

Tsunami-generating rock fall and landslide on the south coast of Nuussuaq, central West Greenland

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During the afternoon of 21 November 2000 the village of Saqqaq in central West Greenland was hit by a series of giant waves. Ten small boats were destroyed, but luckily neither humans nor dogs were killed. The following day a police inspection by helicopter revealed that the giant waves were caused by a major landslide at Paatuut, c. 40 km north-west of Saqqaq on the south coast of Nuussuaq (Figs 1, 2). The landslide deposits were dark grey-brown in colour, in marked contrast to the snow-covered slopes, and protruded as a lobe into the Vaigat strait. Along the adjacent coastlines the snow had been washed off up to altitudes about 50 m a.s.l. and severe damage had been caused at the abandoned coal-mining town Qullissat on the opposite side of Vaigat.

Landslides in Greenland

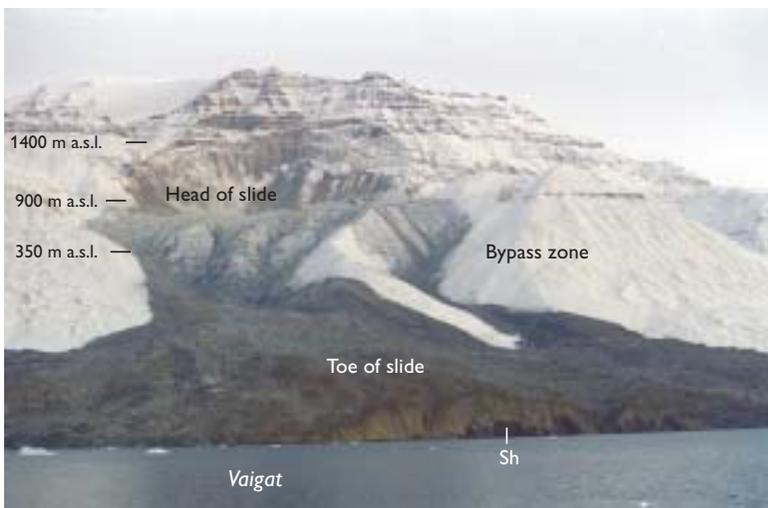
Landslides in Greenland are influenced by permafrost, glacial ice, high topographic relief and repeated freezing and thawing (Pedersen *et al.* 1989). In most parts of

Greenland where gneisses and granites dominate, slides are rare. By contrast, the Nuussuaq Basin comprises weakly consolidated sedimentary rocks overlain by a thick pile of dense volcanic rocks. This stratigraphical succession is favourable to the generation of slides. Consequently, large parts of Disko, Nuussuaq and Svartenhuk Halvø are strongly affected by landslides, especially along the coasts (Fig. 2).

Tsunamis

In coastal areas landslides may reach the sea and generate swells which may travel considerable distances. The swells present a much larger risk than do the landslides because they affect much larger areas. A wave (swell) may not be noticeable in open waters off the coast, but grows rapidly as it approaches the shore. Swells of this type are known as tsunamis and are frequently generated by submarine earthquakes. The giant waves which hit Saqqaq, Qullissat and the shores of the Vaigat in November 2000, are referred to below as a tsunami, although they were initiated by a landslide.

Fig. 1. The 21 November 2000 landslide at Paatuut, viewed from the sea a few days later. The slide lacks snow cover; cf. Fig. 4. Note the black shale (**Sh**) cropping out in the lower part of the coastal escarpment. Photo: Christoffer Schander, Arktisk Station, Qeqertarsuaq.



