Maydena sub-ice community workshop

October 10-12, 2023
Maydena, Tasmania (a.k.a. North Antarctica)

Over the course of three enriching days in the deglaciated landscapes of rural Maydena, 31 dedicated polar scientists gathered to discuss emerging sub-ice research directions. The workshop focused on the interconnected components of the subglacial landscape, the new technologies used to study this environment, and pathways for enhancing the integration of subglacial knowledge into ice sheet models. This workshop also featured discussion activities and field excursions to deglaciated sites around Maydena. The purpose of this document is to serve as a reminder of the thought-provoking discussions that took place and to facilitate further discussion and collaboration. This document also synthesizes the high-priority potential future research ideas and provides recommendations for maintaining the momentum of the workshop discussions.

Table of contents

Organizers and sponsors

This workshop was co-convened by Tobias Stål (Physics, University of Tasmania) and Emma "Mickey" MacKie (Department of Geological Sciences, University of Florida), with support from Anya Reading, (Physics, University of Tasmania) and Poul Christoffersen (Institute for Marine and Antarctic Studies, University of Tasmania). Nick Roberts from Mineral Resources Tasmania planned and led the field excursions and presented a keynote lecture.

This workshop received funding support from the Australian Centre for Excellence in Antarctic Science (ACEAS), Securing Antarctica's Environmental Future (SAEF), and Geological Society of Australia. Support is also expected from the Australian Antarctic Partnership Program (AAPP). This support greatly enhanced the participation of early career researchers.

AAPP Australian Antarctic Program Partnership

ACEAS Australian Centre for Excellence in Antarctic Science

SAEF Securing Antarctica's Environmental Future
Australian Research Council Special Research Initiative

Geological Society of Australia Incorporated

Tasmanian Government

Overview of workshop

This workshop brought together an international community of subglacial investigators to share research ideas and brainstorm future collaborative research activities. This workshop was set in Maydena, about 1.5 hours from Hobart. Some of the highlights of the accommodations included platypus sightings and the excellent catering by Origin Catering arranged by Toby.

The scientific program included sessions on the paleo glacial record, subglacial hydrology, geothermal heat flux, subglacial geology, ice sheet change, and new techniques for data interpretation and integration. There were a number of presentations on geophysical data assimilation and passive seismic interpretation. Machine learning and Markov Chain Monte Carlo inversion methods were a common theme. Innovations in passive seismic interpretation reveal the capacity for large-scale seismic mapping of subglacial conditions. A couple of the presentations introduced new techniques for extracting quantitative information from archival data sets in order to extend the temporal record of observations of ice sheet change. There was also a lot of enthusiasm for improving our ability to do FAIR (Findable, Accessible, Interoperable, Reusable) science.

The presentations made it clear that the thermal, hydrological, and geological properties beneath the ice cannot be easily separated from each other. The geothermal heat flow depends, in part, on the topography and geology. The meltwater production depends on heating. And the subglacial and groundwater hydrology are modulated by the topography and geology. These conditions then have an integrated effect on the overlying ice sheet, making it difficult to isolate how a single variable controls ice behavior. Furthermore, the lack of constraining geophysical information used in ice sheet model parameterization poses a challenge to validating models with observations. These talks made it clear that multi-geophysical approaches are essential for resolving the complex parameters and processes at the bed, and that new model/data integration approaches are needed for understanding how these conditions affect ice sheet behavior.

Schedule and sessions

Overview of schedule

The workshop organizers developed an ambitious schedule (shown below) packed with field excursions, scientific presentations, and scientific and community discussions. Notably, Mickey MacKie optimistically planned three lengthy discussion activities that were designed to facilitate scientific discussion amongst participants. The purpose of Activity 1 was to brainstorm scientific questions and possible actions to address those questions. Activity 2 involved assigning actions to an “Effort vs. Impact” matrix. In Activity 3, we conducted a “SWOT” analysis (strengths, weaknesses, opportunities, strengths) in order to evaluate internal and external factors that may help or hinder our community’s ability to do impactful science. Due to time constraints, Activity 2 suffered a fatal blow. Nevertheless, participants are encouraged to continue brainstorming high-impact research activities.

	Maydena workshop program (10 Oct)		
	Day 1	**Day 2**	**Day 3**
8:00-8:30			
8:30-9:00		Activity 1	Session 4
9:00-9:30			Includes 1 hr 10 min of presentations
9:30-10:00			and a 20 min panel discussion with presenters
10:00-10:30	Meeting at IMAS	Break, overflow time	Break, overflow time
10:30-11:00		Session 2	Session 5
11:00-11:30		Includes 1 hr 10 min of presentations	Includes 1 hr 10 min of presentations
11:30-12:00		and a 20 min panel discussion with presenters	and a 20 min panel discussion with presenters
12:00-12:30	Field excursion Mt Field	Lunch	Lunch
12:30-1:00	lunch packs provided		
1:00-1:30		Field excursion Gordon Rd + Styx Rd	Session 6
1:30-2:00			Includes 1 hr 10 min of presentations
2:00-2:30			and a 20 min panel discussion with presenters
2:30-3:00			Break, overflow time
3:00-3:30		Session 3	Activity 3
3:30-4:00		Includes 1 hr 10 min of presentations	
4:00-4:30	Arrive at conference	and a 20 min panel discussion with presenters	
4:30-5:00	Check in, get settled	Activity 2	Afternoon departure
5:00-5:30	Session 1: Nick Roberts Glaciations		
5:30-6:00			
6:00-6:30	Dinner	Dinner	Dinner (Hobart)
6:30-7:00			
7:00-7:30			

Sessions

Session 1: Invited

- Tasmania's glacial records and their Southern Hemisphere context
    - Nicholas Roberts

Session 2: Subglacial hydrology and thermal conditions (chaired by Matthias Scheiter)

- Characterizing the subglacial hydrology of the South Pole Basin, Antarctica using COLDEX airborne geophysics
    - Megan Kerr, Duncan Young, Shuai Yan, TJ Fudge, Donald Blankenship, Shivangini Singh
- Analytical framework to model seismic signals from fluid particle collisions in hydrodynamic simulations of glacier melt water
    - Ross J. Turner, Jared Magyar, Sue Cook, Anya M. Reading
- The known unknowns: assimilating sparse datasets to uncover sub-ice heat flow
    - Ben Mather
- The subglacial heat budget – a conceptual investigation
    - Tobias Stål, Anya M. Reading, Poul Christoffersen, Suze Nei Pereira Guimarães, Ian Kelly, Felicity McCormack
- Basal hydrology and mechanics captured seismically on a fast-moving glacier in Greenland
    - Poul Christoffersen, Charlie Schoonman, Samuel Doyle, Bryn Hubbard, Robert Law, Thomas Chudley, Tun Jan Young, Coen Hofstede

Session 3: Subglacial geology (chaired by Jared Magyar)

- Approaches to constraining East Antarctic rheology using seismic measurements from isolated stations
    - Niam Askey-Doran, Ross J. Turner, Tobias Ståll, Anya M. Reading
- Developing ground-based passive geophysics as an efficient tool to map and monitor the Antarctic ice-bed interface zone (IBIZ)
    - Ian D. Kelly, Anya M. Reading, Tobias Stål, Maria Manassero, Alan Aitken, Andrew Bassom
- On East Antarctic Subglacial Boundary Conditions
    - Mareen Loesing
- Probing anisotropic stratification and interannual variations of the Greenland ice sheet by teleseismic P-wave coda autocorrelation
    - T.-S. Pham , A. Sanjayan, H. Tkalčić, B. Tauzin

Session 4: Processes and changes (chaired by Niam Askey-Doran)

- Ice penetrating radar survey of a super-buoyant terminus of San Quintin Glacier, Northern Patagonia Icefield

    - Michal Petlicki
- Surface and Bed Topography Mapping of Foxfonna & Rieperbreen Glacier, Svalbard, 1936-2020
    - Wai Yin Cheung
- What's really going on at the base of the Aurora Subglacial Basin?
    - Felicity S. McCormack, Jason L. Roberts, Christine F. Dow, Tyler Pelle, Bernd Kulessa, Alan Aitken, Lawrence A. Bird, Katharina Hochmuth
- Extracting Ice Thickness Measurements from the Digitized Historical SPRI-NSF-TUD Airborne Radar Echo Sounding at Ross Ice Shelf, Antarctica through Computer Vision Algorithms
    - Angelo Tarzona, Winnie Chu, Hannah Verboncoeur, Matthew Siegfried, Dustin M. Schroeder, Abdullah Altaweel, Brian Amaro, Kiera Tran

Session 5: New directions/technology (chaired by Angelo Tarzona)

- Towards understanding basal condition from geophysical and geological information
    - Lu Li , Alan Aitken, Mareen Loesing, Emma MacKie
- Passive Seismic Monitoring of Hydrological Processes at Sørsdal Glacier, East Antarctica Using Unsupervised Learning and Hydrodynamic Modelling
    - JC Magyar, AM Reading, RJ Turner, S Cook, SS Thompson, B Kulessa, I Kelly, C Schoof
- Integrating data-driven and knowledge-driven analyses for characterizing subglacial conditions
    - Emma "Mickey" MacKie, Michael Field, Lijing Wang
- Instruments and inference approaches: diverse approaches to progressing our understanding of the ice-bedrock interface zone
    - Anya Reading, Tobias Stål, Kate Selway, Felicity McCormack
- Advancing ice sheet models with machine-learning and data science
    - Matthias Scheiter, Poul Christoffersen, Tobias Stål, Emma MacKie

Session 6: Connecting the dots (chaired by Shyla Kupis)

- Well, there used to be ice here. . . " - combining the continental shelf and subglacial observations
    - Katharina Hochmuth
- Glacial deposits and landforms in the upper Mersey and Forth river valleys
    - Nicholas J. Roberts Grace V. Cumming
- The Integrated Digital East Antarctica program
    - Lenneke Jong

Field excursions

Nick Roberts led the workshop on two excursions. The objective was to introduce the group to various subglacial and periglacial landforms and formations and discuss how hydrology can depend on the geology and the landscape.

