MONITORING OF THE TJARNARDALIR LANDSLIDE, IN CENTRAL NORTH ICELAND

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Abstract: The Tjarnardalir landslide is located in the Almenningar area, in the outermost part of the Skagafjordur fjord, in central north Iceland. The landslide is a part of extensive sliding area on the eastern side of the fjord. The Tjarnardalir landslide originally fell as a rockslide from the western side of the Manarfjall Mountain. The front of the landslide reaches the present coast, forming up to 60 m high coastal cliffs that show clear indications of extensive coastal erosion. Geomorphological indications show that the landslide mass has a constant westward movement towards the sea, with mean rate up to 69,2 cm/year. The stratigraphical record confirms that glaciomarine fine grained (silt/fine sand) sediments underlie the sliding material. Groundwater, which penetrates through the coarse landslide material, stops on the fine grained material and thus forms a sliding plain. It is assumed that the main part of the sliding movement takes place on this boundary. There is a clear correlation between the landslide movement and weather conditions. The main sliding movement occurs during the snowmelt period and during the autumn rain period. It is suspected that extensive costal erosion also plays a role in the sliding movement, but the erosion rate is not known. Electrical resistivity measurements indicate that the moisture content in the debris mass is high, which indicates extensive ground water flow.

INTRODUCTION

Large rockslide features are common landforms in the mountainous Tertiary basaltic areas in north-western, northern and eastern Iceland. These areas are characterized by glacially eroded fjords and valley systems, with relative steep mountainsides, often up to 600-1200 m high. The Tertiary bedrock predominantly consists of jointed basaltic lava flows, erupted sub-aerially, with individual flows varying in thickness from 2-30 m, usually separated by lithified sedimentary horizons varying in thickness from a few centimeters up to tenths of meters (Saemundsson 1979, Sæmundsson *et al*. 1098 1980, Johannesson & Sæmundsson 1989). Generally it is thought that the rockslide activity in Iceland was most intensive shortly after the last deglaciation, around 9.000-10.000 ^{14}C years BP (Jonsson 1976). Most of the rockslides, which have been mapped in Iceland, do not show any indication of present-day movement or landslide activity inside the shattered rockslide mass. The Tjarnardalir landslide in the Almenningar area on the north coast of the Skagafjordur fjord (figure 1) on the other hand shows the contrary (Saemundsson *et al.* 2005).

The bedrock in the Almenningar area is of Tertiary age, i.e. ca. 10-15 millions years old (Saemundsson *et al.* 1980, Johannesson 1991, Johannesson & Saemundsson 1989). It is mainly composed of jointed basaltic lava flows often separated by 30-50 cm thick lithified sedimentary horizons. The bedrock is heavily jointed and intersected by dikes. The general dip of the lava beds is towards the southwest, varying from 10-22° (Haflidason 1982).