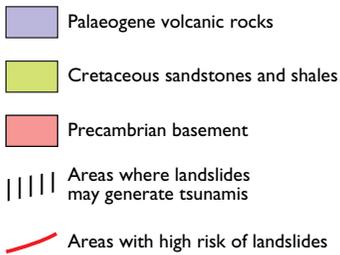
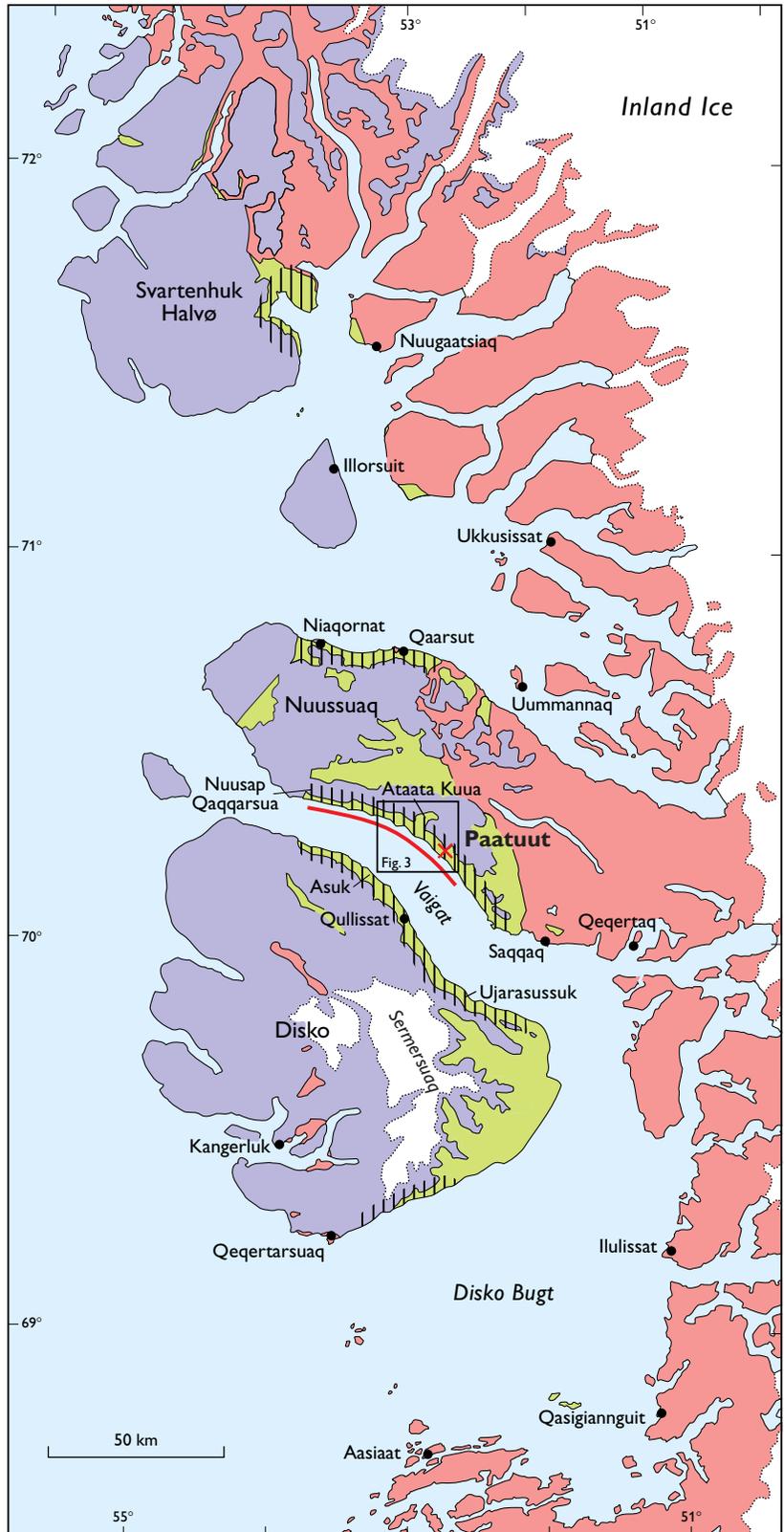


Fig. 2. Geological map of the Nuussuaq Basin with the landslide-prone areas indicated. Frame shows location of Fig. 3, a detailed map of the Paatuut area.



Landslides may move at different speeds, and slowly moving slides or debris flows are not considered dangerous. To initiate a tsunami the landslide must almost instantly displace huge volumes of water, and the likelihood of such an event increases with the steepness of the coast. The risk of tsunamis following landslides is consequently particularly high along the steep south coast of Nuussuaq where erosion is rapid and large volumes of debris accumulate at high altitudes (Fig. 2). Furthermore, tsunamis generated along the south coast of Nuussuaq are confined by the narrow Vaigat strait and are reflected from the opposite coast.

Rock falls and landslides in the Disko–Nuussuaq area

Old slide areas are recognisable from their geomorphological expression, and sometimes also by brick-red colours produced by self-combustion in slipped carbon-rich shales. Such burnt lithologies are prominent at Paatuut and Ataata Kuua (Fig. 3) and indicate a high frequency of slides. Many slides are indicated on the Survey's 1:100 000 geological maps of the region. Most of these slides must be less than 10 000 years old, as they post-date the last glaciation. In the period 10 000–3000 B.P. relative sea level was falling in the Disko Bugt area, and marine terraces as well as

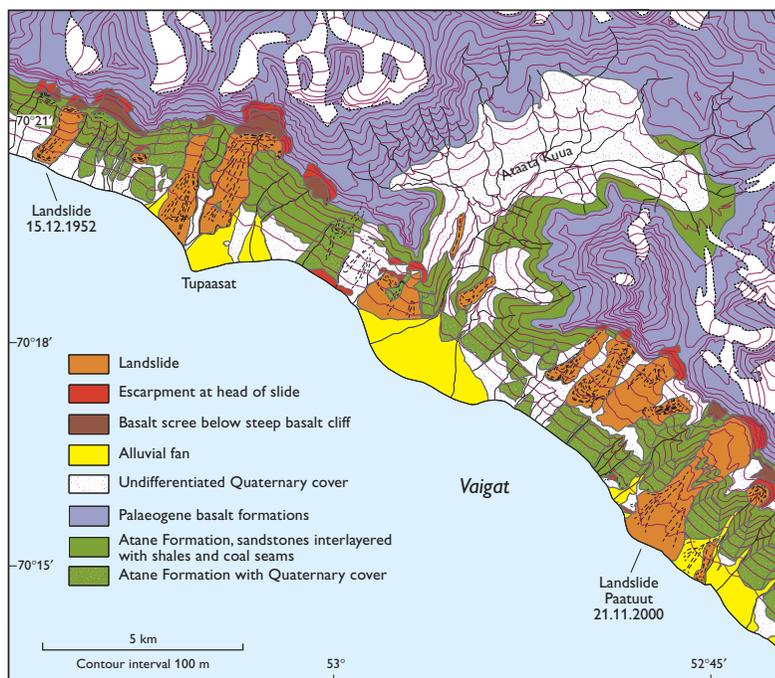
raised beaches were formed. Since 2800 B.P. sea level has been rising (Long *et al.* 1999). Along that part of the south coast of Nuussuaq where landslides are frequent, marine terraces are generally not seen; this indicates that the landslides present are probably younger than 3000 B.P.

