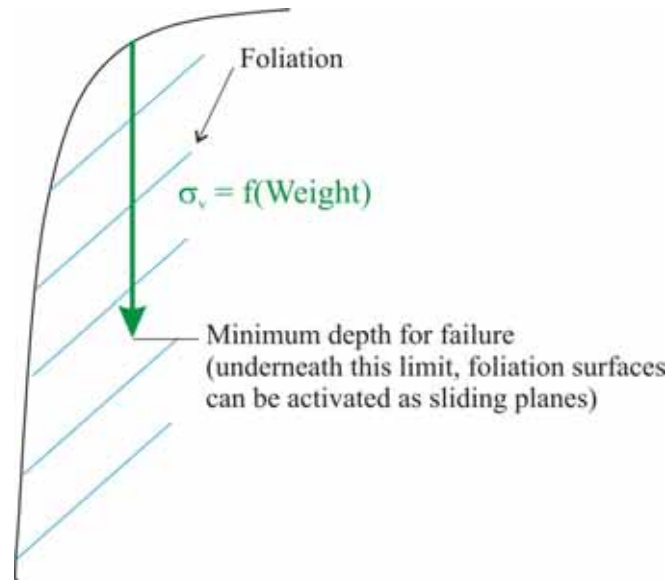
**Figure 65:** The influence of the dip angle of the basal plane on the stresses,  $\sigma_n$  and  $\tau$ , acting on the plane for a vertical stress  $\sigma_v$  fixed ( $\sigma_n$  'closing' the plane, acting against the shearing), 45 degrees of dip angle being the limit over which  $\tau > \sigma_n$ ,

Further work will be possible on this topic when the LIDAR data becomes available and it is possible to determine the volume and geometry of the involved rockmasses. It will then be possible to compute the shear stress at any given point on the sliding plane given an angle of shear plane development and block thickness. This type of study, combined with field data, will therefore contribute significantly towards the understanding of the failure criteria for different landslides with different geometries and unstable block sizes.

#### 4.3.2 Determination of the minimum depth of the sliding plane development

If the cohesion of fault rocks (this can range from coarse breccias to soft mica-rich layers to very fine-grained and extremely weak clay-rich gouges) or of mica-rich layers of foliation is known then it is possible to calculate the minimum depth at which the shear plane will develop in a given rockmass (Figure 66). If the shear stress on the plane, which is deduced from the weight of the column of unstable rock, should exceed the cohesion of the material on that particular plane, then failure will occur. A detailed geotechnical investigation of the spectrum of different fault rocks

produced in the different potential rock-slide sites will allow for such a calculation for each site and therefore allow a determination of how close to the critical value of the failure each geometrical situation produces.



**Figure 66: Estimating the minimum depth of shear plane development with the dip angle of foliation and the vertical stress ( $\sigma_v$ ) acting on such planes ( $\sigma_v$  as function of the weight of the column acting on the foliation planes).**

We also aim to estimating the value of the cohesion on the sliding plane looking at sites where rockslides have already occurred. For example, two parameters are required:

- (1) Further field analyses will document the sliding plane angle ( $\Phi$ ) on sliding planes which have already failed.
- (2) Reconstruction of the geometry of the missing block by correlation with the surrounding slope geometry will obtain the height of the block.

From these parameters we will be able to assess the shear and normal stresses which were acting of the plane that led up to failure and solving the Coulomb equation (as a simple approach and written as  $\tau = \text{cohesion} + \sigma_n \tan\Phi$ ) will determine the value of cohesion. Such studies, in which we approximate the conditions for shear failure of palaeo-slides will lead to a better understanding of the failure criteria for those unstable blocks which are yet to reach failure criteria.

### **4.3.3 Shear strength determination of fault rocks in the laboratory**

On all of the sites with a rockslide geometry where there is clear evidence for recent movement, a fault-rock breccia or gouge is developed. This is a non-cohesive fault rock which consists of the fractured and crushed remnants of the wall-rock to the shear plane (see Figure 14). Recent studies by NGU in conjunction with the ICG project has demonstrated that there is a complex spectrum of fault-rock products formed during the crushing down due to movement on the shear plane, despite the fact that the initial wall-rock starting material is very homogenous. This suggests a different response of the sheared products during movement dependent on the shearing angle, the amount of unstable rock weighing down the shear plane and on the amount of time the shear plane has suffered movement. This work also shows that the shear strength of the sliding plane and therefore the stability of the rockslide block is a function of the grain size of the fault-rock material. The smaller the grain size and the more elongated the grains, then the lower the cohesion of the fault-rock material and therefore the more likelihood that the rockslide block will be unstable. This work on the fault-rock, as part of the ICG project is ongoing and will most certainly impact on the studies of the fault rocks and the inferences about the stability of different sites in this regional study.

