**NERC GEOPHYSICAL EQUIPMENT FACILITY SCIENTIFIC REPORT**

# Loan 887: Hydraulics and sediment deformation beneath an ice stream: A multi-component geophysical AVO investigation

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## Abstract
A set of geophysical experiments on Rutford Ice Stream in the 2009-10 austral summer produced new data addressing the physical conditions and flow controls at the ice stream bed. NERC GEF seismic and GPS equipment were used to support active seismic and ice-penetrating radar surveys. Data analyses are at an early stage. So far, GPS monitoring of ice flow confirms a known periodic variability and surface elevation grids have been used to process seismic and radar data. Future work will analyse the seismic data (reflection and AVO) to determine the physical nature of the bed material, allowing modelling of groundwater flow beneath the ice stream. An inability to recover the majority of the passive seismic data means they are of little value to the project.

## 1. Background
Three Leica 1230 GPS receivers and six Reftek high frequency seismic stations from the NERC Geophysical Equipment Facility (GEF) were used as part of a combined set of geophysical experiments on Rutford Ice Stream, West Antarctica (Fig. 1) during the 2009-2010 austral summer. The GEF equipment complemented ice-drilling, active seismic recording and ice-penetrating radar equipment provided by BAS.

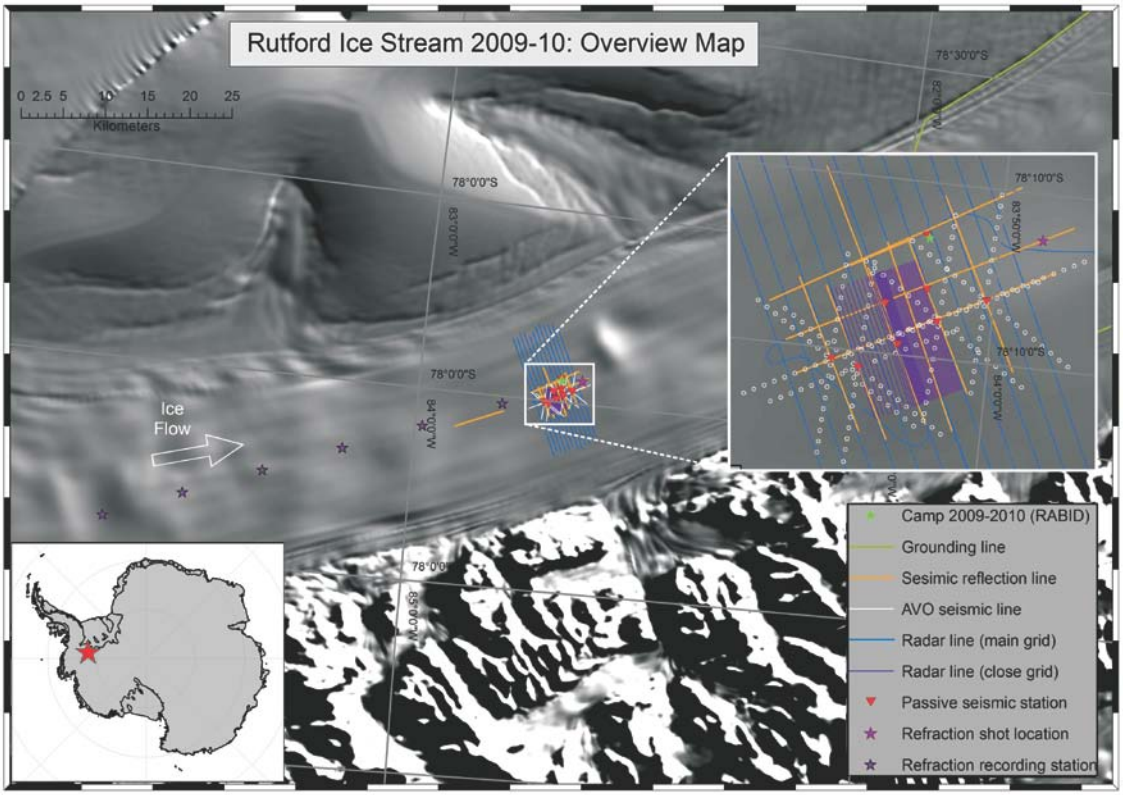


**Figure 1.** Location map. Inset (white box) shows acquisition details in the core project area.

The dynamics of modern ice streams are profoundly influenced by fast flowing ice streams. Modelling efforts are directed at understanding their operation and at forecasting their future behaviour, but currently the lack a physically-based basal boundary condition is a major limitation. The project's aim is to test the theory that sediment deformation is linked to drainage and

