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UNDERSTANDING LONG-TERM SLOPE DEFORMATION FOR STABILITY ASSESSMENT OF ROCK SLOPES: THE CASE OF THE OPPSTADHORNET ROCKSLIDE, NORWAY

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ABSTRACT

The Oppstadhornet rockslide is a 10 Mm^3 slide that occurs on the island of Otrøya in westernmost Norway. Terrestrial cosmogenic nuclide dating indicates that the Oppstadhornet rockslide became active ca. 16.6-14.2 kyrs ago when the retreat of the Scandinavian ice sheet exposed the island from the continental ice cover. Sliding along the main sliding surface was active during the late Pleistocene and Holocene. Our data suggest that the paleo-slip rate in the Late Pleistocene was slightly faster than in the Holocene however large uncertainty margins ask for care with this interpretation. Present day displacement rates of ca. 2 mm/year measured with differential Global Navigation Satellite Systems are similar to the paleo-slip rates, however they vary over the entire rockslide body and at several locations after 10 years we could not yet measure any significant displacement. The long-term activity of this rockslide suggests that - in contrast to dynamic stability models - moderate earthquake shaking with a recurrence time of 475 years will not cause the Oppstadhornet rock slope to fail.

Key words: *long-term behavior of rockslides, terrestrial cosmogenic nuclide dating, differential Global Navigation Satellite System, paleo-slip rate, displacement rate, seismic triggering*

INTRODUCTION

On the globe only a small number of natural slopes have collapsed under monitored conditions (e.g. Voight, 1988, Agostini *et alii*, 1991; Crosta & Agliardi, 2003 and references therein). However, historical data on 32 failures from Norway, the European Alps, and other places indicate that rock slope deformation takes place for at least several years to decades and accelerates prior to failure (Hermanns *et alii,* 2012a and references therein). This is especially true under non-seismic conditions. Under seismic conditions the acceleration phase is in general only a few seconds long (Hermanns & Longva, 2012). Long-term slip behavior of rockslides in Norway is not understood due to the lack of long-term monitoring data (monitoring of rock slopes has been carried out in Norway on 58 sites for up to max. 10 years only (Hermanns *et alii*, 2013).

The goal of this project was to determine long-term slip rates of the Oppstadhornet rockslide in order to be able to recognize acceleration of movement prior to failure in future. The Oppstadhornet rockslide on the island of Otrøya in western Norway involves an estimated 10 million cubic meters of schistose gneiss that has slid towards the fjord as indicated by a 20-m-high sliding surface exposed on the head scarp of the slide (Derron *et alii*, 2005). This is one of 140 unstable rock slopes in Møre og Romsdal county that are known after several years of systematic mapping by the Geological Survey of Norway and the County geologist of Møre og Romsdal (Fig. 1, Oppikofer *et alii*, 2013). Failures of such unstable rock slopes have caused considerable damage and high numbers of death in the Møre and Romsdal County in historic times. Two catastrophic rock slope failures in Møre og Romsdal County are among the 10 events with highest death toll in Norway: the Tafjord rockslide in 1934 that caused a displacement wave resulting in the death of 40 persons and the Tjelle rockslide in 1756 that also set off a displacement wave drowning 32 persons in the inner part of the Langfjord (Hermanns *et alii*, 2012b).

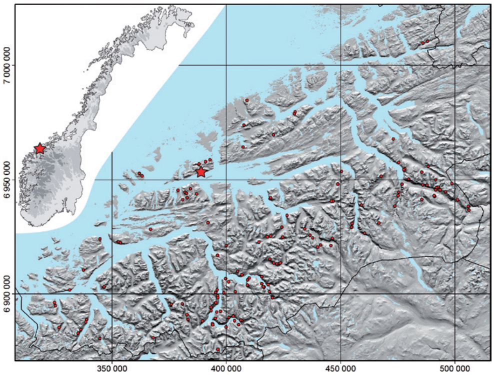

Fig. 1 - Unstable rock slopes characterized so far in the Møre og Romsdal County and location of the Oppstadhornet rockslide (star)

