Final Report (October 2010) for NERC-GEF Loans 863, 864, 865: Present and Future Stability of the Larsen C Ice Shelf (SOLIS) – GPR/GPS/Seismic

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ABSTRACT

In partial fulfilment of the NERC-AFI grant SOLIS (Present and Future Stability of the Larsen C Ice Shelf, NE/E012914/1) we conducted a major field season on the Larsen C ice shelf, Antarctic Peninsula, in the austral summer of 2008-09. This is a joint report for the three GEF loans that supported our fieldwork, which include ground-penetrating radar (GPR, Sensors & Software PE Pro), differential GPS (Leica Geosystems 1200) and passive seismic (SAQS) equipment. We are submitting a joint report for the three loans not only to avoid much repetition because all three types of data are intimately related to each other, but also because our time in the field was significantly curtailed (from ~ 2 months to ~ 3 weeks) due to logistical problems with BAS aircraft in that field season. We were therefore forced to place a focus on our planned multi-component seismic reflection surveys (not reported here since they used equipment owned by Swansea), and were only able to collect skeleton GPR (~ 50 km of skidoo-towed common-offset data, and multi-azimuth (at 30º increments) common-midpoint (CMP) data in two locations), GPS (2 receivers) and passive seismic data (1 SAQS station). Nonetheless, these skeleton data proved to be highly valuable for our AFI project, revealing the presence of a large body of marine ice on the underside of a thin flow stripe in the southern part of the Larsen C ice shelf (GPR). Since the ice-flow rates of this thin stripe are statistically the same as those of the surrounding ice (GPS), the flow stripe is not

