AFI8/25: Isolating the Larsen-C Ice Shelf mass instability.

Determining melt rates at the base of the ice shelf.
Field report: November 2009 – January 2010.

Principal Investigator:	Professor Andrew Shepherd (University of Leeds)
Co-investigator:	Dr. Adrian Jenkins (British Antarctic Survey)
Field Scientist:	Mr Malcolm McMillan (University of Edinburgh, report author)
Field Assistant:	Mr Ian MacNab (British Antarctic Survey)
Post-doctoral Researcher:	Dr. Noel Gourmelen (University of Leeds)

1. Rationale

Over the past 50 years, the Antarctic Peninsula has been one of the fastest warming places on Earth. During the same period, 10 ice shelves fringing the peninsula have diminished in size, and several have undergone complete disintegration. In total, an area of 27 000 km^2 has been lost from Antarctic Peninsula ice shelves. Observations from the Larsen and Wordie Ice Shelves have indicated that, following ice shelf removal, there was a rapid and sustained acceleration of the grounded ice feeding the ice shelf. This provides evidence of a mechanism through which ice shelf collapse initiates increased ice mass loss from its tributary glaciers and accelerates rates of sea level rise. Studies suggest that both atmospheric and oceanic melting have contributed towards the collapse of ice shelves on the Antarctic Peninsula, yet the relative influence of each factor remains unclear.

The Larsen-C Ice Shelf is the largest remaining ice shelf on the Antarctic Peninsula, and covers an area of ~ 50 000 km^2. Satellite altimetry has shown that, between 1992 and 2001, the surface of the ice shelf was lowering by up to 27 cm per year, suggesting that the ice is, in places, thinning rapidly. In order to understand these changes and to predict the likely future behaviour of the Larsen-C, the causes of this trend must be determined. This project aims to determine the relative contribution of atmospheric and oceanic melting to the mass balance of the Larsen-C Ice Shelf. This report describes work undertaken during the 2009-10 field season to determine rates of ocean melting occurring at the base of the ice shelf.

2. Field Sites

On the basis of satellite altimetry measurements, three field sites (J1, J2 and J4 – *figure 1*) were chosen, which spanned a range of latitudes and longitudes. At J1 and J2, measurements were taken along a 10 km by 10 km cross underlying altimeter track crossing points, to ensure that ground and satellite observations were comparable. J4 was chosen to be as close to the grounding line of the Mobil Oil Inlet as possible (crevassing prevented us from reaching the grounding line itself). Here measurements were taken along two transects, one approximately in the flow direction and the other across the flow direction. Each site was visited twice so that repeat measurements, separated by 3 – 4 weeks, could be made. The locations of the three sites were:

J1: S 67° 06.489' W 061° 17.249' (centre of cross).
J2: S 68° 18.023' W 064° 08.910' (centre of cross).
J4: S 68° 23.684' W 064° 42.785' (crossing point of the 2 transects).