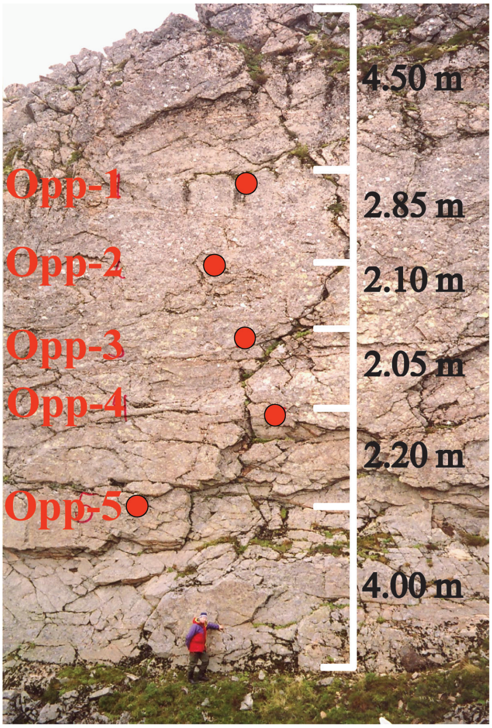

Fig. 2 - Back scarp with sample locations and sample numbers (person for scale is 1.8 m tall)

We followed the approach of Bigot-Cormier *et alii* (2005) also described in Hermanns *et alii* (2012c) and sampled the main sliding surface of the rockslide for terrestrial cosmogenic nuclide dating (TCN). We took five samples along the sliding surfaces so that we can calculate slip rates based upon their exposure history.

METHOD

SAMPLE COLLECTION AND SAMPLE TREATMENT

On the sliding surface five samples 1 to 5 cm thick were taken with a chisel from quartzo-feldspatic gneisses on rappel. The position of each sample site was measured with a handheld GPS, an altimeter with 1 m precision and the length relative to the top of the sliding plane determined using a measuring tape. At each sample location the dip angle of the sliding plane as well as the average dip angle above the sample location was measured. The horizontal shielding was measured at each sample location taking the average of 30 degree steps. Quartz-samples were sent to ETH Zurich for quartz purification and production of nuclide targets. ^{10}Be nuclides were measured at ETH Zurich.

AGE CALCULATION

Age calculations were carried out following the principles outlined in Gosse & Phillips (2001), however for calculating shielding of the cosmic ray flux due to the cliff exposure principles outlined in Dunne *et alii* (1999) were applied. No correction for snow cover was calculated as the sliding plane dips everywhere steeper than 60° and no significant snow accumulation can be assumed.

Ages were calculated using the CRONUS Calculator (Balco *et alii,* 2008) and are reported here as mean ages and 1 sigma uncertainties of the spread of outcomes given by the calculator (Tab. 2). We are well aware that locally determined production rates in southern and northern Norway exist (Fenton *et alii,* 2011; Goehring *et alii*, 2011). Using the production rates presented by Fenton *et alii* (2011) & Goehring *et alii* (2011) the ages reported here would be approx. 10% or 5% older, respectively.

We did not calculated the inherited age (pre-sliding-exposure) of the samples, which results from the penetration of the cosmogenic radiation into the rock mass. This is restricted due to the exponential attenuation of the radiation by rock matter to the uppermost meters. Our uppermost sample was taken 4.5 m below the top of the sliding plane. Therefore with the assumption taken here that the surfaces were eroded by glacial erosion during the last glacial maximum and covered by ice until deglaciation no inheritance is expected. The assumption is most likely correct as the sample site lies at 750 m altitude that in this part of western Norway was covered by ice sheets for several thousand years (Vorren & Mangerud, 2008). The inherited age is anyhow insignificant in comparison with the real age and statistical error margins of this method (Tab. 1).

DIFFERENTIAL GLOBAL NAVIGATION SATELLITE SYSTEM MEASUREMENTS

Differential Global Navigation Satellite System (GNSS) surveys have been undertaken with one to three years interval since the establishment of the first survey points in 2003. A total of three fixed points were installed in stable areas and 19 rover points in potentially unstable regions (Fig. 3).