On day one, we visited Lake Dobson and Mount Field. Nick gave an overview of glacial geomorphological terms for participants with different scientific backgrounds and discussed various processes that form the subglacial and periglacial landscape. We discussed the postglacial landscape, moraines, and traces of cirque glaciers. From a lookout over Lake Seal we could observe the lake-filled-U-shaped valley and a few of the end moraines in the Broad River valley. We also discussed various datasets useful for geomorphological mapping of glacial features, particularly lidar and paleomagnetics. Driving back from Lake Dobson, we stopped at a dolerite blockstream below Lake Fenton and discussed how water can be channeled through sediments.

On day two, we drove further up the Tyenna Valley and reached Pontoon Hill. Here, we looked at the contact between subglacial deposits and the till. We discussed different dating techniques and various interpretations of the underlying sediments. We also stopped at Styx Road to look at Paleozoic tillite. This formation is unrelated to the recent glaciations of Tasmania, but provided an insight into lithification and allowed us to discuss the fabric of the till further. Before returning to the venue, we took a short walk to the Junee Cave. The walk went along the river through a beautiful forest with tree ferns. The karst cave was used as an analogy to discuss the volumes of water that might be transported in subglacial channels.

Further details regarding the excursions are provided in the attached field guide developed for the workshop.


Activity 1: Scientific brainstorming

Activity 1 was designed to start a discussion about scientific questions and possible research ideas. In this activity, the participants were split into six teams. First, the teams brainstormed key scientific questions. These questions were intended to capture big picture community needs, but also scientific “curiosities” or potentially overlooked processes that may be important. After this, we came back together as a group to synthesize the different questions into similar themes. We then created brainstorming papers for each of these themes. These sheets of papers were divided into fieldwork and non-fieldwork sections. The different teams then brainstormed field-based and non-fieldwork research activities that could address each scientific topic.

The scientific questions fell into the following categories. Some topics were discussed more than others. Possible actions items are also summarized below:

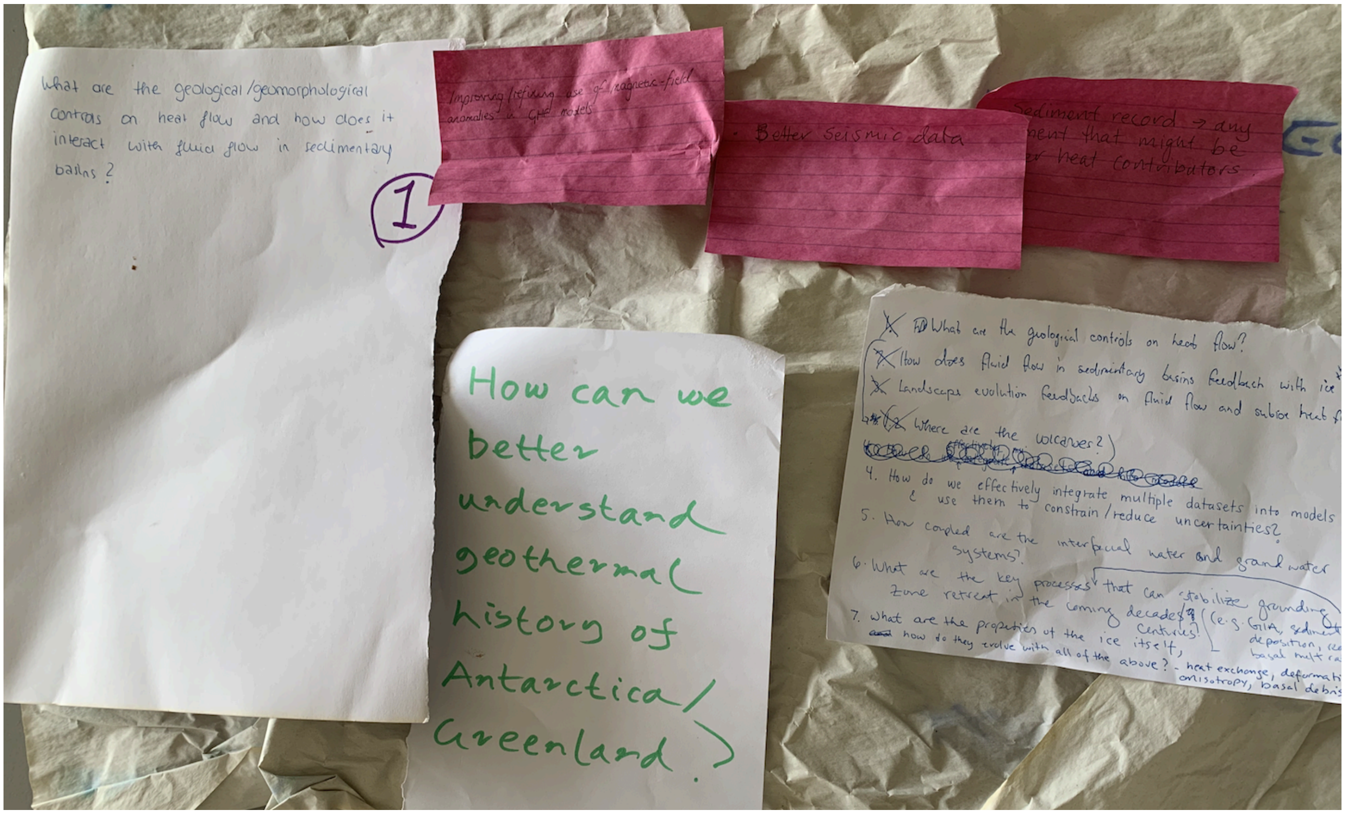
1. **Geothermal heat flow:** What are the geological controls on GHF? What is the thermal history of Antarctica? What are the feedbacks between fluid flow in sedimentary basins and ice and heat flow? How do we effectively integrate multiple datasets into models to constrain/reduce uncertainties in GHF?
    a. Integrate processes into GHF modeling: eg. thermal refraction, thermal advection, steady state vs non-steady state
    b. Consider the scale and resolution for ice sheet modelling purposes. E.g., what are the likely GHF impacts on: the extent of the subglacial hydrological system; volume of meltwater production, particularly where frictional and other heat sources are of relatively small magnitude; and where/how much does GHF impact the deformability of ice?
    c. Constrain thermal parameters (thermal conductivity; heat production) using geophysics (e.g. a high resolution crustal scale Vp model)
    d. Bayesian framework to integrate multiple datasets (how to incorporate the non steady state part?)
    e. How do we quantify uncertainties in a consistent way?
2. **Paleo conditions:** What are the gaps in the paleo record? What can we learn from offshore sediments about the timing of deposition, provenance, and geochronology?
    a. Utilizing older already available material for more detailed and novel analysis
    b. Development of standard practices and datasets to be collected during all campaigns (marine & terrestrial) such as bathymetric data collected from port to port even on logistical voyages
    c. Antarctic continental shelves (especially in East Antarctica) are severely understudied to understand recent and paleo ice sheet retreat.
3. **Englacial properties, ice change:** How can we monitor present ice melt from glaciers? How do the properties of ice (temperature, chemistry, grain size, crystal orientation fabric, liquid water content) vary spatially and temporally, and how do they evolve due to varying basal and surface properties?
    a. What are the relative contributions of ice deformation and sliding on overall ice flow? What data do we need to be able to characterise/quantify the contributions of these two flow processes?
    b. In what detail do we need to know topography to be able to accurately model strain heating near the ice-bed interface, and hence ice deformation?
    c. What is the distribution of temperate ice in Antarctica and what data can we use to constrain this? Are our models capable of modelling temperate ice?
    d. What new processes/parameterisations are needed for our models to capture relevant englacial processes/properties and their influence on ice flow/dynamics?
    e. Analyze multidecadal changes in archival radar data
    f. Satellite gravity consider spatial density variation due to subglacial geology
    g. Some phase radar?

