Arctic tsunamis threaten coastal landscapes and communities - survey of Karrat Isfjord 2017 tsunami effects in Nuugaatsiaq, western Greenland

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Abstract

On the 17th of June 2017, a massive landslide which mobilized ca. 35–58 million m^3 of material entered the Karrat Isfjord in western Greenland. It triggered a tsunami wave with a runup height exceeding 90 m close to the landslide, ca. 50 m on the opposite shore of the fjord. The tsunami travelled ca. 32 km across the fjord and reached the settlement of Nuugaatsiaq with ca. 1-1.5 m high waves, which were powerful enough to destroy the community infrastructure, impact fragile coastal tundra landscape, and unfortunately, injure several inhabitants and cause 4 deaths. Our field survey carried out 25 months after the event results in documentation of previously unreported scale of damages in the settlement (ca. 48% of infrastructure objects including houses and administration buildings were destroyed by tsunami). We have observed a recognizable difference in the concentration of tsunami deposit accumulations between areas of the settlement overwashed by wave and areas where tsunami flooded terrain and return to the fjord. The key tsunami effects preserved in the coastal landscape were eroded coastal bluffs, gullied and dissected edges of cliffed coast in local harbour and compressed tundra by boulders or icebergs rafted on land during the event.

1 Introduction

Although known to the research community for at least 60 years, the occurrence, scale and impacts of tsunamis in cold regions (Arctic and subarctic) still shock the wider public. Their increasing frequency in this rapidly warming region already poses a serious threat to a fragile polar coastal environment and infrastructural needs of human communities.

The unstable nature of cold region landscapes in terms of permafrost-thawing or glacier retreat-or earthquake- induced landslides provide potential tsunami sources. The effects of waves are particularly destructive in fjords and narrow straits, where a constraining topography can amplify the wave heights. For instance, the landslide which entered Lituya Bay in Alaska in 1958 triggered the giant tsunami wave with runup height of over 500 m (Miller, 1960). Another wave (runup over 190 m) recorded in coastal Alaska (Taan Fjord, 2015) was caused by the landslide from local slopes destabilized by the retreat of Tyndall Glacier (Dufresne et al., 2018; Higman et al., 2018; Haeussler et al. 2018, Bloom et al. 2020). In the last hundred years tsunamis were recorded also in Norwegian fjords e.g. the Tafjord 1934 event (e.g. Harbitz et al., 2014).

In Greenland, due to the recent climate change (i.e. shrinking of glaciers and permafrost thawing) many mountain slopes were destabilized and released numerous tsunamigenic landslides. For example, in November 2000 a landslide from Paatuut mountain triggered a tsunami (runup ca. 50 m) which destroyed Qullissat town (Disko Island, western Greenland) and destabilized shores along Vaigat Strait even up to 150 km from the landslide site (Dahl-Jensen et al., 2004; Buchwał et al., 2015). The same region was also hit by a tsunami after the Niiortuut landslide in 1952, as mentioned in the recent inventory of Greenland landslides carried out by Svennevig (2019).

Here we report on the largest documented tsunami wave in Greenland to date (runup height ca. 90 m), which resulted from a massive landslide to Karrat Isfjord and destroyed the settlement of Nuugaatsiaq on the 17th of June 2017 (Figure 1). Based on field survey carried out two years after the event, our study provides insights into the lasting tsunami-induced geo-ecological changes in coastal landscape and in addition presents inventory of tsunami damages to settlement infrastructure.

2 Materials and Methods

This study is based on field observations carried out in July 2019. We followed the post-tsunami traces mapping described in the seminal paper of Szczuciński (2012) on post-depositional changes of onshore tsunami deposits. It is important to note that the visit occurred 25 months after the event, which means that at least two spring melt-out seasons happened between the event and the mapping. It is likely that some of the tsunami traces (particularly fine deposits, tsunami salt covers and iceberg erosional and depositional marks) were partly erased from the landscape. The largest boulders and litter lines were marked with a handheld GPS. We took a careful survey of the vegetation cover change, as suggested by Buchwał et al. (2015) in their study of 2000 Paatuut tsunami impact on an Arctic shrub ecosystem. We photographed each settlement building or facility (e.g. cemetery, playground, harbour, heliport) and noted any visible infrastructure and landscape degradation. We observed some signs of human action on the site, focused on removing most of the toxic substances left in the settlement, that is petrol. In order to properly understand the scale of post-tsunami changes we compared a series of aerial images (available at NunaGIS portal: www.nunagis.gl), field photos, online movies taken in the settlement before and after the wave, and settlement spatial planning maps and risk assessment documents published by the local government. Apart from land-based photos, we collected a number of aerial images using a DJI Mavic Pro drone. As our UAV was not allowed to enter the no-fly zone above the settlement centre, we took oblique images from the recommended distance. Information about landslide genesis and some of the tsunami wave characteristics were extracted from remote-sensing analyses produced by USGS (Bessette-Kirton et al., 2017) and the collection of geophysical reports published soon after the event (Clinton et al., 2017; Chao et al., 2018; Gauthier et al., 2018; Butler, 2019; Poli, 2017; Paris et al., 2019).

3 Research area

3.1 Geographical setting

The surrounding landscape is mountainous (mountain ranges with numerous summits and plateaus reaching 2000 m a.s.l) and is characterized by one of the highest relief in western Greenland (Roberts et al. 2013). The major role in shaping the present-day geomorphology was played by retreating Uummannaq ice stream system (UISS) which left the diverse set of glacial landsystems in fjords, mountains and valleys of the region. The landscape was dissected by selective linear glacial erosion with lowlands dominated by glacial scour and mountain ranges occupied by cirque, plateaus, and valley-type glaciers (Lane et al. 2016). Lane et al (2016) classified banks of Karrat fjord and southern coasts of Qeqertarsuaq island, where studied settlement is located, to areal scour terrestrial landsystem exposed after the retreat of two northern branches of UISS (Umiamako Isbrae and Rink Isbrae). Ice streams significantly modelled the topography of local fjords. Dowdeswell et al. (2016) described submarine landscape (Rink Fjord and Karrat Isfjord) a system with relatively smooth seafloor, broken by bedrock ridges and pinnacles that divide the fjord into several deep basins. Bathymetry maps derived from multibeam echo soundings data acquired in 2007-2014 and compiled by Rignot et al. (2016) revealed that the entrance to Karrat Isfjord is 600 m deep, 5 km wide, with a sill at 400 m depth about 160 km from Rink Isbrae The deepest basin of the fjord (1100 m) is located ca. 25 km to the east of Nuugaatsiaq. Fjord near the settlement is shallow with seafloor depths 0-240 m.