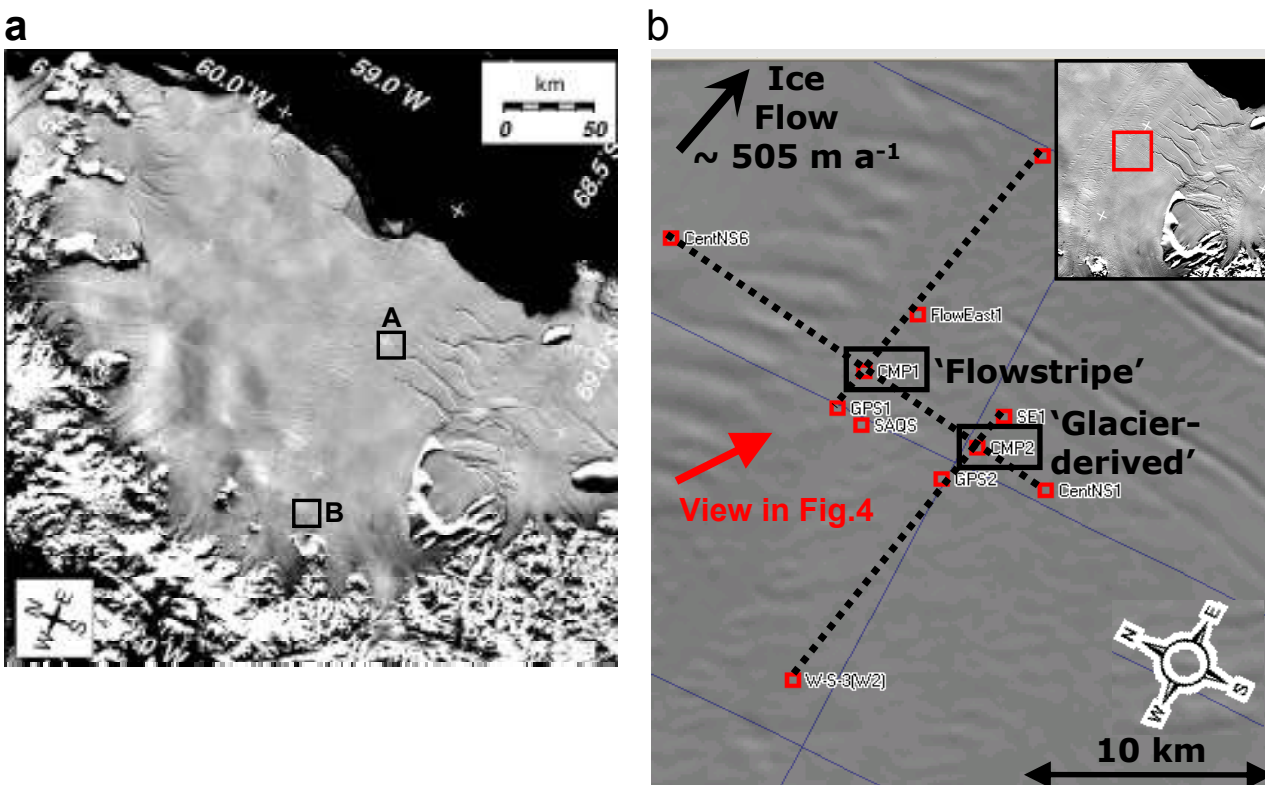

Figure 1. a. *Overview map of the Larsen C ice shelf and originally envisaged locations of the two study sites.* ***b.*** *Actual study location in the southeastern portion of the ice shelf (inset), together with a zoomed-in-view of it. The dotted lines indicate the extents of the skidoo-towed GPR lines, and 'CMP1' and 'CMP2' mark the two locations of the multi-azimuth GPR and seismic CMP surveys. Also shown are the locations of the two GPS receivers on the presumed flow stripe (GPS1) and to the south of it (GPS2), as well as of the SAQS passive seismic station at the estimated boundary between the flow stripe and the ice to the south of it. View direction in Figure 4 is indicated by the red arrow.*

mechanically decoupled from the surrounding ice. In conjunction with our seismic reflection data we can therefore confirm the key hypothesis of our AFI project, concluding that structurally and mechanically heterogeneous ice critically affects rates of rift propagation (observed to effectively halt when rift tips arrive at the thin flow stripe) on the Larsen C ice shelf, and thus ultimately also its stability (which is quantitatively supported by continuum-mechanical ice-flow and fracture-mechanics modelling). Our SAQS passive seismic data are virtually devoid of noticeable events, which qualitatively agrees with the notion that rift propagation has virtually halted at the flow stripe owing to the presence of the marine ice body. Preliminary analyses tentatively suggest that crystal anisotropy, as inferred from our the seismic and radar CMP data, does not modulate ice mechanical heterogeneity. In contrast, we can reject the hypothesis that critical slowing down of rift propagation at the thin flow stripe is caused by mechanical decoupling between this stripe and surrounding ice. Our findings are therefore likely to have far-reaching consequences for Pan-Antarctic ice-shelf stabilities.

I. BACKGROUND

In the wake of the successive disintegration of the northernmost part of the Larsen ice shelf (Larsen A) in 1995 and its southern neighbour (Larsen B) in 2002, the stability of the central (Larsen C; Figure 1a) portion comes into question if the present warming trend continues [Shepherd et al., 2003]. Indeed, the -9º mean annual isotherm is considered as the current limit of ice shelf viability on the Antarctic Peninsula [Morris & Vaughan, 2003]; this isotherm is encroaching upon the northern reaches of the Larsen C ice shelf, which is by far the largest (~ 48600 km^2) ice shelf on the Antarctic Peninsula. Elucidation of the present and future stability of the Larsen C ice shelf is thus a current research priority challenging the international scientific community.

The umbrella project (SOLIS) funded by a NERC AFI Round 8 grant aims to [a] identify the role of spatiotemporal changes in ice-shelf structural and mechanical properties in regulating present stability of the Larsen C ice shelf; and [b] simulate likely future scenarios of rapid retreat of this ice