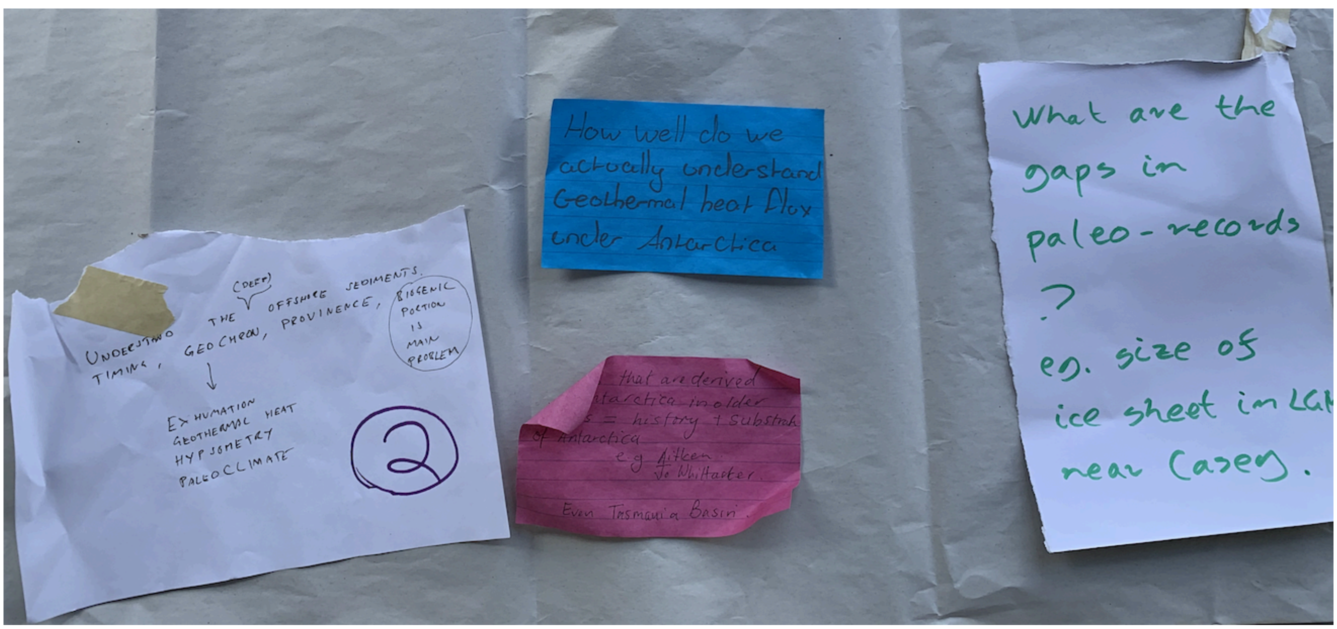
    h. Some ice mechanics work?

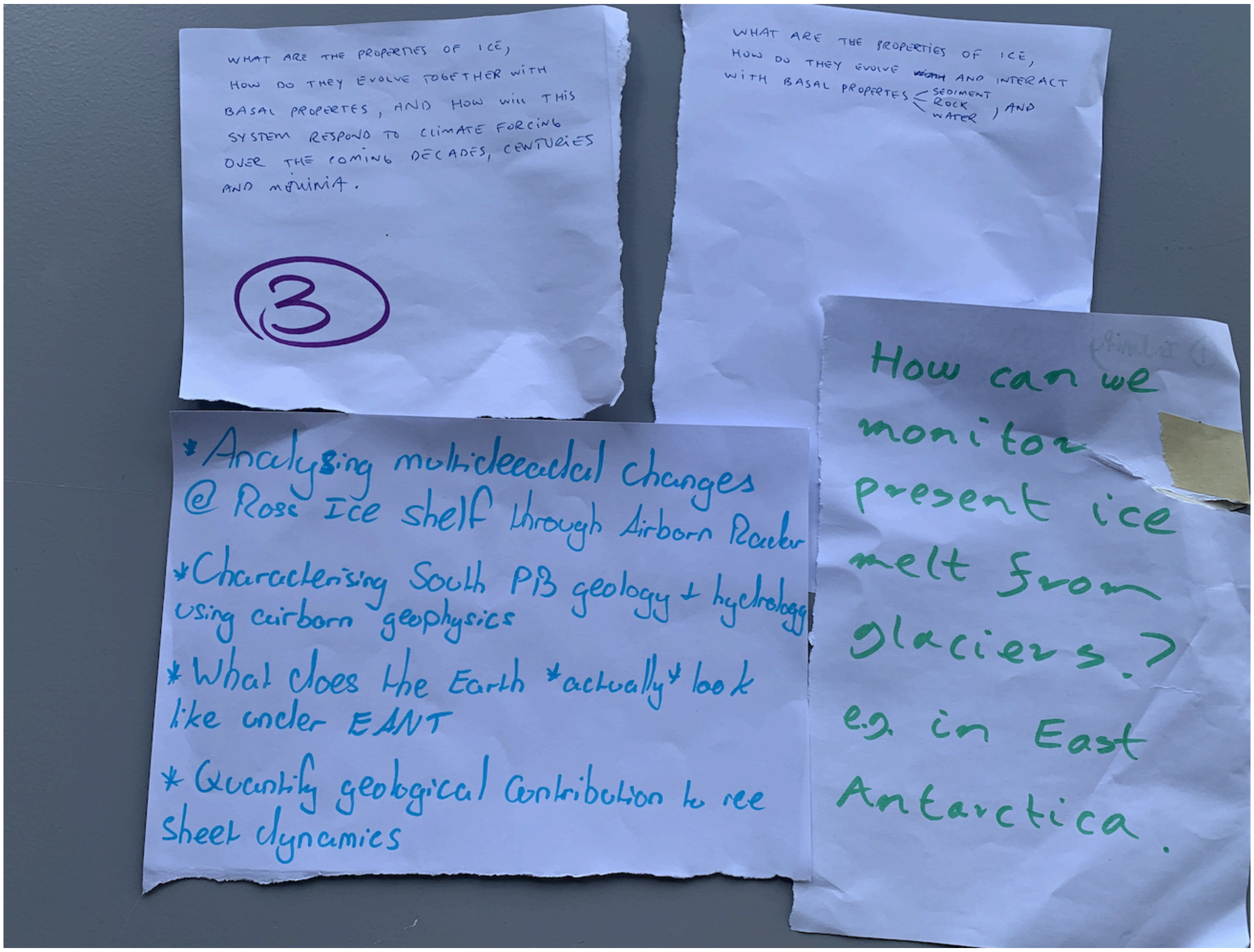
4. **Groundwater/subglacial hydrology:** Groundwater (what, where, how)? How do we incorporate subglacial hydrology into ice sheet models? Are subglacial channels widespread, or is distributed drainage dominant? How do we characterize subglacial transient discharge and/or steady flow?
    a. Conduct more multi-geophysical campaigns (i.e. MT, radar, seismics)
    b. Conduct long-term borehole studies.
    c. Measure subglacial permeability
    d. Develop enhanced theoretical models on distributed flow.
    e. Develop models to capture ice/water/sediment interactions
    f. Develop instruments for measuring in situ subglacial sediment properties such as permeability and porosity
5. **Groundwater/subglacial hydrology:** (repeat. 4 and 5 were combined)
6. **Observational innovations:** Are we biased by focusing primarily on rapidly changing glaciers? How do we effectively integrate multiple datasets covering different spatial and temporal resolutions? How do we quantify uncertainty?
    a. Analyze archival geophysical records
    b. Use gradiometry to improve the resolution of gravity and magnetic inversions???
7. **GIA:** How much does GIA matter in East Antarctica, and which areas are most sensitive?
    a. Need some GNSS time series
    b. Joint multi-geophysical investigation to constrain mantle viscosity
    c. Think about the elastic response of crust
8. **Basal friction, sliding, topographic controls:** What bed resolution matters for ice sheet models? Where is the ice sheet flowing by sliding vs deformation? What processes are missing from sliding laws (e.g. transition between sedimentary to crystalline base and how that impacts sliding)? How do we incorporate physical processes/properties into the friction coefficient to constrain sliding? How can we use geophysics to better validate/constrain model physics and parameter estimation?
    a. Conduct additional airborne RES surveys, repeat surveys, and ApRES surveys to look at anisotropy
    b. Conduct co-located seismic and radar surveys and register with ice core data to study ice deformation and anisotropy
    c. Explore data-driven approaches to initializing ice sheet models (e.g. Bayesian inference). Integrate geophysical observations into friction inversions.
    d. Incorporate geostatistical simulations of bed topography into ice sheet models.
    e. Test ice sheet models at different resolutions and roughnesses.
    f. Conduct synthetic, process-based modeling experiments and compare to ice sheet system models.