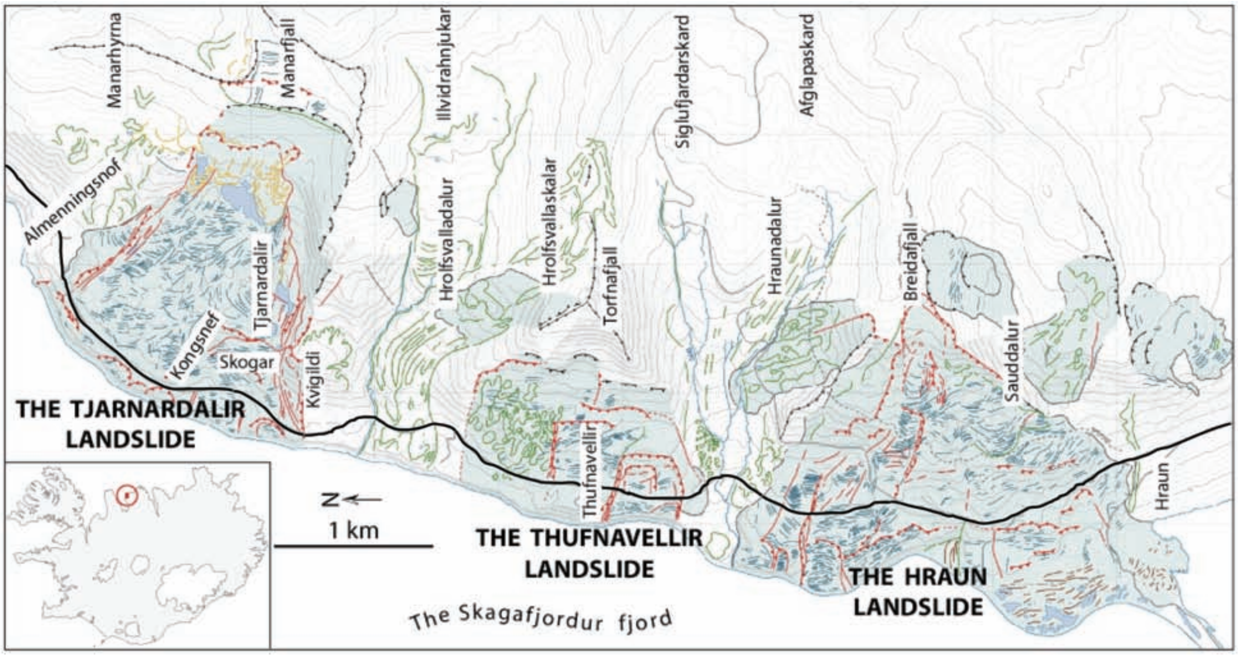


Figure 1. The Almenningar area, in the outermost part of the eastern side of the Skagafjordur fjord. Three large rockslides and several smaller ones have been mapped in the area and resent landslide activity and sliding movement is distinct inside some of them, especially in the three largest one. The main road to the community Siglufjordur crosses the area (black line). The Tjarnardalir landslide is the northernmost one (modified from Saemundsson *et al.* 2005).

During the last three years, extensive studies have been carried out in the Tjarnardalir landslide area, in order to look for the cause of the landslide movement that takes place inside the old rockslide mass and to understand the triggering factors of that movement (Saemundsson *et al.* 2005). The landslide mass shows constant westward movement towards the present coast. This movement has been monitored since 1977, giving exceptional opportunity to study the behavior of the movement and its character, and also to correlate the rate of the movement to external factors such as weather and costal erosion.

In 1965, a road was constructed through the Almenningar area in order to open a year-round traffic connection to the town of Siglufjordur, north of the area (figure 1). Shortly after the construction was completed severe damages to the road were observed, mainly in the Tjarnardalir landslide area. These damages were opening of large transversal and lateral crevasses. Ten years later a new segment of the road further from the shoreline was constructed in the Tjarnardalir area, where it was supposed to be more stable. In spite of that effort, damages continued to occur in the road and in 1977 the Icelandic road authorities started monitoring the sliding movements. Since then hazardous conditions have frequently occurred and the maintenance of the road has been high.

THE TJARNARDALIR LANDSLIDE

The Tjarnardalir landslide is located in the Almenningar area, on the eastern side of the outermost part of the Skagafjordur fjord, in central north Iceland (figure 1). The landslide is part of a more extensive sliding area, which extends about 4 km from the farm Hraun in the south, northwards to the Almenningsnof. Three large rockslides, as well as several smaller ones, have been mapped in the area (figure 1).