The accuracy of the coordinates are estimated for each GNSS-point and are generally ca. 1 mm in planimetry and ca. 2 mm in elevation. These values are found to be too optimistic and a factor of 3 is thus used to obtain realistic accuracies. Thus, the error on the total horizontal, vertical and 3D displacement, $\sigma_{tot.H}$,

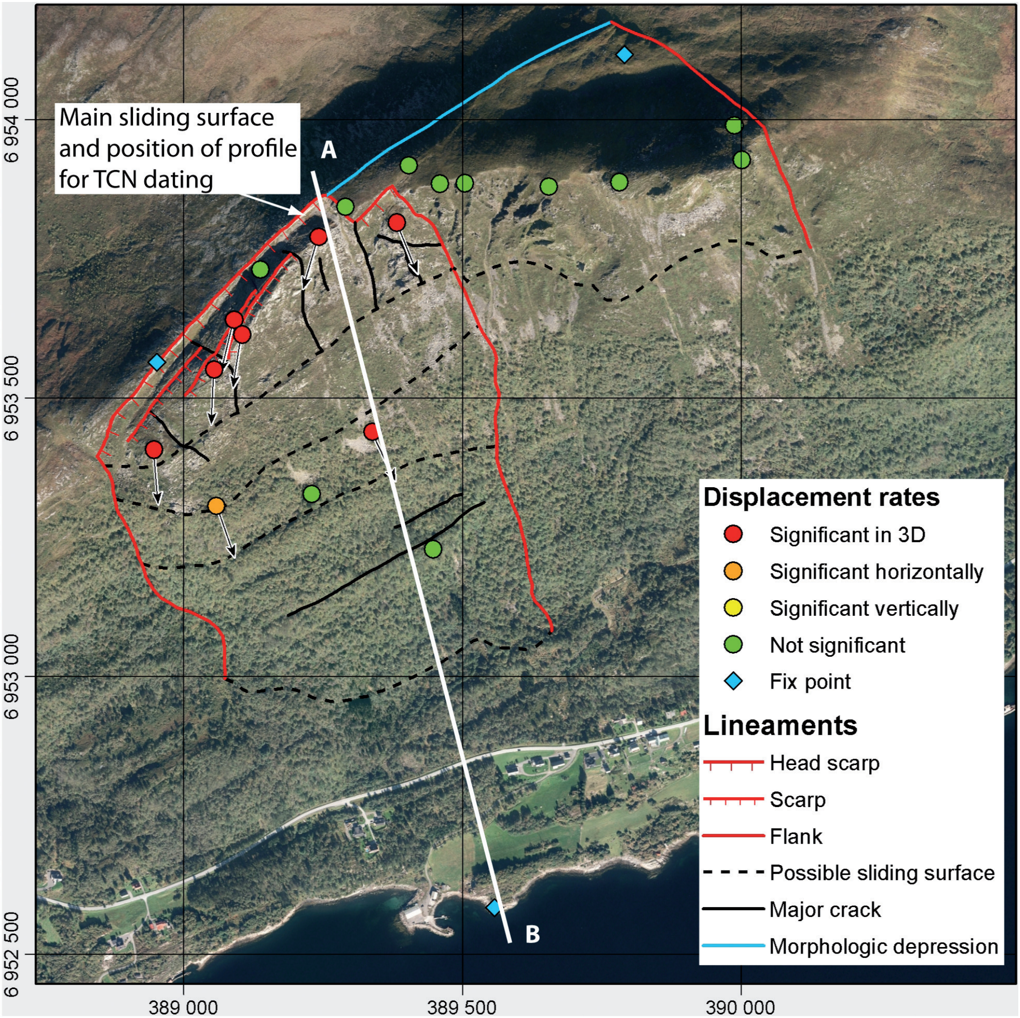

Fig. 3 - Aerial photograph of the unstable rock slope at Oppstadhornet with main structural features of the slide and location profile for TCN dating as well as of dGNSS stations classified after significance level. The profile A-B is shown in Fig. 4