A final step relating the fault rocks to the rockslope stability is a comparison of the maximum values of stresses acting on the plane (see section above) with the value of the shear strength of the fault rocks on the sliding plane. If the stresses acting on the plane are much higher than the shear strength of the fault rocks then it may be possible to predict the stability of the rockslides blocks at different sites and therefore make a large contribution to the understanding of the rockslope stability in the Storfjorden area.

## 5 CONCLUSIONS

- Pre-fieldwork analysis of aerial photos allowed the identification of 49 different sites in the Storfjorden area which required field investigation. This was based on the presence of pronounced lineaments, obvious detached block or the presence of active talus slopes.
- From the 49 sites identified, extensive fieldwork determined that 35 of these may have evidence for recent movement.
- Analysis of the structural data shows that at sites in which several geometrical and mechanical parameters are met, active block movement is likely. These parameters are
  1. Foliation dipping towards the fjord at between 20-35°.
  2. The development of a sliding plane (Basal Shear Plane) along the foliation, aided by the previous development of exfoliation planes.
  3. The development of a non-cohesive breccia along the Basal Shear Plane
  4. The development of an extensional fracture at the back of the potentially sliding block ('back-crack') to detach it from the mountainside.
- If these criteria above are achieved, there is always strong evidence for active movement of the sliding block. This evidence includes: i) the development of extensional fractures disintegrating the sliding block; these fractures detach onto the Basal Shear Plane; ii) depressions in the topography and/or changes in vegetation which suggest movement; iii) the opening up of fractures between sliding blocks and recent features such as talus slopes suggests recent movement.
- Comparison of the regional foliation in Storfjorden with the orientation of the different fjord systems shows that the areas that we have determined as the most vulnerable to active movement are those areas in which the foliation is

favourably oriented for down-dip gravitational movement towards the fjord. Therefore, in fjords with an orientation where the foliation is dipping towards the fjord, the development of rock-slides is more likely. However, in areas where the foliation is dipping into the mountainside and other parameters are favourable for the disintegration of the mountainside, then a toppling mechanism of movement is more possible. We predict that in different parts of the Storfjorden fjord system then rock-sliding of toppling will be more likely as a failure mechanism. These susceptibility maps, based on geometrical and topographical interaction, are a fundamental basis for further hazard analysis.

- Figure 63 summarises the state of the study made at each sites. Among the sites studied in 2005, 15 (in red on Figure 63) should be visited again in 2006 to collect more data and improve the knowledge of structures involved in the rockslides and to collect new GPS measurements to determine the magnitude and direction of displacement.
- Our study demonstrates that it is possible, through the analysis of field structural data to determine the evidence for movement activity in active fjord systems, to determine the likely areas of landslide activity and the different failure mechanisms that may be possible in different areas and thereby help to provide a better foundation for hazard analysis.

## **6 Acknowledgments**

We wish to thank Prof. Alvar Braathen (University of Bergen) and Lars Harald Blikra (NGU) for reviews of the report and Stranda Kommune that made the field studies possible.



