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The Character and Extent of subglacial Deformation and its Links to Glacier Dynamics in the Tarfala Basin, northern Sweden

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ABSTRACT

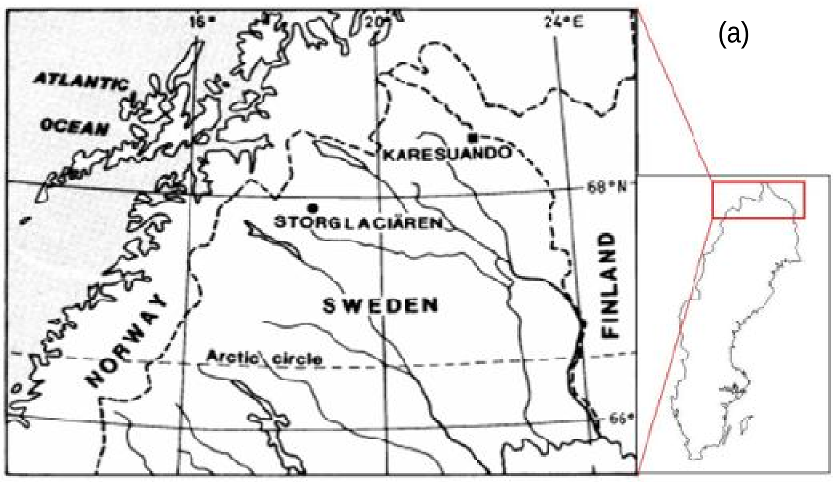
A pilot passive seismology experiment was conducted across the main overdeepening of Storglaciaren in the Tarfala Basin, northern Sweden, in July 2010, to see whether basal microseismic waveforms could be detected beneath a small polythermal arctic glacier and to investigate the spatial and temporal distribution of such waveforms in relation to known glacier flow dynamics. The high ablation rate made it difficult to keep geophones buried and well-coupled to the glacier during the experiment and reduced the number of days of good quality data collection. Event counts and the subsequent characterisation of typical and atypical waveforms showed that the dominant waveforms detected were from near-surface events such as crevassing. Although basal sliding is known to occur in the overdeepening, no convincing examples of basal waveforms were detected, which suggests basal microseismic signals are rare or difficult to detect beneath polythermal glaciers like Storglaciaren, a finding that is consistent with results from alpine glaciers in Switzerland. The data- set could prove useful to glaciologists interested in the dynamics of near-surface events such as crevassing, the opening and closing of englacial water conduits, or temporal and spatial changes in the glacier's stress field.

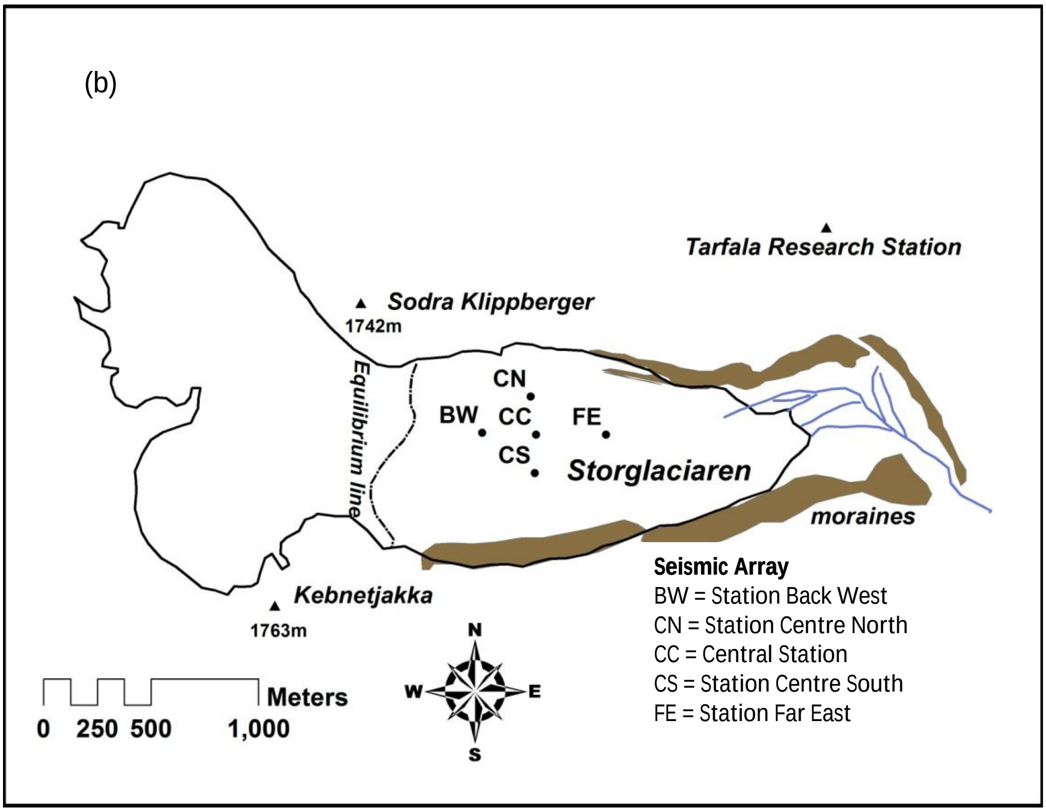
Background

Smith (2006) found that pervasive soft-bed deformation characterised parts of the Rutland Ice Stream in West Antarctica and produced 6 times fewer basal microseismic signals than regions where basal sliding or stick slip movement dominated. As such, Smith argued that passive seismology could be used to map out the nature of subglacial processes beneath glaciers. This may be true in Antarctica where there is a general lack of melt. However, in alpine environments, the dominance of near-surface events associated with meltwater flow and crevassing can make basal signals difficult to detect. For example, Walter and co-workers (2008) conducted passive seismology experiments on Gornergletscher in the Swiss Alps and reported that basal waveforms were very rare and tended to occur only in the early morning; they attributed the temporal clustering of basal signals to the process of the glacier re-coupling to its bed and not to basal sliding.