subglacial hydraulic structure, by deducing the hydraulic characteristics of the sediment beneath Rutford Ice Stream – a large, fast-flowing glacier that drains part of the West Antarctic Ice Sheet. We will determine a full set of geotechnical properties of the bed from seismic data, complemented by an assessment of changes in the subglacial sedimentary and hydrological systems. To achieve these aims we completed a set of active seismic and radio-echo sounding experiments in an area where previous work has shown the ice is underlain by water-saturated sediments. Some of this sediment is actively deforming; elsewhere the ice is sliding over it. In one particular area, the overall spatial distribution of deforming *vs.* non-deforming sediment is known and this was the focus of the fieldwork campaign. The primary use of the GEF equipment was in support of the active seismic and radar work.

## 2. Survey Procedure

### *2.1 GPS receivers*

- One GPS receiver ran continuously at the base camp for the duration of the fieldwork (29 Nov 2009 – 6 February 2010). Most of the time it was in static mode but it was reconfigured as an RTK base station when required (see below). Sample interval was 1 s. The antenna was mounted on a standard survey tripod; the RTK antenna was mounted on a 4 m pole.
- The second receiver was used in RTK rover mode for accurate identification and surface elevation measurements of shot-hole and geophone spread locations for the active seismic experiments. These were achieved using the base station as a real-time reference. An occupation was logged at each location; sample interval was 1 s. Standard GEF rucksack and detail pole were used for these surveys (Fig. 2a).
- The third receiver was used as a rover to survey surface elevation profiles and tracks for the radar grids. Sample interval was 1 s. Positions were determined from the Leica data by post-processing. The radar includes transmitter and receiver antennas that are towed in-line behind a skidoo approximately 70 m apart and it is the track of the mid-point between the antennas that is needed. This was achieved by securing the GPS in a pulk sledge attached at the correct point between the antennas (Fig. 2b). Receiver and antenna were housed inside a BAS-supplied Leica transit case which had been modified to include a weather-proof access port. External power was fed through this port giving sufficient power for long surveys. This completely protects the equipment from snow and makes the sledge's centre of gravity low, keeping it stable even when travelling over sastrugi.

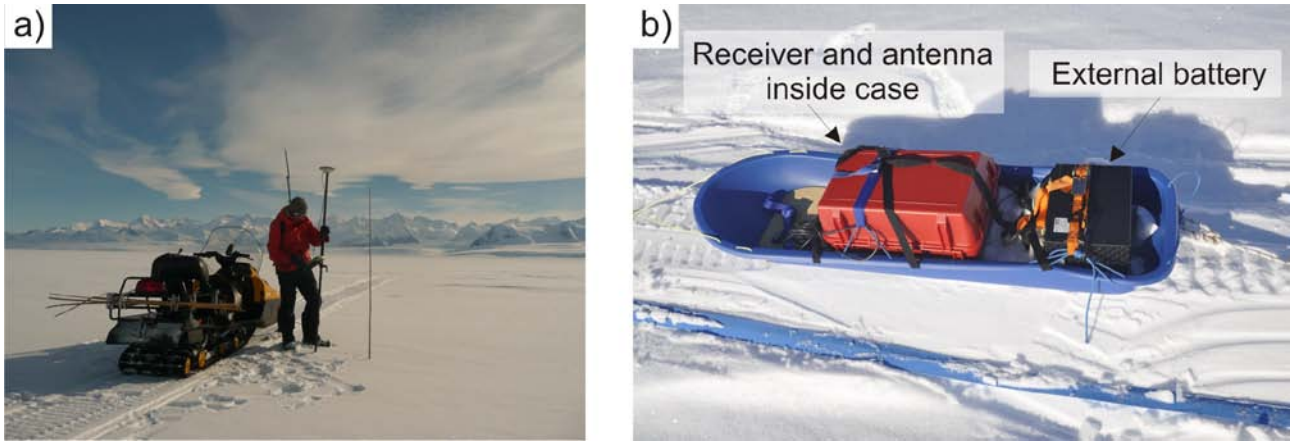


**Figure 2.** a) RTK GPS rover in use to locate shot hole positions. b) GPS rover mounted in pulk sledge to record radar antenna tracks. Both GPS antenna and receiver are housed in the red case; antenna performance did not appear to be significantly degraded, despite being inside the case.