## 7 Appendix 1: Selected Targets

| PRIORITY | SITE No. | AIR PHOTO | E UTM  | N UTM   | LOCATION  | DESCRIPTION  |
|----------|----------|-----------|--------|---------|---|--|
| X        | 1        | M51 / L50 | 396000 | 6902000 | WEST SIDE OF SUNNYLVSFJORDEN                                    | NNE-SSW MINOR FRACTURES. NOT MUCH DISPLACEMENT.  |
| X        | 2        | N47       | 396000 | 6900000 | WEST SIDE OF SUNNYLVSFJORDEN                                    | N-S OPEN FRACTURES WITH WSW-ESE TRANSFORM FAULTS   |
| X        | 3        | N47       | 396500 | 6898000 | WEST SIDE OF SUNNYLVSFJORDEN                                    | N-S OPEN FRACTURES WITH WSW-ESE TRANSFORM FAULTS   |
|          | 4        | P44       | 394000 | 6893700 | WEST SIDE OF SUNNYLVSFJORDEN. SOUTH OF AKNES                    | N-S OPEN FRACTURES. SOME DISPLACES SMALL BLOCKS VISIBLE.                                     |
|          | 5        | P15       | 393500 | 6893000 | WEST SIDE OF SUNNYLVSFJORDEN. SOUTH OF AKNES                    | SOME MINOR NW-SE TRANSFER STRUCTURES AND N-S OPEN FRACTURES.                                 |
|          | 6        | S12       | 391000 | 6887000 | EAST SIDE OF SUNNYLVSFJORDEN. AT END OF FJORDEN                 | N-S TRANSFERS AND NE-SW DETACHMENTS.   |
|          | 7        | S15       | 395000 | 6886000 | SOUTH SIDE OF GEIRANGERFJORDEN.                                 | WNW-ESE OPEN FRACTURES.  |
| X        | 8        | S17       | 396500 | 6885000 | SOUTH SIDE OF GEIRANGERFJORDEN.                                 | E-W OPEN FRACTURES CONTROLLED BY VERY PRONOUNCED N-S TRANSFER FAULTS.                        |
|          | 9        | S20       | 399000 | 6885000 | SOUTH SIDE OF GEIRANGERFJORDEN.                                 | E-W DISCONTINUOUS STRUCTURE E & W OF N-S RIVER.  |
| X        | 10       | Q26       | 404500 | 6888000 | EAST END OF GEIRANGERFJORDEN                                    | E-W 'BOWL' WITH NE-SW TRANSFER STRUCTURE AT EAST END. LOOK AT EN-ECHELON STRUCTURES 1KM WEST |
| X        | 11       | Q28       | 406500 | 6889000 | EAST END OF GEIRANGERFJORDEN                                    | N-S STRUCTURES. APPEARS TO BE A BIG BLOCK DETACHMENT.  |
|          | 12       | Q22       | 401000 | 6889000 | NORTH SIDE OF GEIRANGERFJORDEN                                  | SOME INCIPIENT NE-SW FRACTURES OVER 2KM.   |
|          | 13       | Q17       | 394500 | 6889000 | NORTH SIDE OF GEIRANGERFJORDEN AT JUNCTION WITH SUNNYLVSFJORDEN | SOME WSW-ENE STRUCTURES. POOR AIR PHOTO COVERAGE.  |
| X        | 14       | O10       | 397000 | 6893000 | EAST SIDE OF SUNNYLVSFJORDEN                                    | N-S FRACTURE (BACK-FAULT) CUTTING NNE-SSW FRACTURES IN HANGINGWALL                           |
| X        | 15       | O9        | 399000 | 6894500 | EAST SIDE OF SUNNYLVSFJORDEN                                    | N-S FRACTURES. 3 DISPLACED BLOCKS.   |
| X        | 16       | N49       | 399000 | 6900000 | EAST SIDE OF SUNNYLVSFJORDEN                                    | LARGE TRIANGULAR DETACHMENT  |
|          | 17       | L50       | 398500 | 6902000 | EAST SIDE OF SUNNYLVSFJORDEN                                    | VERY MINOR N-S FRACTURES.  |
| X        | 18       | J4        | 400500 | 6907000 | SOUTH SIDE OF STORFJORDEN.                                      | BIG E-W STRUCTURE TERMINATED BY N-S TRANSFER FAULTS.   |