The Paatuut area is characterised by large landslides (Fig. 3). Between Paatuut and Ataata Kuua in particular, large lobes of rock debris superpose the glacial morphological surface. Huge solitary blocks of volcanic rocks on the slopes facing Vaigat are evidence of occasional rock falls, some of which may have generated tsunamis.

The first published account of a landslide in Greenland is that of Steenstrup (1900), who recorded an event that occurred in 1870 near Ujarasussuk on the north coast of Disko. A mudflow with large floating blocks of basalt built a lobe into the sea and hindered passage on foot along the coast. This landslide does not appear to have caused a tsunami or any damage to houses or inhabitants in Ujarasussuk.

Landslides are a recurring phenomenon near Niaqornat in northern Nuussuaq. In most cases spontaneous combustion in shales is reported about one year after the slide (Rosenkrantz 1967; Henderson 1969). The village Niaqornat was hit by falling rocks in 1978, and west of the village the risk of future slides is high (Pulvertaft 1979).

Fig. 3. Map of part of the south coast of Nuussuaq showing the many large and small landslides in the area, including the new slide at Paatuut. The contours are drawn from vertical aerial photographs at scale 1:150 000 taken in 1985 and, for the Paatuut slide, from oblique photographs taken in July 2001.



On the south coast of Nuussuaq, west of Tupaasat (Fig. 3), a large landslide occurred on 15 December 1952. The slide was initiated 700 m a.s.l. and had a width of 1 km where it reached the sea. It generated a tsunami which caused some damage in Qullissat; areas 50–100 m from the shoreline were flooded, the electricity plant was damaged and a boat (22 ft cutter) with a crew of three was washed ashore with the loss of one man.

In the period 1984–1988 a mudflow at Paatuut was active. Black shales derived from an altitude of 800 m constituted the bulk of the flow. This section of the coast appears to have been affected by a number of flows ranging from dilute mudflows building alluvial fans to denser mudflows. The last of these occurred in 1997 and is not reported to have generated a tsunami.

Evidence from geophysical investigations

The Vaigat strait is up to 650 m deep with a U-shaped cross-section. This is interpreted as the result of erosion during the Pleistocene by the Vaigat Ice Stream, which drained from the Inland Ice into the Davis Strait. During the summer of 2000, the Survey acquired a large number of reflection seismic profiles in Vaigat with a 600 m streamer and 40 l airgun array (Marcussen *et al.* 2001). In the seismic profiles a number of chaotic local accumulations of sediment are apparent, which are interpreted to be old submarine slides or subaqueous aggradations from subaerial landslides. The thickness of such slide-deposited sediments is generally 50–100 m, but may locally exceed 200 m. The data do not allow a distinction between sediments deposited by a single slide and the composite accumulations formed by numerous slides.

The 21 November 2000 landslide

Stratigraphy

The stratigraphic succession at Paatuut comprises siliclastic sediments of the Cretaceous Atane Formation and the Danian Quikavsak Formation, overlain by hyaloclastite breccias and subaerial lava flows of the Paleocene Vaigat and Maligât Formations (Pedersen & Pulvertaft 1992; Pedersen *et al.* 1993; Dam & Sønderholm 1998; Dam & Nøhr-Hansen 2001).

The Atane Formation is exposed up to altitudes of 800 m. Lithologies consist of white to yellow, weakly consolidated 1–10 m thick sandstones interbedded with

dark grey, 2–15 m thick shales and coal seams typically 0.5–1 m thick. In places the coal seams have undergone self-combustion after landslides, and the black shales are converted into brick-red, orange or pink tiles. The Quikavsak Formation constitutes palaeovalley fill and is exposed locally at altitudes of 400–900 m. It consists of whitish pebbly sand overlain by black mudstones. The mudstone level around 900 m a.s.l. corresponds to the level above which material was removed during the landslide. This level is clearly seen in the post-slide terrain model (see below).

The lowest volcanic rocks are 260 m thick hyaloclastite breccias of the Ordlingassoq Member of the Vaigat Formation. At altitudes of 1160–1450 m these are overlain by thin, greyish picritic subaerial lava flows of the same member. The volcanic rocks above 1450 m a.s.l. are brownish subaerial lava flows of the Maligât Formation. Dykes and up to 20 m thick sills cut the succession, and the sills often form prominent ledges on the sandstone slopes. Blocks of all the volcanic and intrusive lithologies have been recognised amongst the material in the landslide.