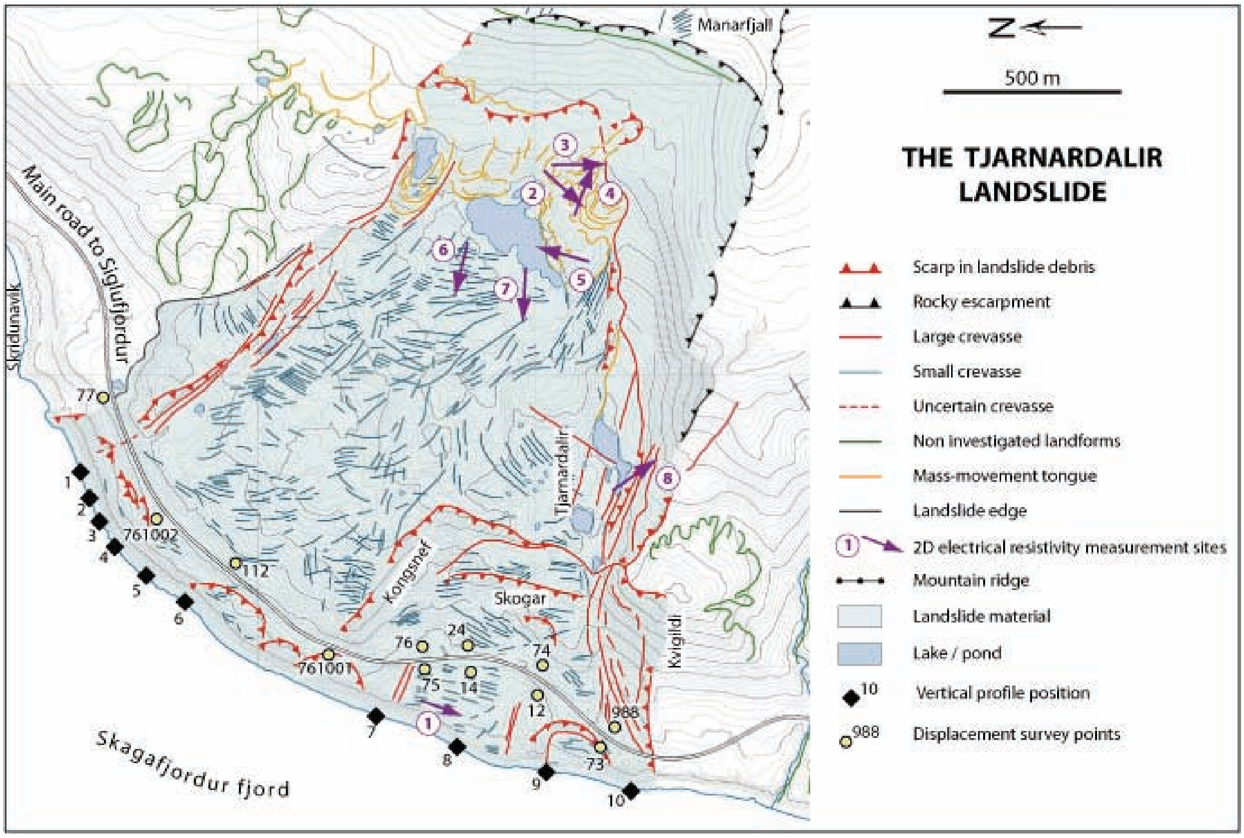
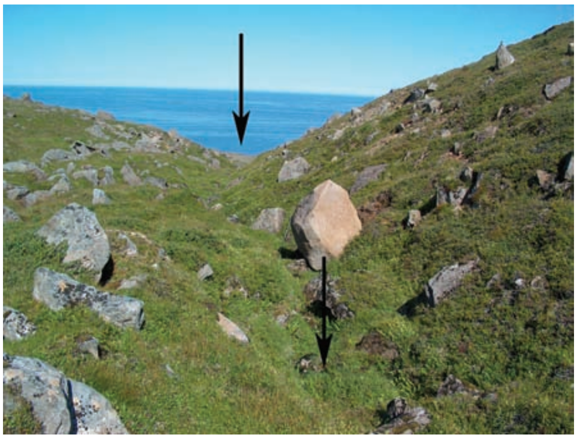


Figure 2. Detailed map of the Tjarnardalir landslide in the Almenningar area (modified from Saemundsson *et al.* 2005).

The Tjarnardalir landslide is inside an old rockslide which originally fell from the western side of the Manarfjall Mountain. The scar of the old rockslide is steep and L-shaped, ca. 800 m long from north to south and ca. 850 m long from east to west. The mean width of the sliding body is around 1400 m and mean length ca. 1550 m (figure 2). The average thickness of the debris mass is around 50 m and the total volume is estimated to be at least 110,000,000 m^3. The surface of the landslide is boulder rich and characterized by streamlined landforms. Many small faults and crevasses, indicating recent movements, occur both on the surface in the middle part of the landslide and along the edges of the slide (figures 3A&B). On the northern side of the landslide a fault system can be traced from the uppermost part of the landslide down to the shoreline. North of the faults a small hill like sedimentary landform occurs, which indicates the height of the original rockslide surface (figure 3A). In the uppermost part of the landslide few small lakes and ponds occur, indicating the high groundwater level in the landslide material (figure 3C). On the southern side of the landslide a similar fault system occurs as on the northern side reaching from the headwall down to the coastline. Along this side a small valley, Tjarnardalur occurs which can be traced from the uppermost part of the slide down to the Skogar area (figure 2). This landform provides evidence of a much higher movement rate than on the northern side of the slide. A brook and several small ponds are visible on the valley floor (figures 2&3D). On the northern slope of the Kvigildi Mountain, a ridge like landforms occurs, indicating the original height of the rockslide surface, as on the northern side (figures 3C&D).

A



B

C

D

E

F

Figure 3. A: The fault zone on the northern side of the Tjarnardalir landslide. The small hill like landform on the right side of the picture (arrows) indicates the original height of the rockslide material. B: Faults and crevasses on the northern side of the landslide. C: Several small lakes and pounds occur in the uppermost part of the landslide. The small ridge-formed landforms in the slope of the Kvigildi Mountain, in the centre of the picture indicate the original height of the rockslide (arrows). D: The large depression on the southern side of the landslide, the Tjarnardalur valley. Note the small ridge like landforms in the Kvigildi Mountain, on the left side of the picture indicating the original height of the rockslide (arrows). E: The Skogar area. Note the main faults crossing the road (black lines). F: The northern part of the Tjarnardalir landslide. The road is located at 60 m a.s.l. and below there is a steep coastal cliffs and above the road a steep 30-40 m high slope is located. The black line points out one of many faults crossing the road in this area (Photos. Th. Saemundsson 2004 & 2005).