The aim of this project was to conduct a passive seismology pilot experiment on a small polythermal arctic glacier to see whether:
a) Distinctive basal microseismic waveforms could be detected
b) Whether such basal waveforms clustered in time and space, and
c) How such signals related to glacier flow dynamics.

If successful, the aim was to conduct a full experiment in the summer of 2011 which covered a much larger area of the glacier.





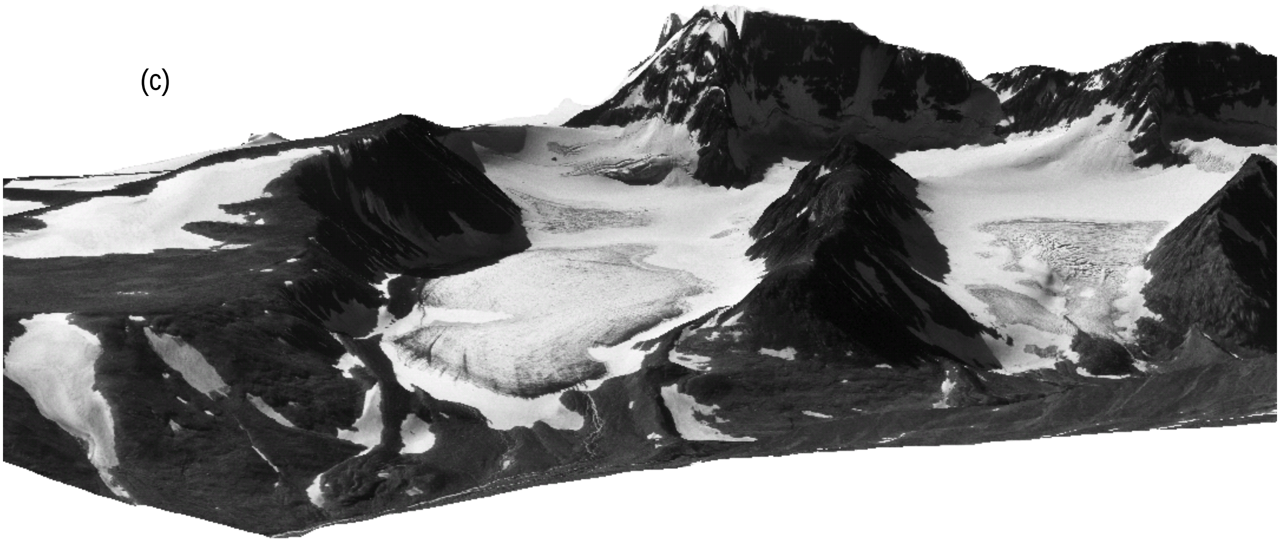


Figure 1 Location of Field Site: (a) Location of Storglaciaren (b) Outline of Storglaciaren showing array deployment across the overdeepening (c) View looking west with Storglaciaren on the left and Isfallsglaciaren on the right (*produced in Arc View using a DEM produced by Stockholm University and an aerial photograph taken in 2001 by Lantmateriet).*

Choice of Study Site

Storglaciaren is a small valley glacier located on the eastern side of the Kebnekaise Mountains in the Arctic region of northern Sweden (67°55' N, 18°35' E). Storglaciaren was chosen as a suitable study site for the pilot experiment because it is typical of many arctic polythermal glaciers and, as such, its subglacial processes serve as an analogue for arctic glaciers in general. Furthermore, Storglaciaren is easily accessed from the Tarfala Research Centre, which is run by Stockholm University, and has been the focus extensive glaciological research since 1949. The glacier covers an area of 3.12 km^2 and has a volume of 0.38 km^3; presently, the cold surface layer is approximately 30m deep and the glacier has retreated 750m since 1910 (Holmlund *et al*, 1996). The climate has a mean annual temperature of -3.9 °C, summer and winter averages of 5.5 °C and -8.9 °C respectively, and an annual precipitation total of 950 mm yr^{-1} (Hock and Holmgren, 1996). The longitudinal profile of the valley is controlled by a series of prominent bedrock riegels and overdeepend basins. Storglaciaren reaches its maximum depth (approximately 200-250m) in the main overdeepening, which occurs just below the present equilibrium line. Figure 1a shows the location of Storglaciaren and figure 1b&c the site chosen for the pilot experiment. The main overdeepening was chosen as a suitable field site for three reasons:

1) The work of Iverson and co-workers (1995) suggested that basal sliding and stick-slip movements were likely in this area, and these processes are thought to generate basal microseismic signals

2) Maximum ice thickness gives the best chance of p and s wave separation, which was required for accurate event location

3) Safety and Access considerations – rockfalls are common above the equilibrium line where deep snow-filled crevasses make glacier travel hazardous. The overdeepening area is flat enough to allow helicopter lifts of heavy equipment and can be safely accessed from a nearby lateral moraine.