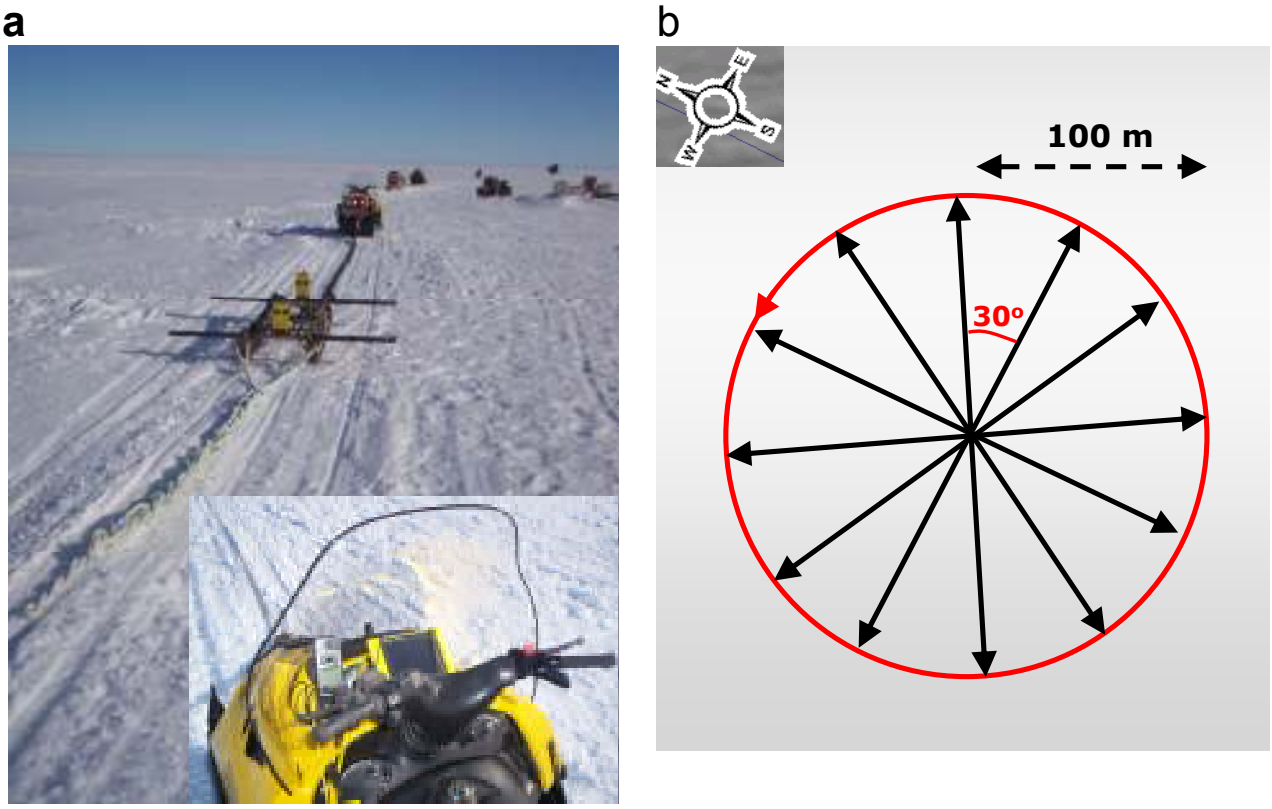

Figure 2. a. *Photograph of the skidoo-towed radar setup. The transmitter and receiver were set up (using self-amalgamating tape) on a Half-Nansen sledge, which was stabilised with a rope anchor. The fibreoptic cables were protected by plastic bags where possible. The fibre optics were inserted into plastic aquarium piping, and connected the 'antenna sledge' with the PE Pro's control unit that was housed, together with a 100 Ah battery for warmth, in a Zarges box on the back of the skidoo. The battery was continuously supplied by a solar panel mounted on top of the box. The PE Pro's VDU and hand-held GPS were mounted on the dashboard of the skidoo (inset), allowing continuous quality control of the data.* ***b.*** *Layout of the multi-azimuth GPR CMP and associated CO data collected.*

shelf. This is being achieved using a field geophysical campaign targeting two sites on the southern Larsen C ice shelf (Figure 1) combined with Linear Elastic Fracture Mechanics (LEFM) modelling and satellite remote sensing. It is particularly important to investigate these two sites because [a] at Site A the tips of sub-parallel rifts align along what we hypothesize is softer ice; and [b] this softer ice apparently originates at Site B. The original specific objectives (SO) of the field geophysical and glaciological campaign were to:

[SO1] Determine the surface velocity and strain-rate fields at both study sites;
[SO2] Map the ice-shelf internal structure;
[SO3] Characterise the spatial distribution of firn and ice softness and the material densities;
[SO4] Identify the spatial and temporal patterns of rift propagation;

The ground-penetrating radar (GPR) equipment on loan from GEF was required to deliver on the specific objectives SO2 and SO3, the GPS equipment to deliver on SO1 and SO4, and the passive seismic equipment to deliver on SO4. Unfortunately much of SO1 and SO4, and particularly the planned rift monitoring campaign, had to be cancelled owing to the greatly curtailed field season.

II. SURVEY PROCEDURE

1. Ground-penetrating radar data (GPR)

We used GEF's Sensors&Software PE Pro system with a 1000V transmitter for all of our GPR surveys. We collected both three main lines of skidoo-towed GPR data (dotted lines in Figure 1b; Figure 2a). Following an initial series of tests with a range of antenna frequencies (25, 50, 100, 200 MHz), we concluded that, within the time constraints, the 50 MHz antennas yielded the best compromise between depth penetration and vertical resolution. 50 MHz antennas were therefore used exclusively for GPR data acquisition during this field season. Following further tests with different acquisition settings, we found that a sampling interval of 0.8 ns with 8 stacks and a time window of ~ 500 m depth equivalent was particularly well suited. At a skidoo-towed survey speed of ~ 12 m/s we were thus able to collect one radar trace approximately every three metres. A handheld Garmin 76S GPS was plugged into PE Pro control unit (Figure 2a), and provided GPS locations for each radar trace at a spatial resolution of approximately ± 5 metres. Prior to the field season we had envisaged to be able to collect several 100s to > 1000 of line kilometres of skidoo-towed radar data in two locations (Figure 1). Allowing for testing of the GPR setup and acquisition

