Scientific Report: Gauging Rutford Ice Stream Transients (GRIST)

NERC GEF Loan 852
H.D.Pritchard[1], A.M.Brisbourne[2], E.C.King[1], G.H.Gudmundsson[1], A.M.Smith[1]
[1]British Antarctic Survey, [2]SEIS-UK, Univ. Leicester

Abstract

A field survey on the Rutford Ice Stream, West Antarctica, in austral summer 2008-9 has yielded substantial new GPS, passive seismic and radar datasets. Preliminary analysis reveals the extent of tidal modulation of flow on the ice stream, the distribution of bedforms associated with bed deformation and basal sliding down to the grounding line, and the spatial and temporal pattern of basal seismic events in relation both to these flow mechanisms and to the periodic tidal flow modulation. Further processing is planned in support of efforts to derive new ice stream flow laws.

Background

This survey was designed to collect data on resistance to ice stream flow and how it varies with external forcing. Potential changes in this flux remain the single greatest uncertainty in forecasts of sea level rise. A previously unknown ice stream flow mode governed by ocean tides, possibly linked to a non-linear response of basal sediment[1], allows us to observe the impact of periodic changes in stress at the grounding line (GL) on ice stream flow over many kilometres upstream. Ultimately, this work contributes to flow laws that will be used to model ice stream flow in past and future scenarios. Specifically this survey aimed to help address these questions:

- Ocean tides strongly affect the flow rate of the Rutford ice stream[1]. Is this because the tidal forcing affects basal or marginal resistance?
- How far inland does the ocean-tide effect reach?
- Ice streams can flow by deforming their beds or sliding over them. How do these two mechanisms vary as the forcing varies?
- Sliding and deformation involve many small failure events at stress concentrations on the ice stream bed. Where do these failures occur?
- How is the flow of the ice stream affected by the topography of its trough?
- What is the spatial distribution of deforming and non-deforming bed landforms?

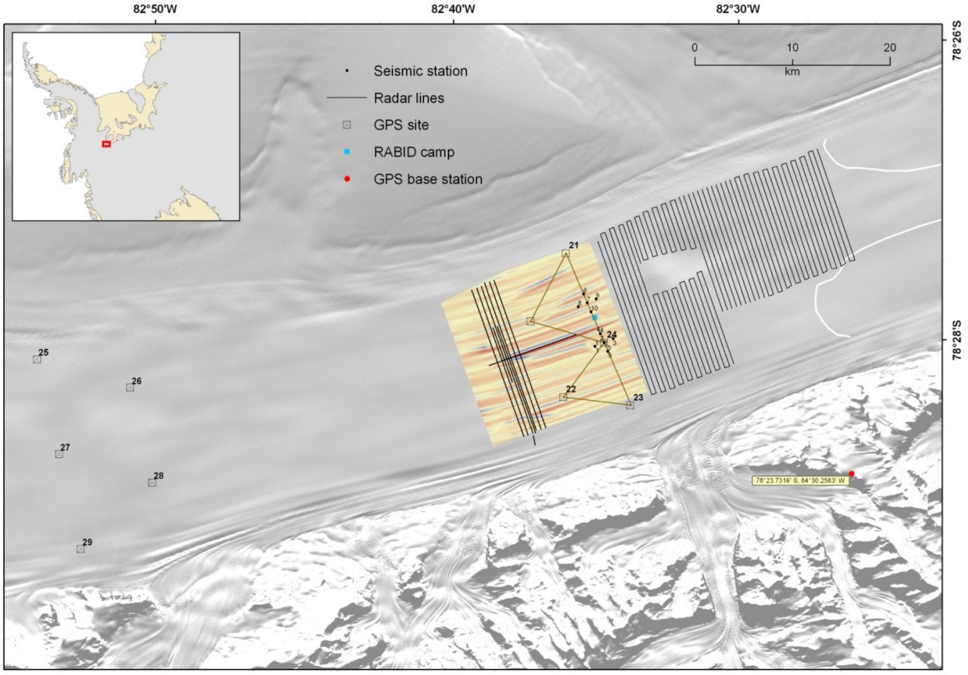


*Figure 1: S*ite location map, Rutford Ice Stream.

Survey Procedure

This survey was carried out by a two-man British Antarctic Survey team (H.Pritchard and C.Griffiths) in austral summer 2008/9 on the Rutford Ice Stream, West Antarctica. Input was delayed by seven weeks due to aircraft certification problems and bad weather, with arrival in the field on December 28th 2008, departure on 4th February 2009.