The frontal part of the landslide shows much clearer indications of displacement. On the basis of the topography and the type of sliding movement, the toe area can be divided into two parts. The southern one, from the Kongsnef cliff south to the Kvigildi Mountain, is characterized by a 450-500 m wide and 250-300 m long slide scar, named the Skogar area. On both sides of the scar clear faults and crevasses can be traced from the headwall above the road, across the road and down towards the shoreline (figures 2&3E). In this area several survey points have been installed (figure 2) and they show westward movement up to 69,2 cm/year on average. The highest displacement rates were recorded close to the road in the Skogar area, showing rate of movement more than 1 m/year (table 1). The coastal cliffs in this part of the landslide are between 20-40 m high. They are subjected to intensive costal erosion and to slumping activity. The northern side of the landslide, from the Kongsnef cliff north to the Skridnavik cove, is characterized by up to 60 m high coastal cliffs. In this part the road is situated 20-50 m from the cliff edge, at about 80 m a.s.l. The coastal cliffs below the road are steep, subjected to high sliding and slumping activity and to extensive coastal erosion. Several large fresh faults and crevasses occur in and above the road, showing clear indications of the extensive new movements further up in the slope. Above the road a steep 30-40 m high slope is located (figures 2&3F). Several survey points have also been installed in this area highlighting a westward movement, with average yearly rate up to 22,5 cm/year (figure 2 & table 1).

Stratigraphic correlations

In order to recognize the origin of the sliding activity, a study of ten vertical profiles of the sediments in the landslide mass was preformed. All the profiles are located along the coast from the Skridnavik cove in the north towards the Kvigildi Mountain in south (figure 2). On the basis of stratigraphical correlation the sediments were divided into three units (figure 4). The lowermost unit (unit A, figure. 4) is composed of consolidated, matrix-supported diamicton overlying the bedrock. This unit was only observed in the northern and southern part of the landslide area, (figure 4). It is interpreted as a lodgement till deposited at the time when a large outlet glacier flowed out of the Skagafjordur fjord. On top of this lowermost stratigraphical unit lays another unit composed of grain sizes varying from stratified fine grained silt and sand, up to poorly sorted gravel sediments (unit B, figure 4). The fine grained sediments in this unit are often compact and partly lithified, due to high concentration of unstable glass in the sediments which has been stabilized by the process of palagonization (Jakobsson 1972 and 1978). The sediments in this unit show considerable deformation structures and irregularity in composition, which indicates a highly unstable sedimentary environment during the deposition. This unit is interpreted as glaciomarine ice contact sediments deposited in front of retreating ice margin. It can be traced in all sections across the landslide and its maximum thickness is between 10-15 m (figure 4). The uppermost unit (unit C, figure 4) is composed of poorly sorted sediments, ranging in grain size from clay up to boulders often with sharp edges, with clast size up to several meters. Irregular beds of reddish clay rich sediments occur in these coarse grained sediments. The maximum thickness of this unit is around 65 m. It is interpreted as landslide material formed by a rockslide occurring from the western side of the Manarfjall Mountain, shortly after the last deglaciation about 9.000-10.000 ^{14}C years BP. The landslide material contains a mixture of material from the bedrock of the old mountain side. The boulder rich material is thought to be remains of the original lava units in the bedrock of the mountain side and the irregular reddish clay bed are interpreted as remains of sedimentary horizons from the bedrock which have somewhat kept their original layering inside the rock- and landslide material. Similar layering has been described from the Vatnsdalsholar rockslide in N Iceland (Jonsson *et al*. 2004) and from similar landslide masses in Europe (Dikau e*t al.* 1996).