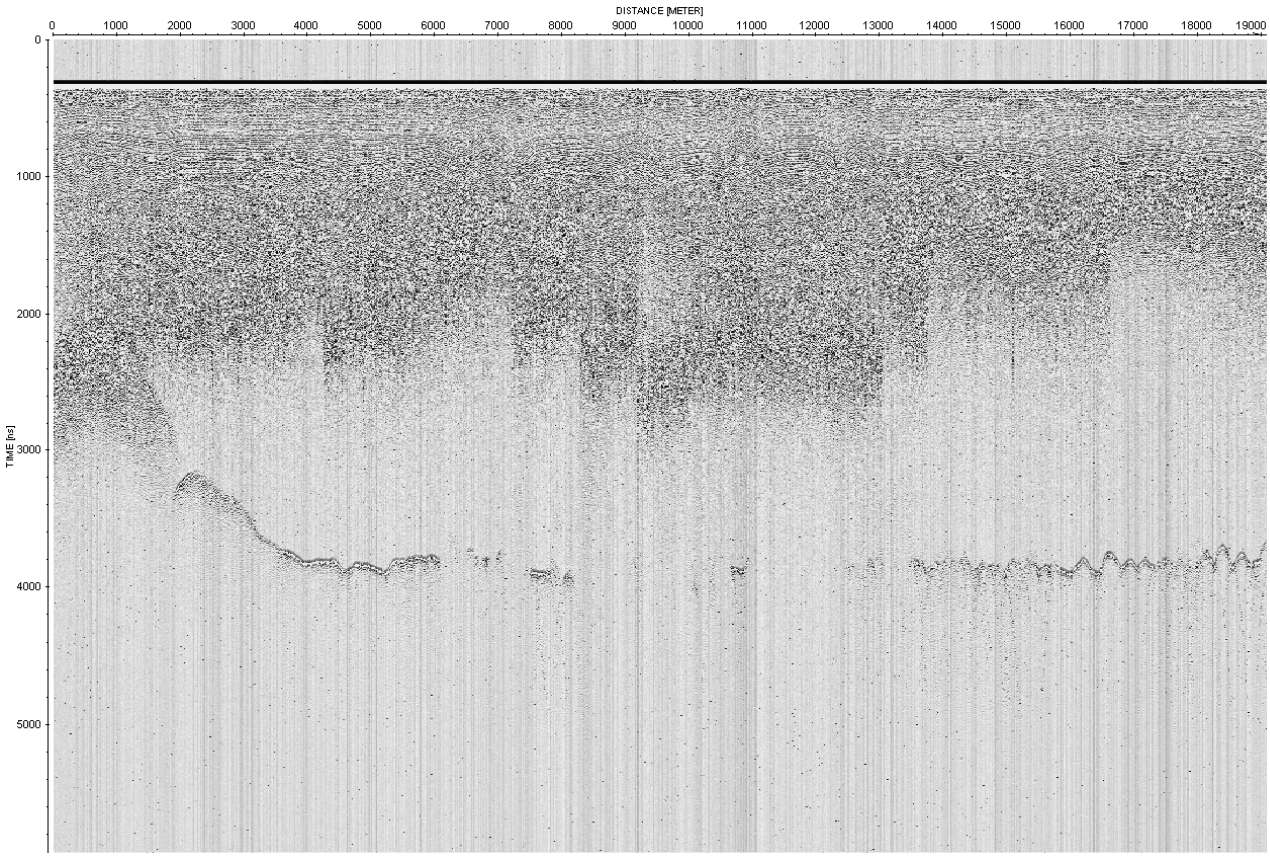

Figure 3. *Raw radargram for the N-S line (Figure 1b), displayed with an AGC window of 50 ns.*

parameters, we were eventually only able to collected some 50 line km of GPR data in key locations (Figure 1b).

Using the 50 MHz antennas together with the long fibreoptic cables provided (80-100m), we also collected multi-azimuth GPR CMP data at one location on the flow stripe (CMP1), and one adjacent to it (CMP2) (Figures 1b and 2b). Antenna step sizes of between 0.5m and 1m were used, and the number of stacks was increased to 32. To be able to correct for sloping subsurface layers during data processing, we also collected common-offset GPR data along each CMP line, as well as in a circle around the outside of the circle spanned by the CMP lines (Figure 2b).

2. GPS and passive seismic stations

Two Leica 1200 geodetic GPS receivers were deployed at locations CMP1 and CMP2 respectively on and to the south of the flow stripe (Figure 1b), to measure surface flow speeds and potential relative movement across the boundary of the flow stripe. The stations were deployed in early December 2008, and uplifted by BAS personnel at the end of austral summer, giving approximately 3 months worth of GPS data from both locations. The receivers were mounted on 3m long aluminium poles that were inserted firmly into the surface snow, until the GPS antennas were less than one metre above the snow surface. The GPS controls units were deployed in Zarges boxes together with 100 Ah batteries for warmth, and then buried in surface snow to avoid exposure to strong winds. The batteries were continuously supplied by solar panels, and antennas-snow surface distances were re-measured regularly during the field season.