Slide morphology

The morphology and main features of the landslide can be clearly seen in the photographs of Figs 1 and 4, taken respectively a few days after the event and in July 2001. The slide was initiated at altitudes of 1000–1400 m a.s.l., referred to as the head of the slide (Fig. 1). The material transported by the slide comprises partly blocks of basalt that formed a steep scree prior to the slide, and partly solid slabs of basalt broken off from the cliff.

The central part of the slide is a series of gullies and ridges in the Atane Formation; the material was transported downwards through these pre-existing gullies. They were not deepened significantly due to erosion during the slide, and this area is classified as a bypass zone.

The lower part of the slide is a lobate accumulation of material deposited on the former alluvial fan at the base of the slope (Fig. 4). This aggradational toe of the landslide has a width of *c.* 2 km and is bounded seawards by a coastal escarpment (Fig. 4). The research vessel *Porsild* collected a number of echo sounder profiles off the coast of Paatuut in July 2001. These data provide the first approach to a detailed map of the sea floor (Pedersen *et al.* 2001, fig. 29) and reveal a rapid increase in water depth and very uneven sea-floor topography. Earlier seismic investigations have also

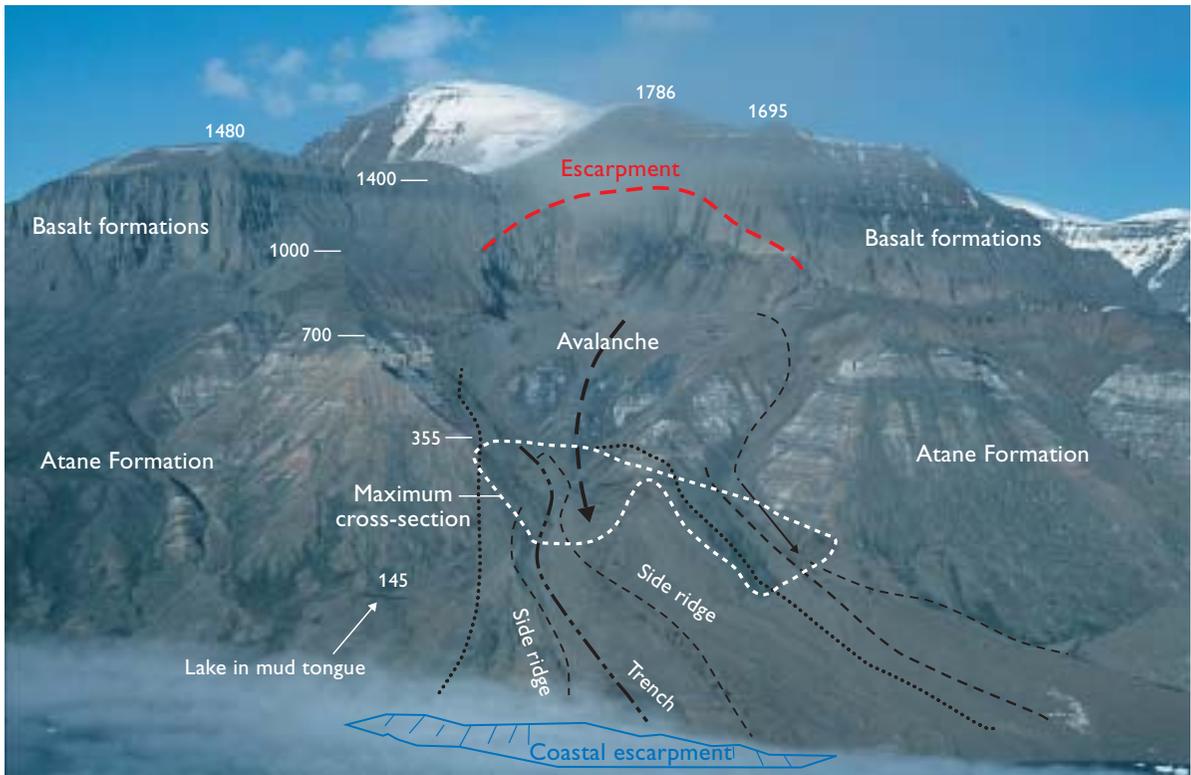


Fig. 4. Oblique photograph of the Paatuut landslide taken in July 2001 from a helicopter. The photograph was used in the multi-model photogrammetric work; low-lying areas are concealed by coastal fog. The direction of main flow in the bypass zone is indicated by an **arrow**, and the cross-section of the avalanche at its maximum is marked by a **dotted contour**. Some ridges and trenches in the toe of the slide are indicated. The light, smeared patch above the escarpment is a dust cloud raised by continuing small rock falls from the back wall. Elevations are in m a.s.l.

documented an uneven topography offshore Paatuut (Marcussen *et al.* 2001), which is believed to reflect the distribution of a succession of submarine slides.