$\sigma_{tot.V}$ and $\sigma_{tot.3D}$, respectively, is given (OPPIKOFER *et alii*, 2013):

$$\sigma_{tot.H} = 3 \cdot \sqrt{\bar{\sigma}_X^{\,2} + \bar{\sigma}_Y^{\,2}}$$
$$\sigma_{tot.V} = 3 \cdot \bar{\sigma}_Z$$
$$\sigma_{tot.3D} = 3 \cdot \sqrt{\bar{\sigma}_X^{\,2} + \bar{\sigma}_Y^{\,2} + \bar{\sigma}_Z^{\,2}}$$

where σ_X, σ_Y and σ_Z are the averages of the accuracies estimated by the processing software for the entire time-series and a given point.

Robust linear regressions over the entire time series were used to calculate average yearly displacement rates, *v*, as described in BÖHME *et alii* (2012).

If *v* exceeds the errors on the displacement, σ_{tot}, divided by the time interval between the first and last measurement, Δt (in years), then the displacements are considered as statistically significant from a methodological point of view (OPPIKOFER *et alii,* 2013):

$$v > \frac{\sqrt{2} \cdot \sigma_{tot}}{\Delta t}$$

This equation is used for horizontal, vertical or 3D displacement rates using the matching σ_{tot}. Further, all GNSS points were checked for the coherency of the displacement trends as described in BÖHME *et alii* (2012). Only GNSS-points with statistically significant displacements and coherent trends are considered as significant in this report. The displacement trend (horizontal direction) and plunge (vertical angle) were computed for every GNSS-point with significant horizontal and/or vertical displacement based on the regression results.

THE OPPSTADHORNET ROCKSLIDE

The Oppstadhornet rockslide was mapped out in the field and it has an up to 20-m-high back scarp that stretches slope parallel for 1 km. It can be divided in a more active SW part characterized by internal deformation (BRAATHEN *et alii*, 2004) and a rather inactive NE part that is characterized by a depression that connects to the main sliding surface of the SW part but that has no significant displacement in the past 10 years and does not show any internal deformation (Fig. 3). The rockslide in the SW part stretches from a near shore level up to the peak of Oppstadhornet. The estimated volume of the unstable rock slope is in the range of 10 Mm^3 (BRAATHEN *et alii*, 2004; BHASIN & KAYNIA, 2004; DERRON *et alii,* 2005).

It is characterized by crevasses and clefts reflecting block movements in various quartzo-feldspatic gneisses, some mica-rich and schistose (ROBINSON *et alii*, 1997; BLIKRA *et alii*, 2001). The field is bounded by three main structures; an upward bounding main sliding surface and two marginal flanks to the southwest and northeast.

The main sliding surface is clearly displayed as an escarpment, up to 20 m high, forming a half-graben. This surface is superimposed on the steeply SE-dipping foliation as well as a narrow zone of cataclasite and carbonate cemented fault breccia (BRAATHEN *et alii,* 2004). The southwestern marginal flank strikes NW-SE and dips steeply NE. It is seen as a fracture zone, which reactivates an older fault. This structure is a transfer fault marked by down-oblique sliding. In the east, the termination of rockslide is seen as a NNW-SSE striking and steeply SW dipping fracture zone, which acted (or acts) as a transfer structure.

Internally, the rockslide is segmented into large blocks by two sets of steep fractures (mainly faults), which strike NW-SE and NE-SW. The NE-SW set is sub-parallel to the main sliding surface and the foliation in the rocks (Fig. 4). While no breakup of the two lower blocks could be observed the uppermost block is breaking apart along scarp-parallel cracks (Fig. 3). Mapping indicates that the sliding surface of all three blocks daylight on the slope above sea level (BRAATHEN *et alii*, 2004) (Fig. 4).