### *2.2 Seismic stations*

A Huddle test was performed at camp from 30 November to 16 December 2009 (Fig. 3). This is probably longer than strictly necessary but during this time, we were completing the seismic reflection and radar surveys needed to determine the precise location for each Reftek stations. After the huddle test, only one data card was readable. Communications with SEIS-UK suggested this was a known problem and that, as all other indications were that the stations were working correctly, all the data could be successfully retrieved back in Leicester. The one card that was readable showed good quality data with identifiable events occurring at the ice stream bed – these

are the ones we are particularly interested in. All stations were therefore redeployed and assumed to be working correctly for the rest of the project. Despite later attempts, no further data could be retrieved until they were returned to Leicester.

One Reftek station operated at base camp (Table 1). The other five were located at the centres of the active seismic STARs (or in one case, in the centre of the survey area to improve the accuracy of event location). Each STAR comprised three Amplitude *vs.* Offset (AVO) experiments orientated at 60° to each other, centred around a specific point on the ice stream bed. Seven potential sites were identified for this purpose; 4 were completed. Care was taken to place the station at a safe distance (~10 m) from the active seismic operations (explosions, vehicles, drilling operations), whilst still being located effectively at the centre of the STAR.

**Figure 3.** Huddle test, during deployment

At each seismic station, the 4 Hz, 3-component geophone was placed at the base of a ~1.5 m deep hole in the snow, levelled using the bubble spirit level and the N arrow aligned in the upstream ice flow direction (292°Mag/333°True). The maximum possible separation between geophone and logger was used to minimise wind noise (e.g. spindrift on the Zarges case or through the solar panel mounting poles). Power was provided by 100 Ah sealed gel lead-acid battery, 40W solar panel and SEIS-UK regulator. Solar panels were mounted on 2 m poles; orientation was vertical facing North. The GPS antenna was mounted on one of these poles. Data on all three channels were sampled continuously at 1000 samples per second; record length was 600 s.

The final experiment of the project was an un-reversed seismic refraction line. The ice stream bed has an elevated central ridge running almost its full length (>100 km). This refraction line, although very basic, was designed to investigate this feature and determine if it is composed of bedrock or subglacial moraine. The six Refteks were redeployed at 10 km spacing (Fig. 1) and a 300 kg shot detonated at the downstream end of the main survey area.

## 3. Data processing and quality

### *3.1 GPS*

GPS data recovery was almost 100%. Two days' radar grid survey data were lost due to an intermittent power cable fault. Co-incidentally, these lines also suffered radar failures, so were repeated anyway, with no further GPS problems.

Although the base station was operated in static mode, the ice at this location is actually moving at ~1 m day$^{-1}$. It is this motion, including variations from constant speed, that this receiver was primarily measuring. Data were processed by colleague Hilmar Gudmundsson (BAS) using Bernese Precise Point-positioning software[1].

Position and height for the active seismic shot-hole and geophone spread positions were taken from the logged real-time rover positions, referenced to the base station receiver. The rover data from the radar tracks were post-processed using the on-line facility of Natural Resources Canada (http://www.geod.nrcan.gc.ca/products-produits/ppp_e.php).

### *3.2 Seismic*

The early inability to read the huddle test data was actually part of a far more fundamental problem. Although SEIS-UK believed they would recover all the data once the cards were returned to Leicester, the issue was not what they were expecting and two thirds of the data were lost. The fault appears to have been with the new cards supplied to SEIS-UK, only just in time for