The survey was made up of: 1) two GPS arrays for characterising ice stream flow; 2) deep-looking radar for characterising the ice stream bed, and; 3) two seismic-station arrays to investigate ice stream sliding.

Equipment from NERC consisted of 10 seismic stations (3 Reftek, 7 SAQS) and 7 Leica 1200 GPS.

GPS survey

We deployed the two arrays of five GPS (Figure 1) timed to capture a full tidal cycle, with a further rock base station in the Ellsworth Mountains (aircraft input). All were powered by 60W solar panels and 12v gel-cell batteries. Antennae were screw-mounted on 2 m aluminium poles embedded in the snow except the base station, mounted on a low tripod. Sampling interval was 15s, survey was 'static', elevation mask was set to 0°. All sites ran continuously and without problems from 30th December 2008 to 1st/2nd February 2009.

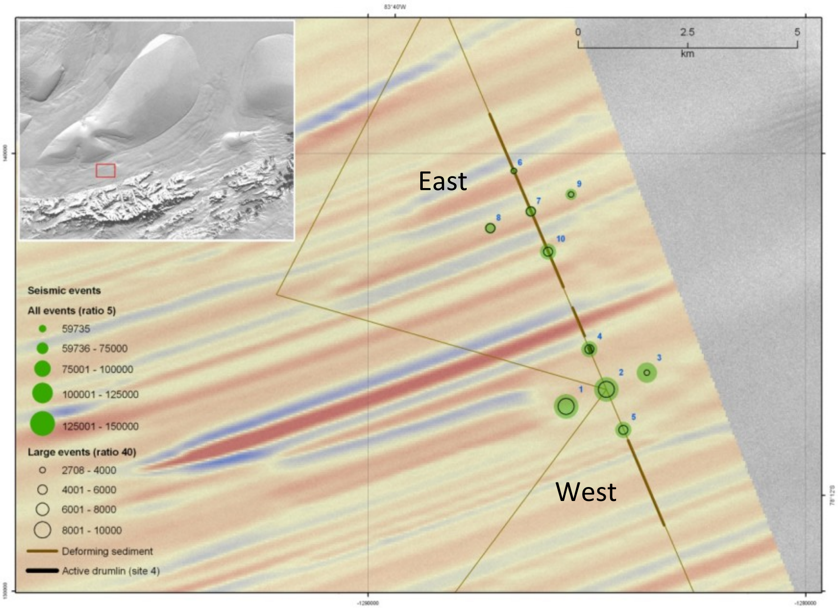
Radar survey

We spent three weeks mapping the ice stream bed and internal layers using a towed 2MHz radar with 1 kHz PRF and digitisation period of 10ns driven along 15-20km long cross-lines at 500 m intervals downstream of the camp (Figure 2), adding to a previous survey (coloured area upstream of the camp, Figure 1). These surveys established the basal context for the passive seismic and GPS survey.

Passive seismic survey

After a huddle test, we deployed the seismic stations in two cross-arrays of five with spacing 1 km oriented perpendicular/parallel to flow (sites 1-10 in Figure 1 and Figure 2). Three-component geophones were oriented with components parallel/perpendicular to flow and buried at ~ 1m depth. Power supply was as for the GPS stations. The two arrays were sited over known contrasting bed types previously surveyed using active seismics (Figure 2). Sites 1-5 were located over a hard-bedded area where we expected greater basal friction and hence greater seismic activity, sites 6-10 were over an area interpreted as deforming sediment (note streamlined bedforms) where lesser friction was anticipated. Stations 2,4,5,6,7 and 10 were sited along a previous active-seismic survey line, with station 4 sited on top of an area of recent active drumlin formation[2]. All stations were visited 14 days after initial deployment and half were found to have failed (pre-amp batteries had run flat at 4 SAQS (sites 1,4,6 and 10) due to unexpectedly high power consumption, one (SAQS site 9) had a failed solar regulator. These records have data gaps. The Refteks worked with few problems except for some corruption of data on the flashcards.

