AntArchitecture: Archiving and interrogating Antarctica's internal structure from radar sounding

Workshop to establish scientific goals, working practices, and funding routes

School of GeoSciences, University of Edinburgh,
18th and 19th July 2017

Final Report

SAGES Scottish Alliance for Geoscience, Environment and Society

THE UNIVERSITY OF EDINBURGH
School of GeoSciences
Institute of Global Change

Contents

Introduction to *AntArchitecture* and goals of the workshop

AntArchitecture is the name ascribed to a proposed new science programme whose underpinning goal is to use radar-imaged information on the internal structure of the Antarctic Ice Sheet - i.e., its internal architecture – to inform palaeoclimatic reconstruction and ice-sheet modelling of the future contributions of the ice sheet to global sea level. This is important for global society because many observations are demonstrating that the current Antarctic Ice Sheet, containing >90% of Earth's ice by volume, is in a state of retreat, and that high-population coastal regions will be vulnerable to the incurred sea-level rise, expressed for example as higher-frequency storm surges, over the next centuries. An improved understanding of the Antarctic system and how it may contribute to future global sea-level rise is therefore imperative, and Antarctica's radar-imaged internal layering stands out as under-used major resource in this regard.

To date, a handful of studies have married regionally mapped internal surfaces or layers to regional-scale ice-sheet modelling in Antarctica, showing promise for the use of internal layering for reconstructing accumulation variations over glacial-interglacial cycles. A more continent-wide extrapolation of the layering has never been attempted. That mapping internal surface across a whole ice sheet is achievable, that the product can provide significant information such as an age-depth structure across an entire ice sheet, and that it can inform ice-sheet modelling, is now demonstrated by a precursor programme to *AntArchitecture* conducted over the last 5 years across the Greenland Ice Sheet by Joe MacGregor of NASA and colleagues. To undertake the same exercise across Antarctica is, however, challenged by the fundamental issue that, unlike for Greenland where the ice sheet has been comprehensively surveyed with a single tool (the US Center for Remote Sensing of Ice Sheets, CReSIS, radar system), Antarctica has been surveyed by multiple radar systems by multiple institutions exercising multiple practices for processing and lodging data.

The underpinning goal of this 2-day workshop was therefore to assemble representatives of the international community who would potentially be interested in aligning to form a science programme for *AntArchitecture*, and to discuss plans for developing this goal through future collaborative scientific activities. The workshop was overall structured so that the first day concentrated on scientific challenges and aspirations, and the second day on strategies for formalising support for *AntArchitecture*, primarily through its potential formalisation as a sponsored science programme and through future grant-raising activities.

Workshop sponsorship and participation

It was imperative for the success of the workshop that it attracted sufficient international attendees from the principal Antarctic programmes in Europe and North America. This was achieved with sponsorship that we gratefully acknowledge from the Scottish Alliance for Geoscience, Society and Environment (SAGES), and from the University of Edinburgh School of GeoSciences' Research Institute for Global Change (RIGC).

Overall 25 delegates participated from 14 institutions, representing a strong spread across the main international communities who have acquired Antarctic aerogeophysical data over the last five decades, and a number of the main data users across the international Antarctic community. Delegates thus attended from Germany, the USA and the UK, while representatives from France and Norway attended by skype. Table 1 overleaf lists the attendees.

We anticipate that as *AntArchitecture* develops, the overall membership and reach of the science programme will expand to incorporate the even wider community of international scientists who have Antarctic data and/or interests in working with those data. Indeed, one of our outcomes, reported below, is to develop *AntArchitecture* as a Scientific Committee for Antarctic Research (SCAR) Science Programme, which should formalise this objective.

Table 1: Workshop Participants:

Dr. Robert Bingham	University of Edinburgh; host, UK
Dr. David Ashmore	University of Liverpool, UK
Dr. Marie Cavitte	University of Texas Institute for Geophysics, UT Austin, USA
Frazer Christie	University of Edinburgh, UK
Dr. Indrani Das	Lamont-Doherty Earth Observatory, Columbia University New York, USA
Damon Davies	University of Edinburgh, UK
Richard Delf	University of Edinburgh, UK
Dr. Anja Diez	Norwegian Polar Institute, Tromsø, Norway
Professor Julian Dowdeswell	Scott Polar Research Institute, University of Cambridge, UK
Professor Olaf Eisen	Alfred Wegener Institute, Bremerhaven, Germany
Dr Nick Frearson	Lamont-Doherty Earth Observatory, Columbia University New York, USA
Dr Dan Goldberg	University of Edinburgh, UK
Dr Nicholas Holschuh	University of Washington, USA
Dr Jonathan Kingslake	Lamont-Doherty Earth Observatory, Columbia University New York, USA
Dr Tom Jordan	British Antarctic Survey, Cambridge, UK
Dr Joseph MacGregor	NASA Goddard Flight Center, USA
Dr Carlos Martín	British Antarctic Survey, Cambridge, UK
Dr Gail Muldoon	University of Texas Institute for Geophysics, UT Austin, USA
Professor Pete Nienow	University of Edinburgh, UK
Dr Frédéric Parrenin	Joseph Fourier University, Grenoble, France
Dr Neil Ross	Newcastle University, UK
Dr Dustin Schroeder	Stanford University, USA
Professor Martin Siegert	Grantham Institute, Imperial College London, UK
Dr Kate Winter	Newcastle University, UK
Dr Duncan Young	University of Texas Institute for Geophysics, UT Austin, USA