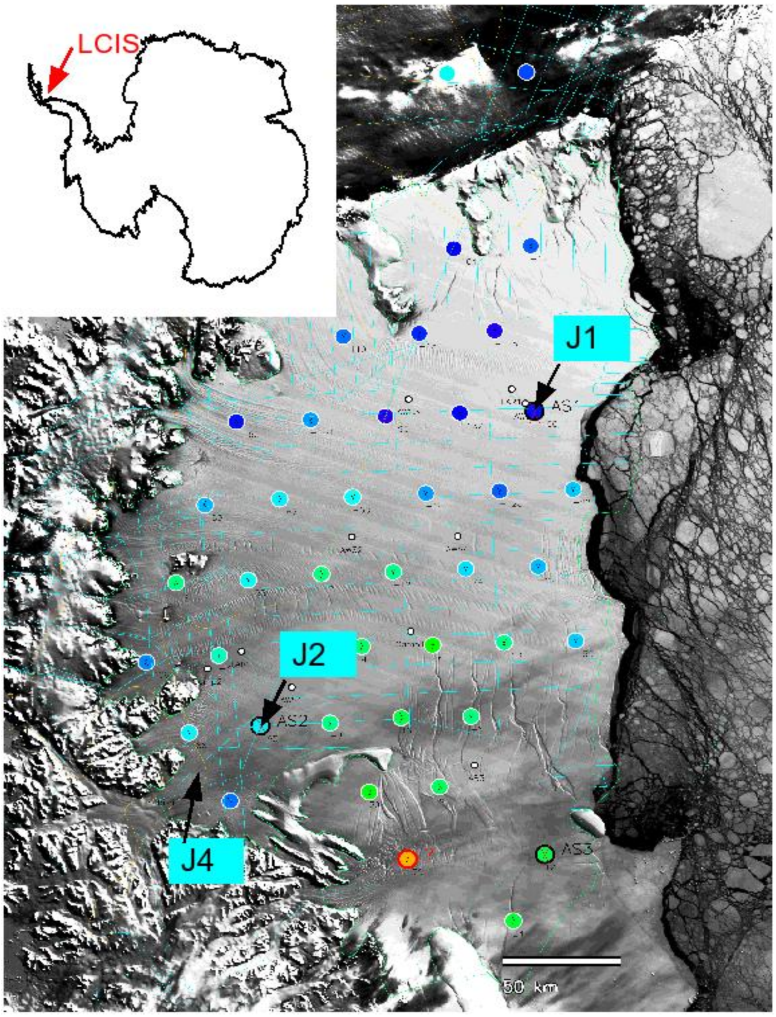

Figure 1. Location of the three field sites J1, J2 and J4.
Inset: Location of the Larsen-C Ice Shelf (LCIS).

3. Experiments

Throughout the fieldwork, two experiments were conducted. Phase-sensitive radar was used to determine precise measurements of ice thickness, and a network of 3 GPS stations was used to measure ice displacement. At every location where measurements were taken, flags were placed to enable measurements to be repeated in the same place on our return visit.

3.1 Phase-sensitive Radar

The phase-sensitive radar was carried on a de-metalled Nansen Sledge. The antennas were mounted for and aft of the sledge on metal poles, and were separated by a distance of ~ 5 m. The radar was operated at a central frequency of 305 MHz, with a bandwidth of 70 – 140 MHz, and either 801 or 1601 frequency steps were used. At each site we employed the radar in 3 different ways.

3.1.1. Profiling mode. Here we used the radar to determine a profile of the underside of the ice along each transect. This mode was also used to locate sites where we received a strong basal reflection, and that would be suitable for performing static shot experiments. At J1 the ice was relatively thin (~ 270 m) and so it was sufficient to drag the sledge at slow speeds (~ 5 km/hr) whilst continuously recording data. At J2 and J4 the ice was thicker (~ 450 m and 500-580 m, respectively) and so two alternative techniques were used. Firstly, we employed a semi-continuous profiling technique. Here the radar was dragged for a distance of 200 m, then left stationary for the time required to obtain 1 shot (60 – 140 seconds), before being dragged on a further 200 m. Secondly, in instances were the semi-continuous technique did not identify any locations with a strong base return, we used a multiple-static method. Here we dragged the sledge 500 m and then performed a single shot. If there was no return we would move the sledge 10 m and take another shot, repeating this until we were successful in acquiring a base return (always less than 5 attempts). We would then move on another 500 m and repeat the method. This latter strategy resulted in coarser sampling but was much more successful in identifying locations for static surveys where the ice was thick.

3.1.2. Static mode. This method was used to determine the precise estimates of ice thickness required for determining rates of basal melting. At ~ 16 locations at each site we acquired 4 sets of 4 radar shots, with the radar stationary as each shot was collected, and each set of shots being separated by a distance of 25 cm. This allowed us to compare multiple shots and to check for consistency between shots.

3.1.3. Continuous static mode. Here we left the radar running whilst the sledge was static for periods of 8-24 hours. The aim of these experiments was to see whether it was possible to measure basal melting and tidal flexure of internal layers over such a period.

Figure 2. Radar sledge

3.2 GPS

We used GPS instruments to record the tidal- and flow- displacement of the ice surface as we conducted our radar experiments. These data will be used to determine tidal motion, strain rates and isolate ice thickness changes due to basal melting. At each site we deployed three GPS's in a triangle; one GPS was sited at camp (intersection of the 2 transects) and the other two were located ~ 5 km along either transect. The GPS's were deployed upon arrival at each site and uplifted as we moved to our next site, so as to ensure the longest possible data record. Difficulties powering one of the units led to an intermittent record from one unit during our second visit to each site.

4. Preliminary Results

4.1 Radar profiling

Radar profiling resolved the base of the ice shelf at all 3 sites. As we travel from J4 towards the grounding line, the ice thickened by ~ 80 m over a distance of ~ 8 km *(figure 3).* At this point the signal returned from the base became weaker and then disappeared.