Figure 2 (following page): Detailed layout of the seismic arrays. Background colour shows basal topographic features[3]. Note contrast in bed forms between the two seismic arrays (East and West). Seismic event counts for the 14 days of operation common to all stations are displayed for all events (STA:LTA ratio > 5) and larger events (STA:LTA ratio > 40). Deforming sediment (from a previous active seismic survey) underlies sites 6, 7 and 10 and is interpreted at sites 8 and 9 from the bedforms[3,4]. Active seismics indicate lodged sediment under the west array. At Site 4, rapid basal erosion and drumlin formation between was detected from 1997 and 2004[4].



Data quality and processing

Seismics

Passive-seismic data reached a sufficiently high quality for this study. Basal slip events have simultaneous spikes in the horizontal components and a spike in the vertical lagged by a period determined by the ice thickness and the difference in travel speeds for the P and S waves[5]. Pre-amplification added to the SAQS systems improved performance and allowed event detection with short-term-average (STA) to long-term average (LTA) amplitude ratios of 5:1 (Figure 3). Events were counted automatically using the spike criteria and amplitude ratios 5, 20 and 40 (A.M. Brisbourne).

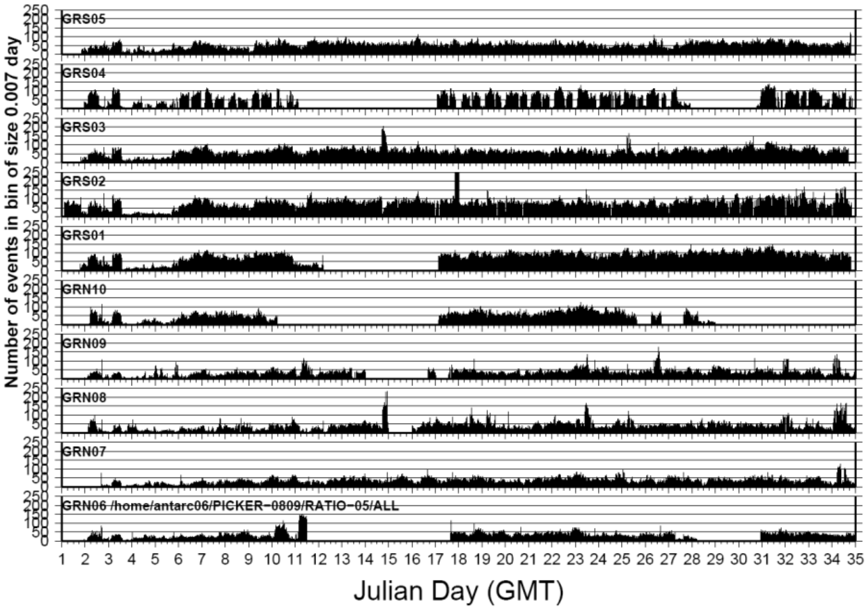


Figure 3: Seismic event counts (STA:LTA ratio 5:1). Data gaps are present in sites 1,4,6,8,9 and 10.

GPS

GPS data were pre-processed and kinematic single-epoch point positions calculated every hour using Bernese GPS software and ocean-loading corrections were applied[6] (G.H. Gudmundsson). For the static base station, standard deviation was ~3 mm in latitude and longitude and ~12 mm in altitude.

Radar

The radar data are of sufficiently high quality to identify and migrate the basal reflector (Figure 4) and were processed as previously[3] (E.C. King).

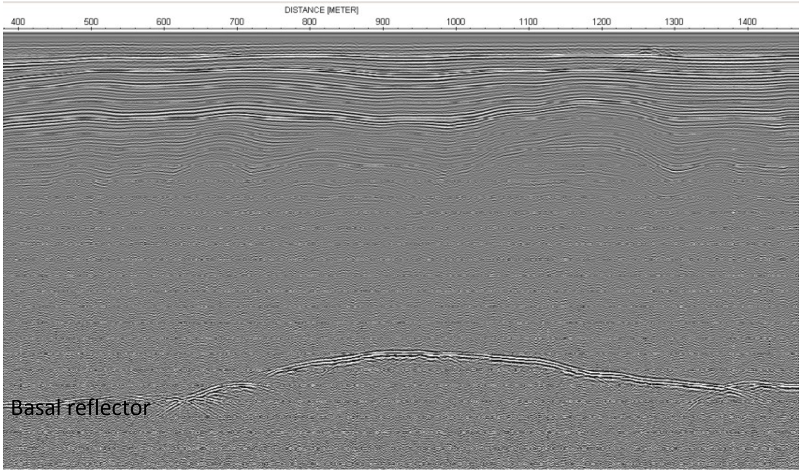


Figure 4: Unmigrated radar line crossing the Rutford ice stream.