The SAQS passive seismic station was deployed on the presumed boundary between the flow stripe and the adjacent ice. This location was chosen because, in addition to potential tidally-modulated seismicity or rifting events (as illustrated in Figure 1b all of our surveys were conducted

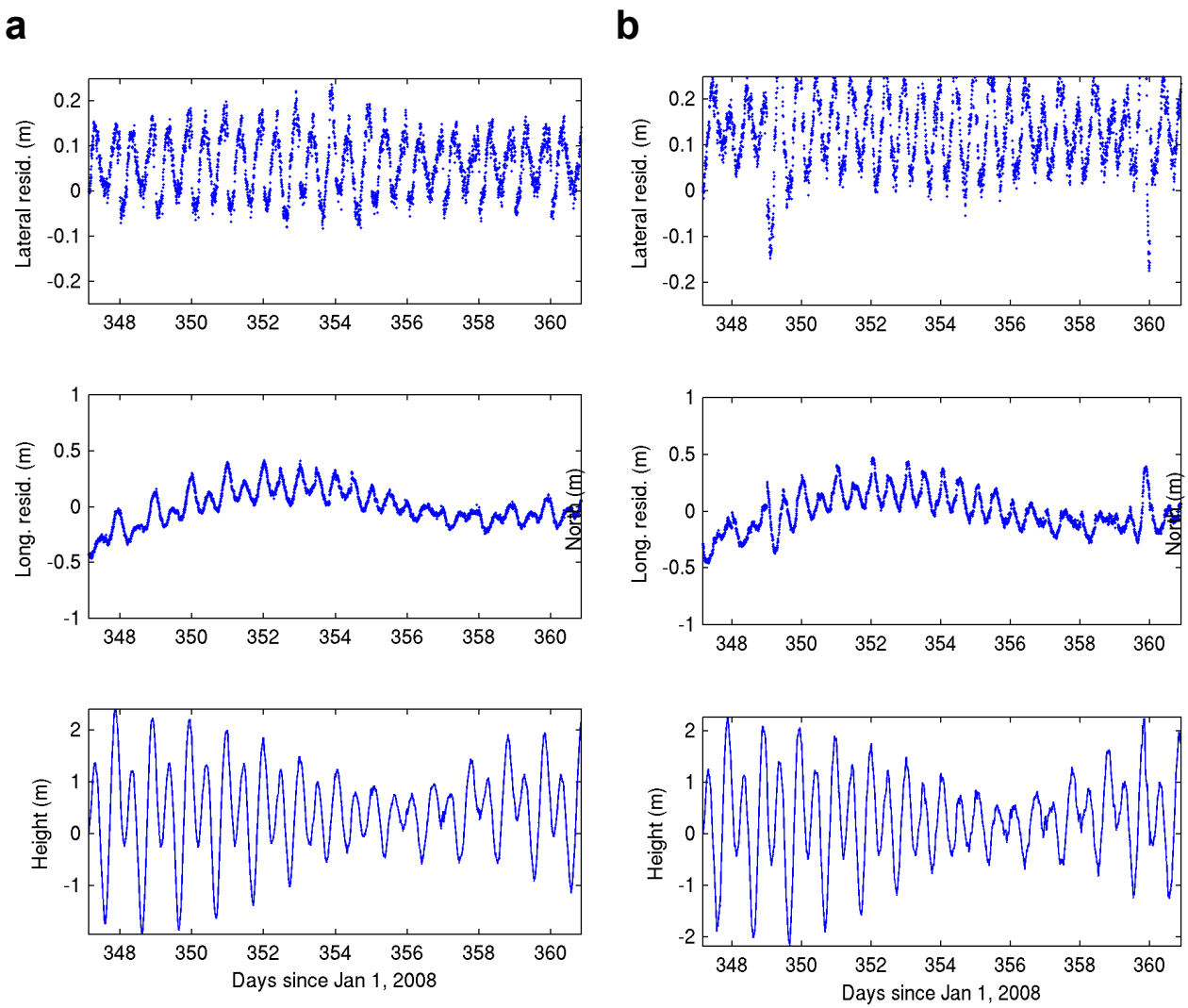

Figure 4. *Example residual lateral (top row), longitudinal (middle row) and vertical motion of the GPS receivers on the flowstripe (a, left column) and to the south of it (b, right column).*

in the vicinity of a prominent series of rift tips to the south and/or east of all survey locations), it was anticipated that potential mechanical decoupling or relative flow between the flow stripe and the adjacent ice may also cause seismicity. The three-component geophone was mounted on a wooden base plate (to void melting-in and tilting of the geophone) that was deployed in a snow pit ~ 1m deep. The SAQS logger and preamps were deployed in a Zarges box together with the battery power supplies for warmth. The box was buried in surface snow as far away from the geophone as the cable would stretch. A solar panel was deployed on two aluminium poles on the opposite side of the Zarges box, again as far away as feasible from the geophone to minise deployment-related noise. All passive data were logged at 1000 Hz using the settings programmed by SeisUK. The SAQS station was located in the immediate vicinity of an IRIS Passcal 100 Hz geophone / logger that we deployed for a US colleague (Koni Steffen). We will thus be able to directly compare the performance of the two types of instruments with each other.