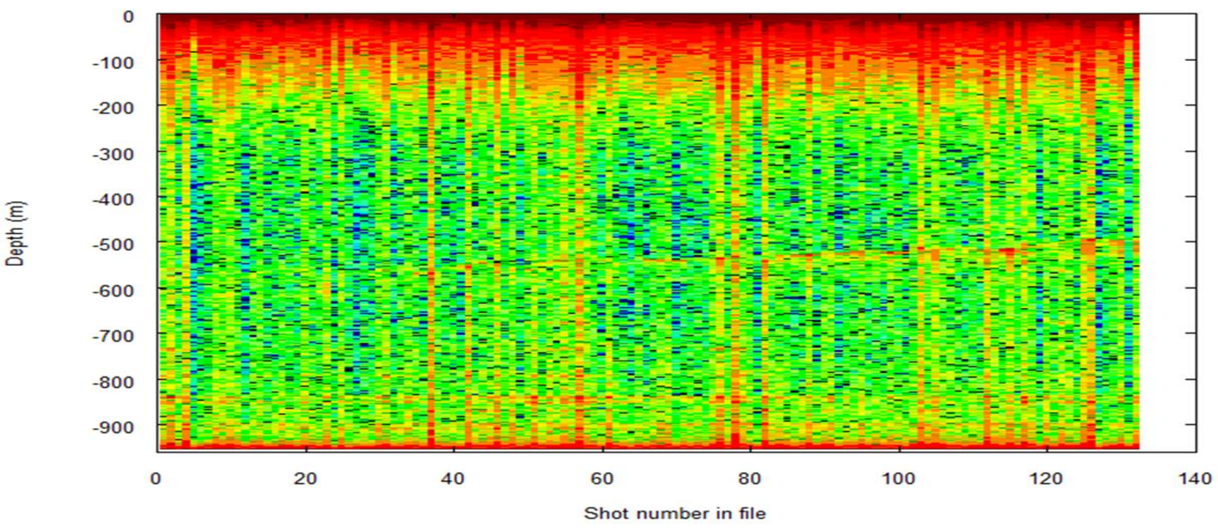

Figure 3. Profile from inland limit (shot 0) to J4 (~ shot 132).
Basal reflection (red) shows intermittently at a depth of 500 – 600 m.

4.2 Radar statics

Static shots have identified the base at multiple locations at each site.

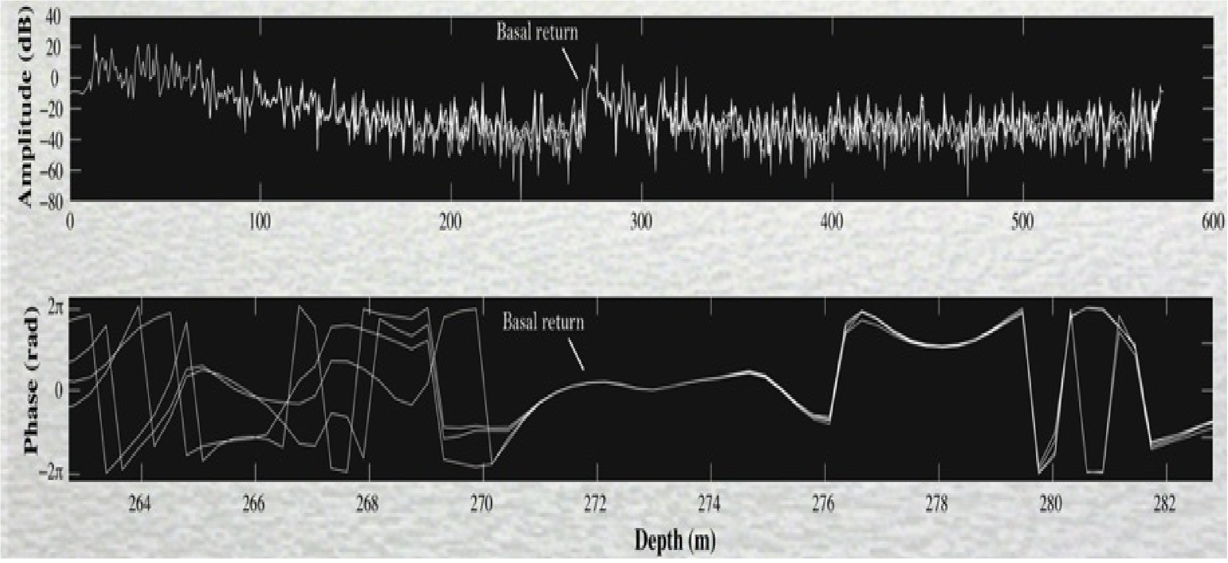

Figure 4. Amplitude (top) and phase (bottom) of four static radar shots plotted as a function depth, at site J1. Internal layers are resolved in the amplitude plot to a depth of 130 m. Basal return visible as a 'spike' in the amplitude of the returned signal, and as a convergence of the phases of multiple shots in the phase of the returned signal.