Interpretation and preliminary findings

GPS

Tidal modulation of grounded ice stream flowline speed is apparent in the GPS data when it is detrended. Figure 5 shows a strong bi-weekly (MSf) modulation by ±14% of the flow rate at site 24, in agreement with previous findings[1]. A smaller (±1%) diurnal signal is also apparent after detrending and removal of the biweekly signal (Figure 6). This resembles a diurnal/semi-diurnal tide but a strong diurnal signal due to GPS data artefacts is also present in the base station data processed in the same way. Full differential processing will remove these artefacts.

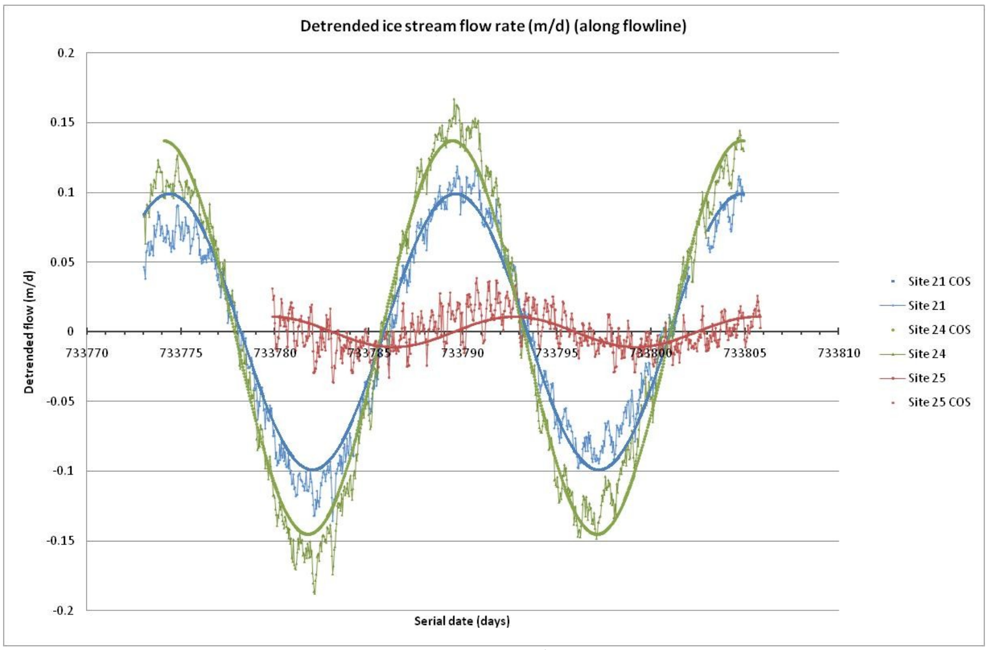
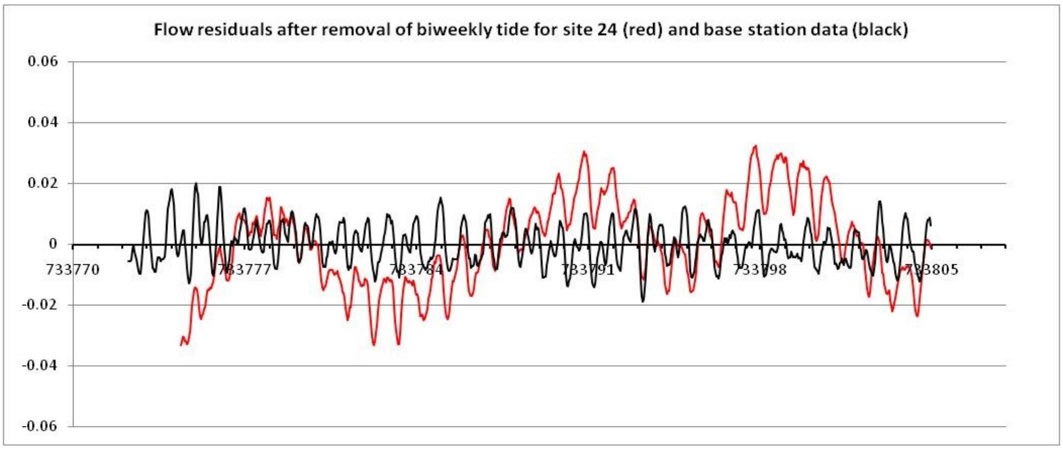


Figure 5: Linearly-detrended flowline displacement (md^{-1}) for GPS 21 (eastern margin), GPS 24 (mid-stream) and GPS 25 (eastern shear margin) (40 km, 40 km and 95 km upstream of GL respectively). GPS 24 modulation has amplitude 0.14 m, period 14.765 days.