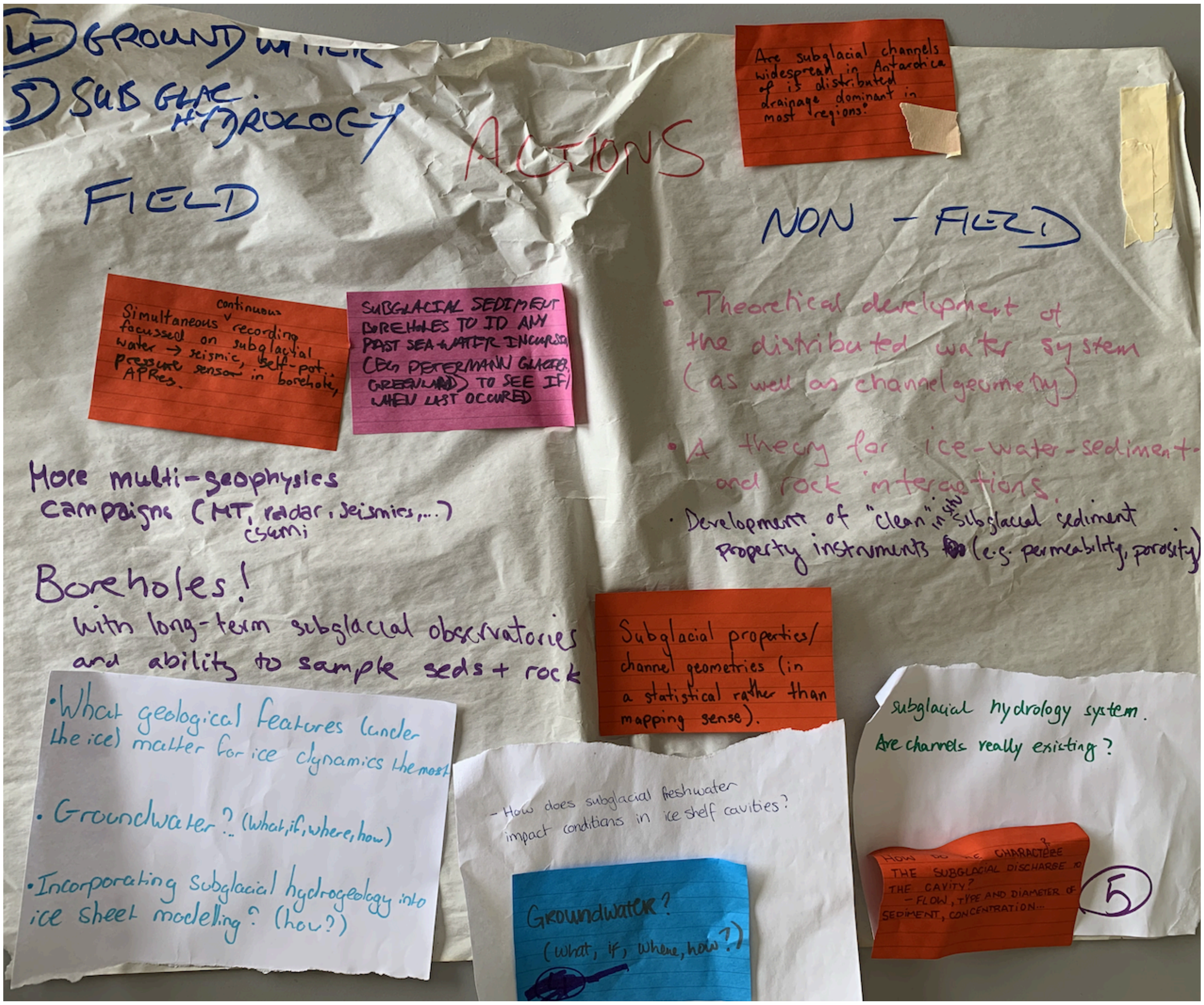
g. Flexible ice sheet model framework, could incorporate spatial variable processes (e.g sliding law).
h. How well do we know about englacial fabrication and quantify its influence on ice sheet deformation?

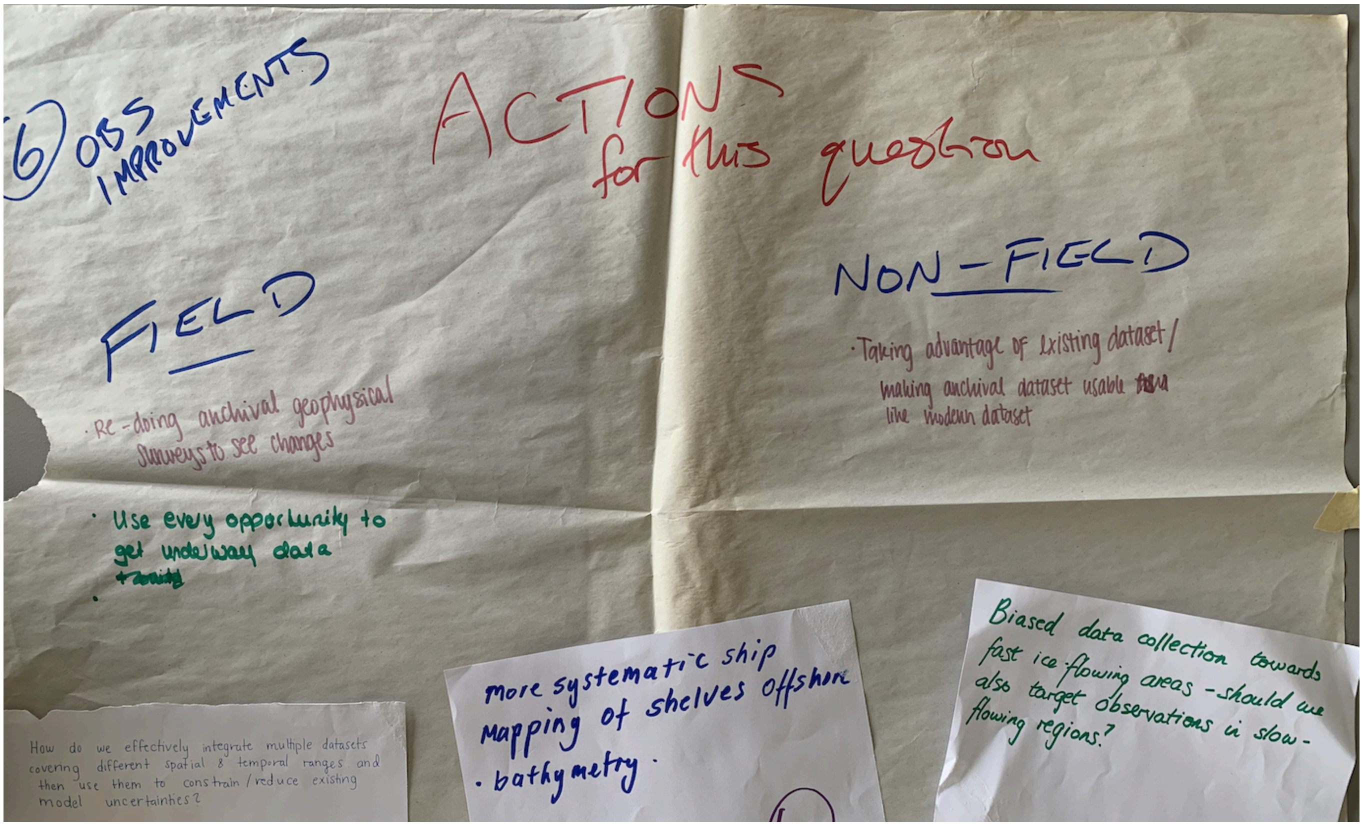
Unfortunately, there were some casualties to the brainstorming documents due to rain (my sincerest apologies to GHF). The survivors are shown below.