Nuugaatsiaq coastal landscape is predominantly rocky with an undulating and ragged coastline dissected by narrow coves and headlands (Fig.2a). Rocky coves along southern coast of Nuugaatsiaq are filled with narrow beaches underlaid by rocky bedrock (Fig. 2a). Beach deposits are thin (< 1m) and composed of mixed coarse sand and gravel deposits as well as boulders deposited by icebergs or left along the shores by retreating ice streams. The largest cape in the area, located to the SW of the settlement centre is characterized by bare rocky surface with well-preserved signs of glacial scour e.g. striations and polished bedrock (Fig.2b). Close to the shoreline most of smooth rocky hollows were filled with accumulations of boulders (ca. 0.2-0.5 m in diameter). The Nuugaatsiaq harbour (site 7 in Fig. 1c) is backed by the cliffed coast (between 2-4 m high) formed in bedrock (ca. 0-2 m .a.s.l.) and overlaid by 1.5 – 3 m layer of soils/glacial deposits and covered with dense tundra (Fig. 2c). At the base of the cliff narrow (1-3 m wide) mixed sand-gravelly beaches are present.

3.1.2 Geology

The dominant rocks in the region are Archean gneisses mixed with supracrustal rocks of the Palaeoproterozoic Karrat Group (Sørensen and Guarnieri, 2018). The slopes of Ummiammakku mountain where the tsunamigenic landslide occurred are composed of gneisses (Archean) overlain by quartzites (Palaeoproterozoic) and schist of the so-called Karrat Group (Mott et al., 2013).

3.1.3 Permafrost

The study area was historically included in the continuous permafrost zone (Christiansen and Humlum, 2000). Most recent northern hemisphere permafrost map based on the modelling of temperature at the top of the permafrost (2000-2016) at the 1 km^2 scale presented by Obu et al. (2019) place it close to the boundary zone between continuous and discontinuous permafrost zone. To our knowledge no direct ground temperature measurements have been conducted in the close surroundings.

3.1.4 Vegetation

This area is a part of the mid-arctic oceanic vegetation zone (Bay 1997). The vegetation comprises a shrub-grassland system, with commonly found circumpolar species including *Carex ursina*, *Cassiope* heath, *Salix glauca*, *Festuca groenlandica, Puccinellia groenlandica*. Coastal grasslands are dominated by dense Honckenyo-Elymetum mollis associations (Lepping & Daniëls 2007). Inspection of satellite images and photographs taken in Nuugaatsiaq before the event suggest that grassy-tundra covers dominated the top of coastal bluffs and stripe of coastal lowlands between the predominantly rocky shore and main coastal road passing the settlement from west to east. During our fieldwork we noticed very dense and relatively high (0.4 – 0.6 m) grassy meadows covering coastal lowlands, and recolonizing abandoned playgrounds, roads, backyards. The observed post-event vegetation cover in study area was significantly denser and higher than in other settlements visited in the region in the same season.

3.2 Settlement history & economy

Nuugaatsiaq is a settlement in the district of Uummannaq in the Avannaata Kommunia. Nuugaatsiaq is located in the south of the Qeqertarsuaq Island (Fig.1), dominated by Snehætten (Nuugaatsiap Qaqqaa) mountain range The island is separated from Karrat Island located between Karrat Fjord and Karrat Isfjord by the Torsuuk strait. The closest settlement is Illorsuit and lies about 35 km south-west.

Nuugaatsiaq was probably settled shortly after 1918. In 1923 it was proposed in Grønlands Landsråd to divide the municipality of Illorsuit. For this purpose, a new Udsted had to be built. Udsted (roughly translatable as outlying settlement): Udsteder were smaller trading settlements, which were administered by an Udsteds administrator. Most of the Udsteders later became villages. In 1925 Nuugaatsiaq was granted Udsteds status and in the same year a dwelling was built for the Udsteds administrator. In 1926 the village received a school chapel. In 1930 Nuugaatsiaq already had 119 inhabitants. In the same year a shop with a warehouse was built and in 1936 a packing house (Madsen 2009). In 1960 the population reached its maximum with 159 people. In 2017 the settlement had 102 inhabitants (bank.stat.gl).

Nuugaatsiaq has been living mainly from halibut fishing, while some time ago there was still seal hunting and catfish fishing. A small trading branch of Royal Greenland with a maximum of ten employees stored the fish. Other jobs were in administration, at Pilersuisoq, in tourism and at Atuarfik Saamu School, which taught twelve students in grades one to nine and also offered a library and youth leisure activities. There was also a day care centre, the post office, an infirmary, and a village hall. Majority of buildings were located on undulating coastal lowland between 1 to 4 m a.s.l. (Fig.3a)

There is a small quay on the headland that gives the village its name. Most of the boats were usually launched directly at the water's edge in small harbour. In the north is the heliport Nuugaatsiaq. In winter, the traffic was by snowmobile and dog-sledge.

Nukissiorfiit (state utility company) supplied the village with electricity via the power station in the east and with fresh water via a tank. Garbage was burned or dumped into the sea. TELE Greenland provided the telecommunications.

The events of June 17th 2017 resulted in the evacuation of settlement and abandonment of community which last till present. Currently former inhabitants of Nuugaatsiag were relocated to Uummannaq and Qaarsut settlement placed over 100 km south of Nuugaatsiaq (Fig.1).

4 Results and discussion

4.1 Landslide and tsunami characteristics

According to the analysis of seismic precursors of the Event carried out by Butler (2019), the tsunami was a direct result of the landslide triggered by the following sequence of processes. An earthquake ruptured the fault surface and released the hanging wall ca. 1000 m above the sea, and a head scarp was created and transformed into a rock avalanche which entered the fjord, causing the wave. Gauthier et al. (2018) calculations suggest that the Karrat fjord landslide was much larger (~35-58 x10ˆ6 m^3) than the famous tsunamigenic rockslide into Lituya Bay, Alaska in 1958 (~30x10ˆ6 m^3). Interestingly, on the map of the Nuussuaq Basin showing landslide prone areas published by Pedersen et al. (2002), the Karrat Fjord region is not marked as a potential risk area.

A field survey carried out by a group of researchers led by Professor Fritz from the Georgia Institute of Technology (Schiermeier, 2017; https://ce.gatech.edu/news/after-recon-trip-researchers-say-greenland-tsunami-june-reached-300-feet-high) found evidence that the wave runup height was ca. 90 m at the landslide site, and up to 50 m on the opposite side of the Karrat Fjord. Numerical modelling of the landslide and wave performed by Paris et al. (2019) indicates that the Nuugaatsiaq located ca. 32 km from the landslide was hit by three 1 – 1.5 m high waves, inundating the settlement over a period of ca. 3 minutes.