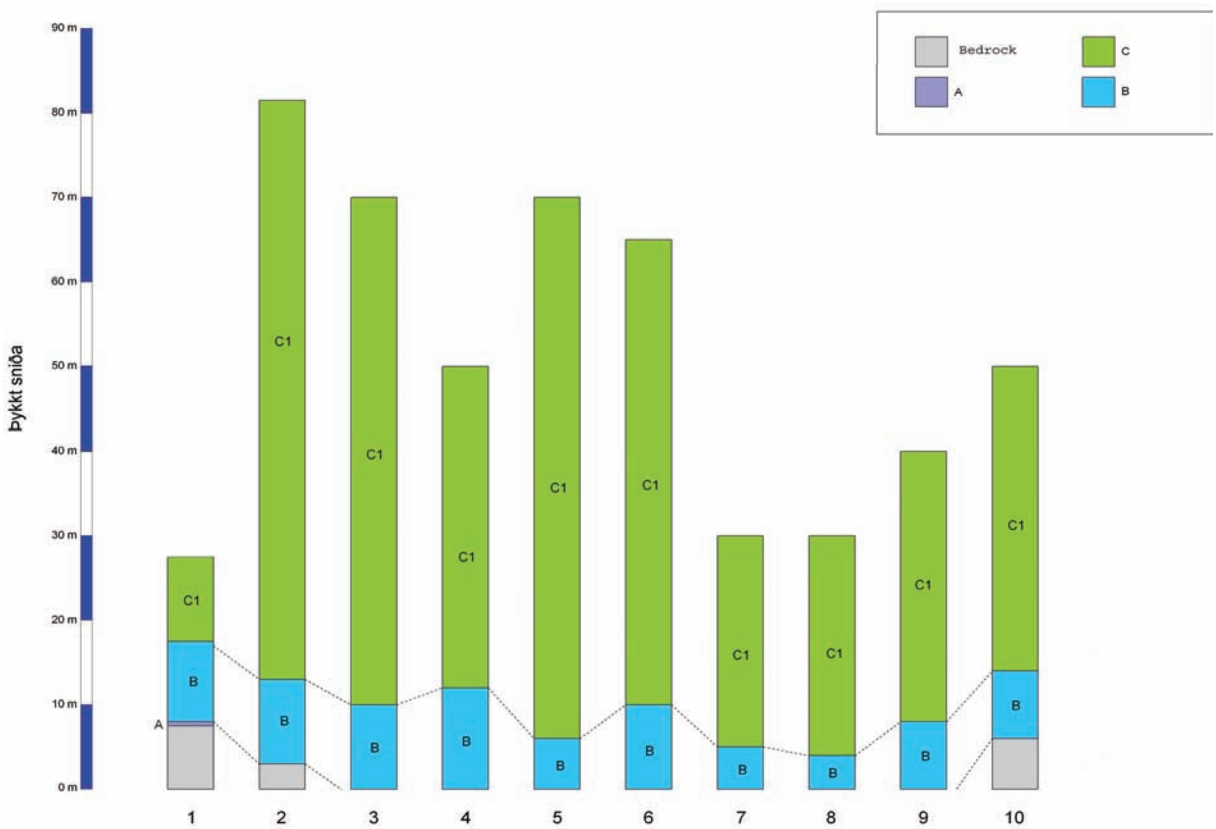


Figure 4. Stratigraphical cross section from the Tjarnardalir landslide. Locations of the profiles are shown in figure 2. Legend: Gray: Bedrock, A: Lodgement till, B: Glaciomarine ice contact sediments: C: Landslide deposits (modified after Saemundsson *et al.* 2005).

The compact and lithified glaciomarine fine grained sediments in unit B form an impermeable boundary between units B and C. This boundary prevents groundwater, which flows through the poorly sorted sediments above in unit C, to percolate further down. It is clearly visible in the coastal cliffs and in heavy rain periods and during the snowmelt season small streams have been observed on this boundary. The fine grained sediments in unit B can be traced in similar height across the landslide, but the thickness of the above lying sediments, unit C, varies considerably (figure 4). It is therefore assumed that the sediments in unit B are relative stable and the movement of the landslide mass does not take place in or under that unit. To be able to explain the movement of the landslide mass and the variable thickness of unit C, it is assumed that the sliding in the frontal part of the landslide occurs mainly in unit C or on the boundary between units B and C and thus creating a sliding plane. The extent of this impermeable unit B inland underneath the landslide material is unknown.

Movement rate and external triggering factors

The sliding activity in the Tjarnardalir landslide occurs in the whole landslide mass, but at a different rate. The movement rate is slower on the margins and in the middle and upper parts of the landslide masses. There indications, such as fresh looking faults and crevasses systems along the margins and in the upper and middle part, clearly indicate a constant movement. The rate of this movement is not known, but based on measurements of survey points on the margins of the landslides, it is assumed to be less than 1 cm/year (Saemundsson *et al*. 2005). The cause of this movement is not fully understood but extensive coastal erosion along the frontal part of the landslide might be the main triggering factor. In the lower part of the landslide along the coast, the movement rate is much higher, up to 109 cm/year, and more noticeable in the landscape. There the movements occur both as individual rapid events, and as a series of smaller and slower events, both in small and larger areas. The rate of these displacements is highly variable from year to year and the causes can be divided into two types. One is directly connected to coastal erosion, when wave action undercuts and destabilizes the above lying sediments. Evidence of this type of movement can be seen as slumps in the frontal part of the landslide, along the entire coastline. Evidence of the second type occurs as series of small scale events and can be seen over larger areas in the frontal part of the landslide, both as scars, crevasses and as rotational sliding. The sliding is primarily thought to take place on the sliding plain between unit B and C and the occurrence and rate of this type of movement is directly connected to weather, e.g. snowmelt or heavy rain usually during the spring and autumn months (Saemundsson *et al*. 2005).