Workshop format and outcomes

The workshop was run over two days, following the programme given below (pp 5-6).

On the first day, discussion revolved around the scientific and logistical challenges of building up the hypothetical *AntArchitecture* database. An initial session ran over the motivation and potential applications. In the second session, data providers summarised the data coverage available from existing surveys and survey plans for the next few years. As part of this discussion, we considered how best might the community converge on practices for sharing data and storing them in common, or easily transferrable, formats. In the afternoon, discussion focussed on research that has been conducted to date on tracing internal layers or characterising internal-layer geometry, and on how we may begin to join information on Antarctica's internal architecture from multiple datasets acquired with different radar systems and/or processed in varying manners.

On the second day, the discussion turned to more pragmatic matters of how *AntArchitecture* can proceed as a science programme. Several initial science targets were identified as activities that could be used to prime a larger, funded programme. Possible routes to funding the programme were then identified.

Over the two days of the workshop, a number of outcomes were generated, which are listed below. More detailed notes of the discussions are provided as a "Record of the Meeting" (pp. 7-12).

Principal outcomes:

- Circulate meeting report via sponsor website (SAGES) and email lists.
- Approach Scientific Committee for Antarctic Research (SCAR) to propose *AntArchitecture* as a formal SCAR Science Programme.
- Produce a white paper, intended for submission to a relevant peer-reviewed journal, e.g. Global and Planetary Change, Climate of the Past, Frontiers of Earth Sciences, outlining the need for an Antarctic layers database, the potential applications, and methods for achieving it (i.e. summarising this meeting).
- As part of the above, build up a table of the main datasets, their attributes and processing flows, plus the current formats of the data.
- As part of the above, compile a list of the main applications/users of internal layers, pointing out wider areas of glaciology/geoscience where radar layers are/can be used (e.g. future predictive model development that can integrate models).
- As part of the above, compile a table of the different approaches so far used to trace or characterise internal layers.
- As part of the above, or as a separate paper, upgrade the SPRI Folio Map on internal layers, identifying areas of Antarctica where layering is traceable, and, more importantly, areas where it is not ("points of failure"). This paper could be underpinned by running the Karlsson et al (2012; *EPSL*) continuity-index code through available data. A further useful output would simply be the identification of overlapping radar lines, to form areas for radar-data intercomparison.
- Form focus group representing main Antarctic radar-data providers, to identify best format and practices for lodging and sharing data. Report back to wider AntArchitecture group at SCAR Symposium, Davos, June 2018.
- Undertake further radar data intercomparison exercises. Good target areas include Institute Ice Stream (David Ashmore investigating) and PIG/Thwaites (possible UTIG/BAS investigation).
- Ultimately develop a document outlining the optimised processing flow for different datasets used to construct Antarctic-wide database.
- Leverage white paper and associated studies (e.g. radar-intercomparison papers) for funding applications.

The forthcoming SCAR Symposium in Davos, June 2018, was identified as a good target to work towards for the white paper and for the progression of *AntArchitecture*'s next stages.

STOP PRESS: A meeting room for an *AntArchitecture* Workshop is now requested for Friday 15 June, immediately before the SCAR Open Science Meeting that takes place 18-22 June.

STOP PRESS: Following the *AntArchitecture* Workshop, we have been invited by SCAR to propose *AntArchitecture* as a SCAR Action Group. Rob Bingham to coordinate this initially.

Programme

Venue: Edinburgh Centre for Carbon Innovation

Tuesday 18 July

09:00 – 09:15 Welcome; Introduction to Objectives of the Workshop

- Robert Bingham

09:15 – 10:30 Previous work on internal layers / motivation for *AntArchitecture* [Chair: Robert Bingham]
[To get us all thinking about what could be achieved with AntArchitecture. *Each talk 15 mins + 3 mins Q&A]*

- Joe MacGregor (Greenland)
- Martin Siegert (Previous work with SPRI layers in Antarctica)
- Fred Parrenin / Olaf Eisen (Potential modelling applications / Oldest Ice)
- Duncan Young – (Work with layers from WAIS/EAIS surveys)

10:45 – 11:15 Break

11:15 – 12:30 What radar data exist across Antarctica? How have they been exploited in studies to date? [Chair: Joe MacGregor]
[Starting with a map of existing data coverage, delegates may speak to the quality of data from their groups in terms of overall visibility and traceability of internal layers. What form are each of the data in? Where are they stored? At what level of processing, i.e. migrated, 2D or 3D SAR-processed, etc.