4.2 Landscape degradation

4.2.1 Soil and tundra cover

The striking feature of the Nuugaatsiaq post-tsunami landscape is a dense and high (0.4-0.6 m) grass that covers a significant part of the settlement (Fig. 2a). Two years after the event most of the blocks of eroded soil, rafts of tundra, boulders, or litter that were found were almost entirely hidden in a high grass cover (Fig. 4a). The wave has torn blocks of tundra (shrubs, mosses, grass) off the coastal slope and deposited them on land (Fig. 4 b, c). We have noticed that a significant removal of tundra cover, soil erosion, and associated formation of rills or small gullies (0.2-0.6 m deep) concentrated on surfaces exposed after the washing away of buildings. Tundra and soil were also eroded along the cliffed coast of the harbour (Fig. 4 d, e). At a few places along the main road and in the surroundings of the playground the vegetation cover (grasses) was covered by a thin layer of tsunami deposits (3 – 7 cm) composed mainly of marine gravels mixed with coarser sands. Salty patches with dead-vegetation were observed mainly across the saddle between southern coast and local harour (site 6 in Fig. 1c). After analyzing the video coverage of the event and post-event images (please check list of online resources in references), we assume that some parts of the grass cover were compressed by the fragments of icebergs or ice-floes washed on shore by tsunami. In sites where ice-berg or ice-floe were deposited and melted away grasses were weighted down and melt-out sediments (gravel, sand, mud) was observed between grass blades. Such spots were surrounded by lush grassy tundra. Tundra was compressed also by tsunami-derived boulders both eroded from beaches and melted out of icebergs (Fig. 3b).

4.2.2 Coastal erosion

We recognized two main effects on coastal geomorphology induced by tsunami impact. The tsunami erosion was concentrated on the low bluffs of tundra along the coast between narrow beaches (section of the coast between sites 1-4-5 in Fig. 1c, Fig 2a). Eroded blocks of tundra cover were deposited on land (Fig. 4b). The returning wave caused additional erosion of bluffs edges and dissected them by a series of rills/gullies (Fig. 4d). The direction of the wave flow recorded in the orientation of deposited litter, buildings, marine deposits, boulders, and tundra blocks suggest that the wave overwashed the section of settlement through a saddle (site 6 in Fig. 1c) between the middle beach (site 4 in Fig. 1c) and local harbour (site 7 in Fig. 1c), and modified the relief of cliffs in the harbour. The edges of the sedimentary cliffs were gullied, and the steep cliff slopes were spread with eroded blocks of tundra and litter (Fig. 4e). Two years after the event, normal coastal processes (wave and tidal action) did not manage to remove or redistribute the eroded blocks of tundra and litter from the slopes and bases of the cliffs (Fig.2c).

4.2.3 Tsunami deposits and boulders

During the field survey the tsunami deposits were found in two areas located in the direct proximity to small beaches in the central part of settlement (between sites 4 and 5 in Fig. 1c). Sand and gravel washed from narrow and thin beaches was deposited along the main road (ca. 30 - 50 m from the shore), where the thickness of deposits exceeds 8-10 cm (Fig. 5 a,b). Thin layer of tsunami deposits (3 – 5 cm), most probably reworked by snow-melt flow (Fig. 5 e, f) were found in the saddle (playground area) between site 4 and 7 (see Fig. 1c). The general scarcity of tsunami deposits can be explained by the geomorphology of the local coastal zone, dominated by sediment-free rocky capes and coves with narrow (7-20 m wide), gravel-dominated beaches (Fig 2a). Apart from gravel deposits washed from local beaches waves transported boulders which were found in the inundated terrain in 2 main types: groups of smaller boulders (a-axis ca. 0.2-0.4 m) deposited on marine gravels along the local road, and separated larger boulders (a-axis over 1.0 m), washed up to 100 - 120 m inland between beach and local harbour (Fig. 5 b,f). In a few places we found pats of marine gravels and boulders deposited up to 100 m from the shore and surrounded by dense grass cover (Fig. 5 c,d). Based on the inspection of videos taken during the event we correlated their location with the deposition of icebergs. In comparison with other Greenlandic coastal zone transformed by a tsunami i.e. Paatuut 2000 tsunami (Buchwał et al., 2015) the thickness, extent, and diversity of tsunami deposits found in Nuugaatsiaq was much smaller, what we associated with sediment-poor beach source and predominantly rocky coastal relief with sediment-free and glacially scoured surfaces. We detected the recognizable difference in tsunami landscape modification between the areas of wave overflow covering most of the saddle in central part of settlement (site 6, Fig. 1c) and area of wave uprush and drainage covering eastern part of the settlement (terrain between sites 1 and 2, Fig. 1c). In the first zone, tsunami eroded material (sand, gravel, boulders) from largest beach in the settlement and fragments of sedimentary and tundra bluffs covering rocky coastal slopes (site 4– Fig. 1c) and transported this mixed load of deposits through settlement to the harbour (site 7, Fig. 1c). This explains larger number of sites and zones with accumulations of tsunami deposits, signs of tsunami erosion and infrastructure destruction concentrated in this zone. In the second area, tsunami waves approached rocky coastal zone, almost sediment free, and inundated grassy lowland carrying mainly community litter and only small amount of sediments, which was difficult to trace in lushy tundra vegetation inspected 2 years after the event.

4.3 Settlement degradation

4.3.1 Infrastructure damage

Before the tsunami event the Nuugaatsiaq community infrastructure was composed of 94 buildings (houses, services and administration buildings, dog kennels, technical facilities etc.). The wave destroyed 45 buildings (48% of the original infrastructure) within: 22 buildings were fully swept away from land, 23 buildings were partly broken and 11 of them were moved between 2 m to over 100 m from original location (Fig. 6). Most of the buildings were constructed on a wooden frame, covered with wooden boards and settled on pier foundations. Only a few of the settlement buildings were built on a metal frame coated with corrugated metal sheet settled on a concrete frame foundation. The first type of building (with pier foundations) were not strong enough to resist the wave impact and were pushed by the tsunami or in some cases washed away to the fjord (Fig. 7 a,c).

In those buildings which were not moved but still affected by the wave, we observed some damage of their wooden lining, as well as a deposition of marine sediments and litter in the ground floor area. The typical damages observed in buildings which were pushed by the tsunami but remained on land were: *broken windows and doors, devastated interior*. In contrast to buildings with pier foundations, much smaller damages were observed in buildings with concrete frame foundations. These, due to a more stable anchoring in the ground, gave a much higher resistance to the wave impact. The most common damages included broken walls, bowed and twisted metal construction frames (Fig. 7 b, d). It should be considered extremely fortunate that the fuel tanks situated at the power plant (which were one of the first parts of infrastructure hit by tsunami) were not destroyed and no leakage of petrol was reported (Fig. 7b).

4.3.2 Assessment of social, economic and environmental impacts of tsunami in Nuugaatsiaq.

The Karrat fjord tsunami, which hit Nuugaatsiaq settlement in 2017, was the first event which had such a devastating effect on inhabited Arctic settlement, both in terms of landscape modification and infrastructure damage. Previous waves known from the Arctic region such as Lituya (1958), Taan (2015) flooded unpopulated and remote areas. In Greenland the Paatuut tsunami (2000) damaged the infrastructure of Qullissat, however in this case, due to the closure of unprofitable coal mine (1972) the settlement was already abandoned years before the event. Therefore, this is the first time an assessment of social and economic effects of a tsunami in this region was possible to undertake (Table 1).