Head of slide (denudation zone)

The slide escarpment along which material slipped and slid bounds the head of the slide (Figs 1, 4). The escarpment comprises two steep (*c.* 60°) surfaces, which meet at a high angle. Along the eastern escarpment surface the slip was down-dip, and the vertical offset seen on the denudated surfaces ranges from 121 m to 182 m; this surface is interpreted as a pre-existing fault plane, and the newly exposed rock has a pale colour (Fig. 4). The western surface constitutes a side escarpment which was clearly affected by oblique lateral movement during the landslide event, as indicated by groove mark striation on the cliff. Based on the disrupted character of the landslide material and the

steepness of the slide escarpment, the process at the head of the slide is interpreted as a rock fall.

A platform at an altitude of 800–900 m occurs at the base of the escarpment. Prior to the landslide this platform was characterised by accumulation of glacial deposits. The platform may mark the boundary between the shaly lithologies and the sandstones of the Quikavsak Formation and the hyaloclastite breccias of the Ordlingassoq Member. After the slide, the platform appears as a barren landscape characterised by huge blocks and chaotic disrupted material on which frost mounds have subsequently developed (Pedersen *et al.* 2001).

Central part of slide (bypass zone)

The central part of the slide is a bypass zone where the slide material was transported through the gullies in the Atane Formation. The gradient in the gullies varies



Fig. 5. Blocks and boulders in the central part of the toe of the Paatuut landslide are interpreted as grain flow deposits. **Arrow** indicates person for scale. Photograph taken July 2001.

from 26° to 36°. Field work in 2001 showed that some slide material was deposited about 200 m above the floor of the gullies during transport through the bypass zone. Groove marks with a gentle plunge towards the coast were observed on the sides of the gullies. A minor quantity of white sandstones of the Atane Formation was removed from the top of a gully and deposited in a separate lobe in the aggradation zone (lower right corner of Fig. 4). This suggests that the transport and deposition of the sandstones occurred as a discrete event during a late phase of the slide.

The drape of mud, stones and boulders on the sides of the gullies outlines the space taken up by the flow. The maximum cross-sectional area through which the avalanche passed is calculated to 70 000 m². Seismic data (see below) show that the main event lasted for approximately 80 seconds; however, the maximum cross-section would only have been sustained during a considerably shorter period. This gives a *minimum* velocity of the slide through the bypass zone of 60 km/h, indicating that in the bypass zone the landslide had the character of a rock avalanche. The seismic data give considerably higher average velocities.

Toe of slide (aggradation zone)

Morphologically the lower part of the slide comprises two lobes which merge downwards into one, with a surface lined by trenches, ridges and flats (Figs 4, 5). The floors of the trenches may be as much as 50 m below the crests of the ridges. The alluvial fan upon which the landslide was deposited had a dip of 6°–9°,

and the aggradation is up to 60 m (see later). The ridges consist of clast-supported, apparently matrix-free conglomerates and are interpreted as grain flow deposits. The flats consist of clast-supported, matrix-bearing conglomerates and matrix-supported conglomerates, indicating deposition from modified grain flows and debris flows. In the flat areas frost mounds are common, indicating the presence of fine-grained sediment at the base of the deposit.

On the western side of the landslide a tongue of mud extends away from the main slide. Field observations (Pedersen *et al.* 2001) indicate that this tongue formed due to gravity spreading of the avalanche as it settled on the alluvial fan. In the tail end depression of this tongue a small lake was formed, dammed by the toe of the slide (Fig. 4).

The toe of the slide reached the coast and advanced into the sea, where a steep (37°) escarpment terminates the subaerial part of the slide. This coastal escarpment provides the only exposed section through the slide deposits (Fig. 1); it shows a predominance of matrix-supported conglomerates at the base of the slide and a clast-supported boulder-conglomerate at the top. Locally the slide contains a significant proportion of black shales, probably originating from the mudstone level around 900 m a.s.l.

The coastal escarpment indicates the collapse of a protruding tongue which originally formed the front of the toe. The collapse is believed to have generated a submarine slide and subsequently the tsunami. Volume calculations (see below) suggest that about 30 million m³ of material slid below sea level.

Effects of the tsunami

The tsunami generated by the landslide affected not only Saqqaq but, as noted above, also the abandoned coal mining village of Qullissat 20 km across the fjord where buildings at altitudes below 30 m a.s.l. were almost completely destroyed. A line of timber debris 100–250 m from the coast marks the upper limit of the tsunami. A hut on the shore at Asuk 20 km from Paatuut (Fig. 2) was completely destroyed.

On the large alluvial fan at the outlet from Ataata Kuua 7 km north-west of Paatuut, several icebergs were stranded 300–700 m from the coast. Wreckage, including fish crates, was scattered across the alluvial fan up to 800 m inland and at altitudes up to 40 m a.s.l., and in the summer of 2001 certain vegetation species in the same area had withered, presumably due to saltwater incursion.