III. Data quality and processing

Although the radar sledge was de-metalled prior to use, we found that the data were 'riddled' with noisy 'spikes' (Figure 3) that were challenging to remove by processing. The spikes did appear only in the skidoo-towed radar data, but not in the CMP data, suggesting that the radar setup on the sledge/skidoo caused the problem. The origin of this problem so far remains uncertain, however. Otherwise the data were of appreciable quality, and all data were processed with the PC-based software ReflexW that is available at Swansea and at BAS.

The GPS data were processed by Matt King at the University of Newcastle, who generated Precise Point Positioning solutions using the GIPSY v4.04 software. The data were of excellent quality, and as expected show tidal modulation in the along (and a little in the across) flow directions (Figure 4). The data revealed average flow speeds of 511.5 ± 11.3 m a^{-1} at CMP1, and 500 ± 12.6 m a^{-1} at CMP2 (see Figure 1b for station locations).

The SAQS passive seismic data were downloaded and split into minute mini-seed files. Visual examination of the data using the PQL2 software revealed that very few seismic events (other than explosive seismic shots used for the seismic reflection surveying) are present on the data. For this reason analysis of the SAQS data has been a low priority since last year compared to the analysis of the seismic reflection and GPR data, as well as the considerable modelling tasks to be completed as part of our AFI project. We hope to dedicate time to the analysis of the passive seismic recordings in 2011.

IV. Interpretation to date, preliminary findings and conclusions

The key discovery for our AFI project is the large body of marine ice on the underside of the thin flow stripe in the southern part of the Larsen C ice shelf (Figure 4), along which the tips of a

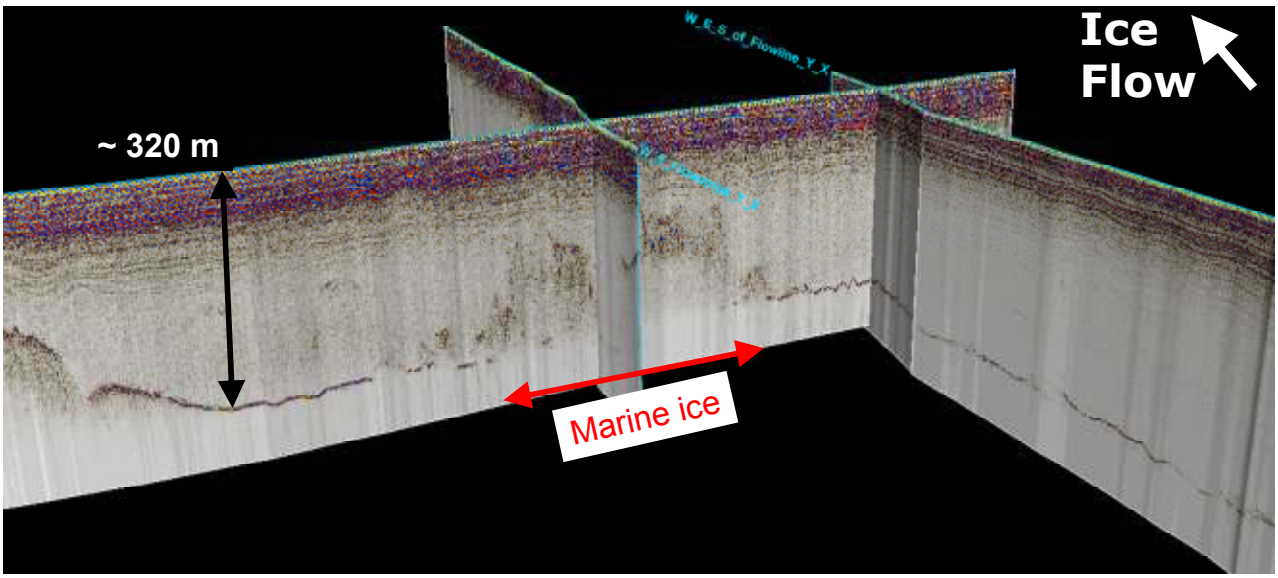

Figure 4. *Fence diagram of the three main radar lines collected (Fig. 1b). The anomalous body of marine ice, marking the lower portion of the thin flow stripe, is readily apparent in the N-S radar line (as labelled). It clearly contrasts with an an otherwise much smoother ice shelf base. Rapidly thinning ice in the far North (left side of the diagram) is interpreted to indicate a bottom crevasse. A mean ice thickness of ~ 320 m is obtained using a radar ice velocity of 0.168 m ns^{-1}.*