Sliding in the central and the NE upper part of the instability is towards the SE and therefore parallel to the schistosity (Figs. 5, 6c). In the central part displacement is slower in the SW with velocities of ~2 mm/yr and faster in the NE with velocities of ~4.3 mm/yr (Fig. 5). In the NW part sliding is towards the

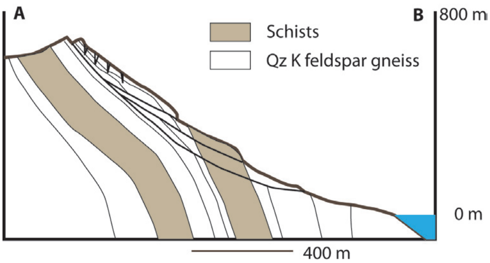

Fig. 4 - Geological model of the Oppstadhornet rockslide (after BRAATHEN et alii, 2004)

south and therefore oblique with respect to the schistosity (Figs. 5, 6a). Displacement rates are uniform between 2.1 and 2.7 mm/yr (Fig. 5). In the lower part the schistosity steepens to nearly vertical and the sliding surfaces cross cut the schistosity, however no significant movement can be observed (Fig. 5).

Based upon this geological model static and dynamic slope stability models were calculated (Bhasin & Amir, 2004). The seismic acceleration with a return period of 475 years was taken as input data into the dynamic model that was taken from the seismic zonation map of Norway (Norsar & Ngi, 1998). The static stability model indicated that the slope is stable under aseismic conditions while the dynamic model suggested failure of the uppermost block under seismic conditions (Bhasin & Amir, 2004).

RESULTS

RESULTS OF ^{10}BE DATING

Unfortunately from the five samples taken only three could be finally analyzed. This is due to the mineral composition of the sampled rock. Also all samples had visible a high enough quartz content most samples had also a very high K-feldspar content and the K-feldspar minerals were much larger than the quartz minerals. After dissolution of K-feldspar un-