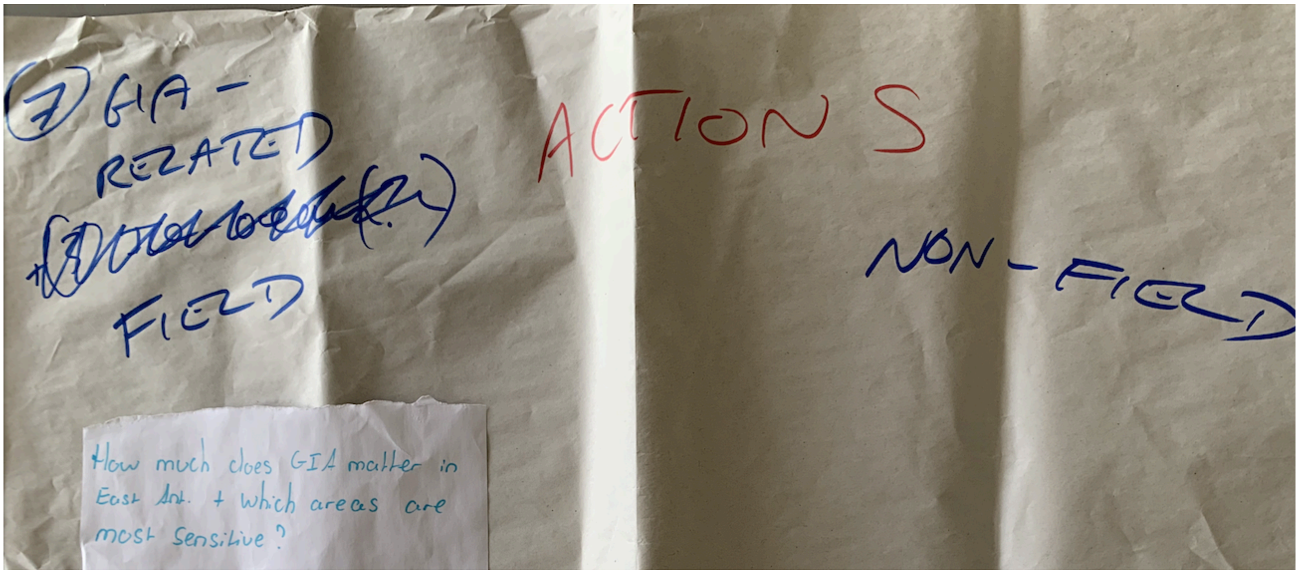

What are the geological/geomorphological controls on heat flow and how does it interact with fluid flow in sedimentary basins?
1
Improving/refining use of magnetic-field anomalies in GHF models
Better Seismic data
How can we better understand geothermal history of Antarctica/Greenland?
What are the geological controls on heat flow?
How does fluid flow in sedimentary basins feedback with ice
Landscape evolution feedbacks on fluid flow and subice heat
Where are the volcanoes?
4. How do we effectively integrate multiple datasets into models & use them to constrain/reduce uncertainties?
5. How coupled are the interfacial water and groundwater systems?
6. What are the key processes that can stabilize grounding zone retreat in the coming decades/centuries?
(e.g. GIA, sediment deposition, basal melt
7. What are the properties of the ice itself, how do they evolve with all of the above? - heat exchange, deformation, anisotropy, basal debris


How well do we actually understand Geothermal heat flux under Antarctica
UNDERSTAND THE (DEEP) OFFSHORE SEDIMENTS. TIMING, GEOCHEM, PROVINENCE,
BIOGENIC PORTION IS MAIN PROBLEM
EXHUMATION
GEOTHERMAL HEAT
HYPSOMETRY
PALEOCLIMATE
2
that are derived
Antarctica in older
= history + substrate
of Antarctica
e.g. Aitken
Jo Whittaker
Even Tasmania Basin
What are the gaps in paleo-records?
eg. size of ice sheet in LGM near Casey.

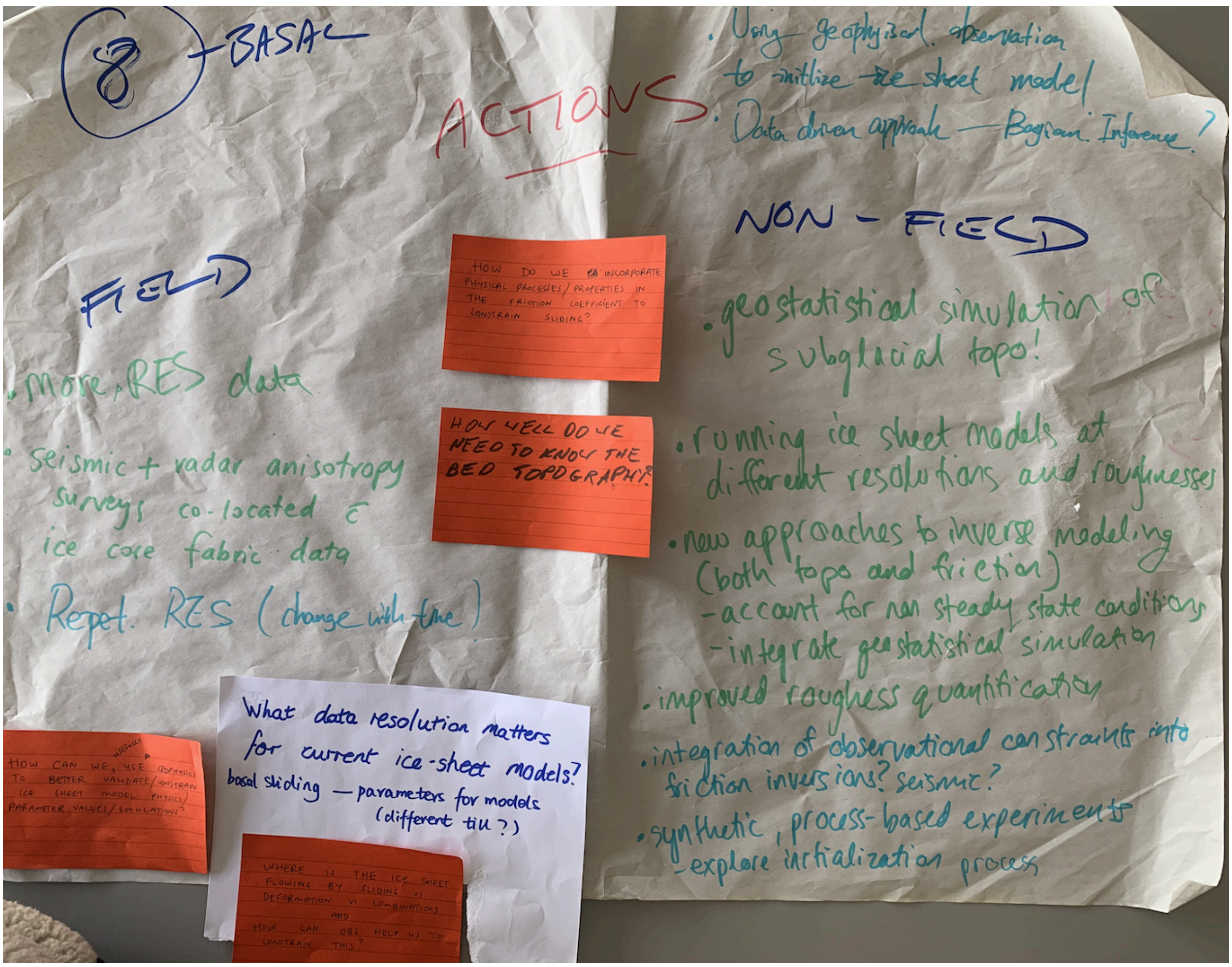

WHAT ARE THE PROPERTIES OF ICE, HOW DO THEY EVOLVE TOGETHER WITH BASAL PROPERTES, AND HOW WILL THIS SYSTEM RESPOND TO CLIMATE FORCING OVER THE COMING DECADES, CENTURIES AND MILLENNIA.
3
WHAT ARE THE PROPERTIES OF ICE, HOW DO THEY EVOLVE ~~WITH~~ AND INTERACT WITH BASAL PROPERTES SEDIMENT ROCK WATER, AND
*Analysing multidecadal changes @ Ross Ice shelf through Airborn Radar
*Characterising South PB geology + hydrology using airborn geophysics
*What does the Earth *actually* look like under EANT
*Quantify geological contribution to ice sheet dynamics
How can we monitor present ice melt from glaciers? e.g. in East Antarctica.


4 GROUNDWATER
5 SUB GLAC. HYDROLOGY
ACTIONS
FIELD
NON - FIELD
Are subglacial channels widespread in Antarctica or is distributed drainage dominant in most regions?
Simultaneous continuous recording focussed on subglacial water → seismic, self-pot, pressure sensor in borehole, ApRES.
SUBGLACIAL SEDIMENT BOREHOLES TO ID ANY PAST SEA-WATER INCURSION (EG PETERMANN GLACIER, GREENLAND) TO SEE IF/WHEN LAST OCCURED
• Theoretical development of the distributed water system (as well as channel geometry)
• A theory for ice-water-sediment-and rock interactions.
• Development of "clean" in situ subglacial sediment property instruments (e.g. permeability, porosity)
More multi-geophysics campaigns (MT, radar, seismics, ...) (sEMi)
Boreholes!
with long-term subglacial observatories and ability to sample seds + rock
Subglacial properties/ channel geometries (in a statistical rather than mapping sense).
subglacial hydrology system.
Are channels really existing?
• What geological features (under the ice) matter for ice dynamics the most
• Groundwater? (what, if, where, how)
• Incorporating subglacial hydrogeology into ice sheet modelling? (how?)
- How does subglacial freshwater impact conditions in ice shelf cavities?
Groundwater? (what, if, where, how?)
THE SUBGLACIAL DISCHARGE TO THE CAVITY?
- FLOW, TYPE AND DIAMETER OF SEDIMENT, CONCENTRATION...
5


6 OBS IMPROVEMENTS
ACTIONS for this question
FIELD
· Re-doing archival geophysical surveys to see changes
· Use every opportunity to get underway data
NON-FIELD
· Taking advantage of existing dataset / making archival dataset usable like modern dataset
How do we effectively integrate multiple datasets covering different spatial & temporal ranges and then use them to constrain / reduce existing model uncertainties?
more systematic ship mapping of shelves offshore
· bathymetry.
Biased data collection towards fast ice flowing areas - should we also target observations in slow-flowing regions?