4.3 Radar continuous statics

Continuous statics (e.g. *figure 5*) were conducted at all sites. Initial analysis suggests that these may show internal layers responding to tidal motion (*figure 6*).

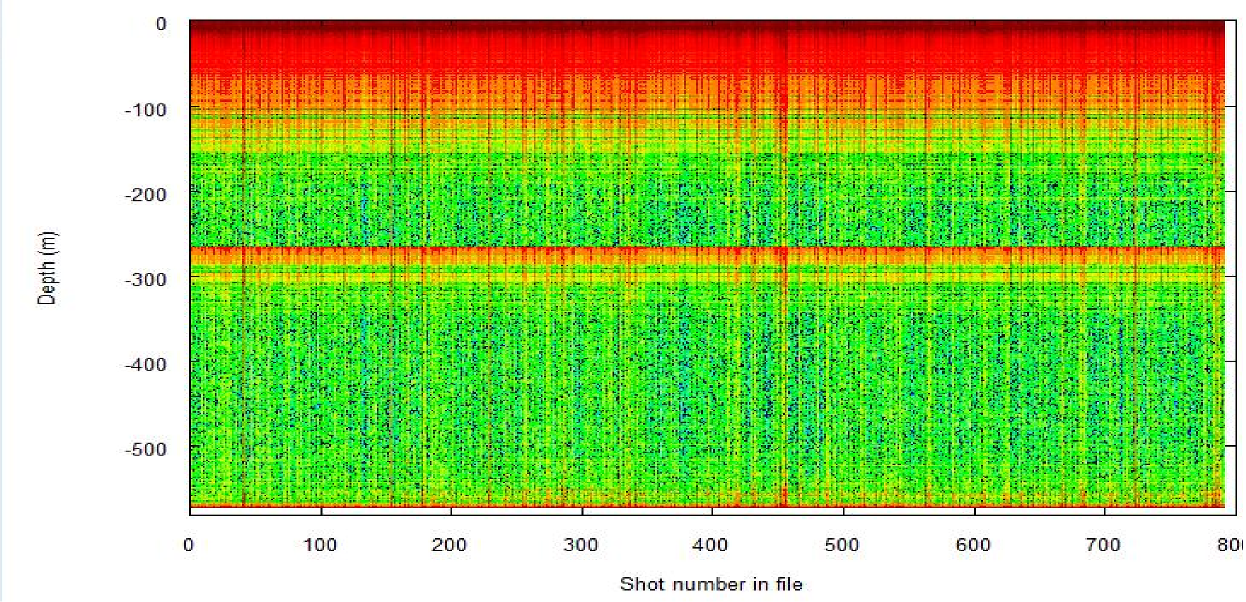

Figure 5. Continuous static acquired over ~ 9 hours at site J1. Base return at ~ 270 m and internal layers down to ~ 130 m.