Survey Procedures

Between the 8th of July and the 5th of August 2010, five seismic stations were deployed in a four-point diamond array across the main overdeepening area and set to continuously record events in the 0-500 Hz range at a sampling rate of 1000sps. Each station was placed approximately 200m from its nearest neighbour, a distance that reflected the depth of the glacier in this area. Persistent rockfalls from the valley sides and the opening up of large crevasses, moulins, and supraglacial channels made it unsafe to locate the lateral stations any nearer to margins of the glacier and placed restrictions on the location of Station FE. As such, the array was more linear than originally intended, with the distance from the Centre Station to Station FE being just over 300m. A 0.5m deep pit was excavated at each station and a 3-channel geophone buried perpendicular to flow. It typically took 1-2 hours digging by 2 people to excavate each pit and early in the summer the presence of excessive surface water from snow and ice melt meant that the excavated pits simply filled with meltwater. On polythermal glaciers in early summer, meltwater cannot percolate through the impermeable cold ice surface layer and the pooling of water on the glacier surface delayed the deployment of the seismic array. As the melt season progressed, the glacier drainage system became more organised and sufficient surface meltwater was evacuated to allow pits to be excavated. Within each pit the 3-channel geophone sat on a levelled block of pre-moulded concrete. The concrete block had 3 holes drilled through it to allow the geophone legs to be inserted through the concrete and frozen into holes drilled into the ice below. This arrangement has been shown to provide a good glacier-geophone couple (Brisbourne, 2010, personal communication), and helped to keep the geophone level and correctly orientated to north. A plastic bucket was then placed over each geophone and the pit back-filled with ice. A 30-50cm high rock cairn was then constructed on top of the pit to reduce surface noise and to add protection from melt. Each geophone was attached to a pre-amp and a SAQ data logger, which were housed inside Zarges boxes. The Zarges boxes and connecting cables were buried in ice pits and protected by rock cairns to prevent them becoming exposed.

Issues and Recommendations

The ablation rate caused problems throughout the duration of the experiment. Air temperatures near to the array reached as high as 9.79°C at 1382m altitude by late-July, with melt rates of surface ice being as high as 10cm per day (Matthews, 2011, personal communication). There were also a number of severe storms with wind speeds in excess of 35ms^{-1} and these conditions meant that each seismic station had to be re-deployed on four separate occasions because cairns had collapsed and cables and geophones had become exposed, or the geophones were so badly tilted they required re-levelling. The main recommendations relate to potential ways for future researchers to try to reduce the melt rate around seismic stations on alpine and subarctic/arctic glaciers. One recommendation would be to paint or coat surfaces of equipment with a high albedo material. The metal bases of the solar panels in particular melted at unequal rates into the ice and ended up causing excessive tilt, and black cables quickly became exposed. Geotextile covers, like those used in the Alps to reduce snow melt, could be used to blanket the surface around the seismic station and to cover all equipment and reduce the ablation rate. Geotextile covers such as IceProtector 500 and Toptex 350 have been shown to reduce summer snow melt by up to 65% in alpine and arctic regions (Olefs and Fischer, 2008; Pomeroy, 2009). Similarly, small ventilated tents with high albedo could be placed over each station to reduce the melt rate, although keeping these in place on a glacier surface may prove taxing.

Data Quality

The geophones remained buried, well- coupled to the glacier and level on approximately 18 of the 29 days of the pilot experiment for Stations BW, CC, and CS, and for all 5 stations between July 26th and August 1st, and August 3rd to the 5th, and these days yielded data of sufficient quality to allow for a characterisation of the typical and atypical waveforms present. An automatic picker (Nippress *et al*, 2010) was used to generate event counts with a short-term average (STA) to long-term average (LTA) amplitude ratio of 20:1 (see figure 2) and 10:1 respectively. Figure 2 shows that over 250 events were recorded every 10 minutes during peak periods of seismic activity, which tended to occur on all stations in the afternoon or when major storms occurred, which probably reflects the dominance of near-field events related to the diurnal cycle of meltwater production and associated changes in the glacier's velocity, and to the opening and closing of englacial conduits and crevasses. Figure 2 also shows a decrease in the number events recorded on most stations towards the end of the experiment. Figure 3 shows examples of the most common waveforms observed (type 1), which probably represent surface ice-quakes at different epicentral distances from the stations (Walter, 2010, personal communication). High frequency events resembling basal waveforms, with impulsive onset and vertical p-wave motion, were very rare and were not recorded on more than two or three stations at once, which suggests these events did not originate from near the bed (Brisbourne 2010, personal communication). Figure 2 also shows the delay in deploying Station FE due to battery damage and an initial problem with data recording on Station CN, which was caused by bent pre-amp pins and then problems with excavating a suitable pit in this part of the over-deepening. Direct observations showed that ablation and storm damage caused cables and/or geophones to be partly or fully exposed on all stations deployed on the following dates: 11th, 12th, 18th, 19th, and 25th July, and the 1st and 2nd of August. Stations BW, CC, Cs and CN were re-deployed in newly dug pits at the same sites on the following dates: 13th, 20th, and 26th of July and the 3rd of August.