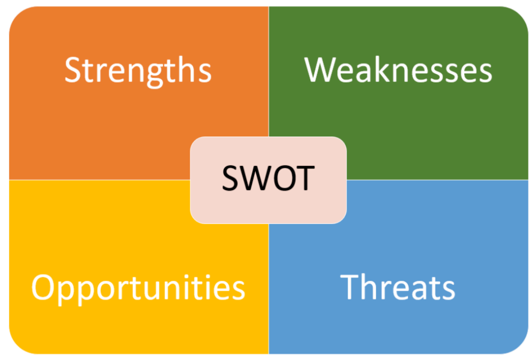
7 GIA - RELATED
FIELD
ACTIONS
NON-FIELD
How much does GIA matter in East Ant. + which areas are most sensitive?



8 BASAL
ACTIONS
FIELD
· more RES data
· seismic + radar anisotropy surveys co-located ē ice core fabric data
· Repet. RES (change with time)
HOW DO WE INCORPORATE PHYSICAL PROCESSES / PROPERTIES IN THE FRICTION COEFFICIENT TO CONSTRAIN SLIDING?
HOW WELL DO WE NEED TO KNOW THE BED TOPOGRAPHY?
What data resolution matters for current ice-sheet models?
basal sliding — parameters for models (different till?)
HOW CAN WE USEFULLY USE GEOPHYSICS TO BETTER VALIDATE/CONSTRAIN ICE SHEET MODEL PHYSICS/PARAMETER VALUES/SIMULATIONS?
WHERE IS THE ICE SHEET FLOWING BY SLIDING VS DEFORMATION VS COMBINATIONS AND HOW CAN OBS HELP US TO CONSTRAIN THIS?
· Using geophysical observation to initlize ice sheet model
· Data driven approach — Bayesian Inference?
NON-FIELD
· geostatistical simulation of subglacial topo!
· running ice sheet models at different resolutions and roughnesses
· new approaches to inverse modeling (both topo and friction)
- account for non steady state conditions
- integrate geostatistical simulation
· improved roughness quantification
· integration of observational constraints into friction inversions? seismic?
· synthetic, process-based experiments
- explore initialization process

Activity 3: SWOT brainstorming outcomes

For our final activity, we took a step back and discussed community issues. Activity 3 involved the creation of SWOT (strengths, weaknesses, opportunities, threats) matrices. In this activity, the participants were divided into six teams. Each team filled out a sheet of paper like the diagram shown on the right. Afterwards, each group presented their chart. The sections are defined as follows:



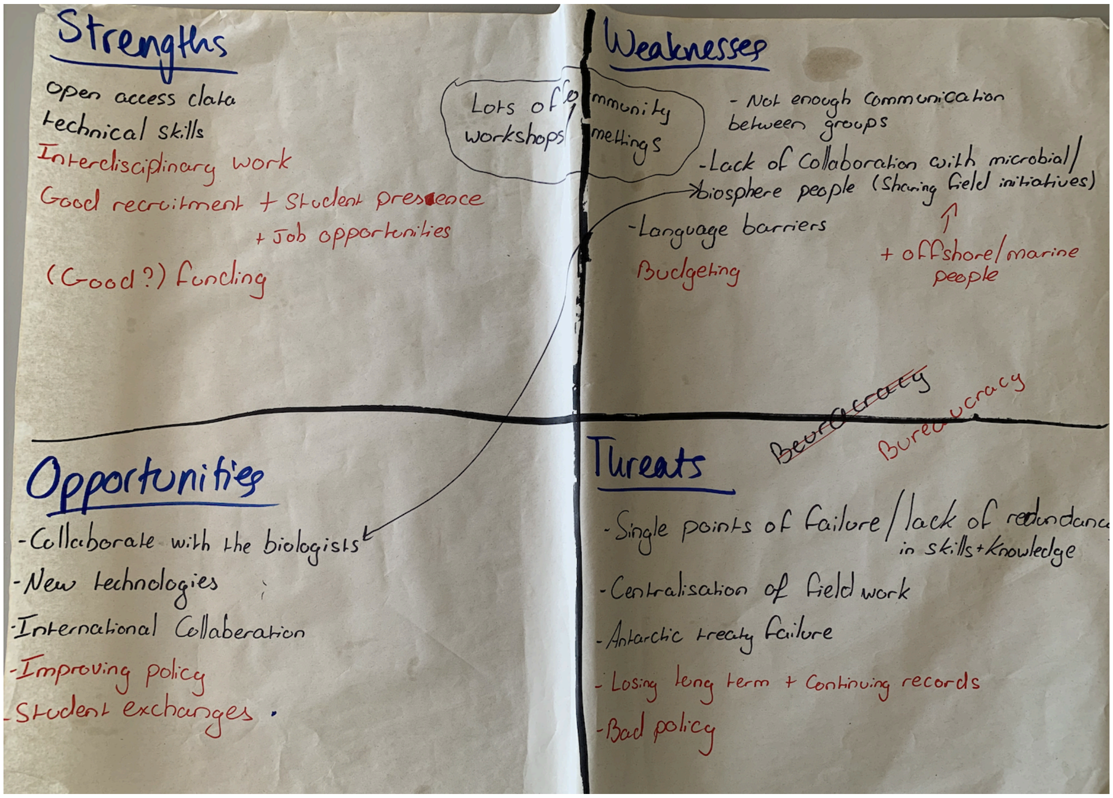
- **Strengths:** What are the strengths of our community? What makes us well positioned to do impactful science?
- **Weaknesses:** What are our weaknesses as a community? Do we have scientific blindspots or areas that we need to improve in? Skills that we don't have in our community?
- **Opportunities:** What opportunities are there to strengthen our community and our science? What emerging technologies, political factors, funding changes, new resources, or cultural factors, etc. can we take advantage of? Are there new partnerships we should form? Other funding opportunities to consider?
- **Threats:** What factors or external pressures (technological, economic, political, funding-agency related) threaten to undermine our success? What do we need to watch out for? What obstacles do we face?

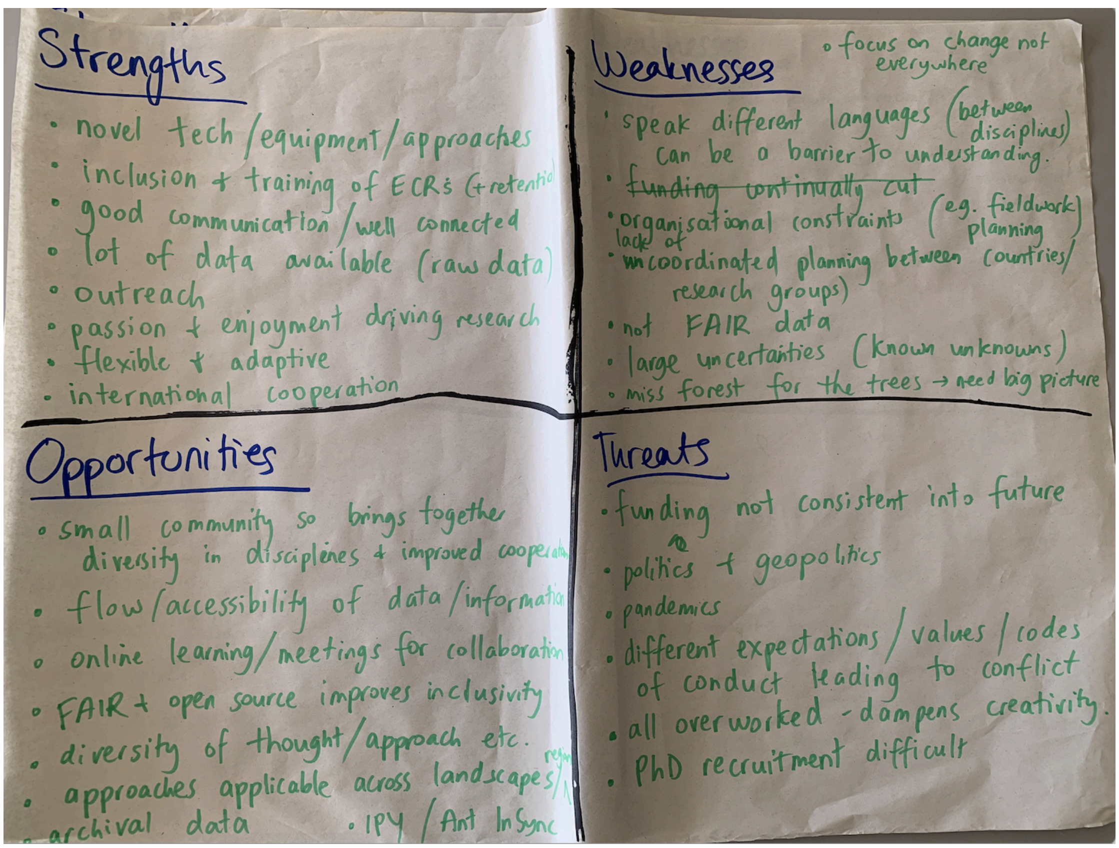
The following themes emerged from the SWOT discussion:

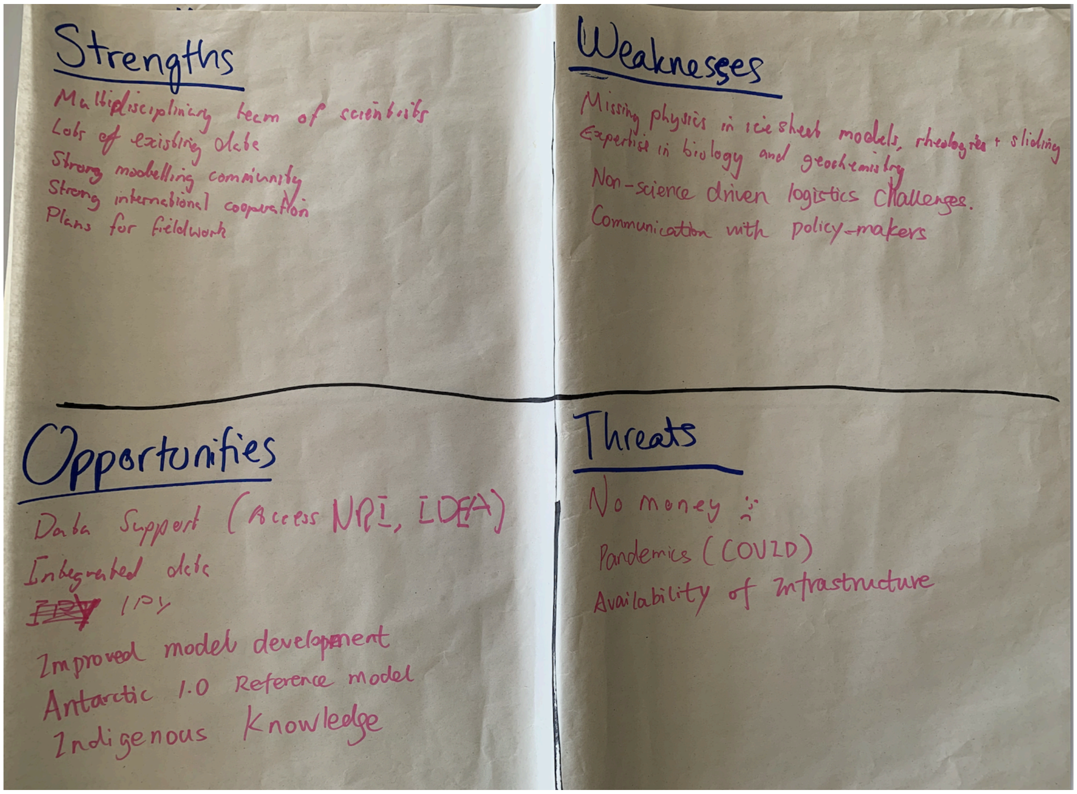
- **Strengths**
  - We are a diverse, passionate group of individuals who support each other.
  - We have a strong early career cohort.
  - Our community has a wider set of technical expertise than ever before.
  - There is a lot of enthusiasm for making data and methods open-access.
- **Weaknesses**
  - Accessing data remains a challenge. It is often unclear where to go to get data.

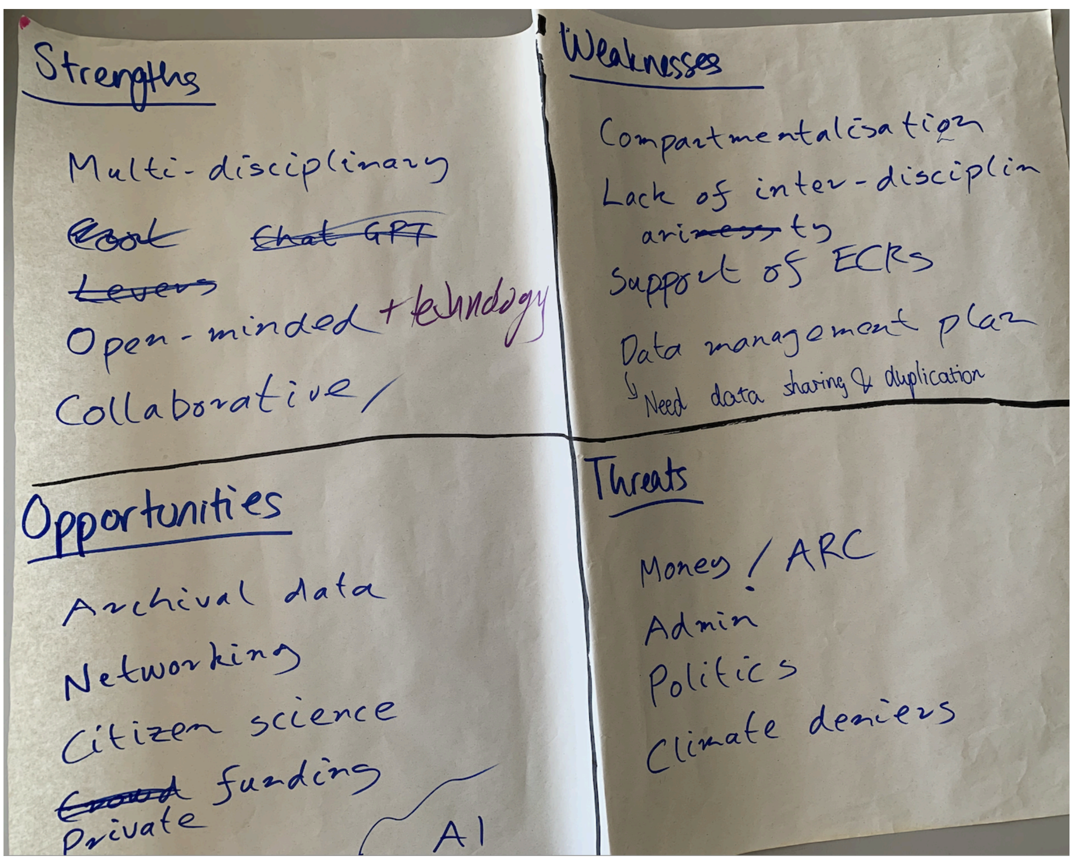
    - There are some "single points of failure." Specifically, there is some technical expertise that only a few individuals have. If they were to retire/leave, then that expertise would no longer be available.
    - Some data is not properly archived. What happens to that data when the person who gathered it retires?
    - We focus a lot on the exciting, rapidly changing glaciers. Are we missing something by neglecting the "boring" glaciers?
    - Are we at risk of "missing the forest for the trees" or losing sight of the big picture?
    - We continue to lack an understanding of critical physical processes involved in ice flow. Modeling and observational communities are somewhat siloed.
    - Multi/inter-disciplinary research takes a lot of time and effort, particularly due to different disciplines having unique "language" that takes time to learn
- **Opportunities**
    - New technologies such as AI can be used to enhance our research.
    - There is growing support to create centralized, accessible data repositories (including efforts led by Lenneke Jong, yay!)
    - Archival data can be leveraged to enhance the temporal resolution of our science.
    - We should do more student exchange (have students visit other institutions to foster international collaboration).
    - Arctic and Antarctic science problems can be tackled together.
    - Additional support for ECRs (e.g. conference, travel, inclusion in strategic planning discussions).
    - The whole is bigger than the sum of the parts: when we collaborate effectively, are open, honest, and work with integrity, we can achieve more (than if we're protective of our ideas/data and unwilling to share)
- **Threats**
    - Lack of stability in funding streams could hinder scientific progress. It was noted that collaborative research and proposals are important for absorbing some of the uncertainty and variability in funding.
    - Field logistics and aging infrastructure will continue to be a growing barrier to effectively conducting fieldwork.
    - Field work opportunities are centralized amongst a few individual groups/scientists.
    - Some universities charge high visitor fees for visiting scientists, which limits international collaboration.
    - Political instability creates uncertainty in funding opportunities.