Figure 6 (following page): Detrended flowline displacement with biweekly tide largely removed (red). A diurnal signal is prominent (x-axis units are days), with an amplitude of ~0.02 m. Equivalent data from the static base station processed in the same way is in black and shows a very similar diurnal (artefact) signal.



The bi-weekly tidal signal is also clearly evident in the lateral shear margins, e.g. Site 21 in Figure 5. At this site, mean flow is lower and the bi-weekly signal has a lower amplitude (11% of flow rate), though the signals are in phase (Table 1). Similarly, at Site 23 (western shear margin, not shown), the amplitude of the biweekly perturbation is smaller, as is the proportion of total speed (12% of flow rate) (Table 1). At Site 25, 95 km upstream of the grounding line and 55 km upstream of Site 24, the same tidal signals are present (Figure 5). This demonstrates the great extent of the tidal modulation of flow, far inland and into the shear margins.

At site 25, mean flow rate is 0.70 m/d and the biweekly (MSf) amplitude is 0.015 ±0.002 m/d (2% of total flow) with a phase shift relative to Site 24 of ~63°, equivalent to 2 days and 14 hours. This implies a transmission rate of 0.26 m/s (lower than the 1-2 m/s and 10±4 m/s reported separately over the lower 40 km of the grounded ice stream[1,6,7]), supporting an interpretation of variable propagation rates[7]. Although the biweekly signal is attenuated at this distance from the grounding line, it is notable that the diurnal/semi-diurnal signal is as great as at the lower sites and that they are in-phase within the errors of the phase measurements (Table 1, Figure 5), supporting the interpretation of diurnal GPS noise.

GPS Site	MSf Phase (° with 95% CI uncertainties)	Amplitude (m)	Mean flow rate (m/d)	% modulation of flow
21	132 ±2	0.096 ±0.003	0.919 ±0.0002	11 ±0.35
23	132 ±10	0.122 ±0.021	0.987 ±0.0002	12 ±2.15
24	127 ±3	0.139 ±0.006	1.053 ±0.0002	14 ±0.59

Table 1: Phasing of the biweekly signal at two marginal (21 and 23) and one mid-stream GPS sites (24).

These findings are significant in terms the mechanism behind the biweekly flow signal. The proposed model[6] explains the modulation as the result of a non-linear strain response to the basal shear stress imposed by the tides specifically in the basal sediment, but the resistance to flow comes both from the bed (~65%) and the lateral margins (~35%). It is possible that the non-linearity lies within the lateral margin resistance and not the basal sediment. The observation that the two marginal sites (21 and 23) are in phase (or slightly lagged) with the mid-stream site and that the proportional modulation of flow is greatest in mid-stream (Table 1, significant at least for sites 21 and 24) supports the interpretation of a basal origin for the signal.

Seismics

As anticipated, we find that the lodged-sediment section of the ice stream generated substantially more seismic events than the deforming-sediment area. The central sites (2 and 7, Figure 2) of each array were occupied by identical Reftek stations that ran continuously over a 32-day period. Site 2 (lodged) yielded 299,575 events, site 7 (deforming) yielded 137,559 (at STA:LTA ratio 5). All stations were running on 14 of the survey days and the data from these days are displayed in Figure 2. The largest number of events was generated at the upstream edge of the lodged area for ratios of 5, 20 (not shown) and 40, i.e. this was the most active area for large and small seismic events (note though that the array is designed for larger events to be detectable at more than one station). This implies that this area acts as a ‘sticky spot’ that resists ice stream flow.

When the seismic event counts are plotted through time along with the modulations in surface flow rate from the GPS (Figure 7), we find no apparent dependence on the biweekly tidal signal although in some cases there is evidence of higher-frequency periodicity (Site 4, Figure 3). Further tidal analysis on the seismic event counts should help identify the cause of the periodicity that could result from ocean forcing, as suggested previously[7] or from an internal stick-slip mechanism.