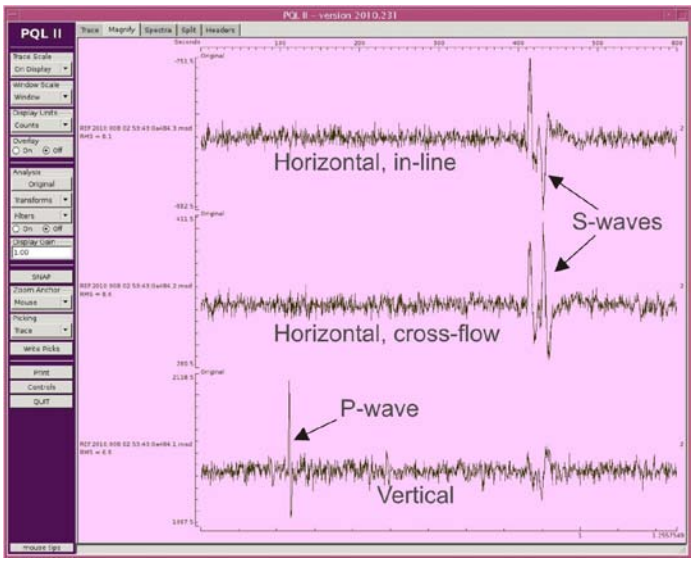


**Figure 4.** Screen-grab of typical seismic event from the ice stream bed.

deployment on the project. The data that could be retrieved are good quality and events from the ice stream bed can be identified clearly. Due to the limited data recovery and the loss of virtually all the data required to support interpretation of the STAR experiments (see 4.4, below), very little has been done with the passive seismic data: a check has been made to confirm whether or not relevant stations were successful during active seismic experiments and a 2-hour section of successfully recovered data has been scanned visually to confirm that basal events are present (Fig. 4), S/N levels are as anticipated and an initial indication of typical seismicity levels (~20 events hour$^{-1}$).

## 4. Interpretation and Preliminary Findings

### *4.1 Ice stream motion*

The mean ice velocity during the project was 372 ma$^{-1}$. The de-trended processed base station position data, i.e. with the mean flow removed ("detrended ice flow") are shown in Figure 5, which also shows the vertical tidal displacement at the grounding line ~40 km downstream. Flow values >0 indicate displacement further ahead than would be expected from the mean speed alone, values <0 show motion retarded relative to the mean. This flow variability reflects a non-linear amplification of the spring-neap tidal cycle that results from interaction of the main species in the ocean tides[2]. This effect is well-documented for this ice stream, so the result is not new. The importance to this project is that we know the particular nature of the ice flow at the time that each STAR experiment was acquired. There are some indications[3] that basal seismicity is also influenced by tidal range and flow variability (e.g. maximum tidal range, maximum ice acceleration and basal seismicity are correlated), so this is important supplementary information for interpretation of the active seismic data.

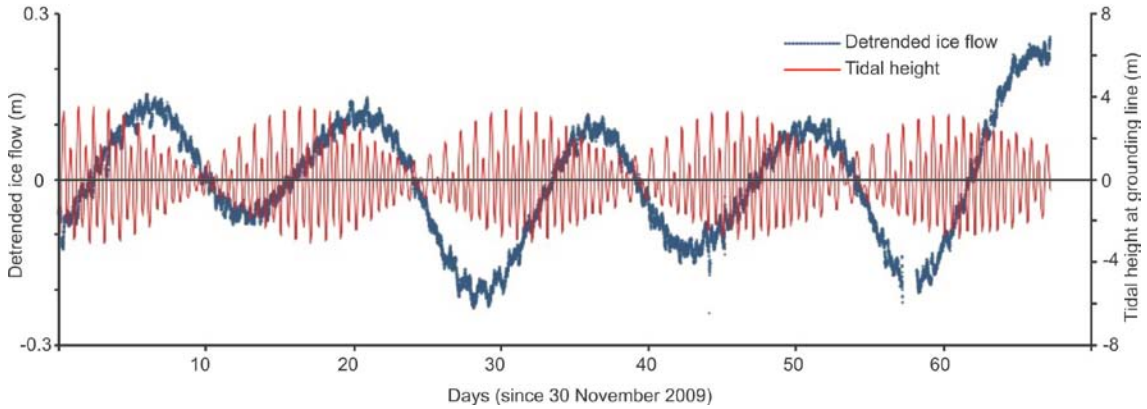


**Figure 5.** Results of the GPS data from the base camp occupation.

### *4.2 Surface elevation*

The main use of the surface elevation data from the two GPS rovers is to correct the seismic and radar data and hence, determine the ice stream bed elevation. A preliminary example of a processed seismic reflection line is given in Fig. 6 (upper panel). This particular line is co-incident (geographically) with ones that have been acquired previously on three occasions since 1991, to detect temporal variations in the ice stream bed. Fig. 6 (lower panel) shows the bed elevation for all four lines (i.e. incorporating the GPS surface elevation data). These show no significant changes except for around 2500-3000 m (distance range). On previous occasions[4] this area showed remarkably high subglacial erosion (6 m, 1991-1997), followed by the formation of a new

drumlin (1997-2004). The new data suggest that no further changes have occurred during the past 5 years.