- BAS data (Tom Jordan, Carlos Martin, David Ashmore?)
- NERC/AFI (Neil Ross, Martin Siegert, Kate Winter)
- US airborne (UTIG, Dustin Schroeder, Nick Frearson, Jonathan Kingslake)
- NASA IceBridge (Joe MacGregor)
- SPRI-NSF-TUD (Julian Dowdeswell, Dustin Schroeder)
- ICECAP including PEI/PRIC (Martin Siegert)
- AWI (Olaf Eisen)
- PolarGap (Tom Jordan, Anja Diez?)
- Additional (all suggestions invited!)

12:30 – 13:15 Lunch

13:15 – 14:00 *AntArchitecture* applications [Chair: Olaf Eisen]
[What would be the purpose, or the main applications, for AntArchitecture? *Some of the themes will have been touched upon in the opening morning session, but here let us try to formalise the main applications of mapping internal layers across the continent.]*

14:00 – 15:20 Strategies for tracing internal layers [Chair: Kate Winter]
[A series of talks highlighting different ways in which internal layers/surfaces have been traced and used so far. Which method(s) are feasible for Antarctic-wide recovery and lodging? Each talk ~10 mins + 3 mins Q&A/discussion]

- Nick Holschuh
- Carlos Martin
- Tom Jordan
- Robert Bingham – use of commercial packages – ReflexW, Schlumberger Petrel

- Olaf Eisen – AWI work with Landmark/Epos & Matlab tools
- Neil Ross/Kate Winter – OpenDTect
- UTIG representative
- [Could be Joe again, specifically focussing on detail of layer tracing-workflow from Greenland work not given in morning talk]

15:20 – 15:40 Break

15:40 – 17:30 Strategies for working with multiple datasets [Chair: David Ashmore]
[An opening talk from Olaf on Winter et al. 2017, followed by discussion on various bullet points. Can we develop a workflow / flow diagram for AntArchitecture?]

- Olaf Eisen - Winter et al 2017 study on EAIS/Dome C multiple radar-system study
- Strategies for dealing with unmigrated data versus SAR-focussed data
- Cross-cutting datasets – examples where the "same" layer cannot be seen by 2x radar systems, or the "same" layer is recovered at different depths by 2x radar systems
- Layers versus surfaces
- Interpolation strategies
- Layer/surface dating (ice cores?)

17:30 Close

20:00 Dinner

Wednesday 19 July

09:00 – 10:00 – Practical challenges of assembling Antarctic-wide data [Chair: Neil Ross]
[What are the practical implications of what would be a large, multiple-institution project?]

- Whom can trace layers, or otherwise produce useful products from internal layers, from each dataset? What would institutions require in terms of time/staff?
- Where can we lodge traced layers?
- QC procedures.

10:00 – 10:30 – Break

10:30 – 12:00 – Workshop Outcomes – White Paper and Funding Applications [Chair: Robert Bingham]
[Close the meeting with a discussion of how we can each take the vision for achieving AntArchitecture *forwards]*

- Suggested structure of white paper
- SCAR Science Research Programme
- EU ETN scheme – who is interested/eligible?
- Other international opportunities

12:00 Workshop Closes

Record of the Meeting

Tuesday 18 July 2017

Introduction *Robert Bingham*

- This workshop was developed as a detailed follow-on to a 2016 *American Geophysical Union* Town Hall Meeting, chaired by R. Bingham, J. MacGregor and N. Ross, and attended by ~100 members of the international community. Some of the ideas grew out of a 2013 workshop on radar-imaged internal layering hosted by Dorthe Dahl-Jensen in the Niels Bohr Institute, Copenhagen, in May 2013.
- Opening questions were posed as follows:
  - Scientific:
    - What are the products that can be generated per radar dataset (e.g., traced layers, interpolated surfaces, slopes…)?
    - How will these differ, how can the products be reconciled, between data gathered from different radar systems?
  - Practical:
    - How can we, as an international community, best leverage funding and staffing for the work needed, and overall best facilitate the international coordination required? (inspiration = ice-core community)
- In advance of the workshop, delegates had been invited for each session to deliver short presentations and/or lead discussion on the session topics/themes.