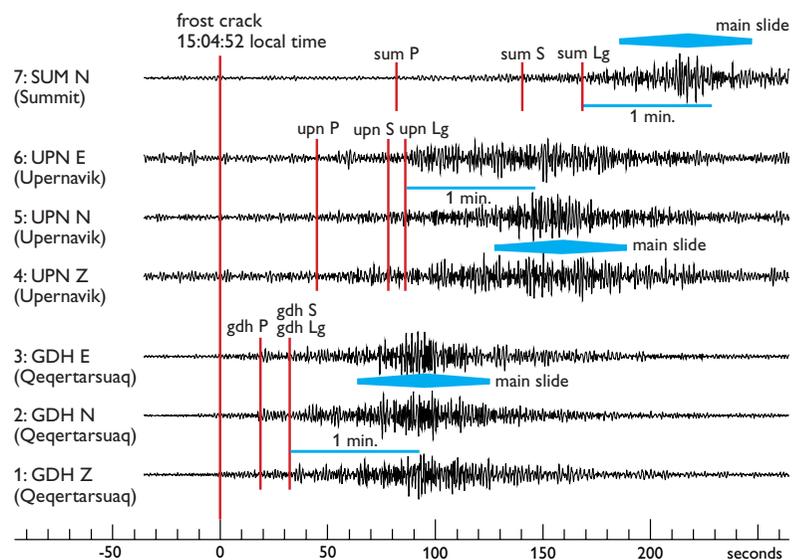
Seismic activity

A seismometer at Qeqertarsuaq registered a distinct seismic signal on 21 November 2000 at 15:05:10 local time (Fig. 6). People in Saqqaq noted that the tsunami arrived at 15:15, and the seismic signal is thus clearly

related either to the landslide itself or to an earthquake which triggered the landslide. Seismic stations at Upernavik *c.* 250 km north of Paatuut and at Summit, the drilling camp at the centre of the Inland Ice *c.* 550 km to the east (Fig. 2), also registered a seismic event on 21 November 2000 (Fig. 6). An analysis of the seismic records suggests that a seismic event occurred at 15:04:52 at Paatuut, and that it was probably caused by the release of the basaltic cliff at the head of the slide (Pedersen *et al.* 2001). This event is seen as the arrival of the primary wave (P) and secondary and surface waves (S and Lg) at all stations (Fig. 6). The following stronger signal reflects the surface waves generated by the activity of the avalanche, estimated to have a magnitude of 2.3 on the Richter scale. The constant time difference between the surface waves from the first and the second events at seismic stations at increasing distances from Paatuut indicates that the two seismic signals were generated at Paatuut, separated by approximately one minute. The main slide event was accomplished within approximately 80 seconds. With an average slide distance of 3 km, this implies an average slide velocity of 140 km/h. Maximum velocities would have been close to 200 km/h.

The analysis of the seismic signals does not support the hypothesis that a deep-seated earthquake generated

Fig. 6. Seismic events related to the rock fall and landslide at Paatuut 21 November 2000 recorded at Qeqertarsuaq, Upernavik and Summit (Fig. 2). The **red lines** mark the calculated arrival times of **P** (primary), **S** (secondary), and **Lg** (surface) waves from an initial release event at Paatuut. The time is determined by interpreting the P arrival at Qeqertarsuaq. The initial release of the fall occurred at 18:04:52 GMT (15:04:52 local time) and generated P, S and Lg waves. Subsequently, the energy released by the sliding of 90 million m³ of rocks down onto the coastal slopes is visible as an additional surface wave culminating approximately one minute after the initial event. This second and much larger event – estimated at 2.3 on the Richter scale – is also visible in seismograms from Nuuk, Tasiilaq, Thule and possibly Alert in Canada. **E**, **N** and **Z** are the east–west, north–south and vertical components in the ground movements.



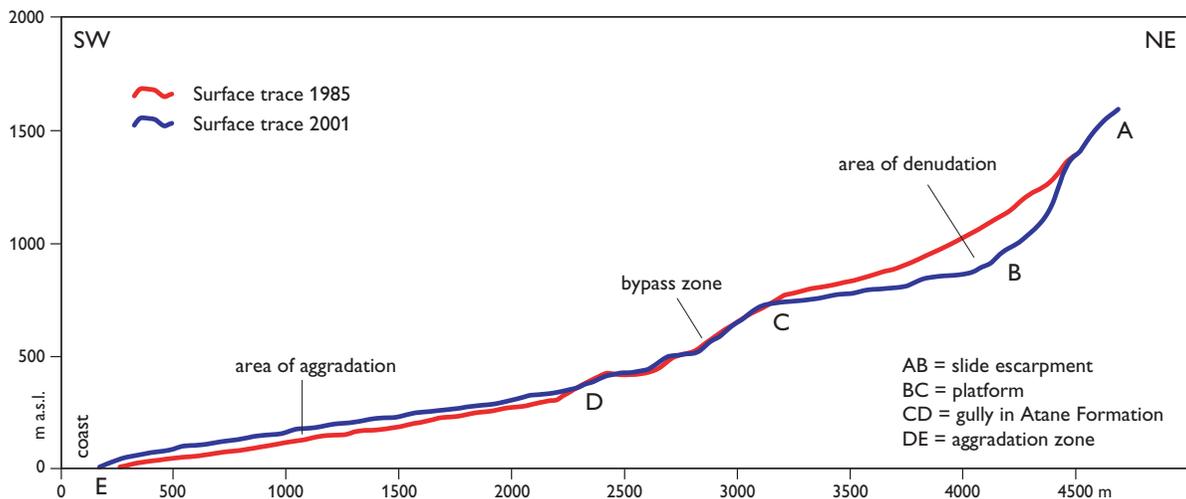


Fig. 7. The relationship between denudation (removal) and aggradation (deposition) regimes in a vertical topographic profile along the landslide area, based on aerial photographs from 1985 and 2001.

the landslide. This is in line with the statistics provided by Keefer (1999), who noted that earthquakes with magnitudes below 4 are unlikely to generate landslides.