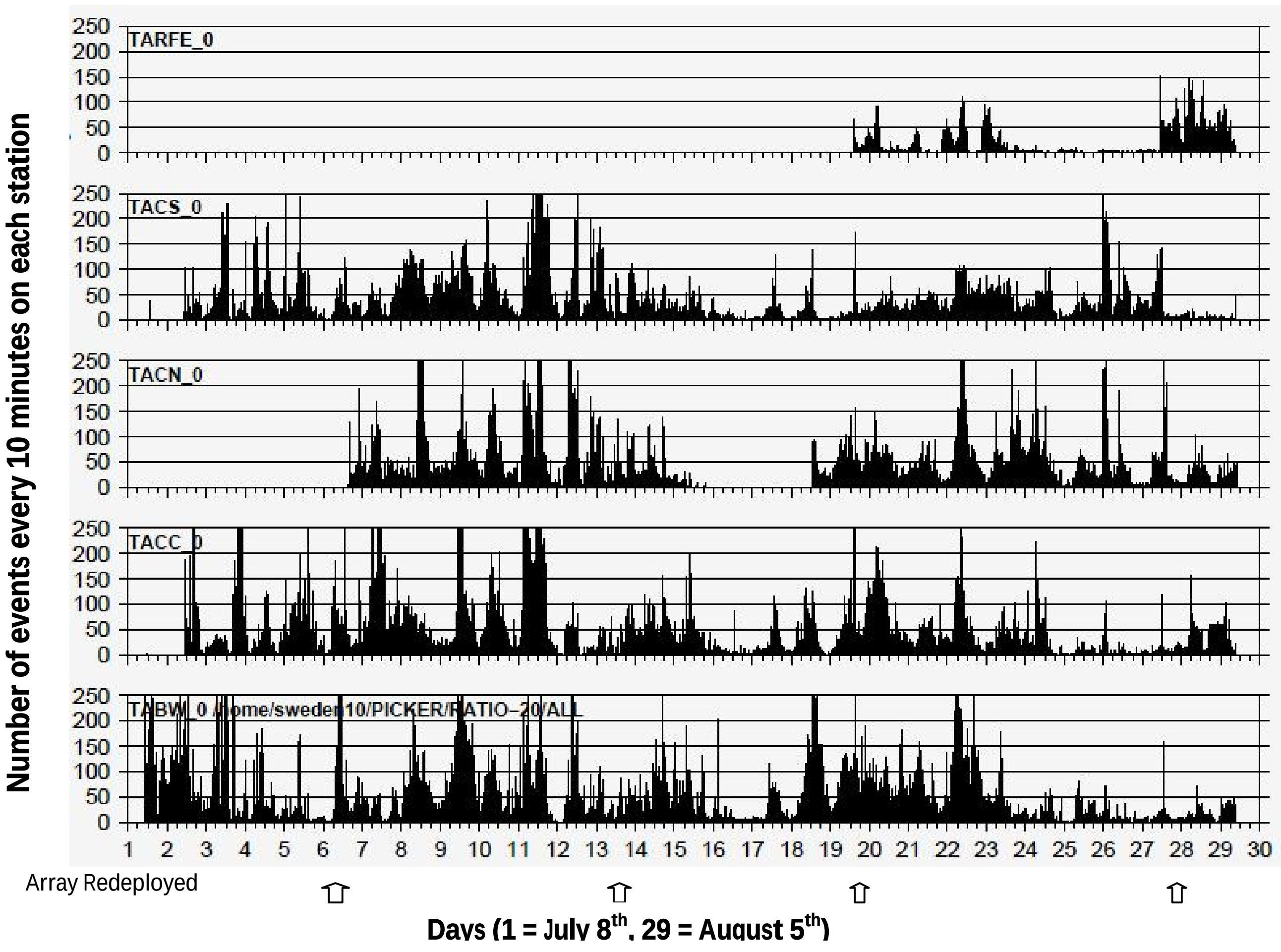


Figure 2 Event Count STA/LTA amplitude ratio 20:1 for all stations. *Note: TARFE is station Far East [FE], TACS is station Centre South [CS], TACN is station Centre North (CN), TACC is station Centre (CC), and TABW is station Back West (BW). The major ticks at the beginning of each day represent midnight GMT and 2.00am local time*

Processing / Modelling

A detailed manual inspection of four 24-hour periods of good quality data was undertaken using PQL II software in order to characterise the typical and atypical waveforms present. A 100Hz high pass filter was applied to help distinguish high frequency basal events from long period surface events. The aim was to identify basal waveforms and to use the examples found to set up and run a cross-correlation routine of the whole dataset using an automatic picker (Nippress *et al*, 2010). Simulations run using a synthetic model which assumed a flat surface and a bed-depth of 200m suggested that SDX Event Location Software could be used with confidence to detect bed events across the array (Brisbourne, 2011, personal communication). Unfortunately, most of the events identified as possible basal events only occurred on one or two stations, making use of the event location software impossible. However, the particle motions of these events suggested a near-field origin. Moreover, where possible basal events did occur on three of four stations they were shown to be located near to or at the surface of the glacier. As such, no convincing example of a basal event was detected.