Session 1: Previous work on internal layers / motivation for *AntArchitecture* Chair: *Robert Bingham*

Joe MacGregor: "Proof of concept: Greenland"

- MacGregor and collaborators have, in recent years, already undertaken an exercise similar to *AntArchitecture* for the Greenland Ice Sheet, already yielding several high-impact publications (MacGregor et al., 2015a, JGR; 2015b JGR; 2016a Science; 2016b JGR).
- Emphasis that seeing the layers is easy but interpreting them is challenging…
- For Greenland work, the analysed radar data all came from a single platform, CReSIs.
- MacGregor developed bespoke Matlab software, and then employed 4-5 undergraduate geophysicists over ~2 years to pick internal layers. Software is reposed on Github.
- Experience emphasises the need for an efficient workflow between reflector tracing, dating, ice-flow modelling and echo-intensity analyses.
- Tracing workflow involves steps of predicting layer geometry, "flattening" by the predicted geometry to aid traceability, and then tracing layers. Significant user quality control = time still required.
- Based on Greenland work, foreseeable Antarctic challenges:
  - Antarctic data from multiple platforms and institutions – significant international collaboration needed
  - Data coverage across Antarctica often more widely spaced
  - Unconformities are more common especially in East Antarctica
  - Quasi-Nye dating of layers as practised for Greenland layer-dating may not work because of areas of lower accumulation and/or the greater overall variability of accumulation seen across Antarctica.
  - Scientific questions to be addressed in Antarctica inherently over longer timescales.

Martin Siegert: "Internal layers: lessons from history"

- Siegert and collaborators have used internal layers in Antarctic data (mostly SPRI-NSF-TUD) for a number of applications over last two decades.

- Emphasis that the basic motivation for *AntArchitecture* could/should be about recovering the "big picture." There is an enormous volume of information and there is a danger of being too detailed in the challenge we pose ourselves.
- Previous applications with much more limited layer coverage than *AntArchitecture* would hope to achieve include:
  - Mismatch of traced layers with modelled layers evincing historical surface ablation zone in East Antarctica (Siegert et al., 2003, Quaternary Research).
  - Using distinctive englacial layer associations to reconstruct past ice-flow direction change (Siegert et al., 2004, Science).
  - Using internal layers to reconstruct accumulation history, e.g. for Talos Dome (Siegert et al., 2007, J. Env. Eng. Geophys.), for WAIS (Siegert and Payne, 2004, GRL).
  - Using layer "buckling" to detect ice streams (e.g. Siegert et al., 2003, Annals Glac.; Rippin et al., 2003, Annals Glac.; Bingham et al., 2007, JGR).
  - Connecting ice cores, e.g. Cavitte et al., 2016, J. Glac.).
- Major requirement for more (better) data.
- Synthesis of existing data a major gap.
- Discussion at the end of the talk revolved around whether an *AntArchitecture* product could act as a useful guide to focus drilling/ice coring. Could be used to identify areas of clear layering, areas of low/high uncertainty…

Olaf Eisen, w/ Fred Parrenin: "Reconnaissance of Oldest Ice: Where Are We Now?"

- As part of IPICS' "Oldest Ice" consortium, Eisen and collaborators are leading the European consortium "Beyond EPICA – Oldest Ice", which involves non-European partners as well. It aims to locate the optimal location to drill an Antarctic ice core containing the world's oldest ice for climate record analyses. The more integrated view of Antarctica's internal structure that *AntArchitecture* can provide would be an excellent complement to this project.
- Possible sites for oldest ice reconnaissance surveyed by the consortium and collaborators at Little Dome C and near Dome Fuji.
- Dome Fuji heavily surveyed by AWI since 2016. Most other data are Russian from much earlier in time, with inertial navigation and thus less reliable.
- At AWI, modelling is being undertaken with PISM to produce an Antarctic age model for identifying the oldest ice. Forcing is currently predominantly driven by marine records.
- Parrenin is leading modelling of Dome C and Little Dome C, currently a 1D approach (Parrenin et al., 2017, Quaternaire).
- Layers = validation for the modelling. At the moment, due to limited coverage, modelling validation is limited to local (1D). Desire to move to 2D/3D inverse approach.
- Example of structural geology doing similar work: Bons et al. (2016) Nature Clim. Change.

Duncan Young, w/Marie Cavitte & Gail Muldoon: "Recent Work on Internal Layers"

- Previous applications have included:
  - WAIS ice core site selection (Morse et al., 2003, Annals Glac.)
  - Englacial Attenuation measurement (Matusoka et al., 2010, JGR)
  - Englacial Attenuation estimation (Carter et al., 2007, GGG; 2009, J. Glac.)
  - South Pole ice flow (Bingham et al., 2007, JGR)
  - Thwaites Glacier Ice flow (Fudge et al., 2014, Annals Glac.)
  - Thwaites Glacier Accumulation (E. Leuro thesis)
  - Volcano-layer association (Lough et al., 2013, Nature Geosc.)
- Recent work includes detailed data/modelling connecting radiostratigraphy between Dome C and Vostok (Cavitte et al., 2016, J. Glac.). Supports the use of internal layers as isochrones.