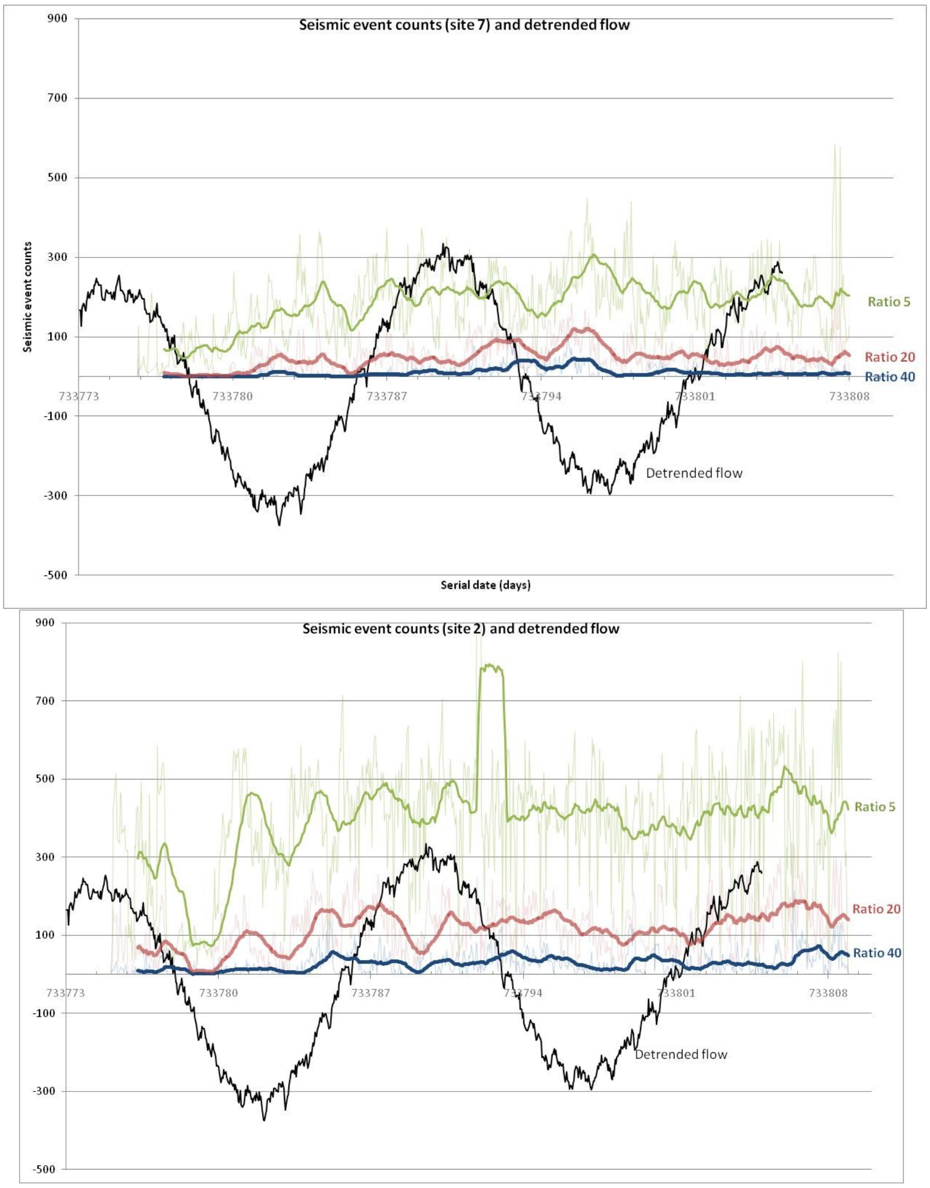


Figure 7: Time-varying seismic activity for events detected at STA:LTA ratio 5, 20 and 40 (green, red, blue data and moving-average smoothed lines) for a) site 7 (deforming sediment), and b) site 2 (lodged sediment), plotted with the detrended along-flow ice stream displacement (with prominent biweekly cycle). There is no visible indication of a biweekly signal in the seismic events.

Radar

The bed depths picked and interpolated from the radar data (this and a previous survey by E.King) show highly elongated, streamlined bedforms that flow around a large basal ridge in the middle of the ice stream and aligned with the main trough (Figure 9). The streamlined bedforms are associated with deforming sediment (from active seismic surveys). They indicate the distribution of deforming and lodged sediment and major form-drag features that influence the flow of the ice stream.