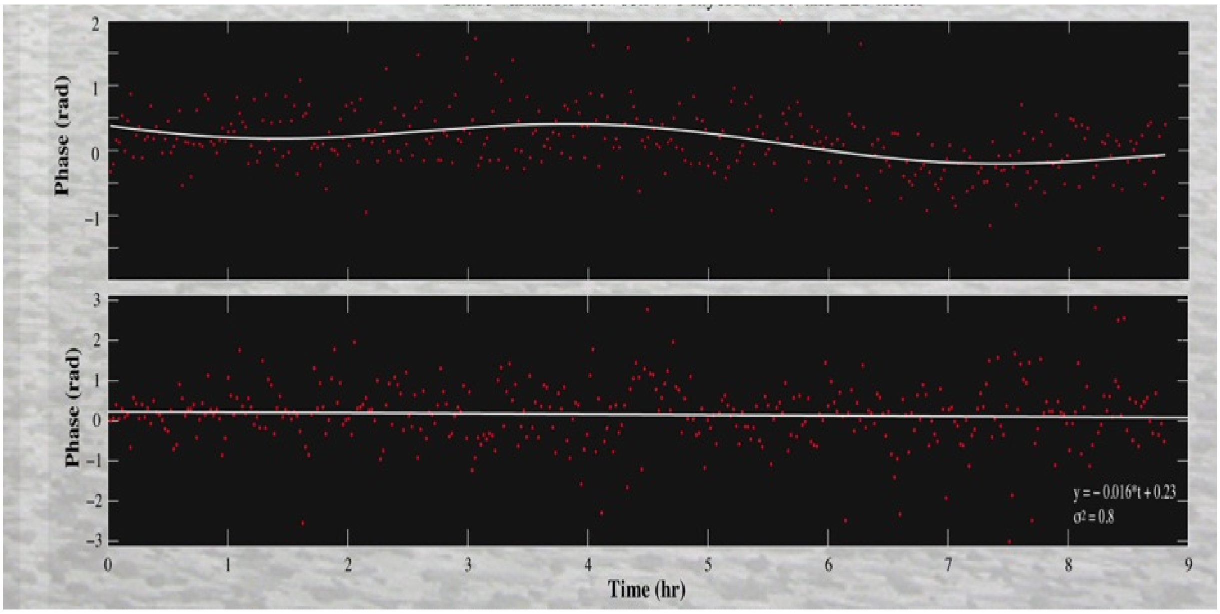

Figure 6. Temporal variation in the phase difference between 2 internal layers at 105 m and 220 m (top) and between an internal layer (220 m) and the base at 450 m (bottom), acquired from continuous static at J2. Variation in phase difference between 2 internal layers has periodicity of 6 hours and may be a consequence of tidal effects. No variation in phase between 220 m internal layer and the base.

AFI8/25: Isolating the Larsen-C Ice Shelf mass instability.

Quantifying variations in firn density at the Larsen-C ice shelf.
Field report: November 2009 – December 2010.

Principal Investigator: Professor Andrew Shepherd (University of Leeds)
Co-investigator: Dr. Adrian Jenkins (British Antarctic Survey)

Sledge team Juliet Alpha
Field Scientist: Mr Steven Palmer (University of Leeds, report author)
Field Assistant: Mr Alan Hill (British Antarctic Survey)

Post-doctoral Researcher: Dr. Noel Gourmelen (University of Leeds)

1. Rationale

Over the past 50 years, the Antarctic Peninsula has been one of the fastest warming places on Earth. During this period, 10 ice shelves fringing the peninsula have diminished in size, and several have completely disintegrated. In total, an area of 27 000 km^2 has been lost from Antarctic Peninsula ice shelves. Observations from the Larsen and Wordie Ice Shelves have indicated that, following ice shelf removal, there was a rapid and sustained acceleration of the grounded ice feeding the ice shelf. This provides evidence of a mechanism through which ice shelf collapse initiates increased ice mass loss from its tributary glaciers and accelerates rates of sea level rise. Studies suggest that both atmospheric and oceanic melting have contributed towards the collapse of ice shelves on the Antarctic Peninsula, yet the relative influence of each factor remains unclear. The Larsen-C Ice Shelf (LCIS) is the largest remaining ice shelf on the Antarctic Peninsula, and covers an area of ~ 50 000 km^2. Satellite altimetry has shown that, between 1992 and 2001, the surface of the ice shelf was lowering by up to 27 cm per year, suggesting that the ice is, in places, thinning rapidly. In order to understand these changes and to predict the likely future behaviour of the LCIS, the causes of this trend must be determined. This project aims to determine the relative contribution of atmospheric and oceanic melting to the mass balance of the LCIS.

This report describes work undertaken during the 2009-10 field season by sledge team Juliet Alpha. The aim was to measure variations in the sub-surface density across the LCIS via extraction of shallow ice cores and deployment of a Neutron Probe (NP). In conjunction with data obtained by sledge team Juliet Bravo, these measurements will be used to calculate the surface mass balance at 3 sites at the LCIS.