- Re-investigation of South Pole palaeo-dynamics (Beem et al., 2017, GeolSoc Spec. Publ.)
- Isochrone age-depth modelling for locating Oldest Ice (Cavitte et al., 2017, TC; Parrenin, Cavitte, in review).
- Modelling 3D layers for comparison with data across the WAIS (work in progress from Gail Muldoon). Model (ymir) runs to steady state and then quantify deviations in observed layering from modelled layers.

Session 2: Inventory of existing Antarctic radar data and quality Chair: *Joe MacGregor*

Tom Jordan, on behalf of British Antarctic Survey (UK)

- Datasets available for both West and East Antarctica, largely acquired with airborne PASIN system.
- Data stored as ASCII and SEGY.
- Processing is varied per survey – some data are SAR-processed, some are not.
- Workflows to be considered when using/distributing data are:
  - Stacking parameters on acquisition.
  - Processing, and processing record-keeping.
- For the BAS data, the SEGY format may represent the most portable format for distribution to *AntArchitecture*.

Neil Ross, Institute-Moller Antarctic Funding Initiative (IMAFI) survey (UK)

- Collaborative 2010/11 survey between multiple UK universities and BAS, using the PASIN system. The raw data are held in the BAS repository previously discussed (hence ASCII/SEGY format), but have been particularly exploited and processed multiple times.
- Survey links/interleaves with BBAS/PolarGap/IMAGE-GRADES (PASIN surveys), CASERTZ (UTIG/SOAR) and ITASE Byrd-South Pole ground survey.
- 2-D SAR-processed output has been generated – this 'crops' upper 200 (of 1400) samples. Release of IMAFI 2D focused SAR data via UK Polar Data Centre imminent [Jeofry et al., Earth System Science Data, in prep].

Dustin Schroeder, Julian Dowdeswell – scanning/digitising of SPRI-NSF-TUD data (UK-USA)

- The most extensive pan-Antarctic radio-echo sounding dataset is that collected by SPRI-NSF-TUD throughout the 1970s. It contains numerous internal layers. However, the data have not been utilised to their full potential due primarily to the analogue nature of the original records, and secondarily because the navigation (by inertial navigation) is poorly constrained compared with modern data.
- Coverage and previous work on the internal layers by Bingham, based on scanning of the SPRI films by Siegert in the early 2000s can be viewed at:
  https://legacy.bas.ac.uk/bas_research/data/access/res/
  The scans on which this earlier work was based, while having advanced much research, were not undertaken with a sophisticated scanning system capable of capturing the full range of radiometric and geometric resolutions.
- In summer 2016, Schroeder and colleagues spent several days at SPRI scanning the SPRI-TUD-NSF films with a sophisticated scanner traditionally used in old movie restoration.
- The new data should ultimately allow integration of the SPRI-NSF-TUD records with all other radar data across Antarctica.
- This is early stages, and an update will be presented by Schroeder at AGU 2017.
- Queries from the floor mentioned that other analogue radar data were acquired by Russian teams and the Wisconsin team. Julian Dowdeswell offered to make contact with Russian colleagues per this.

Joe MacGregor, on behalf of NASA/IceBridge (USA)

- Radar data have been collected across Antarctica since 2009 as a by-product of NASA's Operation IceBridge (OIB) campaign.

- Radar layering is not generally as clear as in most of the other datasets we are discussing.
- Centre frequency/bandwidth vary by year and even flight and this is an important consideration for using/reconciling data.
- This coming season, further OIB Antarctic deployments are anticipated out of Ushaia w/NASA P-3/McCORDSv2, 195 MHz centre frequency 30 MHz bandwidth, covering the Antarctic Peninsula and English Coast, and out of McMurdo & possibly other EAIS bases w/Basler/DC3, "new" McCORDs 150-600 MHz centre frequency, similar to that currently deployed on the AWI Polar-5. Potentially this latter system should be much better for internal layers.
- With the anticipated launch of ICESat-2 in September 2018, the coming season may be the last for OIB.
- McCORDS data are available on the Kansas ftp site, often before the OIB Portal.

Nick Frearson, on behalf of Lamont-Doherty Earth Observatory Polar Geophysics group (USA)

- Major survey coverage acquired over interior East Antarctica in 2009/2010 as part of AGAP, the Antarctic Gamburtsev Province survey.
- AGAP survey interleaves with UK PASIN AGAP survey, and has connections to Vostok, South Pole, Dome Fuji. Also surveyed over Recovery Lakes. Connections with PolarGap and NASA/OIB surveys.
- Multiple picking techniques have been trialled to pick the bed. With respect to layers, there are multiple discontinuities and "onlaps" present within the englacial layering. Major challenge for *AntArchitecture*.
- Layer picking ultimately done with in-house Matlab code developed by Mike Wolovick. Stored on Github.
- LDEO "IcePod" has VHF radar, centre frequency 150 MHz 10 µs pulse similar to PASIN, McCORDs, plus shallow radar 600 MHz.
- Major recent focus of the group has been ROSETTA survey of Ross Ice Shelf, wherein further lessons/experience can be learnt regarding layer tracing.