| PRIORITY | SITE No. | AIR PHOTO | E UTM  | N UTM   | LOCATION   | DESCRIPTION  |
|----------|----------|-----------|--------|---------|--|--|
| X        | 19       | J6        | 403500 | 6905500 | SOUTH SIDE OF STORFJORDEN.                                     | BIG E-W STRUCTURE TERMINATED BY N-S TRANSFER FAULTS.                       |
|          | 20       | J8        | 405000 | 6904000 | SOUTH SIDE OF STORFJORDEN.                                     | E-W STRUCTURES & NNW TRANSFER FAULT.                                       |
| X        | 21       | J12       | 409000 | 6904000 | SOUTH SIDE OF STORFJORDEN.                                     | NNE-SSW MAJOR STRUCTURES.  |
|          | 22       | J12       | 408500 | 6904500 | SOUTH SIDE OF STORFJORDEN.                                     | TWO SETS OF FRACTURES: N-S & NNE-SSW. NO MAJOR DISPLACEMENT.               |
| X        | 23       | J12       | 409500 | 6906000 | SOUTH SIDE OF STORFJORDEN.                                     | N-S STRUCTURES. APPEARS TO BE MAJOR DETACHMENT.                            |
|          | 24       | J14       | 411500 | 6906000 | SOUTH SIDE OF TAFJORDEN  | E-W STRUCTURES WITH N-S TRANSFER FAULT.                                    |
| X        | 25       | J16       | 413500 | 6905000 | SOUTH SIDE OF TAFJORDEN  | LOOKS LIKE MAJOR E-W COLLAPSE WITH N-S TRANSFER FAULTS.                    |
|          | 26       | J17       | 415000 | 6904500 | SOUTH SIDE OF TAFJORDEN  | MINOR ENE-WSW FRACTURES.   |
|          | 27       | J17?      | 416000 | 6903500 | SOUTH SIDE OF TAFJORDEN  | E-W FRACTURES IN THE CLIFF-FACE ?  |
| X        | 28       | P17       | 398500 | 6891000 | RIDGE BETWEEN SUNNYLVSFJORDEN & GEIRANGERFJORDEN (GEITFJELLET) | E-W DETACHMENT WITH LARGE BLOCKS IN BASE OF E-W VALLEY.                    |
|          | 29       | O14       | 404000 | 6894000 | EIDSHORNET   | MINOR NW-SE FRACTURES AND SOME DETACHED BLOCKS IN SITU WITH E-W TRANSFERS. |
|          | 30       | O16       | 405500 | 6894500 | EAST SIDE OF EIDSDALEN   | NNE-SSW FRACTURES WITH MANY LOOSE BLOCKS IN BASE OF N-S VALLEY.            |
| X        | 31       | N6        | 407000 | 6896500 | EAST SIDE OF EIDSDALEN   | NW-SE FRACTURES DOWNTHROWING TO WEST.                                      |
|          | 32       | N5        | 405000 | 6896000 | EAST SIDE OF EIDSDALEN   | ###  |
|          | 33       | H3        | 405000 | 6908000 | NORTH SIDE OF STORFJORDEN                                      | NNE-SSW MINOR STRUCTURE.   |
|          | 34       | H5        | 407000 | 6909000 | NORTH SIDE OF STORFJORDEN                                      | SOME SMALL DEBRIS FANS WITH MINOR SW-NE STRUCTURES.                        |
|          | 35       | E4        | 396000 | 6917000 | STORDALEN  | E-W FRACTURES. MAYBE SOME MINOR DISPLACEMENT.                              |
|          | 36       | E5        | 399000 | 6917000 | STORDALEN  | E-W FRACTURES.. APPEARS TO BE NE-SW EN-ECHELON FRACTURES IN HW TO NORTH.   |
|          | 37       | E6        | 400500 | 6916000 | STORDALEN  | ONE E-W FRACTURE. SMALL DISPLACEMENT.                                      |
|          | 38       | F11       | 421000 | 6914500 | VALLEDALEN: ALSTADFJELLET                                      |  |
| X        | 39       | F14       | 422000 | 6914000 | VALLEDALEN: ALSTADFJELLET                                      | N-S MAJOR FRACTURES. DOWN-SLIP DISPLACEMENT TOWARDS WEST.                  |
| X        | 40       | G17       | 423000 | 6911500 | VALLEDALEN: GRØNNING   | TRIANGULAR LOOSE BLOCK WITH LARGE OPEN FRACTURE.                           |
|          | 41       | L14       | 416500 | 6901000 | EAST END OF TAFJORD  | NE-SW FRACTURES.   |
|          | 42       | K20       | 419000 | 6903000 | EAST END OF TAFJORD  | TWO SMALL FRACTURES.   |
|          | 43       | J21       | 419000 | 6904000 | EAST END OF TAFJORD  |  |

Table 1: Targets selected in the Storfjorden area based on Aerial photo examination.