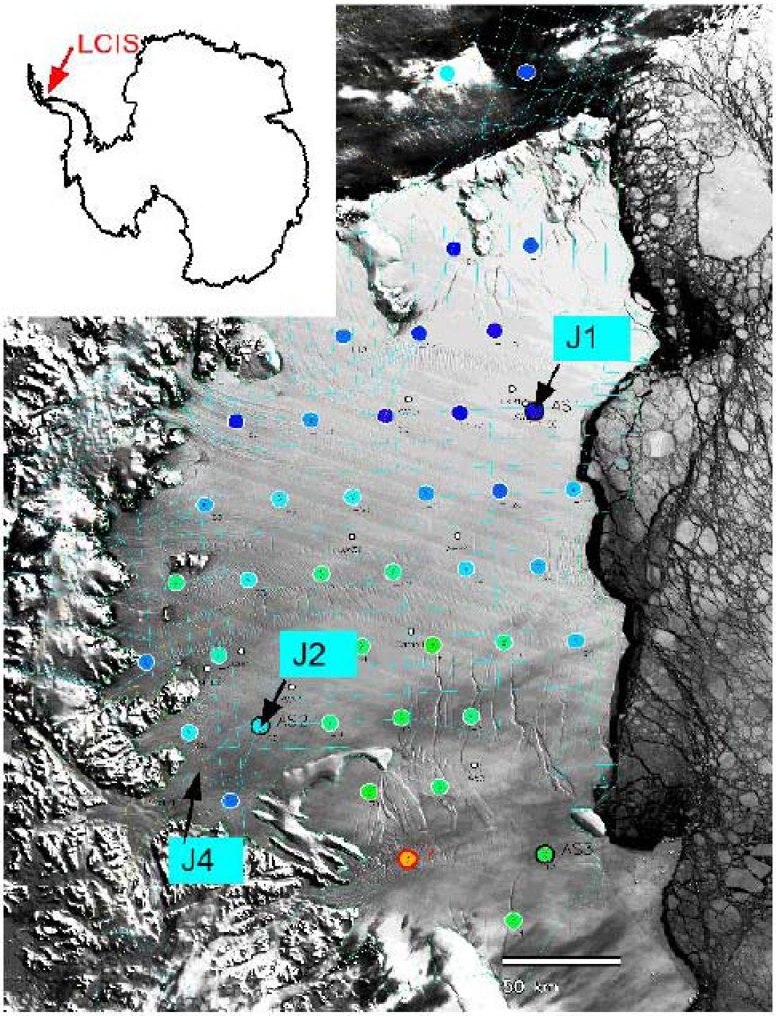

Figure 1. Location of the three field sites J108, J208 and J408. Location of the Larsen-C Ice Shelf (LCIS) is also shown (inset).

2. Field Sites

On the basis of satellite altimetry measurements, three field sites (J108, J208 and J408 – Figure 1) were chosen. The locations of the three sites were:

J108: S 67° 06.489' W 061° 17.249'.
J208: S 68° 18.023' W 064° 08.910'.
J408: S 68° 23.684' W 064° 42.785'.

In addition, we visited two other sites during the field season:

J109: S 68° 23.680' W 064° 42.610'.
Y208: S 67° 33.866' W 063° 15.440'.

3. Experiments

The aim of the fieldwork was to conduct two experiments: (1) To extract and log 2 ice cores for analysis in the UK and for gravimetric density analysis in the field, and (2) to deploy the NP at 4 different sites across the LCIS.

On 22nd November 2009, we were input at site J408 with the ice coring equipment but bad weather confined us to the tent for the first 5 days. After discovering that a crevasse ran through the camp we were relocated to J109 (roughly halfway between J408 and J208) on 2nd December 2009. We extracted a 28 m ice core to be sent for analysis in the UK and a 10 m ice core, which we cut into 10 cm sections and analysed in the field using the gravimetric method. We received the NP on 8th December following testing at Rothera and sent the coring equipment back to base. We augured 4 holes around the 10 m ice core, and deployed the NP in each in order to compare the results of our gravimetric analysis with the NP data. Early on the 14th December 2009 we traveled by skidoo to J208, where we conducted 2 NP casts at the camp, 2 at a location 5 km northwest of the camp and another 2 at a location 5 km southeast of the camp. On 23rd December we traveled by skidoo to site Y208 where we made 4 pairs of NP measurements at 150 m intervals along a fixed bearing in order to investigate a feature at the base of the ice shelf discovered by another field party. Our final camp move was to J108 on 27th December, where we made 6 NP measurements in the same configuration as those made at J208. We were uplifted from J108 on 30th December 2009.

3.1 Shallow ice cores

Using a Kovacs corer, we extracted a 15 m ice core at J408 prior to camp relocation to J109, where we extracted, logged and packed a 28 m ice core for transport to the UK and another 10 m ice core for gravimetric analysis in the field. The ice coring setup showing the tripod and winch can be seen in Figure 2.

Prior to field deployment, we practiced with the ice coring equipment near the caboose above Rothera. This typically took place during the warmest part of the day and we experienced problems releasing core sample, as well as retrieving the corer from the core hole. We believe this was due to the warm conditions and refreezing of melted water during coring. The plastic flights on the outside of the core barrel started to detach and this was repaired at Rothera. We experienced none of these problems in the field, which we believe was due to:

1. Working only at night in freezing temperatures.
2. Not putting any downward pressure on the drill.
3. Stopping drilling once downward progress ceased (even if this was only after gaining a further 10-15cm of depth)
4. Giving a reverse half-turn of the drill before retrieval of the corer.