The financial data from the Government of Greenland (Naalakkersuisut) documents (Forslag til TILLÆGSBEVILLINGSLOV for 2017, from 2018/8), shows the costs associated with the relocation of tsunami victims of 14 877 000.00 DKK (ca. 2 248 085.00 USD [15.05.2020]) which can be treated as a rough estimate of an economic cost of the event. The document also declares a one-off payment to tsunami victims amounting to DKK 50,000 (7548.00 USD [15.05.2020]). In our opinion the total economic cost was significantly higher as the total market value of 45 destroyed settlement infrastructure objects (incl. buildings) was not included in the reports. Nevertheless, the settlement remains abandoned to this day and the threat of another tsunami wave remains active (Fritz et al. 2018; Paris et al. 2019). Apart from the tragedy of 4 fatalities, 9 wounded inhabitants and countless dog deaths, the catastrophe still has its social repercussions. Thirty-nine people were evacuated and separated into the settlements of Uummannaq and Qaarsut. The

Displaced have lost their life's work, their hunting area, sentimental value, and social bounds. In their new places more expensive rent, isolation and adaptation difficulties often awaits them (*personal communication* of local respondent).

From the perspective of environmental protection and coastal management, the remaining material and waste in the settlement area still constitute a serious hazard. Despite the considerable effort from the local government to secure the site through reinforcement of damaged constructions, pumping fuel out of the tanks, the removal of batteries and engines from machines and vehicles, we mapped significant amounts of waste (Fig. 7 e-g). We found broken pieces of electronic equipment, ammunition, rotting food supplies, bags with faecal matter, sledge dog carcasses, and other municipal waste which had not been disposed from the settlement before and after the event (Fig. 7). In Nuugaatsiaq plastic litter is widespread not only along narrow beaches (already mixed with beach sediments), but also spread long main road of the settlement and around overwashed saddle between southern coast and harbour, and subject to further transport by strong winds (Fig. 7). Plastic waste is a serious problem of Arctic coastal environments and Nuugaatsiaq case is unfortunately another contributor to this type of environmental pollution (e.g. Cózar et al. 2017; Bergmann et al. 2017; Jaskólski et al. 2018). After the evacuation of Nuugaatsiaq the disposal of waste and better securing of damaged infrastructure at the site is hindered by the existing high risk of another tsunamigenic landslide in Karrat Fjord (Paris et al. 2019).

4.4 Arctic coastal communities threatened by tsunamis – rising risk and rising awareness

One of the most evident effects of Arctic climate warming is the increased operation of geohazard processes along the circumarctic coasts (e.g. Fritz et al., 2017). The majority of these processes pose a significant threat to Arctic coastal communities and man-made infrastructure (e.g. Forbes et al., 2011; Radosavljevic et al., 2016; Jaskólski et al., 2018). Most of the recent Arctic coastal change studies concentrated on accelerated coastal erosion rates in locations spread across the Arctic region and associated them with diminishing sea-ice extent, longer exposure to storm wave impacts, and thawing coastal permafrost (e.g. Farquharson et al., 2018; Irrgang et al., 2018;; Isaev et al., 2019). Also, in glaciated parts of the Arctic, such as Greenland or Svalbard, coastal research focused on the response of coastal zone to increased delivery of glacial sediments (e.g. Bendixen et al., 2017; Strzelecki et al., 2018) or rocky coast interaction with coastal permafrost (e.g. Strzelecki et al. 2017; Lim et al. 2020). At the same time little attention was paid to Arctic tsunami hazards whose effects are devastating to both human and natural coastal environments. The recent examples of Arctic tsunamis in Alaska (Taan 2015) and Greenland (Paatuut 2000, Karrat 2017) demonstrate how severe impacts on coastal environments and communities can be. It is important to note that with continued warming (favouring permafrost thaw, glacier retreat, or extreme meteorological phenomena), such tsunamigenic landslides are likely to be far more frequent.

To put it into a Greenlandic perspective, the recent mapping of potential tsunamigenic landslides performed by Svennevig (2019) indicated 564 landslides just between Sigguup Nunaa and Qeqertarsuaq in West Greenland. Benjamin et al., (2018) mapped 20 rock avalanches just along one short section (ca. 25 km) of southern coast of Nuussuaq Peninsula in a direct proximity of Vaigat Strait (similar avalanche triggered Paatuut tsunami in 2000). Svennevig et al. (2019) demonstrated that the area around the Karrat Fjord landslide has continued to be active and another tsunamigenic landslide is highly probable.

Although beyond the scope of this study, here it is important to mention another type of extreme phenomena impacting Greenlandic coastal zone - waves triggered by iceberg-roll events that are powerful enough to erode local beaches and wash away coastal infrastructure (Long et al., 2018). Calving of Greenlandic glaciers also produces extreme waves that are able to erode glacial landforms and lead to substantial degradation of coastal landscape (e.g. Lüthi and Vieli, 2016). It is important to note that with continued temperature warming in the Arctic, such landslides, glacier calvings and iceberg rolls are projected to be far more common.

5 Conclusions

Based on the observations we have drawn the following conclusions:

- The Karrat Fjord event is the first known example of Arctic tsunami which directly impacted an Arctic inhabited settlement and forced it evacuation;
- The scale of tsunami damages, including destruction of a majority of buildings (48% of settlement community infrastructure) and a high risk of another event, prevents the community to return to the settlement;
- Apart for housing facilities, 3 waves destroyed most public service buildings e.g. school, power plant, shopping centre, administration centre, seafood processing plant;
- Among the waste accumulations left in the area are: electronic equipment, rotting food supplies, faecal matter, sledge-dog carcass, as well as ammunition and a lot of municipal waste, including a large quantity plastic. Most of the waste is completely unprotected and exposed to weather conditions and wildlife;
- The geomorphological effects of tsunami were less pronounced than in previously described examples of Arctic tsunami impacts (Lituya 1958, Paatuut 2000, Taan 2015) which can be explained by the local coastal morphology and geology (rock dominated coasts with small and sediment-poor beaches) and relatively low waves heights (1-1.5 m);
- Mapped tsunami deposits included gravel-dominated beach sediments, boulders and material which melt out from fragments of ice-bergs stranded on land;
- Two years after the event the effects of tsunami erosion was still detectable on the surface of local roads and edges of sedimentary cliffs along the local harbour;
- In the warming Arctic region, the landslide-triggered tsunamis become one of the most important geo-hazards with profound effects on the functioning of coastal communities and landscapes.

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Data availability. Data in this paper can be made available for scientific use upon request to the authors

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s%2FAttached%2520Files%2FFinans%2FDK%2FFinanslov%2F2019%2FForslag%2520til%2520till%25C3%25A6gs bevillingslov%25202017%2520-%2520DK%2520-%2520til%2520tryk%2520-tilrettet.pdf&usg=AOvVaw2DYonv9AClR7jkkHOTYPo0 , last access: 08 November 2019.