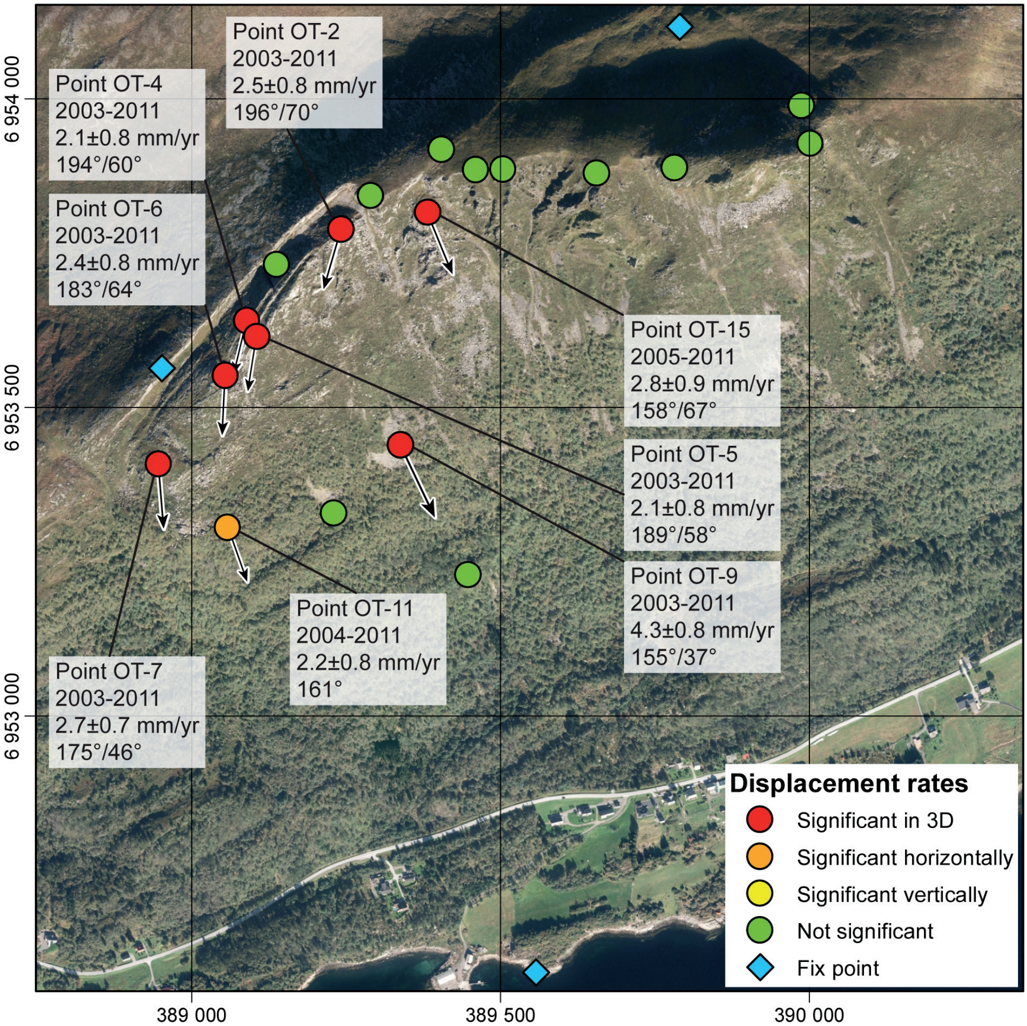

Fig. 5 - Mean displacement vectors and rates after 8 years of dGNSS observations. Examples of GNSS time-series for points OT-5 and OT-11 are shown in Fig. 6

Sample	Length along sliding plane [mm]	Age [kyr]	1σ [kyr]
Opp-1	4500	12.5	1.7
Opp-2	7350	-	-
Opp-3	9450	-	-
Opp-4	11500	10.3	3.2
Opp-5	13700	6.6	0.7
Base of sliding surface	17700	0	

Tab. 1 - Overview of sample locations along the sliding surface (see Fig. 2) including ^{10}Be ages and one sigma uncertainties

Sample numbers	Slip rate [mm/yr]	Uncertainty [mm/]
Opp1 – Opp4	3.2	2.2
Opp1 – Opp5	1.6	0.4
Opp1 – base	1.1	0.1
Opp 4 – Opp5	0.6	0.6
Opp 4 – base	0.6	0.2
Opp 5 - base	0.6	0.1

Tab. 2 Paleo-slip rates calculated based on TCN exposure ages and uncertainties

der HF treatment only three samples had therefore a quartz quantity that was high enough for dating. The calculated ages are consistent with sample position as ages decrease from top to bottom (Tab. 1).

The upper samples at sliding surfaces has an age of ~12.5 kyrs, while the age of the lower samples are 10.3 and 6.6 kyrs, respectively. The lower sample positions lie approx. 4 m above ground, hence sliding continued. As dGNSS data indicate that this block continues moving we set the age for the lowermost part of the sliding surface as 0 (just exposed).

PALEO-SLIP RATES RESULTING FROM ^{10}BE AGES

Based upon the ^{10}Be ages obtained, we calculated the paleo-slip rate between the position of the various samples, as well as today's base for surface parallel sliding in orientation of the sliding surface. In addition, we calculated an uncertainty interval that is based upon the uncertainty of the ages. The results indicate that the Oppstadhornet rockslide had a displacement rate of 3.2±2.2 mm/yr between Opp-1 and Opp-4, 1.5±0.4 mm/yr between Opp-1 and Opp-5, and 1.1±0.1 mm/yr between Opp-1 and the base of the sliding surface. These data thus suggest a deceleration of displacement (Tab. 2). This is also suggested when calculating the slip rate between the lower sample locations and the base of the sliding surface (0.6 mm/yr) (Tab. 2).