Duncan Young, on behalf of University of Texas Institute for Geophysics (USA)

- UTIG's HiCARS radar sounder operates at 60 MHz centre frequency (3 m wavelength in ice), with 15 MHz bandwidth (12 m wavelength in ice, ~ 1 m precision for flat interfaces).
- Surveys from 2008 onwards undertaken under auspices of ICECAP then ICECAP2 international consortia.
- Significant developments in 2D focussing are now allowing recovery of internal layers in areas of steep slopes, where traditionally recovery/tracing of layers has been negligible.
- Surveys 1992-2000 under NSF/SOAR used UT/TUD 60 MHz incoherent radar, 4 MHz bandwidth, no phase.
- 2004/05 AGASEA survey of Thwaites Glacier; near-term plan to release focussed data via USAP-DC.
- Currently collaborating with China, UK and India on survey of Princess Elizabeth Land, East Antarctica.
- All UTIG data are stored in NetCDF format so as to obviate issues of the different formats of SEGY.

Olaf Eisen, on behalf of Alfred-Wegener Institute (Germany)

- Existing data cover most of DML and Dome Fuji. Most data acquired with 150 MHz pulse system, pulse length 60/600 ns. A new ultrawide-band 150-600 MHz system (successor to McCORDs) is being integrated into the AWI airborne platform for future survey.
- Gap not yet filled between Dome Fuji and Dome A.
- Existing data format SEGY.
- Applications have included:
  - Linking ice core chronologies from Kohnen and Dome Fuji (Steinhage et al., 2013, Annals Glac.).
  - Accumulation rate reconstruction along the same profile (Huybrechts et al., 2013, J. Glac.).
  - Determination of physical properties and dating of layers (Drews et al., 2011, J. Glac.).
  - Reconstructing palaeo ice dynamics (Drews et al., 2013; J. Glac.).
  - Intercomparison of internal layers recovered from different radar systems (Winter et al., 2017, TC).
- Prominent tephra layer dating to Toba eruption 74 ka seen in many AWI profiles – a good candidate for tracing across Antarctica?

Nick Holschuh, on behalf of the US/ITASE team, also discussed the various ground-based radar data that exist across Antarctica. Various institutes/countries also have further GPR data to offer, e.g. UK/BAS, UW/St Olaf (Bob Jacobel, Howard Conway). Ground-based data, with lower spatial coverage but usually much more defined internal layering, forms a vital complementary resource for *AntArchitecture*.

Session 3: Strategies for tracing internal layers Chair: *Kate Winter*

Nick Holschuh: "ITASE data and layer-picking challenges"

- Holschuh and collaborators have been leading work on optimising the best strategies for recovering information from internal layering for use in ice-sheet modelling. One of the main datasets being exploited is the 1999-2002 ITASE ground surveys from South Pole to and across the WAIS including a connection to Byrd ice core.
- 17.5 kyr "Old Faithful" layer (dated as such at Byrd) is a well-known distinct layer seen in most ITASE profiles; but in general continuous layering is well seen.
- Holschuh et al. (2014; *Annals Glaciol.*) gives a thorough review of the mechanisms that aid/hinder layer recovery throughout radar acquisition and processing. Important decisions are made in stacking data and SAR processing. This paper gave design recommendations for future survey; for *AntArchitecture*, it gives some important lessons for the interpretation of layering in existing data.
- An important consideration is whether it is sensible for *AntArchitecture* to **trace** layers versus recovering **layer slopes** from existing datasets. Layer slopes can be recovered from images of data, and can be extracted more easily where layer tracing is problematic. Examples of previous uses of slopes are: Sime et al. (2011; *J. Glaciol.*), Panton (2014, *Annals Glaciol.*) and MacGregor et al. (2015; *JGR*).
- Holschuh et al. (2017; *GRL*) presents a conceptual framework for relating along-track reflector slope to gradients in the steady-state velocity field of ice sheets. For *AntArchitecture* to be a useful product, this kind of engagement with ice-sheet modelling is vital.