Figures and Tables

<table>
<tr><th colspan="3">Observed tsunami impacts in Nuugaatsiaq</th></tr>
<tr><th>Environmental</th><th>Social</th><th>Economic</th></tr>
<tr>
<td>• Landscape degradation (tundra and soil erosion, salt residues, coastal erosion)

• hazardous materials left on site and exposed to harsh climate

• waste accumulations

• rotting food supplies easily accessible to wildlife</td>
<td>• separation of the community, relocation of people to Uummannaq and Qaarsut

• loss of a logistic point for expeditions (hunting, fishing) for other settlements

• loss of settlement continuity

• loss of sentimental value

• relocated people forced to pay more expensive rent in new substitute premises

• isolation and adaptation difficulties in a new place

• 39 people evacuated https://knr.gl/da/nyheder/39-evakueret-fra-nuugaatsiaq

• 4 fatalities, 9 injured https://knr.gl/da/nyheder/fjeldskred-i-karrat-isfjorden-skyld-i-flodb%C3%B8lge

• death of sledge dogs (during the inventory found 4 carcasses)</td>
<td>• costs of relocation, reparations and accommodation recognized in the budget for 2018 in the municipality of Naalakkersuisut DKK 14,877,000 (Forslag til TILLÆGSBEVILLINGSLOV for 2017, from 2018/8)

• the need to allocate substitute accommodation and a one-off compensation payment of DKK 50,000

• impoverishment and loss of property (new premises are not given)

• at least 27 sites with destroyed community infrastructure</td>
</tr>
<tr><th colspan="3">Future risk reduction actions in Arctic coastal communities</th></tr>
<tr>
<td colspan="2">Earth science and remote sensing research community:
• mapping and detection of landslides and recently slopes exposed from glacier ice or with significant degradation of permafrost
• mapping/re-mapping seabed topography of deglaciated fjords and embayments
• monitoring of present-day slope processes (slope stability)
• investigations of paleo-records of waves
• design of databases with seismic, remote sensing, geophysical and sedimentological information of past and recent tsunamigenic landslides and associated waves</td>
<td>Local authorities:
• funding tsunami alert network
• preparation of evacuation plans/delimitation of safe zones
• consideration of tsunami and landslide hazard in spatial plans/documents
• establishment of insurance procedures and securing financial reserves to cover post-event costs of relocation and reinstalment of communities in new locations</td>
</tr>
</table>

Table 1. Summary of tsunami effects on coastal landscape and Nuugaatsiaq community and recommended hazard risk reduction actions.

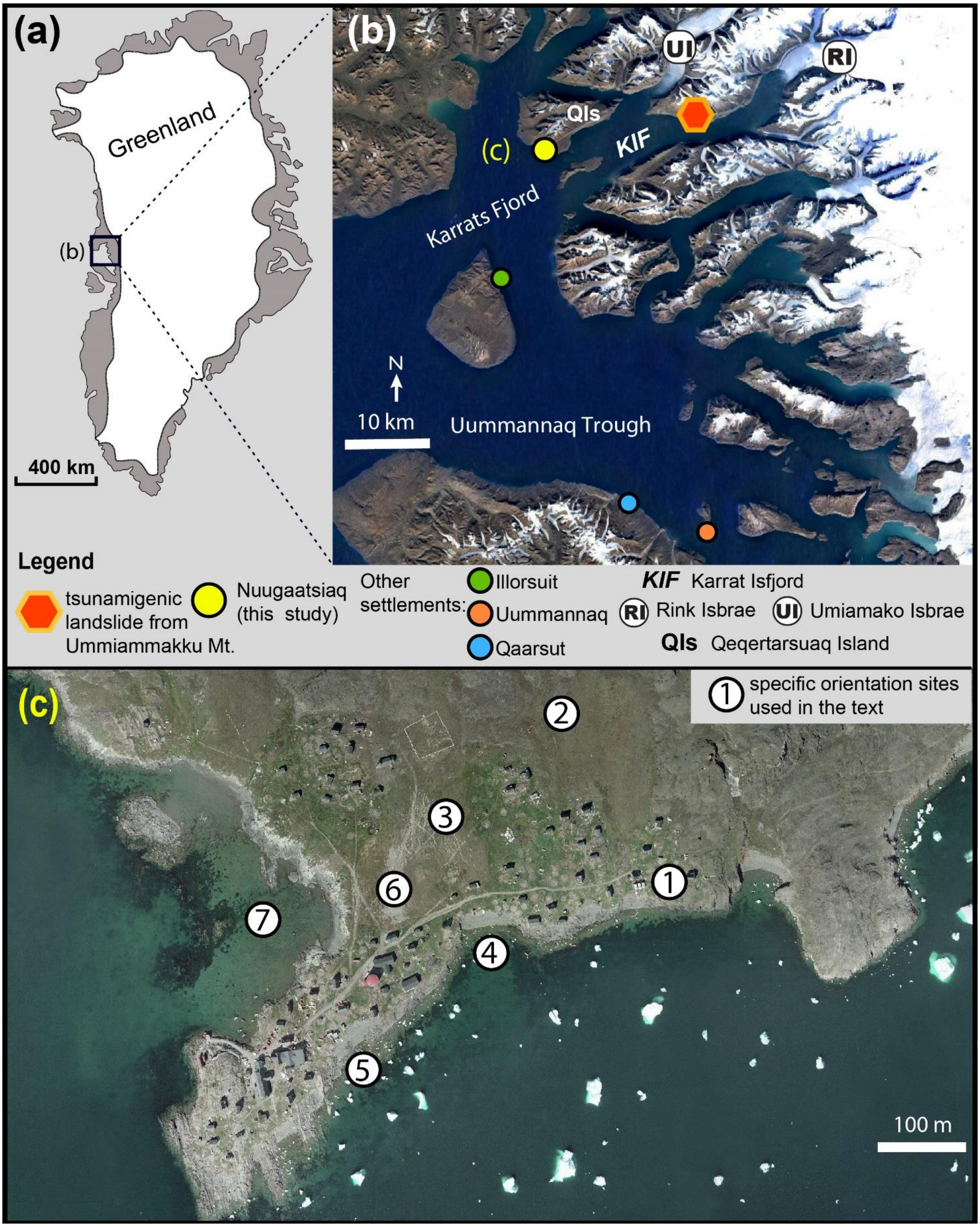

Figure 1. Location of study area. a) General position of Karrat Fjord in western Greenland (Source: Google Earth); b) Karrat Fjord area, where tsunamigenic landslide occurred on 17 June 2017 and inundated settlement of Nuugaatsiaq; c) Aerial image of Nuugaatsiaq before the event (nunuagis.gl), Number in circles mark orientation sites used in the text 1 – area with first line of buildings destructed by tsunami, 2 – heliport above the tsunami inundation limit, 3 – playground area, partly flooded by tsunami, 4 – first beach eroded by tsunami; 5 – second beach eroded by tsunami; 6 – saddle between beach(4) and harbour; 7 – local harbour.

Figure 2. Coastal landscapes in Nuggatsiaq. (a) Densely vegetated (grasses and shrubs) coastal lowland with ragged shoreline dissected by rocky capes and coves with narrow beaches; (b) Main headland with exposed glacially scoured bare rock surfaces, note accumulations of boulders in rocky hollows; (c) Cliffed coast in Nuugaatsiaq harbour. Tops of the cliff were eroded and gullied by tsunami.