Interpretation of Data and Preliminary Findings

Table 1 summarises the main waveforms detected and figure 3a-c shows examples of the typical and atypical waveforms found. The dominance of near-field events often made it difficult to discern p and s wave arrival times for type 2 waveforms. Visual inspections of the data were carried out for additional days to those used in the initial characterisation of waveforms, but no convincing examples of basal waveforms were detected. Type 3 waveforms resembled those produced by basal stick-slip motion (Walter, 2010, personal communication), but they only occurred on one or two stations at once, making event location impossible, and maximum amplitude tended to be in a flow parallel direction, rather than a vertical direction as might be expected with basal signals. However, the observed presence of regelation ice in the basal ice facies, and lodged stoss and lee boulders with flow-parallel striations on the forefield, demonstrate that basal sliding has been an important component of Storglaciaren's previous flow dynamics (Cook, 2011, personal communication). Moreover, the clast-rich and coarse grained subglacial till which is now exposed on the forefield reveals strong flow-parallel clast fabrics indicative of strong glacier-bed coupling, and shows evidence of grain bridging, clast crushing and clast lodgement, which suggests that at least part of the glacier's basal shear stress has previously been taken up by clast/boulder- rich sticky spots. Moreover, Iverson and co-workers (1995) and Fischer and co-workers (1996) conducted borehole experiments in the ablation area of Storglaciaren which demonstrated that enhanced basal slip occurred at times of high basal water pressures, especially early in the melt season before an efficient glacial drainage system had developed. As such, it is surprising that no clear basal signals have been detected, which may suggest that the soft-bed known to exist beneath the over-deepening is deforming pervasively and continuously over its entire area and generating few basal signals, or that the dominance of near-field events makes it extremely difficult to detect basal waveforms on polythermal glaciers. A third possibility is that the development of an efficient englacial/supraglacial drainage network restricts ice-bed decoupling and enhanced basal sliding to an earlier part of the melt season. The greater number of events recorded in the early to middle part of the experiment and during major July storms (figure 2) may relate to ice fracturing caused by the opening of numerous small, 40mm diameter, often water-filled englacial conduits. Englacial conduits have been directly observed and are thought to be an essential component of Storglaciaren's distributed drainage system; they can extend to depths of 131m (Fountain *et al*, 2005). The origin of the englacial conduits is unknown, but they may be caused by extensional ice fracture in the overdeepening and it is possible that the opening and closing of such conduits generates type 3 events. The temporal distribution of type 3 events is worthy of further investigation in relation to known changes in the hydrology of the glacier during the melt season. The reduction in the number of events towards the end of the experiment may also relate to an increase in background noise which reduced the number of triggers, and this also requires further investigation.

Conclusions and recommendations

Given that the pilot experiment was part of a wider research project into subglacial processes in the Tarfala Basin, and given that no convincing basal waveforms were detected, it was decided not to run the full experiment in 2011.

Passive seismology experiments are rendered difficult on glaciers with high surface ablation rates in summer and careful thought needs to be given to findings ways of reducing the melt rate around stations. Protecting stations with geotextile covers such as IceProtector 500 is a possibility. The dataset collected at Storglaciaren is similar to datasets collected on alpine glaciers in that basal waveforms are rare and/or difficult to detect, and the data-set is dominated by a diurnal cycle of near-field events that reaches peak activity typically by mid-afternoon. As such, the Storglaciaren dataset may prove useful to glaciologists interested in englacial processes, the generation and propagation of events related to crevassing, or changes in the glacier's stress-field in relation to known temporal variations in glacier velocity.

Table 1 Typical and Atypical Waveforms Detected

Waveform	Type 1a	Type 1b	Type 1c	Type 2	Type 3
Onset	Impulsive	Weak but impulsive	Impulsive, often preceded by high frequency event of short duration on some channels	Impulsive	Impulsive
Amplitude	Sharp peak soon after onset, but decays across array	Highest amplitude has broader, higher and more rounded peak than type 1a	Event builds towards a later and more pronounced peak than in type 1a and type 1b events, which maybe R-waves	Strong early peak, p wave strongest on z-axis (vertical)	Episodic event, dominant on channel E (flow parallel) with sharp peaks
Spectra	Mainly low frequency, 10-100Hz, peaks at 10-20, and 60-80Hz, small component >100 Hz	Low frequency 10-100Hz, removed by high pass filter (100Hz) as lack higher frequency component type 1c events	Wide range, with distinct peaks at 3Hz, 10-50Hz and > 100Hz. Not removed by high pass filter	High frequency, >100Hz	High frequency event
Duration	Typically 0.5s, but < 1s	< 1s	Typically 0.5s	Short, <0.1s	Up to several seconds
Distribution	Common on all stations, typical event recorded first at BW or CS and moves relatively slowly down-glacier, losing amplitude	Common on all stations	Each event not detected on all stations	Uncommon, but mostly detected in early morning 03.00-05.00 hrs local time. Single events seldom detected on more than one or two channels. Often seem to precede type 1c events	Common, but each event only recorded on one or two stations
Interpretation	The dominant 10-100 Hz frequency, impulsive onset, and duration of <1s of type 1a and type 1b events are typical of ice quakes associated with crevassing, with strong R-waves and weak p-waves. Type 1c waves have a similar duration and low frequency component, but have a wider frequency range and single events are not recorded on all stations, which suggests these may be localised events related to disturbances such as frequent rockfalls or serac collapse. Hydraulic transients have been observed to produce waveforms with a frequency of 3 Hz, but unlike type 1c events they have harmonic tremor and a decaying sine wave associated with resonance in water filled cavities (Stuart *et al,* 2005)			Type 2 events resemble the impulsive onset and high frequency of basal events. However, basal events detected in Antarctica are typically detected on all stations in an array (Smith, 2006). Event location analysis suggests these events are surface/near-surface events	High frequency episodic events with impulsive onset are thought typical of basal stick-slip movement (Walter, 2011, pers.comn.). However, the particle motions of type 3 events are indicative of a near-field origin (Brisbourne, 2011, pers.comn.)