prominent series of rifts align (Figure 1). Since the ice-flow rates of this thin stripe are statistically the same as those of the surrounding ice (~ 500 m a^{-1}), the flow stripe is not mechanically decoupled from the surrounding ice. In conjunction with our seismic reflection data we can therefore confirm the key hypothesis of our AFI project, concluding that structurally and mechanically heterogeneous ice critically affects rates of rift propagation. Based on satellite imagery we found that newly formed rifts at the upstream end of the prominent series of rifts can propagate at rates of up to 23 km a^{-1}, but halt abruptly as soon as they reach the thin flow stripe. Prior to this field season we could only speculate what was causing this abrupt change in rift regime, whereas now we have convincing evidence that the reason for this is mechanically softer marine ice. This marine ice is inferred to cause a local reduction in stress intensities below the threshold required for rifts to continue propagating. Our SAQS passive seismic data are virtually devoid of noticeable events, which qualitatively agrees with the notion that rift propagation has virtually halted at the flow stripe owing to the presence of the marine ice body. This finding is highly significant because rift tip alignment is observed on almost all Antarctic ice shelves. In contrast, we can reject the hypothesis that critical slowing down of rift propagation at the thin flow stripe is caused by mechanical decoupling between this stripe and surrounding ice. We can therefore conclude that ice-mechanical heterogeneity more likely than not has a significant impact of ice shelf stability, and must be included in models of ice-shelf break-up. This is quantitatively confirmed by our continuum-mechanical flow and fracture mechanics modelling (not shown here, for details see Jansen et al., 2010).

We have yet to complete our analyses of the multi-azimuth GPR CMP data (Figure 2b), which are conducting in conjunction with our seismic reflection data. We are currently 'in search' for a unified model of ice density profiles derived from the GPR and seismic data (Figure 5a), and also for evidence of crystal anisotropy in our GPR and seismic reflection data (Figure 5b). Ice density profiles reconstructed from GPR vs. seismics differ markedly from each other, and particularly so for the Northern CMP site on the flow stripe (Figure 5a and 1b). The reason for this is yet to be revealed, and joint seismic-radar inversion is anticipated to solve this problem. Once corrected for the dip of the ice-internal reflectors, we obtain some variation of radar velocities with azimuth (Figure 5a), although we not at present believe that the observed variations are statistically significant. We have yet to analyse our multi-azimuth seismic reflection data for crystal anisotropy, and will therefore be able to shed more light on this issue too.

Our GPS data have now been fully processed by Matt King, and will be included in his new model of tidal forcing of ice-shelf dynamics, which is a focus of his AFI-7 project. We also hope to correlate 'jumps' in the GPS data with seismicity on the ice shelf, and further analyse the passive seismic data for [a] any sources of seismicity (i.e. ocean forcing, rift propagation, etc.); and [b] compatibility with the seismic data generated by the US Passcal instrument.

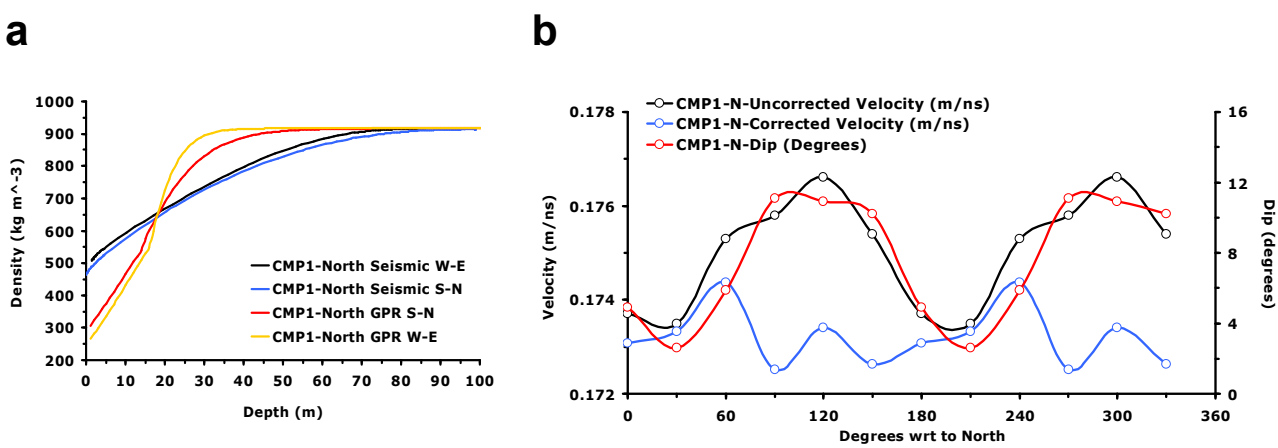

Figure 5. a. *Ice density profiles reconstructed from azimuthal GPR vs. seismic data.* ***b.*** *Search for systematic variations in radar velocities with azimuth. What does initially appear as 'convincing evidence' for velocity variations / crystal anisotropy, largely 'disappears' when corrected for the dip of the internal layers. All records shown are for the CMP site on the flowstripe (CMP1, Figure 1b).*