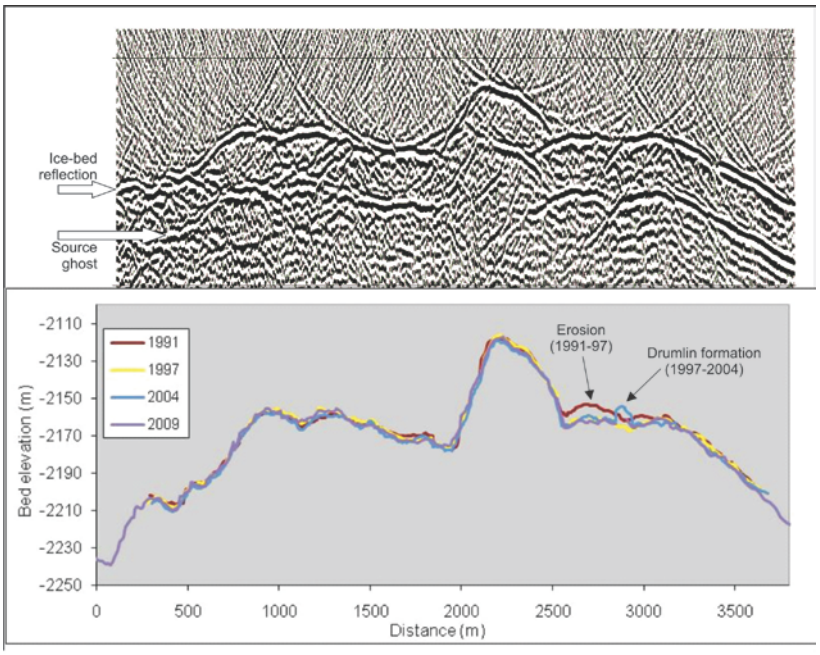


**Figure 6.** Example seismic reflection section (upper panel) and resulting comparison of basal topography over 18 year period (lower panel).

The complete radar data set has been processed, corrected for GPS surface elevation and gridded; the results are shown in Fig. 7. The seismic reflection data show that the bed material here is water-saturated sediments and the long linear features in the bed, aligned in the ice flow direction, are interpreted as drumlins and Mega-scale glacial lineations (MSGL) forming under the fast-flowing ice. Whilst this is an interesting result in itself, the prime use for these data will be to do a detailed line-by-line comparison with equivalent radar data acquired 3 years previously, to detect any changes in the bed topography and evidence for sediment mobility and bedform evolution. This work has yet to be completed.

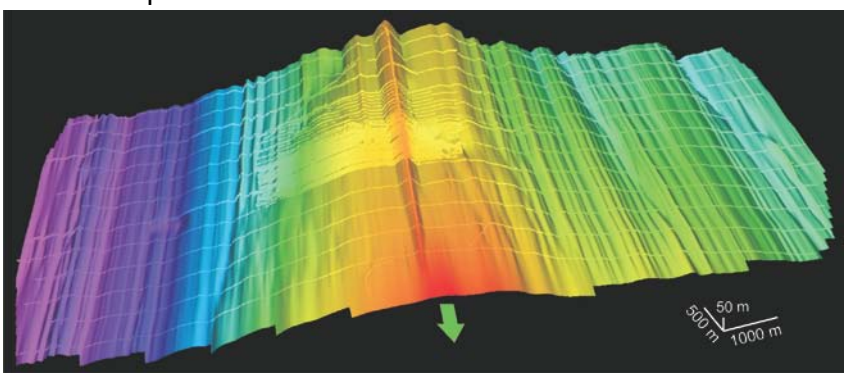


**Figure 7.** Processed bed topography grid from the radar data. Colours indicate elevation (red high, purple low), faint lines show tracks.

*4.3 STAR data*

The primary goal of the project is to determine sediment properties at specific locations from the STAR active seismic data. Work on these data has been delayed by departure of the PDRA. Colleagues in Edinburgh (Prof. G.S. Boulton is PI on the associated NERC grant) are currently resolving this issue.

*4.4 Passive seismic stations*

A summary of the passive seismic stations is given in Table 1. Whilst overall data recovery was around 33%, this hides the fact that data from all the important periods except one, were among those that were un-recoverable. Data from the periods around the acquisition of each STAR experiment was the primary project need, but only one station met this. The majority of the

recovered data, intermittent interim periods at different stations, is of interest but of little rigorous scientific value.