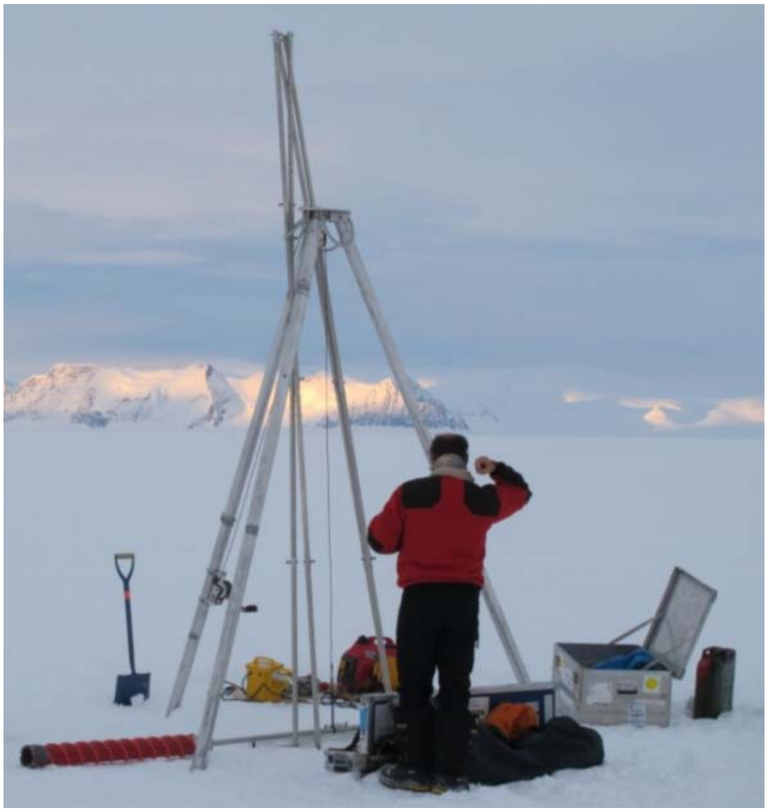

Figure 2. Ice coring setup.

Core sections extracted had a mean length of 30cm and the longest was 92cm. On two occasions we retrieved an empty core barrel, which we believe was due to the dogs being frozen in the ‘out’ position.

3.2 Neutron probe

We conducted 24 NP casts at 4 field sites across the LCIS. The UK Foreign and Commonwealth Office imposed a maximum NP hole depth of 10 m. We used a Kovacs auger to drill the 24 holes required to deploy the NP. Ice shavings invariably fell into the hole during extraction of the auger flights, which reduced the final depth of the augered hole. Typically, 12 auger flights were required to yield a usable hole depth of 10 m.

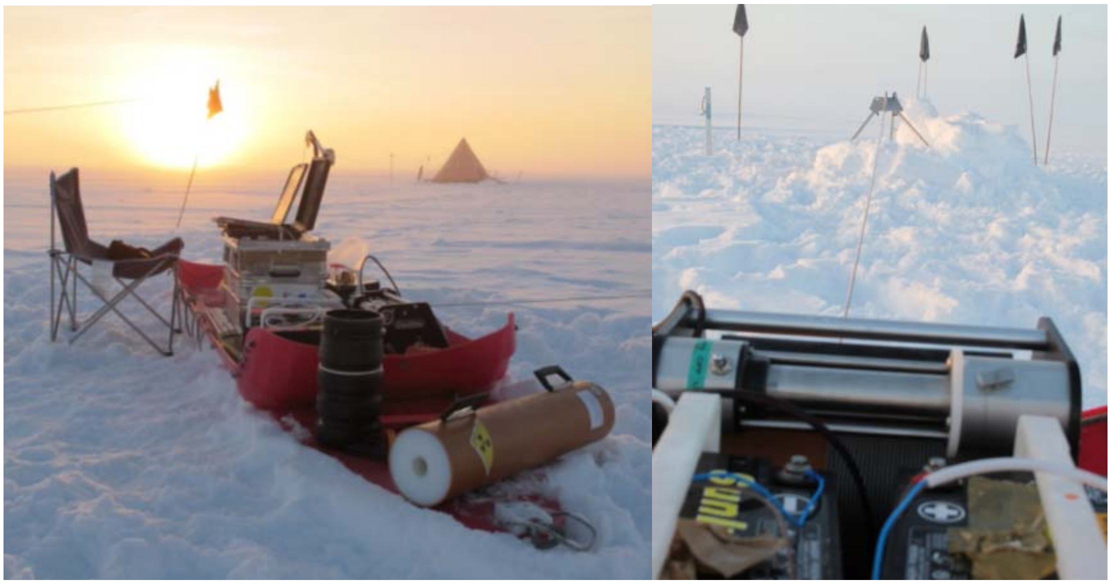
Figure 3. Neutron Probe setup

Prior to NP deployment, a small tripod was placed over the hole and the computer and motorized winch set-up at a distance of 5 - 10 m from the hole (Figure 3). The NP was lowered to the bottom of the hole by hand and winched up a few cm, in preparation for raising the probe against one side of the augered hole, in order to maintain a constant offset. Each NP cast took around 2.5 hours depending on winch speed. Occasionally the winch speed was increased in order to complete the cast more quickly if the weather was deteriorating.