The first written documentation of sliding movements in the Tjarnardalir area dates back to 1916 and 1921, when large slides fell from the landslide edge at the coast, although the geomorphology of the area clearly shows signs of much older movements. From 1976, or since the new road was constructed, several sliding events have been documented, providing an opportunity to correlate them to local weather and to other external factors (Saemundsson *et al*. 2005). The documentation is not complete as no regular monitoring of landslide and debris flow activity was carried out in Iceland prior to 1990. Of those events, which have been documented, a strong correlation is found with climatic factors such as heavy rain and intensive snowmelt periods. The interaction between costal erosion and sliding activity in the area is not fully understood. From the written sources it is clear that the spring months are prone to sliding activity, e.g. during the snowmelt periods. Also the autumn period, commonly rainy, is favorable to mass movements on all scales. According to historical sources considerable movements occurred in the years 1976, 1977, 1981, 1983, 1991, 1992, 1995, 1996, 1999, 2002, 2003 and 2004. Intensive autumn rains were the primary cause for the activity in 1976, 1981, 1991, 1992, 1995, 1996, 1999, 2002 and 2004, and snowmelt was a the primary driver during the spring periods in 1977, 1983, 1999 and 2003.

In the beginning of the monitoring period in 1977, only a few survey points were installed, but as the years passed more points were added, which gives more detailed picture of the movement rate. The location of the survey points is shown in figure 2 and the installation and results of the measurements from the survey points in the Tjarnardalir landslide are compiled in table 1. For the last 12 years or from 1995 the Icelandic road authorities have carried out yearly measurements on the survey points, except in 1998. The measurements were usually done from late September to early November. Prior to 1995, measurements were only done in 1977, 1982 and 1983. As can be seen in the table, the sliding rates in 1996, 1999, 2002 and 2004 were higher than during other years. The weather pattern during these years did show some variation, such as in higher amount of precipitation during the autumn months, than in average year, and more intensive snowmelt periods during the spring months. Although there have not been carried out any direct weather measurements in the area, a direct correlation have been documented between the timing of the movements in the Tjarnardalir landslide and weather measurements in nearby weather stations (Saemundsson *et al.* 2005).

Electrical resistivity surveys

In an attempt to look at the stratigraphical distribution and moisture content in the debris mass at the Tjarnardalir landslide, electrical resistivity measurements were carried out in several profiles both in the uppermost part and in the frontal part of the landslide (figure 2). In these measurements both so called Wenner and Wenner-Schlumberger configurations were used. The Wenner configuration has a moderate investigation depth and has a good resolution for horizontal structures with vertical changes of resistivity. The Wenner-Schlumberger array is a combination of the Wenner array and the Schlumberger array (commonly used for vertical resistivity soundings) with constant potential electrode spacing but logarithmically increased current electrode spacing's, leading to a better depth resolution compared to the Wenner configuration. For the two-dimensional surveys a *SYSCAL Junior Switch* system was applied.

The results of these measurements indicate that all profiles show a rather good conductivity in the subsurface, partly due to the very high soil moisture, as indicated by the low resistivity values (<150 ohm.m). The near-surface material is in some cases markedly drier (higher resistivities, yellow and red colors). Most of the images of resistivities against depth show a general decrease in resistivity with depth with some moist parts and variability of the resistivities at shallow depth or show a more or less overall high conductivity due to high moisture content. From the range of resistivities, it can only be concluded that the subsurface consists of landslide debris with different grain sizes leading to variable moisture contents and thus conductivity.