**Table 1.** Summary of passive seismic stations and data recovery

| DAS | Field site name | Lat (S) | Long (W) | Star | Deployment period | Data recovery | Reason for position |
|---|---|---|---|---|---|---|---|
| All | Huddle | 78 09.1 | 083 53.0 | N/A | 30/11/2009-16/12/2009 | Included below | Huddle test at camp |
| A484 | Reftek 1 | 78 08.2 | 084 00.6 | STAR 1 | 16/12/2009 – 2/2/2010 | 97% | Directly above subglacial drumlin |
| | +30 km | 77 55.5 | 084 21.0 | N/A | 7/2/2010 – 8/2/2010 | | Refraction line |
| A514 | Reftek 2 | 78 09.4 | 083 57.9 | STAR 2 | 17/12/2009 – 20/1/2010 | 20% | Downstream of subglacial drumlin |
| | Reftek 7 | 78 09.9 | 083 56.4 | STAR 5 | 20/1/2010 – 2/2/2010 | | Downstream of subglacial drumlin |
| | +40 km | 77 50.5 | 084 30.2 | N/A | 7/2/2010 - 8/2/2010 | | Refraction line |
| A670 | Reftek 3 | 78 08.5 | 084 00.9 | STAR 3 | 16/12/2009 – 2/2/2010 | 5% | Adjacent to subglacial drumlin |
| | +60 km | 77 40.4 | 084 48.2 | N/A | 7/2/2010 | | Refraction line |
| AA1A | Reftek 4 | 78 08.7 | 083 57.2 | STAR 4 | 16/12/2009 - 20/1/2010 | 60% | Directly above subglacial MSGL |
| | Reftek 8 | 78 09.2 | 083 56.0 | STAR 6 | 20/1/2010 – 2/2/2010 | | Directly above subglacial MSGL |
| | +10 km | 78 05.5 | 084 02.2 | N/A | 7/2/2010 – 8/2/2010 | | Refraction line |
| AAE9 | Reftek 5 | 78 08.9 | 083 59.4 | N/A | 16/12/2009 – 2/2/2010 | 7% | Mid-survey area to improve source locations |
| | +50 km | 77 45.5 | 084 39.2 | N/A | 7/2/2010 | | Refraction line |
| A644 | Reftek 6 | 78 09.1 | 083 53.0 | N/A | 17/12/2009 – 2/2/2010 | 10% | Camp |
| | +20 km | 78 00.5 | 084 11.7 | N/A | 7/2/2010 – 8/2/2010 | | Refraction line |

Loss of all the data from the refraction experiment was particularly cruel, for two reasons. Firstly, data from all six stations were recoverable for the period leading up to just before the source explosion; just a few more hours could have turned failure into success. Secondly, this was a unique opportunity to achieve this experiment and determine whether the subglacial ridge comprises bedrock or moraine. This opportunity resulted from diligent preparation over a number of years to achieve what is probably a once-only availability of both sufficient explosives on site and appropriate recording capability; it is unlikely that this situation will be attainable again.

## 5. Conclusions and recommendations

Scientific conclusions are still at an early stage. Except for the passive seismic stations, the data acquisition stage of this project was very successful and a considerable, comprehensive active seismic, radar and GPS dataset was achieved. The only major recommendation to make at this stage would be for complete system testing of Reftek data cards before providing them to any future projects. Loss of another critical cryosphere seismology data set through equipment failure of the high-frequency stations has been hard to bear.

## 6. Publications

Publications are planned on the seismic reflection data (including comparisons with earlier surveys), radar reflectivity of the bed and its relation to basal water, sediment properties from the STAR data and a synthesis of all these data contributing to groundwater flow modelling. None is expected from the passive seismic.

## References

1. Gudmundsson, G.H., 2007. Tides and the flow of Rutford Ice Stream, West Antarctica. *J. Geophys. Res.*, **112**, F04007.
2. Gudmundsson, G.H., 2006. Fortnightly variations in the flow velocity of Rutford Ice Stream, West Antarctica. *Nature*, **444**, 1063-1064.
3. Aðalgeirsdóttir, G., Smith, A.M., Murray, T., King, M.A., Makinson, K., Nicholls, K.W. and Behar, A.E., 2008. Tidal influence on Rutford Ice Stream, West Antarctica: observations of surface flow and basal processes from closely spaced GPS and passive seismic stations. *J. Glaciol.,* **54**, 715-724.
4. Smith, A.M., Murray, T., Nicholls, K.W., Makinson, K., Aðalgeirsdóttir, G. and Behar, A.E., 2007. Rapid erosion, drumlin formation and changing hydrology beneath an Antarctic ice stream. *Geology*, **35**, 127-130.