To reduce the possibility of the probe getting stuck we only operated at night when the temperature was below freezing. We avoided working in stronger winds or during snowfall when snow may have blown into the hole. A pair of slotted boards was placed over the hole during snow-showers, which reduced the amount of snow falling into the borehole while allowing the NP to be raised to the surface.

We completed NP casts, often two per night. On several occasions, the data connection with the probe failed and as a result the data output was continually monitored during retrieval. Towards the end of the fieldwork recharging the batteries with the solar panels was not possible due to a faulty power regulator. Problems with the probe data link may have been caused by insufficient power.

4. Preliminary Results

Our preliminary results show that annual layers of higher density ice resulting from melting of the LCIS surface during summer are present (Figure 4).

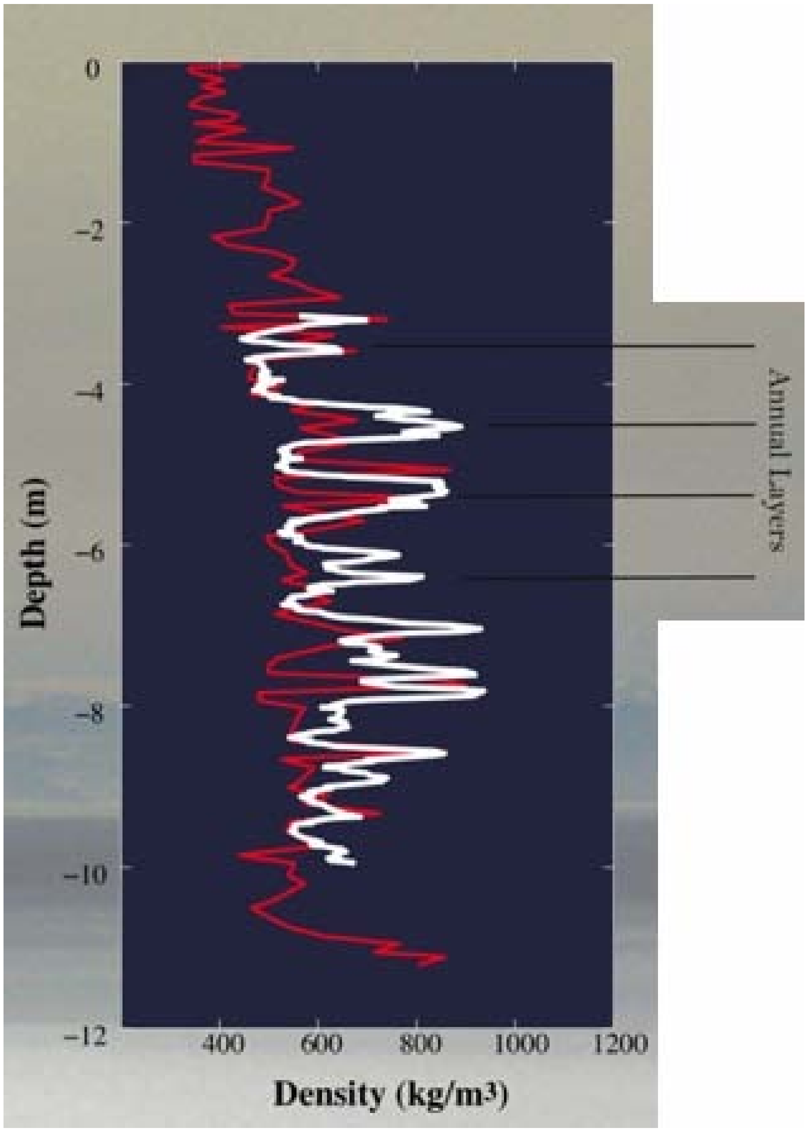

Figure 4. Comparison of density versus depth curves derived from gravimetric (red) and NP (white) methods. Higher density annual layers can be clearly seen in NP measurements. From Gourmelen et al., (2009).

5. References

N. Gourmelen; A. Shepherd; A. Jenkins; N. Houlie (2009). Basal melt rate at the Larsen-C Ice Shelf, Poster C21D-0473, AGU Fall meeting 2009, San Francisco, USA.