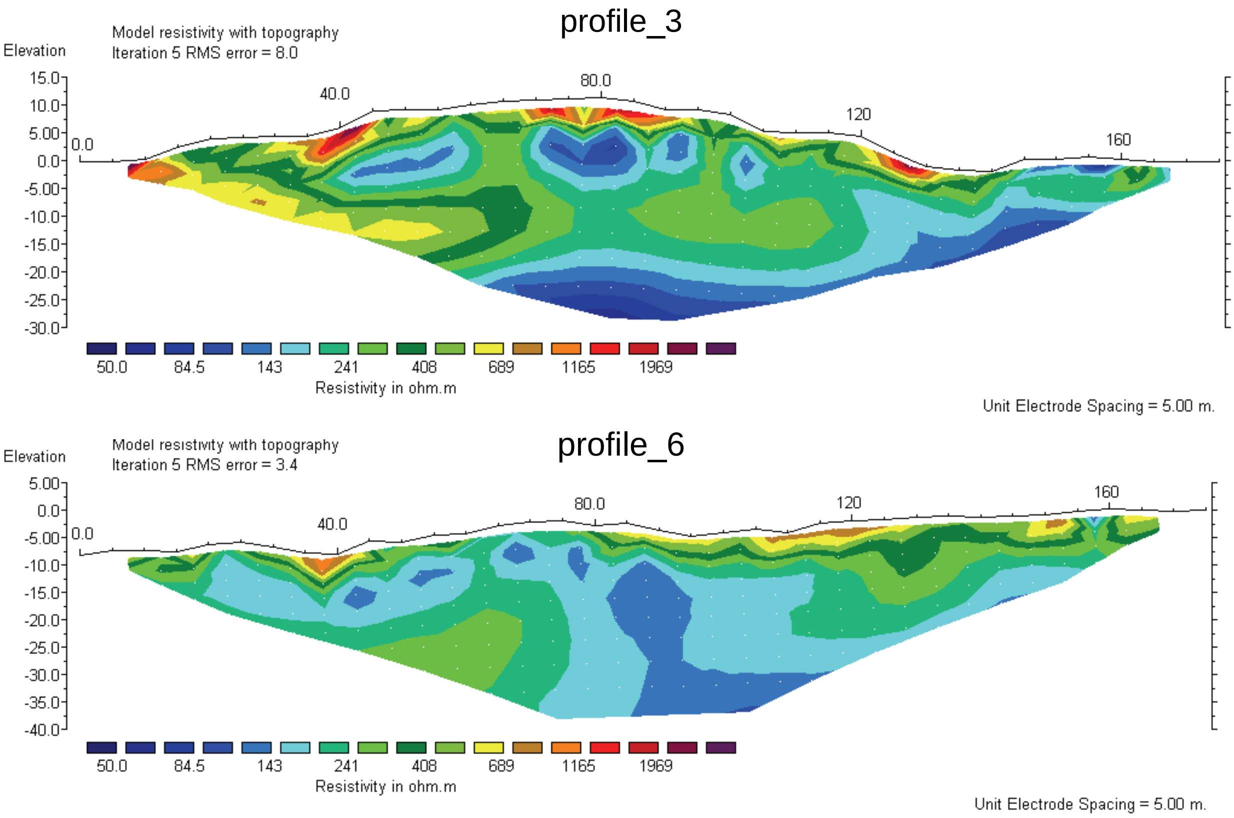


Figure 5. Examples from the electrical resistivity survey in the Tjarnardalir landslide. The locations of the profiles are shown on figure 2. Profile 3 is orientated N – S (left to right) and profile 6 from E – W. Legend: Yellow and red colors = higher resistivity / drier condition. Green and blue colors = lower resistivity / wetter condition.

Table 1. Measurements points along the road over the Tjarnardalir landslide

Since 1977, the Icelandic Road Authorities have preformed measurements along the road crossing the Tjarnardalir landslide. Locations of these points are shown in figure 2 and all distances are in cm. The distances in the table are in horizontal plain and do not give any elevation measurements. (Legend: X: measurements started; *F: timing (month) of measurements*; *MM: major movements according to written documentation; MF: major movements according to measurements*) (Ref: Erlingsson & Hauksson 2001a; 2001b; 2003 & 2006).

Points	77	761002	112	109	761001	76	75	24	14	74	12	988	73	Comments	Comments
Year															
1977		X			X										MM
1978		7,3			12,3										
1979		7,3			12,3										
1980		7,3			12,3										
1981		7,3			12,3										MM
1982		7,3			12,3										
1983		7,3			12,3									??	MM
1984		5			10									??	
1985		11,3			12,5										
1986		11,3			12,5										
1987		11,3			12,5										
1989		11,3			12,5										
1990		11,3			12,5										
1991		11,3			12,5										MM
1992		11,3			12,5										MM
1993		11,3			12,5										
1994		11,3			12,5										
1995		11,3			12,5									??	MM
1996		50			52									Sept	MM
1997		9			8							X		June	
1997		7			7							7		Sept	
1999	X	33			36	X	X	X	X	X	X	43	X	Sept	MF / MM
2000	22	14			15	7	7	63	61	30	43	18	22	Oct	
2001	29	15	X	X	14	13	14	57	55	27	37	16	18	Sept	
2002	36	15	15	4	35	6	7	100	107	35	61	19	23	Oct	MF / MM
2003	17	8	7	2	6	3	3	21	20	12	16	8	10	Nov	MM
2004	19	11	11	4	18	7	8	108	109	38	77	18	21	Sept	MF / MM
2005	12	16	12	7	12	11	10	65	63	31	43	19	22	Oct	
Tot	**135**	**417**	**45**	**10**	**424**	**47**	**49**	**414**	**415**	**173**	**277**	**148**	**116**		
Ave.	**22,5**	**14,9**	**11,3**	**4,3**	**15,1**	**7,8**	**8,2**	**69**	**69,2**	**28,8**	**46,2**	**18,5**	**19,3**		