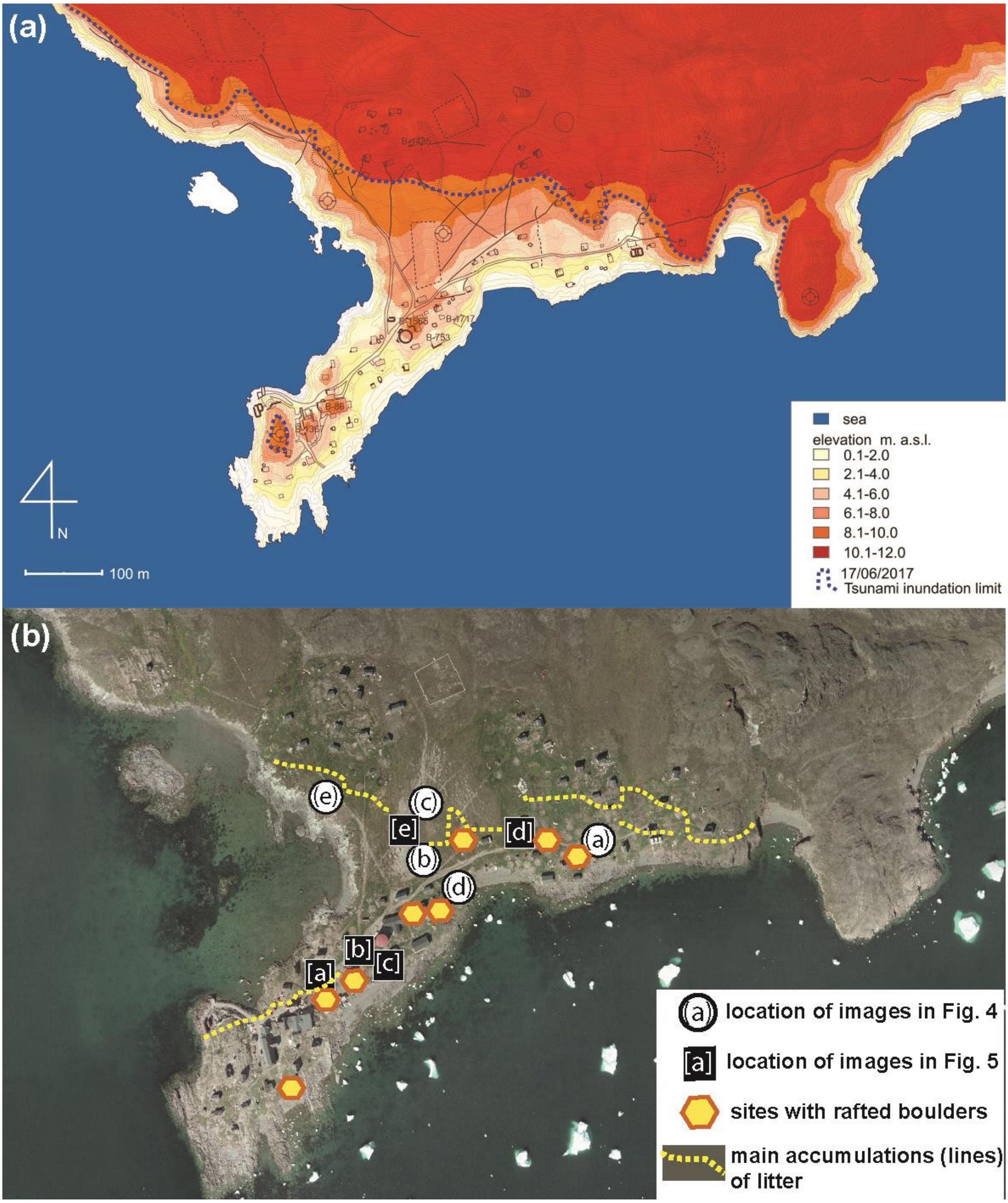

Figure 3. (a) Digital elevation model (2-m DEM, https://www.pgc.umn.edu/data/arcticdem/) of Nuugaatsiaq with marked tsunami inundation limit (wave flooded the terrain up to 8 m a.s.l). (b) Overview map of the settlement with marked location of images from Fig. 4 and 5. Lines of litter visible in the landscape 2 years after the event and sites were large boulders rafted by tsunami were marked too. Background: technical map of settlement from nunagis.gl