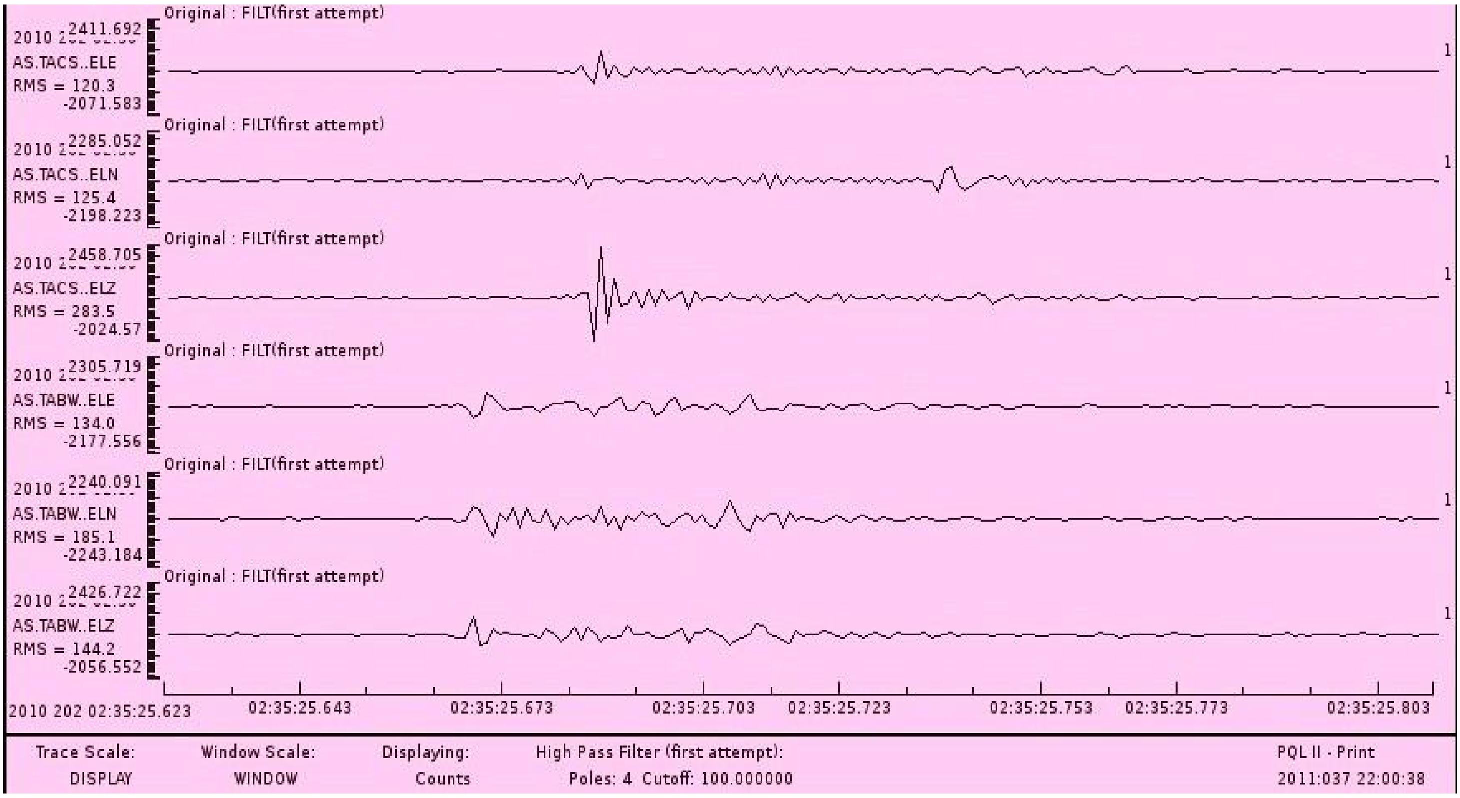


Figure 3a Rare high frequency event with impulsive onset resembling basal waveform, Julian Day 202 (21st July) at 02:35-GMT. The event was only detected on two stations. High pass filter applied (100 Hz)