Terrain model and volume calculations

Photogrammetrical mapping at the Survey has provided two topographical models of the terrain around Paatuut before and after the landslide. The first model was based on vertical aerial photographs taken in 1985 (scale 1:150 000), and the second model on oblique colour stereo photographs taken with a small-frame camera from a helicopter during the field work in July 2001. From these models (Fig. 7) the volume of displaced material (denudation) has been calculated to *c.* 90 million m³. The subaerial volume of the toe of the slide (aggradation) amounts to *c.* 60 million m³, which indicates that *c.* 30 million m³ of rock material entered the sea giving rise to the tsunami.

Discussion of landslide dynamics

The mechanism that triggered the landslide at Paatuut is open to discussion. The seismic data suggest that the event was initiated by instantaneous fracturing. The appearance of the escarpment at the head of the slide indicates that the escarpment may have formed along a pre-existing fault or fracture zone. The disrupted

character of the slide and the number of still ongoing small rock falls accompanied by clouds of dust, as observed in July 2001, support the idea of a fractured cliff. However, the question remains as to what initiated the release of the large volume involved in the slide.

The weather situation in the area prior to the release of the slide may be significant. A week before the event the weather was cold with temperatures below -10°C. Three days before the event a föhn wind blowing from the Inland Ice brought the air temperature up to about +6°C, but on the day before, the weather returned to colder conditions with temperatures down to -6°C. Free water produced during passage of the föhn may have seeped along fractures and fissures, subsequently freezing when it came into contact with the surrounding permafrozen rocks of the cliff and air temperature again dropped below zero. Frost action and resulting increased pore pressure may have triggered the rock fall.

The transformation of the rock fall into an enormous avalanche also raises questions. From the section at the coastal escarpment, black shale can be seen to have been involved in the landslide, and the shale may have acted as a lubricant facilitating the passage of the rock fall. The high velocity of the avalanche during passage through the gullies may have been accentuated by the presence of snow on the slopes. The data available suggest that a combination of grain flow processes and debris flow processes prevailed during transport through the bypass zone.

Grain flow is indicated by the presence of boulders deposited on the shoulders of the gullies at an elevation of 350 m a.s.l. Debris flow is interpreted from the matrix-supported conglomerate at the base of the section at the coastal escarpment, and this is further suggested by the large number of frost-mounds in the flat areas, reflecting the fine-grained character of the subsurface material.

Based on the considerations provided here and on the photogrammetric studies, a four-stage block diagram model of the landslide was constructed and is presented in Fig. 8.

Risk of landslides in the Disko–Nuussuaq–Svartenhuk area

Areas of low risk include most of Svartenhuk Halvø, where the mountains are neither high nor steep, and catastrophic landslides and tsunamis are unlikely to occur. Similarly the south coast of Nuussuaq south-east of Paatuut has a gentle slope, and the basaltic succession is thin and some distance from the coast. Landslides are known to occur in this area (Koch 1959), but mostly as slowly moving coherent slumps or block slides which are unlikely to initiate tsunamis.

Areas of moderate risk are encountered on the north coasts of Disko and Nuussuaq. Around Niaqornat slides form at low altitudes and apparently cause little damage, although houses should not be built closer to the mountain or west of the present village (Pulvertaft