V. Publications

Kulessa, B., E. C. King, B. E. Barrett, D. Jansen, A. J Luckman and P. Sammonds. Joint inversion of multi-component seismic and ground-penetrating radar GPR) data for ice-physical properties, and application to the Larsen C ice shelf. *EOS, Transactions of the American Geophysical Union, Fall Meeting Supplement* (December 2010) (Loans 863 and 864).

Kulessa, B., D. Jansen, E. C. King, A. Luckman, and P. R. Sammonds, B. E. Barrett and M. A. King Present and future stability of the Larsen C ice shelf (SOLIS). *9th Antarctic Funding Initiative Workshop, Cambridge* (September 2010) (Loans 863 and 864) (Loans 863 and 864).

Kulessa, B., D. Jansen, E. C. King, A. Luckman, and P. R. Sammonds, B. E. Barrett and M. A. King Present and future stability of the Larsen C ice shelf (SOLIS). *9th Antarctic Funding Initiative Workshop, Cambridge* (September 2010) (Loans 863 and 864).

Jansen, D., B. Kulessa, A. Luckman, E. C. King, and P.R. Sammonds. Marine ice within the Larsen C ice shelf and its implication for ice shelf velocity. *6th International Workshop on Antarctic Peninsula Climate Change, University of Leeds, UK* (July 2010) (Loans 863 and 864).

Jansen, D., B. Kulessa, A. Luckman, E. C. King, and P.R. Sammonds. Marine ice within the Larsen C ice shelf and its implication for stress distribution. *24th International Forum for Research into Ice Shelf Processes (FRISP), Bad Bederkesa, Germany* (June 2010) (Loans 863 and 864).

Jansen, D., B. Kulessa, P. R. Sammonds, A. Luckman, E. C. King, and N. F. Glasser. Flow, fracture and modelled present stabilities of the Larsen C and northernmost Larsen D ice shelves. *Geophysical Research Abstracts, European Geosciences Union Joint Assembly, Vienna, Austria* (May 2010) (Loans 863 and 864).

Jansen, D., B. Kulessa, P. R. Sammonds, A. Luckman, E. C. King, and N. F. Glasser. 2010. Flow, fracture and modelled present stabilities of the Larsen C and northernmost Larsen D ice shelves. *Journal of Glaciology*, 56(198), 593-600 (Loans 863 and 864).

Kulessa, B. E. C. King, B. E. Barrett, D. Jansen, A. Luckman, P. R. Sammonds, and M. A. King. Is ice mechanical heterogeneity controlling the stability of the Larsen C ice shelf? *2009 Joint WAIS/FRISP Workshop, Eatonville, Washington, USA* (September 2009), (Loans 863 and 864).

Kulessa, B., D. Jansen, E. C. King, B. E. Barrett, M. A. King, A. Luckman, and P. R. Sammonds. Present and future stability of the Larsen C ice shelf (SOLIS). *8th Antarctic Funding Initiative Workshop, Cambridge* (September 2009), (Loans 863 and 864).

Kulessa, B. E. C. King, B. E. Barrett, D. Jansen, A. Luckman, P. R. Sammonds, and M. A. King. Structure and mechanical properties of the southern Larsen C ice shelf from in-situ geophysical measurements - preliminary results. *International Glaciological Society, International Symposium on Glaciology in the International Polar Year, Northumbria University, Newcastle, UK* (July 2009), (Loans 863 and 864).

Jansen, D., B. Kulessa, A. Luckman, P. Sammonds and E.C. King. Modelling Ice flow velocity for the Larsen C: implications for ice shelf stability. *International Glaciological Society, International Symposium on Glaciology in the International Polar Year, Northumbria University, Newcastle, UK* (July 2009), (Loans 863 and 864).

Kulessa, B., D. Jansen, E. C. King, A. L. Luckman, P. R. Sammonds, B. E Barrett, N. F. Glasser, and M. A. King (Invited). Stability of Larsen C ice shelf (SOLIS): results so far from geophysical measurements and modelling. *Climate Change: Global Risks, Challenges and Decisions, Copenhagen, Denmark* (March 2009), (Loans 863 and 864).