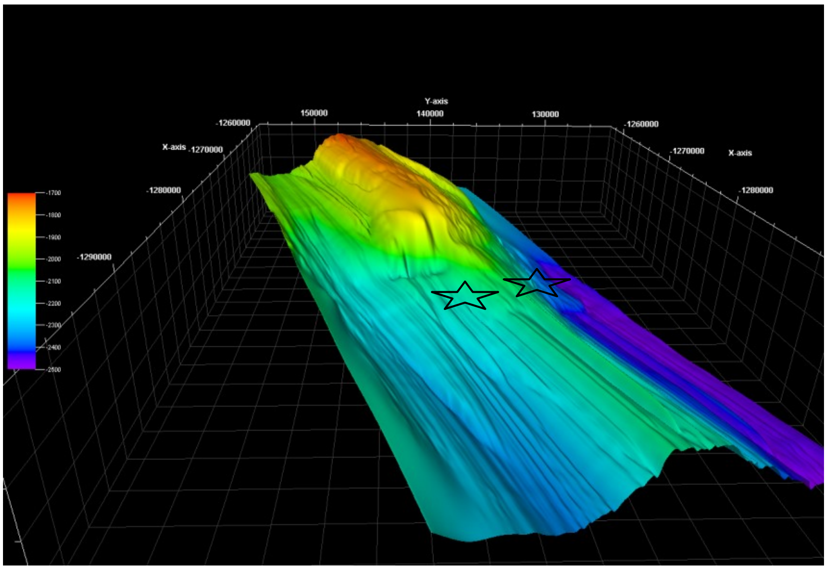


Figure 9: Basal topography of the lower 40 km of the Rutford Ice Stream, from ice penetrating radar data (lines in Figure 1). Flow is into the page. The seismic array locations are starred.

Conclusions and future plans

In conclusion, this field survey has yielded substantial GPS, seismic and radar datasets. They show that ocean tides drive significant fluctuations in ice stream flow not only in the lower, central ice stream but far inland and into the lateral shear margins. Initial processing supports an interpretation of non-linear basal sediment deformation under periodic tidal forcing. We confirm that basal seismic activity is greater over lodged than deforming sediment, supporting the interpretation that the ice stream slides over lodged sediment and that this provides increased resistance to flow. We do not see an obvious biweekly tidal signal in the seismic activity, which is surprising given how much the ice stream flow fluctuates on this time scale. We find from radar mapping that the bedforms associated with flow by sediment deformation continue down to the ice stream grounding line in troughs either side of an elongated central ridge, where bedforms suggest that basal sliding dominates. Our future plans for these data include:

- Full differential GPS processing of each site (with static base station) to reduce location, phase and amplitude errors in the tidal analysis and to test whether any diurnal or semi-diurnal tidal signals remain.
- Analysis of strain and its variation through time in the upstream and downstream strain arrays.
- Full tidal analysis of seismic event counts for each ratio at each site.
- Location of seismic events on the bed for those events that are detected by multiple seismic stations.

References

[1] Gudmundsson, G. H. Fortnightly variations in the flow velocity of Rutford Ice Stream, West Antarctica. *Nature* **444**, 1063-1064 (2006).

[2] Smith, A. M. *et al.* Vol. 35 127-130 (2007).

[3] King, E. C., Hindmarsh, R. C. A. & Stokes, C. R. Formation of mega-scale glacial lineations observed beneath a West Antarctic ice stream. *Nature Geosci* **2**, 585-588 (2009).

[4] Smith, A. M. & Murray, T. Bedform topography and basal conditions beneath a fast-flowing West Antarctic ice stream. *Quat. Sci. Rev.* **28**, 584-596 (2009).

[5] Smith, A. M. Microearthquakes and subglacial conditions. *Geophys. Res. Lett.* **33**, L24501 (2006).

[6] Gudmundsson, G. H. Tides and the flow of Rutford Ice Stream, West Antarctica. *J. Geophys. Res.* **112**, F04007 (2007).

[7] Adalgeirsdottir, G., Smith, A.M., Murray, T., King, M.A., Makinson, K., Nicholls, K.W. and Behar, A.E. 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**, 9 (2008).