Carlos Martín: "Tracing radar layers with a Monte Carlo method based on window cross-correlation"

- Martín and collaborators have been working with internal layering on the Oldest Ice project, specifically attempting to connect Dome C and the Little Dome C (candidate drill site) regions.
- Extensive grid DELORES GPR surveys around Dome C and Little Dome C, with three traverse connections.
- Note that in Dome C core age-depth profiles there are "wiggles" in the profile in lowest ice (<2500 km depth, where ice is ~3200 km deep). These likely represent glacial-interglacial transitions that we should pick up in the internal layering.
- Multiple layers between surface and ~2.5 k depth traced easily between Dome C and Little Dome C, and ages ascribed by reference to Dome C age-depth profile.
- The challenge is to trace the deep layers which are fainter, but of the most importance in determining whether Little Dome C contains older ice than Dome C. The method developed here has potential for wider use in *AntArchitecture* wherever signal-noise is low.
- Method works by choosing a window of +/- 11 adjacent traces, +/- 500 time samples, determining signal delay across the traces using FFT cross-correlation, and from this estimating the layer slope and uncertainty.
- Method obviates the typical problem of local discontinuities in data and provides estimates of uncertainty for model inversions.
- Derived layer slopes contain information about mass balance and rheology.
- Technique is computationally effective and highly parallelisable.

Tom Jordan: "Experiments with layer tracing"

- Jordan and colleagues have recently been working with PolarGap data around the South Pole, where layering can make connections between important potential paleoclimate drilling sites.

- Have been trialling layer tracing using GDAL image recognition on NetCDF files to extract linear features.
- Filters subset of features which are +/- 45 degrees of horizontal.
- Assigns initial "dipstick" at start of line (0 at surface, 1 at bed).
- Intersects layers with dipstick and assigns ages based on intersection.
- Creates second dipstick and recovers ages based on dated layers, assign ages to undated layers based on intersection with dated layers, and iterate…
- Experiments have shown promise that this method can trace/date layers along radargrams.
- Method has a strong advantage over tracing individual layers because it can take advantage of looking at multiple layers iteratively.
- However, problems encountered where there is significant loss of layer continuity.
- Dustin Schroeder commented that absence of layers can give useful information – areas of layer gaps could give information on layer slope (once aircraft roll is discounted).

Robert Bingham: "Applications in Commercial Packages"

- With iSTAR ground-penetrating radar data (DELORES) Edinburgh/BAS have made extensive use of functionality in ReflexW and Schlumberger Petrel to trace layers.
- Disadvantages: Techniques are apparently quite standard/basic relative to those discussed elsewhere in meeting, possibly even a little black box. Reliant on ability to trace individual layers. Also, in the case of Petrel, there is a cost implication if contributing institutions do not have licences – academic licences may be reasonably attained.
- The big advantage of Petrel is the ability to work with layer tracing in 3D which gives excellent overall context. Layers can be traced between profiles at any intersections. To some extent this can overcome the problem of discontinuities.
- Commercial packages also offer *AntArchitecture* some prospects for sponsorship.
- Possible that the greatest advantage commercial packages currently offer is their visualisation capabilities. Bespoke code could eventually replace this, though there is an argument that to get *AntArchitecture* running we can take some advantage of the existing technology.

Neil Ross: "OpendTect"

- Ross and group have been using free open source seismic software Opendtect for some years. Flexible (operates on Windows/Linux/Apple Mac OS). There is a closed source version with commercial plugins that academic users can also use for free.
- Data, input as SEGY, typically preprocessed in ReflexW (time cut, stacking, gain).
- As with Petrel, great advantage of OpendTect is ability to pick in 3D.
- Autotracking, gridding to generate 3D surfaces available. Surfaces and picks can be exported as ASCII.
- Software can interact directly with GMT and Madagascar.

Olaf Eisen added that AWI worked for many years with Landmark software, but in more recent work has transitioned to Epos. **Julian Dowdeswell** noted that Petrel and Kingdom are also commercial packages much used for radar and marine geophysical processing.

Discussion and Action Points

- Duncan Young commented that their group has encountered some scalability issues with OpendTect, with the database becoming unstable for very large datasets. Joe MacGregor added that this can also be an issue with his code.
- We agreed that the *AntArchitecture* community would ideally arrive at a common format/language for storing and lodging data. If we have this, then it may not be so important for the community always to process that data with the same packages. Eisen made an analogy with current practice in the CMIP climate community intercomparison project.

- **ACTION (RGB)** - compile a table of different methods for recovering layers and slopes from radar data.

Session 4: Strategies for working with multiple datasets Chair: *David Ashmore*

Olaf Eisen: "Radio-echo sounding in Antarctica: comparison of system and layer tracing"

- Winter et al. (2017; *Cryosphere*) have undertaken a radar-layer intercomparison exercise for data within 2 km of Dome C. Systems investigated (by centre frequency) are: AWI 150 MHz, BAS/PASIN 150 MHz, OIB/CReSIS/McCORDs 195 MHz, UTIG/HiCARS 60 MHz, INGV (Italian) ground radar.
- Using 10 identified internal layers, the 5x radar systems were compared in terms of:
  - Resolution of internal reflectors
  - Spatial coherence of reflectors
  - Penetration depth
  - Quality of imaging the basal layers
  - Resolution of basal interface
- Issues arising:
  - Systems have varying vertical resolution
  - Systems have varying horizontal resolution, becoming an ever greater issue for compatibility with ice depth (bigger footprint)
  - Different processing, e.g. focussed versus unfocussed, pulse/chirp/sweep
  - Attributes (polarity,phase) vary between systems
  - Different gain functions used.
  - Varying interference per system, in some instances causing internal layers to disappear