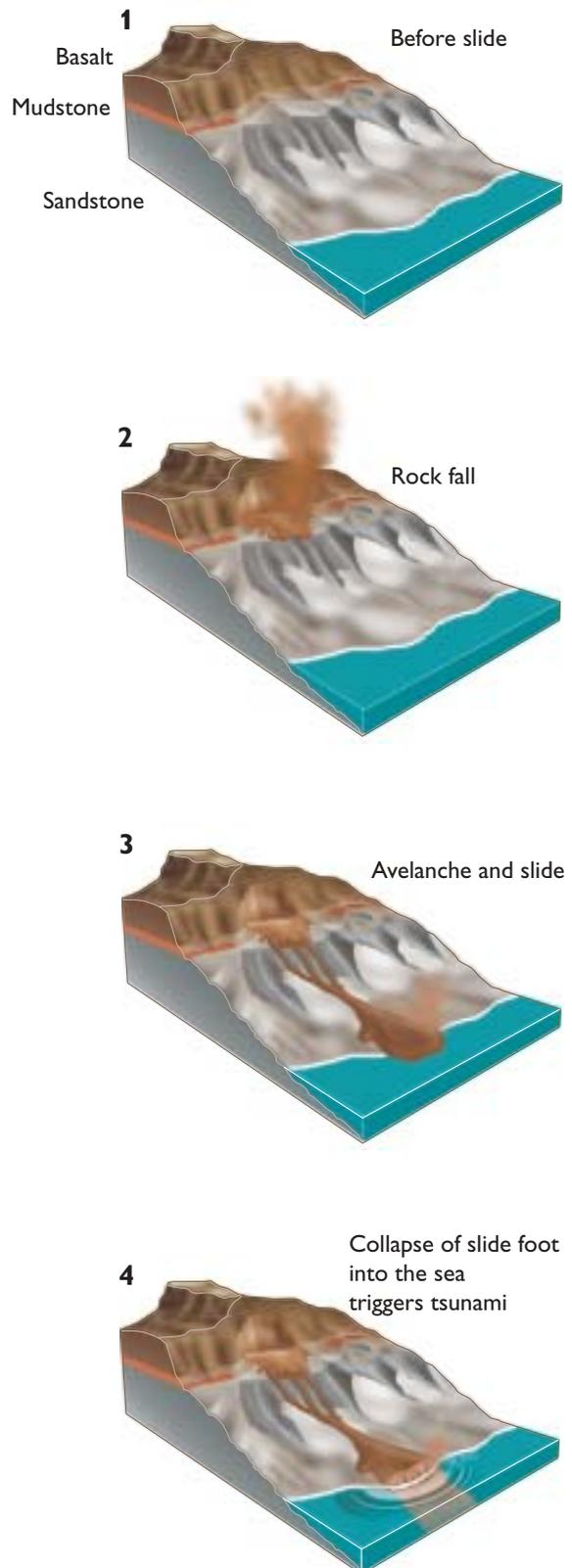


Fig. 8. The development of the landslide event at Paatuut on 21 November 2000, viewed from the west.

1, Cliff and valley slope prior to the landslide event. Note the small crescent-shaped feature in the right side of the diagram which is the head of a slide that was active in the last part of the 1980s.

2, Rock fall is triggered by frost fracturing and cliff cracking at the head of the slide. A large amount of dust is released during the cliff cracking.

3, Rock avalanche, grain flow and debris flow form the deposits at the toe of the landslide, building out into the sea. Note the lobe at the left side of the slide, which is mainly formed by a debris flow squeezed out by gravity spreading from the main landslide aggradation area. In the tailing end depression of this lobe a small lake was later formed, dammed by the toe of the slide.

4, One third of the landslide deposits, forming the tongue built into the sea, subsequently collapses and continues as a submarine slide, generating the tsunami. The steep coastal escarpment constitutes the head of this slide.

1979). Along other sections of the north-facing coasts the slides that occur are slow earth slides or rock glaciers.

Areas with a high risk of landslides accompanied by tsunamis are found on the south coast of Nuussuaq between Paatuut and Nuusap Qaqqarsua (Fig. 2). Here, the very steep slopes and the active erosion of the thick pile of hyaloclastite breccias generate thick, steep, high-lying debris fans, which are unstable and may easily slide.

Studies of aerial photographs show that at least 17 major landslides have occurred in the high-risk section prior to 1985, but only three of these slides are known to have reached the sea. In addition three landslides occurred at Paatuut between 1988 and 2000. Four of the twenty landslides generated within the last 3000 years reached the sea, and the minimum frequency of tsunamis is thus 1–2 per 1000 years. However, two of the four slides occurred within the last 50 years (1952 and 2000), and it may be that some older landslides have not been recognised due to fluvial reworking.

The historical record indicates that catastrophic landslides are not common. The town Qullissat was founded in 1924 and, apart from the slide in 1952 which caused some material damage and the loss of one life, the town has not been damaged by tsunamis in 76 years. In the coastal cliff at Asuk, the tsunami in 2000 disturbed graves several hundred years old. Although the graves were already somewhat damaged by ground creep or perhaps previous tsunamis, it is obvious that a tsunami like the one in 2000 is a rare event.

Prediction of future slides is not possible. However, it is certain that the lithologies and the morphology of the south coast of Nuussuaq from Paatuut and westwards will continue to generate landslides in the future.

Conclusions

The landslide at Paatuut on 21 November 2000 is interpreted as a rock avalanche initiated by a rock fall (Fig. 8). The fall was probably initiated by thawing and freezing in fractures at altitudes of 1000–1400 m a.s.l. The landslide removed 90 million m³ of scree and volcanic rocks which were transported to the coastal area with an average velocity of about 140 km/h. It built a lobe comprising *c.* 60 million m³, and *c.* 30 million m³ continued seawards in a submarine slide which initiated a tsunami and caused heavy damage in the coastal areas of the Vaigat strait. The slide deposited clast-supported conglomerates from modified grain flows, and matrix-supported conglomerates from debris

flows. Despite the high risk of landslides on the south coast of Nuussuaq the frequency of catastrophic landslides and tsunamis is not high. The seismic records make the Paatuut 2000 landslide one of the best-documented events of its type.

Acknowledgements

This project was funded by the Bureau of Minerals and Petroleum, Government of Greenland. Arktisk Station, Qeqertarsuaq, is thanked for use of their research vessel *Porsild* and for support during the field work.

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