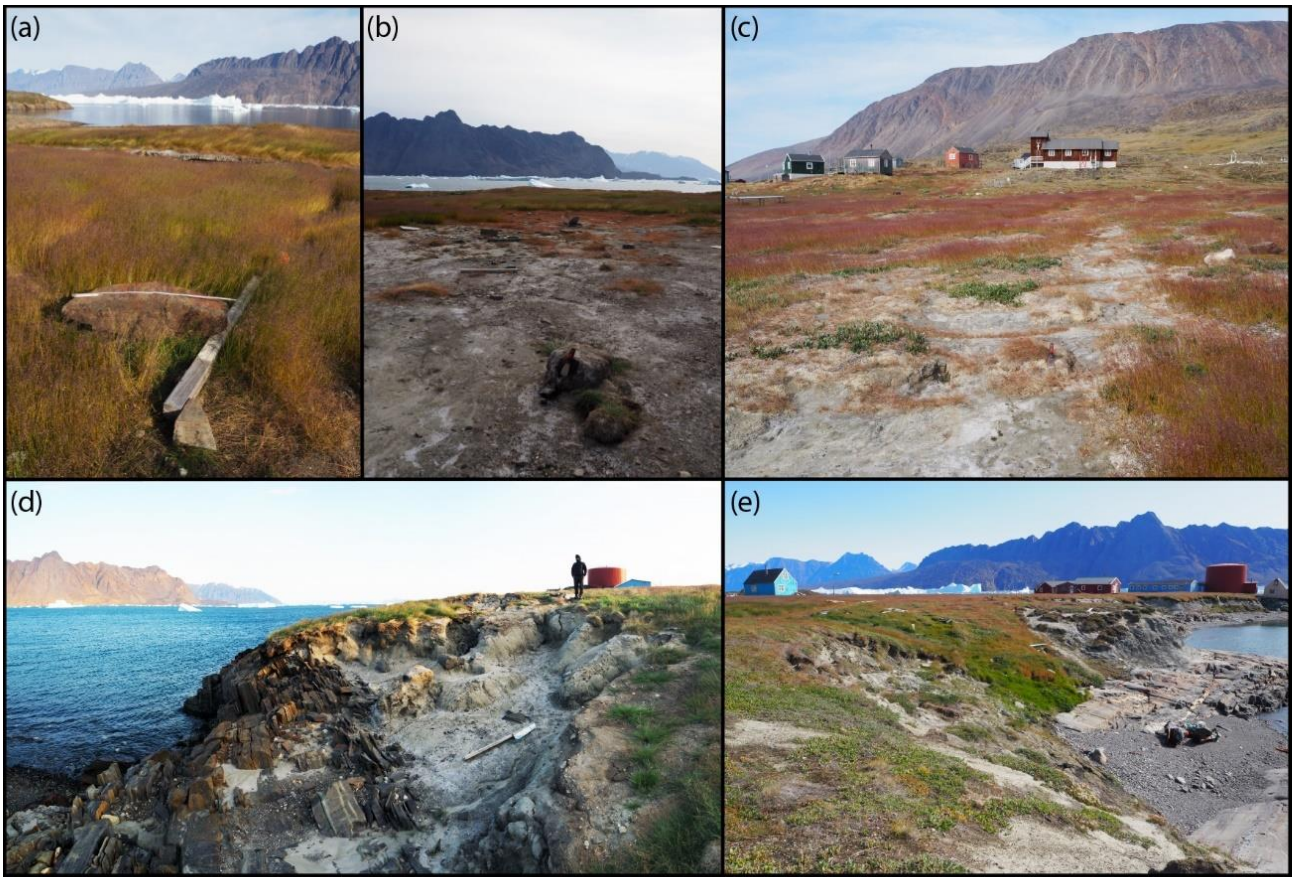

Figure 4. Examples of tsunami effects on tundra and soil covers in Nuugaatsiaq two years after the event. (a) High grass covers eroded tundra blocks, boulders and litter deposited by tsunami; (b) eroded tundra block/raft deposited on the coastal lowland inundated by tsunami with thin layer of redistributed marine sediments and salt covers; (c) deposited tundra and soil blocks and gullied ground surface by wave which backwash to the fjord; (d) eroded edges of low bluffs above the small beach (site 4 in Fig. 1c); (e) cliffed coast heavily dissected by tsunami which overwashed the saddle (site 6 in Fig. 1c) between beach (site 4 in Fig. 1c) and drained to local harbour (site 7 in Fig. 1c).

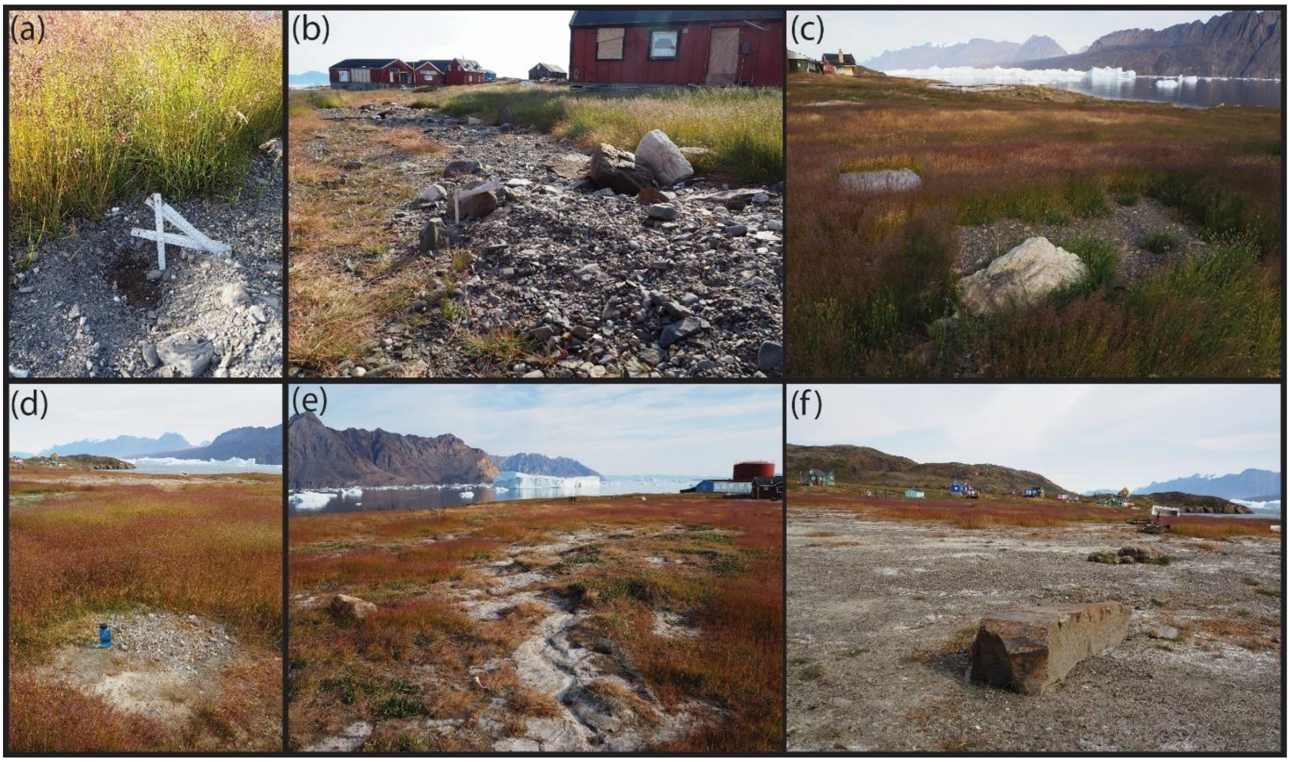

Figure 5. Examples of tsunami deposits preserved in Nuugaatsiaq two years after the event. (a) Ca. 4-6 cm thick cover of marine gravels covering grass vegetation; (b) Up to 10 cm thick layer of tsunami deposits eroded from local beach and deposited on road and grass vegetation; (c) Melt-out material from iceberg (gravels and mud) and ca. 100 cm long boulder thrown onshore by tsunami; (d) Deposits melted-out from iceberg washed on shore by waves; (e) rills eroded in soil and tsunami deposits by returning wave; (f) Over 100 cm long boulder moved by wave on the thin layer of gravels and eroded soil deposits. Note salty surfaces and eroded tundra rafts in the background.