Duncan Young pp Marie Cavitte, Gail Muldoon, Don Blankenship: "Working with multiple datasets"

- Data from the UTIG group represent a prominent example where even data from the same team has different formats as the acquisition parameters and processing have been developed over the years.
- Cavitte et al. (2016; *J. Glaciol.*) performed radar layer intercomparison for datasets between Vostok and Dome C with UTIG/TUD 60 MHz (older UTIG data), UTIG/HiCARS/MARFA 60 MHz (newer, focussed data) and OIB/McCORDS 195 MHz. The latter two were flown along a connecting line Vostok-Dome C, which connect into a Vostok grid flown with the first.
- Layer matching performed between data collected by different systems. Despite different resolutions, a "great" match achieved!
- MARFA and BAS DELORES ~Dome C also compared in this presentation. Layers are clearly different but overall geometry very consistent.

Discussion and Action Points

- The two radar system intercomparison studies discussed above, Winter et al. (2017) and Cavitte et al. (2016) act as examples of practice we need to repeat elsewhere.
- **ACTION (All)** – need to identify additional locations where radar systems and processing can be intercompared.
- **Martin Siegert** drew attention to the Drewry SPRI Folio of 1983 (appended below) which devotes a page to Antarctic internal layering, where it's good and bad. We could conceptualise *AntArchitecture* as a major upgrade to this product. **Neil Ross** posited that a good analogy for this exercise is Jamieson et al.'s (2014) *Antarctic Science* paper, which upgraded an older David Sugden exercise attempting to identify basal geomorphological regimes.
- **ACTION** – Might it be possible to run the continuity index of Karlsson et al. (2012; *EPSL*) on all Antarctic radar datasets so as to identify quickly likely regions of "good"/ traceable internal layering, versus "poor" disrupted layering where tracing is difficult and future survey might be targeted?

- There was discussion around ultimately what products from *AntArchitecture* will best service modelling. There is likely to be interest in gridded products of layer/surface ages, and uncertainties.

Wednesday 19 July 2017

Session 5: Practical challenges of assembling Antarctic-wide data Chair: *Neil Ross*

- Discussion began with what was realistically achievable in terms of datasets that are available now.
- UK/BAS data is currently reposed in the Polar Data Centre, where SEGYs are the most easily available product.
- BAS lacks manpower to provide picked layers per dataset, but universities may be able to provide that manpower through student projects at various levels.
- In terms of storing/sharing data, two models were discussed: (a) there is a central *AntArchitecture* repository that hosts all relevant radar data; or (b) *AntArchitecture* points to institutional data repositories. Model (b) was preferred for several reasons, but this underscores the need to develop common data formats.
- There may be a requirement for a database engineer to set up the initial storage/distribution model.
- It was suggested that once we have a list of who has what data (outcome of Session 2 above), and what we all need to extract from those data (outcome of Sessions 3 and 4 above), then a further outcome should be to draw up a document for processing the data consistently.

Session 6: Workshop Outcomes – White Paper and Funding Applications Chair: *Robert Bingham*

- There was broad agreement that the next steps for *AntArchitecture* should be as follows:
  - Pursue with the Scientific Committee for Antarctic Research (SCAR) the prospect of *AntArchitecture* being formalised as a Science Research Programme. This would facilitate assimilation of further international groups, and provide pump-priming for hosting regular workshops.
    - **STOP PRESS: Following the *AntArchitecture* Workshop, we have been invited by SCAR to propose *AntArchitecture* as a SCAR Action Group. Rob Bingham to coordinate this initially.**
  - Write white paper for *AntArchitecture*, which will be a critical exercise in formalising the research goals and practices, and communicating the possibilities to the wider research community.
  - Apply for funding, either consortium grants or various fellowship options. For European collaborators, ERC provides an obvious starting point. For US collaborators, NASA schemes may represent the best prospect. An action on all was to explore all possible funding avenues that can bring on board staff time towards *AntArchitecture*.
  - EU bids, and to some extent UK grants, are increasingly emphasising industrial/commercial applications of funded research. A route into this could be *AntArchitecture* directly interacting with seismic companies, either through developing software, or contributing to the skills training of future industrial geophysicists.
  - It was agreed that a key exercise for *AntArchitecture*, as part of or supplementing the white paper, will be to undertake intercomparison exercises on overlapping datasets acquired with different radar systems and/or processed differently. In effect, to upscale Winter et al. (2017) and Cavitte et al. (2016) discussed in Session 4.