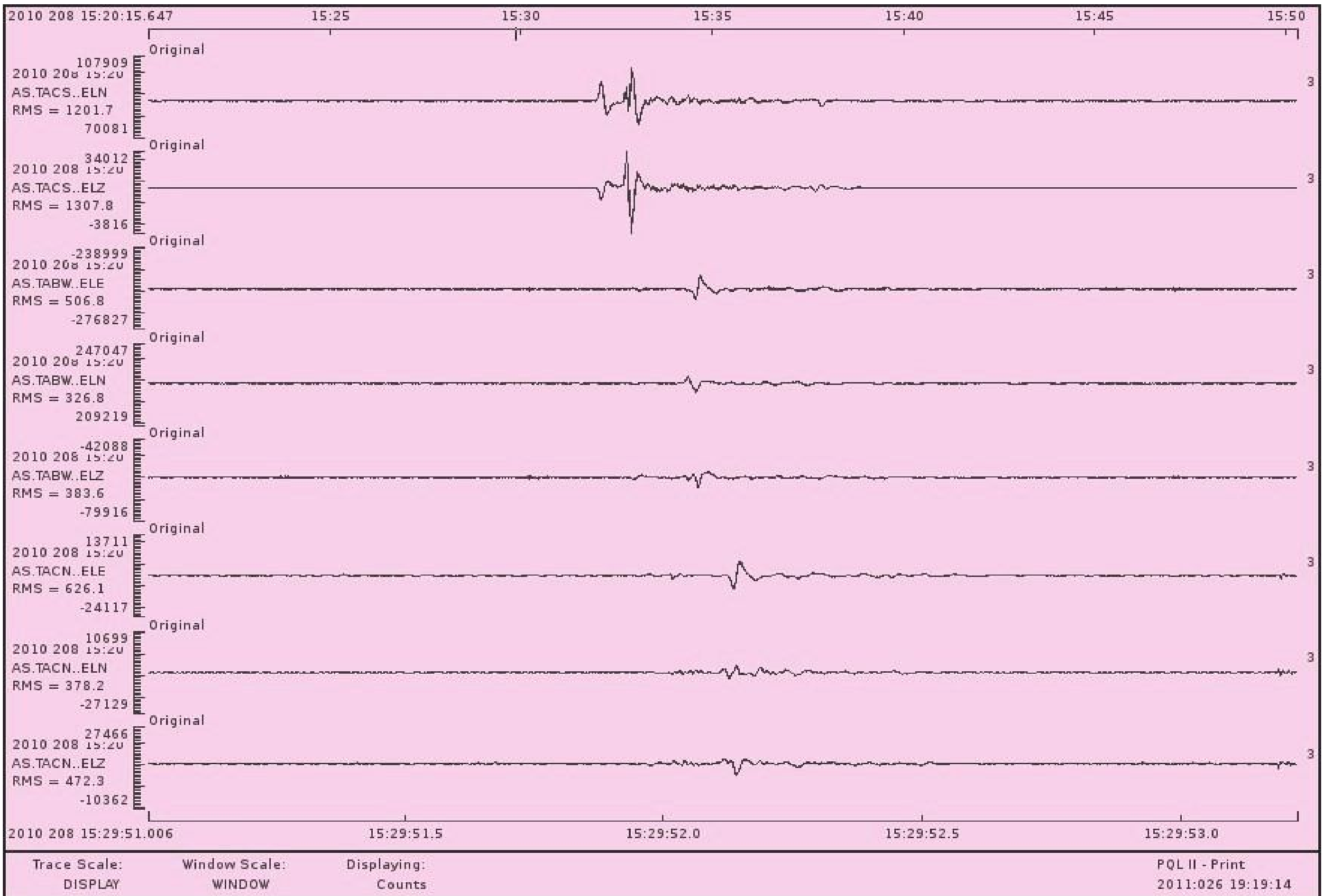


Figure 3b Common Type 1a event, Julian Day 208 (27th July) at 15:29 GMT. The event is first detected at CS with impulsive onset and rapidly decays across the array