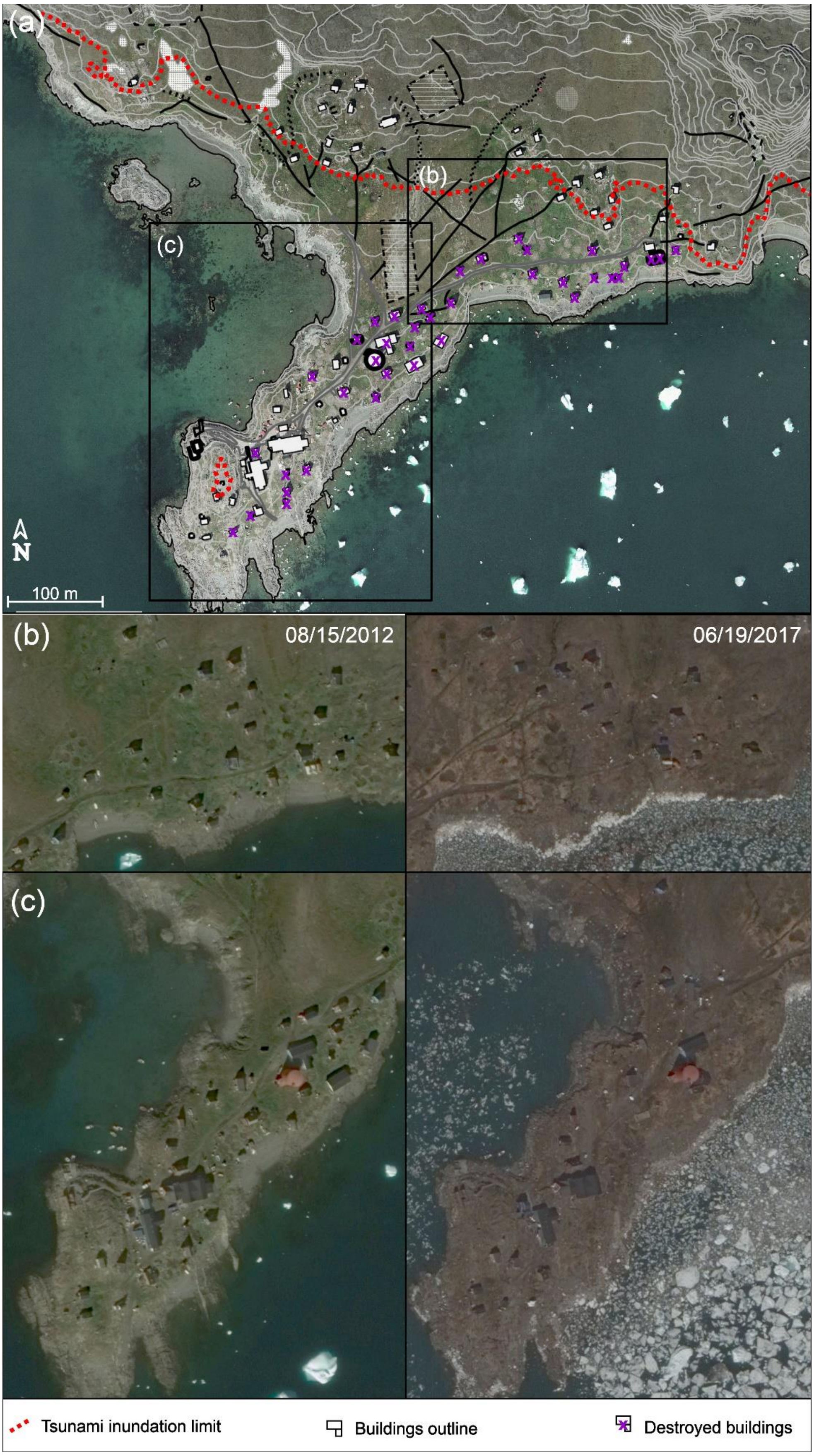

Figure 6. Scale of destruction in settlement infrastructure. (a) General overview of area inundated by tsunami
550 with location of damaged buildings. The inventory of tsunami-induced changes of settlement infrastructure are based on interception of aerial images, local spatial plans and field surveying. Background ortophoto & technicalmap: nunagis.gl.; (b) Satellite image of settlement before the tsunami impact (15th August 2012) and; (c) Satellite image of settlement after the tsunami impact illustrate the scale of destruction and dislocation of buildings (19th June 2017) Background Google Earth Image © 2020 Maxar Technologies.

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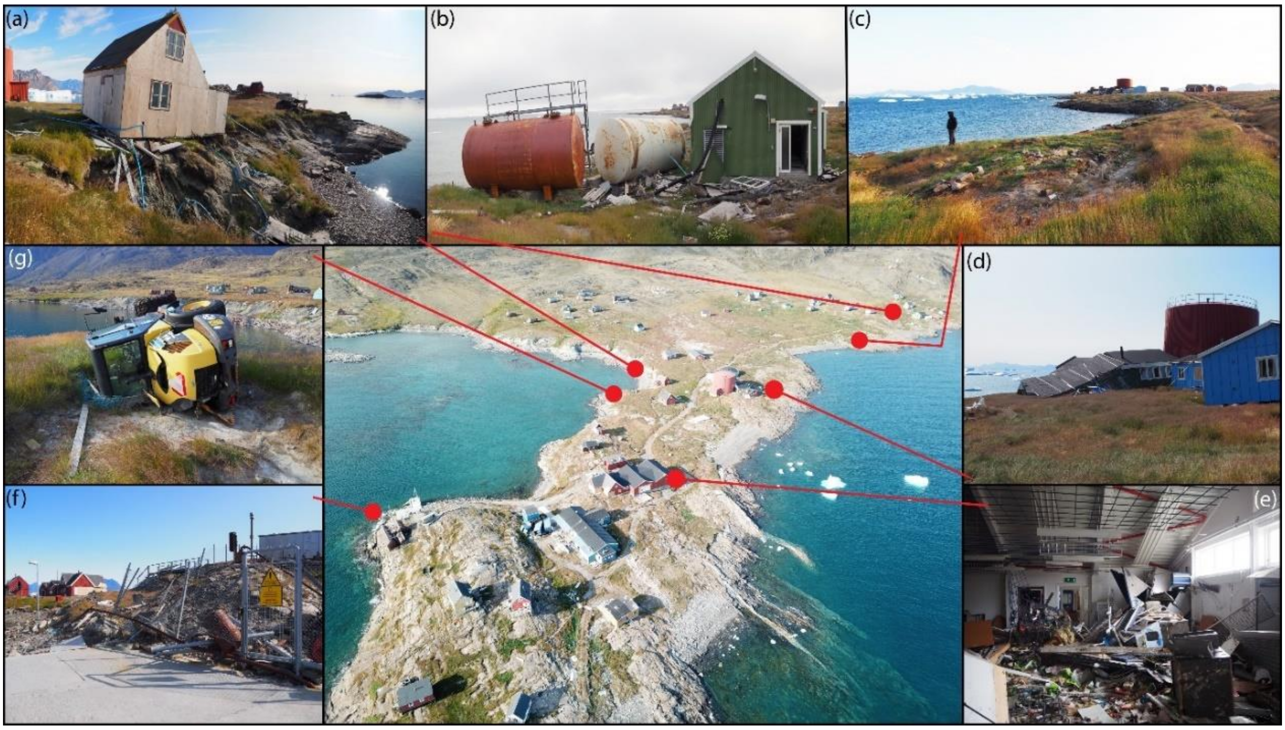

Figure 7. Examples of infrastructure damages caused by 2017 tsunami in Nuugaatsiaq. (a) Wooden house removed by wave from point foundation transported several dozen of meters; (b) Fuel tanks washed away from concrete frames and pushed towards power plant. Note large accumulation of litter and tsunami deposits around and inside the buildings; (c) site of former building position, which was destroyed and swept away by tsunami. Note broken wooden point foundations, media connections and erosional gullies; (d) Smashed and collapsed wooden school building moved towards major water tank; (e) Interior of local shopping centre passed by tsunami. Note large amounts of litter and rotting food supplies and twisted and bowed metal frame construction; (f) Partly-torn metal fence around fuel storage site which acted as a trap for litter transported by tsunami; (g) example of heavy machine knocked over by waves.