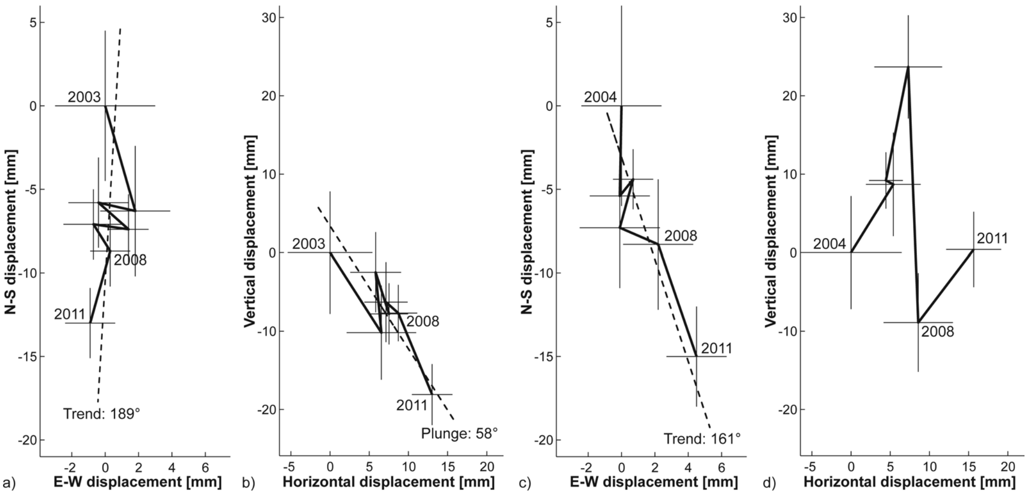

Fig. 6 - Graphs of the GNSS time series for: a) horizontal displacements of point OT-5; b) vertical vs. horizontal displacements of point OT-5; c) horizontal displacements of point OT-11; d) vertical vs. horizontal displacements of point OT-11. Uncertainties on the measured coordinates are shown as error bars. Regression lines are shown as stippled lines for points with significant and coherent displacements. OT-5 for example has significant 3D displacements (horizontal and vertical), while OT-11 has only significant horizontal movement

ESTIMATION OF THE START OF SLIDING BASED ON ^{10}BE AGES AND CALCULATED SLIP RATES

The start of sliding can be estimated by adding the quotient of the length of sliding above the first sample to the age of that sample (Hermanns *et alii*, 2012c). If we take into account the slip rate between Opp-1 and Opp-4 we obtain an age of start of sliding of 14.2 kyr. Using the slip rate between Opp1 and the base of the sliding surface results in an age of 16.6 kyr.

DISCUSSION

POTENTIAL OF THE METHOD

Today there exist multiple tools picturing the deformation within and measuring the displacement velocity of rockslides including ground-based and satellite-based remote sensing techniques and geophysical tools describing deformation of rock mass at depth (e.g., Ganerød *et alii*, 2008; Lauknes *et alii,* 2010, Oppikofer *et alii*, 2011). However, these tools do not allow us to understand the rate of deformation in the past and to understand a rockslide in its evolution over time. One possibility to understand the development of rockslides over time is trenching of disturbed soils on the rockslide in combination with dating of deformed soil horizons (Gutiérrez *et alii*, 2010). However at rockslides, where no soil has formed along the sliding surfaces, TCN dating is the only tool to understand rockslide development.

*TIMING OF SLIDING AND SLIDING RATE*S

Our ^{10}Be ages of the main sliding surface indicate that ~11 m of displacement took place within the Pleistocene, while only 6.2 m of displacement took place in the Holocene, suggesting a decrease of displacement rate. Unfortunately, is the analytical uncertainty margin on the age from the sample that dates the end of the Pleistocene, is very high so that all slip rates calculated with the upper sample are indistinguishable. However, also the comparison of the slip rate calculated for the upper and the lower samples suggest a reduction of the paleo-slip rate in the Holocene. This might have been related to the climatic difference between the Late Pleistocene and the Holocene. Although we cannot penetrate with our few data into the temporal fluctuation of the climatic changes at the end of the Late Pleistocene it is obvious that climatic shifts such as the Younger Dryas have been much more dramatic than climatic variability within the Holocene. Therefore freeze and thaw cycles as well as availability of water during glacial retreat have likely been more intensive in the Late Pleistocene that might have resulted in the higher displacement rates. In addition, an initial "faster" movement could have been related to the debuttressing of the slope and the relaxation of the rock mass due to the decay of the ice sheet; under this hypothesis the rockslide entered a steady state creep movement after deglaciation. Afterwards the rockslide rather found a kind of steady-state creep movement.