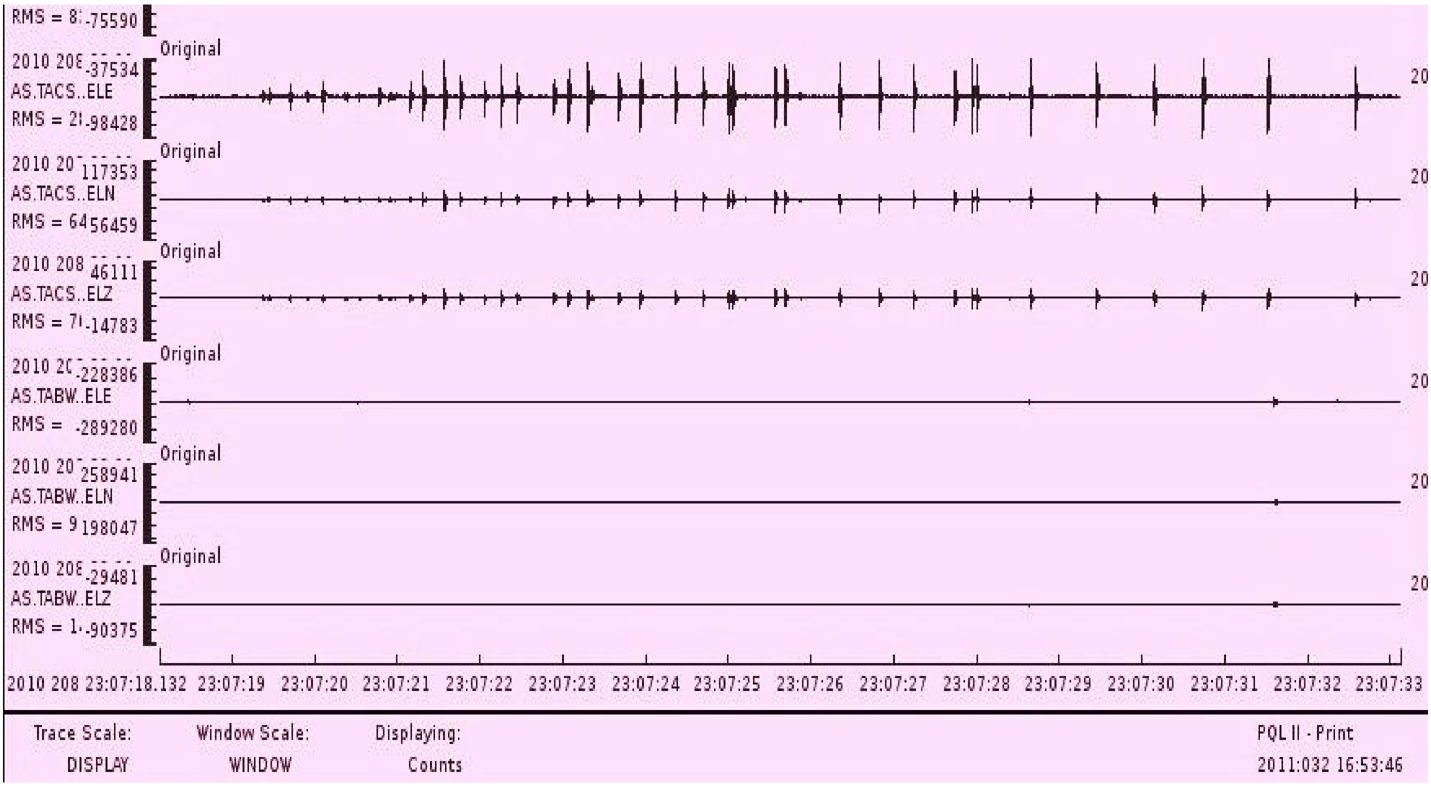


Figure 3c Type 3 waveform, Julian Day 208 ((27th July) at 23:07 GMT. The episodic event was only recorded on Station CS

Publications

We intend to submit a short report to Earth Surface Processes and Landforms 'Earth Surface Exchange Letters'.

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Table 2 Field Deployment Data

Station	**Far East (FE)**	**Centre (CC)**	**Centre South (CS)**	**Back West (BW)**	**Centre North (CN)**
Latitude	67° 54'.188	67° 54'.197	67° 54'.100	67° 54'. 207	67° 54'. 292
Longitude	18° 35'.127	18° 34'.662	18° 34'. 643	18° 34'. 305	18° 34'. 638
Elevation (m)	1345	1369	1368	1390	1371
Serial Number SAQs	QS 030184 ID 10	QS 040005 ID 14	QS 030178 ID 4	QS 030176 ID 2	QS 04004 ID 13
Deployment Date 2010 (Julian Day), [Day from start of experiment on 01]	26th July (207) [19] (16:20 local time/14:17 SAQs time)	9th July (190) [02]	9th July (190) [02]	8th July (189) [01]	9th July (190) [02]
Pull-in Date (Julian Day) [Last day of experiment]	5th August (217) [29]	5th August	5th August	5th August	5th August
Comments Geophones and/or cables exposed all sites on 12th, 13th, 18th, 19th, 20th, 25th and 26th July, and 1st-3rd August. All stations redeployed at same sites in newly dug pits on the 13th, 20th and 26th July, and 3rd August. Geophones were observed to be well-coupled to the glacier and cables buried at all stations on August the 5th when the experiment ended	Delayed deployment because car batteries damaged during helicopter lift. Site near to bedrock riegel in area of large transverse crevasses; glacier C.100 -150m thick, decelerating, with compressive flow. Crevasses restricted location for this site. Nearby ablation stake and occasional ablation stake drilling produced noise. Cables and geophone exposed on 3rd August, station redeployed at same site in new pit. Cables and geophone still well-buried/coupled on 5th August	Glacier 200m thick, centre of overdeepening, fastest surface velocity. System checked 13th July – batteries changed in pre-amp and SAQs disc changed (2227 out, 2220 in) so as to check system was detecting events.	Glacier maximum thickness on southern side (250m). Large crevasses and moulins between CC and CS opened up during season. Frequent rock falls from valley flank. System checked on 13th July and batteries changed, SAQs disc changed (2221 out, 2229 in)	Near to present equilibrium line and below an ice fall, just below zone where ice from two accumulating basins converges. Area of large crevasses and moulins. Noise from nearby erection of a glacier weather station and camp made by mountaineers. System checked on 13th July and batteries changes, SAQs discs changed (2224 out, 2242 in)	Glacier only 100m or so deep and slower moving on N side. Longitudinal and transverse crevasses common and lateral supraglacial channel opened near here by late-July. Pooling of surface water made pit excavation difficult. Inspection on July 13th revealed bent pre-amp pins and flat batteries, resulting in data gap. Batteries replaced and pins repaired on July 13th. Rockfalls from valley side frequent