CONCLUSION AND DISCUSSION

Contradictory hypotheses have been put forward regarding the origin of the landforms in the Almenningar area. Gudmundsson (2000) interpreted the landforms as a result of a local glaciation and of permafrost conditions during the last deglaciation or later, and defined these landforms as either active or stationary rock glaciers in the present climate. Gudmundsson also implies the possibility of buried ice within the debris masses to explain the recurrent movement of the debris masses. Wangensteen *et al*. (2006) carried out some studies on surface displacements and surface age estimates of the moving debris mass in the Almenningar area, stating that the origin of the debris accumulation is uncertain. Saemundsson *et al.* (2005) defined the area as a complex of large scale rock- and landslides, occurring during or shortly after the last deglaciation, in relation with glacial retreat and consequent isostatic rebound after the last glaciation. In 1982, Haflidason also interpreted the Almenningar area as several rockslides bodies that probably occurred shortly after the last deglaciation (Haflidason 1982). Saemundsson et al. (2005) reject that the Almenningar landforms and movements are of glaciogenic or permafrost origin and point out that Gudmundsson (2000) interpretation is contradictory to the general deglaciation history of Iceland (e.g. Ingolfsson 1991, Norddahl & Petursson 2005), to the accepted present scenario of ice extent during the last glaciation on the shelf in N-Iceland (e.g. Eiriksson *et al.* 2000, Andrews *et al.* 2000, Andrews & Helgadottir 2003) and also to the Holocene climate history in Iceland (e.g. Einarsson 1968, Eythorsson & Sigtryggsson 1971, Clark 1983, Stotter *et al.* 1999).

The landforms in the Almenningar area are interpreted as rockslides, occurring during or shortly after the last deglaciation. Similar landforms are widespread in the Tertiary basaltic areas in north-western, northern and eastern parts of Iceland. The landslides inside the rockslide of the Almenningar area, such as the Tjarnardalir landslide show clear indication of constant movement of the debris mass. Such movement has not yet been observed in other rockslide masses in Iceland. The data from the historical record and the monitoring of the survey points give a unique opportunity to correlate the rate of the movement in the debris mass to external factors, such as weather and coastal erosion. According to the data presented here the movements of the Tjarnardalir landslide are strongly reliant both on weather variations, e.g. precipitation and snowmelt and coastal erosion. A slow movement, less than 1 cm/year takes place over the whole landslide mass. Indications of that movement can be seen as fresh looking faults and crevasses systems along the margins and in the upper and middle parts of the landslide, probably primarily caused by coastal erosion along the frontal part. A much faster movement occurs in the lower part of the landslide. There the movements occur both as individual rapid events, and as a series of smaller and slower events. The rate of these displacements is highly variable from year to year and based on the written documentation and correlation to nearby weather stations there is a direct relationship with amount of precipitation during the autumn months and snowmelt during the spring months (Saemundsson *et al*. 2005). Coastal erosion is also thought to play a significant role, although the yearly rate is not known.

According to the resistivity survey high moisture content occur in the debris mass in the Tjarnardalir landslide. No real stratification of the sediments or differentiation of material/grain size was possible from the geoelectrics survey alone and the survey did not give any clear signal that the bedrock was reached.

The prospect for the whole year road to the Siglufjordur fjord, crossing the Tjarnardalir landslide is not bright. The constant damages occurring on the road can lead to severe situation and cause hazardous conditions for the traffic. The situation on the northern side of the Tjarnardalir landslide is thought to be more hazardous than on the southern side. There, the undercutting of the sediments, due to costal erosion and sliding activity in the debris mass have destabilized the sediments underneath the road. New crevasse are opening and it seems that the crevasse zone is slowly merging further upwards into the debris mass above the road. If this continues, large parts of the road will fall or slide down possibly tenths of meters.

Acknowledgments: This work was carried out with financial support from the Icelandic Road Administration, Reykjavik; the Natural Research Centre of North-western Iceland, Saudarkrokur; the Icelandic Institute of Natural History, Akureyri, Iceland and the Department of Physical Geography, University of Wurzburg, Germany.

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