CONDITIONING OF SLIDING

Our ^{10}Be data from the Oppstadhornet rockslide suggest taht the main sliding surface indicate further more that the main sliding surface probably became active between 16.6 and 14.2 kyr. This fits well with the time when the island of Otrøya melted out of the decaying ice sheet after the last glacial maximum as suggested by Vorren & Mangerud (2008) in a map showing the retreat of the Scandinavian Ice sheet. Following that map Otrøya became ice free between 14.3 and 13.7 kyr, however the top of the mountains at 750 m altitude might have melted out of the ice earlier. Therefore this result is very similar to the Skjeringahaugane rockslide in Lusterfjord, in the inner fjord region of Sogn og Fjordane county. That area became ice free at ca. 10 kyr and sliding started immediately at that rock slide (Hermanns *et alii,* 2012c).

Based on the ^{10}Be data alone it is impossible to discuss the process that caused the initiation of sliding whether it was glacial toe erosion, glacial debuttressing or meltdown of the permafrost or a combination of those. However, sliding of the main sliding surface is along the schistosity while it is cross cutting the schistosity in its lower part (Braathen *et alii*, 2004) (Fig. 4). This suggests that sliding started from the top, subsequently increasing stress on intact putting exerting stress on intact rock bridges in the lower part of the slope. Those might have failed during seismic loading that might have been stronger than today due to the fast rebound of Norway after deglaciation.

Present displacement velocities measured with dGNSS are relatively even over the slope with 2.0-4.3 mm/yr. In contrast is the slide direction varying between different compartments. While only a minor block in the upper slope slides parallel to the schistosity most of the rock mass in the upper slope slides with an angle 30° oblique towards the dip direction of the schistosity. This change of slide direction goes together with the inclination of sliding suggested by our dGNSS data. While the upper part is sliding with the same dip as the orientation of schistosity (and the sliding surface) the lower part is sliding with a less inclined angle and cross cutting the schistosity (Figs. 5, 6a). This could be explained by conditioning for sliding in the upper slope by slope parallel debuttressing and by glacial toe erosion in the lower slope. Furthermore, this could indicate that today's displacement direction on the main sliding surface is different from the Pleistocene due to the drop of velocity over the slope and that today the blocks are moving 30° oblique to the dip direction of the schistosity. This would be an alternative explanation that slide velocity apparently has decreased. If the slide would have changed from schistosity parallel to oblique to schistosity the full slip rate would not result in length of surface exposed on the sliding plane since reorientation of sliding direction.

IMPLICATION OF SLIDING HISTORY ON THE STABILITY MODEL

Our ^{10}Be ages also help to evaluate the dynamic stability model calculated by Bhasin & Amir (2004). Those authors postulate that the slope should fail under seismic shaking that could be expected in relation with an earthquake with a recurrence period of 475 years. However, seismic accelerations as used in the dynamic slope stability model have occurred repeatedly in the past and stronger earthquakes with larger recurrence times also did not cause the slope to fail in the past thousands of years. This might be due to the continuous slip over 15 kyr, which just in the past hundred years lead to conditions that the rock may fail under seismic loading today. However, we rather suspect that the geological models for the Oppstadhornet rockslide are simplifications of the real geological conditions. Parameters such as hydrological conditions and the number of intact rock bridges can only be estimated. Hence for those rock slope failures that might have large economic consequences or might cause a significant loss of life more elaborate geological models are needed to improve the dynamic stability models. In addition, including long lasting progressive failures and sliding into improved stability models would allow imaging slope stabilty conditions better.

Therefore we postulate based on our longterm slip rates that the slope is likely more stable under seismic loading with a recurrence of 475 years than previously estimated.

CONCLUSION

Although our ^{10}Be ages are limited they indicate that the Oppstadhornet rockslide became active when the island of Otrøya melted out of the Scandinavian ice sheet and continued to be active through the Late Pleistocene and the Holocene. The data further suggest that sliding was faster in the Late Pleistocene and that the rate slowed down in the Holocene. Today's displacement rates obtained from dGNSS coincides well within uncertainties with paleo-slip rates on the main sliding surface. Finally these data suggest that the slope is more stable than suggested by dynamic stability models and that the next earthquake with 475 years recurrence interval will similar to earlier such events not cause the slope to fail.

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