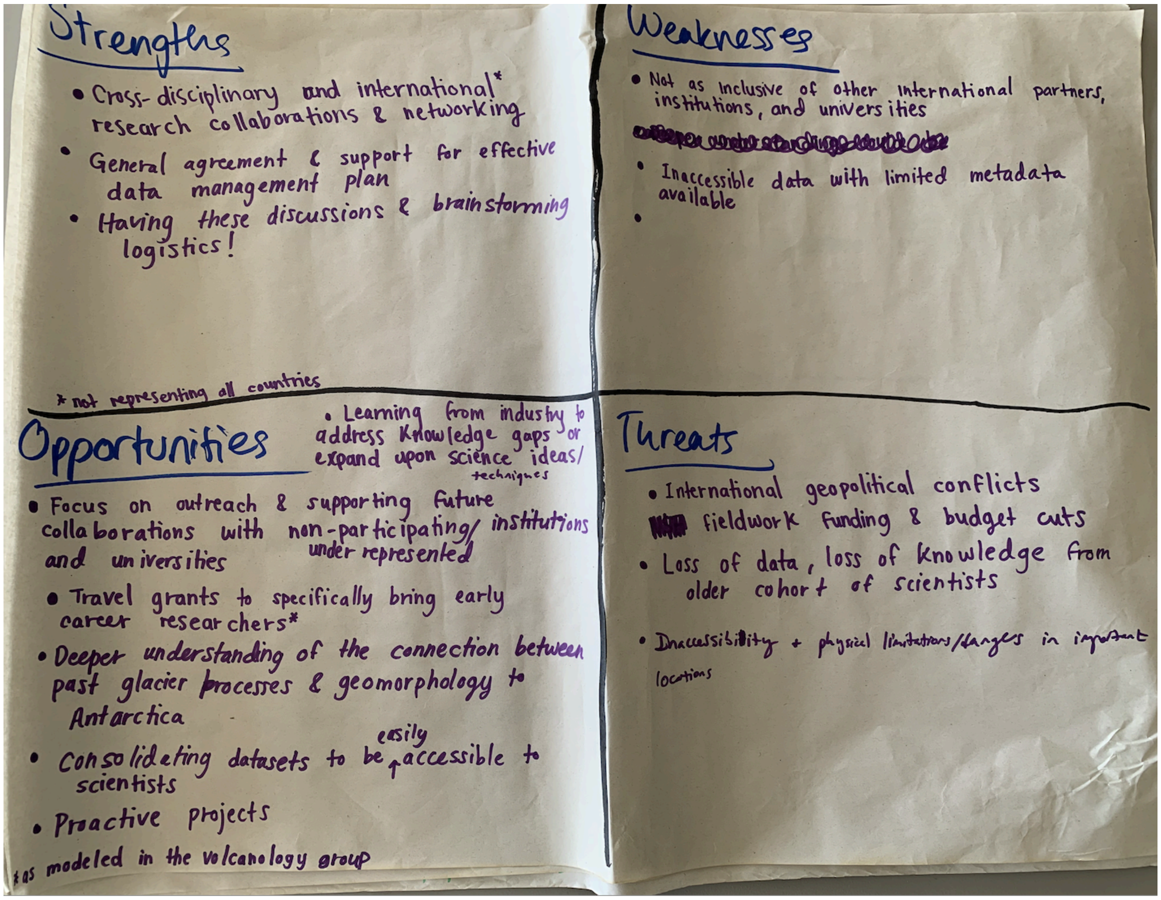
The SWOT sheets from each group are shown below.

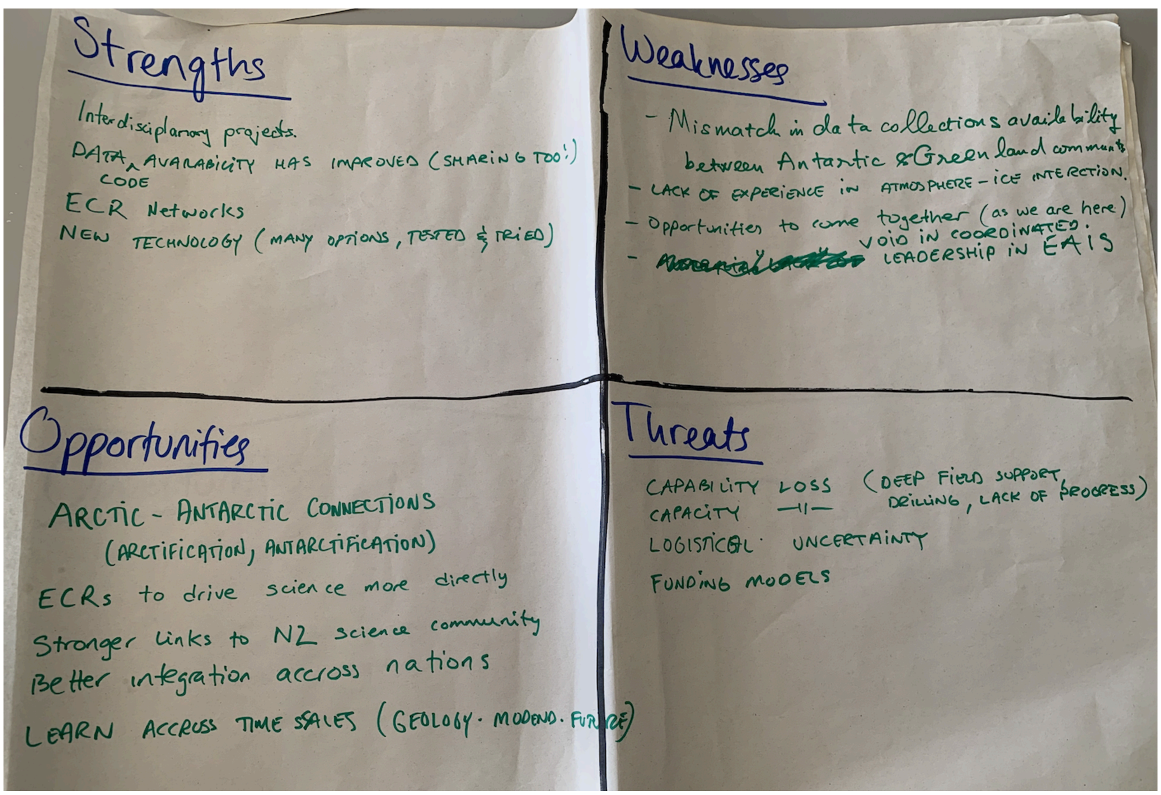

Strengths
open access data
technical skills
Interdisciplinary work
Good recruitment + Student presence
+ Job opportunities
(Good?) funding
Lots of community workshops meetings
Weaknesses
- Not enough communication between groups
-Lack of Collaboration with microbial/biosphere people (Sharing field initiatives)
+ offshore/marine people
-Language barriers
Budgeting
~~Beurocracy~~
Bureaucracy
Opportunities
-Collaborate with the biologists
-New technologies
-International Collaboration
-Improving policy
-Student exchanges
Threats
-Single points of failure/lack of redundancy in skills+knowledge
-Centralisation of field work
-Antarctic treaty failure
-Losing long term + Continuing records
-Bad policy


Strengths
• novel tech/equipment/approaches
• inclusion + training of ECRs (+retention)
• good communication/well connected
• lot of data available (raw data)
• outreach
• passion + enjoyment driving research
• flexible + adaptive
• international cooperation
Weaknesses
• focus on change not everywhere
• speak different languages (between disciplines) can be a barrier to understanding.
• ~~funding continually cut~~
• organisational constraints (eg. fieldwork planning)
• lack of uncoordinated planning between countries/research groups)
• not FAIR data
• large uncertainties (known unknowns)
• miss forest for the trees → need big picture
Opportunities
• small community so brings together diversity in disciplines + improved cooperation
• flow/accessibility of data/information
• online learning/meetings for collaboration
• FAIR + open source improves inclusivity
• diversity of thought/approach etc.
• approaches applicable across landscapes/regions
• archival data
• IPY/Ant InSync
Threats
• funding not consistent into future
• politics + geopolitics
• pandemics
• different expectations/values/codes of conduct leading to conflict
• all overworked - dampens creativity.
• PhD recruitment difficult


Strengths
Multidisciplinary team of scientists
Lots of existing data
Strong modelling community
Strong international cooperation
Plans for fieldwork
Weaknesses
Missing physics in ice sheet models, rheologies + sliding
Expertise in biology and geochemistry
Non-science driven logistics challenges.
Communication with policy-makers
Opportunities
Data Support (Access NRI, IDEA)
Integrated data
IPY
Improved model development
Antarctic 1.0 Reference model
Indigenous knowledge
Threats
No money
Pandemics (COVID)
Availability of infrastructure


Strengths
Multi-disciplinary
Open-minded + technology
Collaborative
Weaknesses
Compartmentalisation
Lack of inter-disciplinarity
Support of ECRs
Data management plan
Need data sharing & duplication
Opportunities
Archival data
Networking
Citizen science
Private funding
AI
Threats
Money / ARC
Admin
Politics
Climate deniers


Strengths
• Cross-disciplinary and international* research collaborations & networking
• General agreement & support for effective data management plan
• Having these discussions & brainstorming logistics!
* not representing all countries
Weaknesses
• Not as inclusive of other international partners, institutions, and universities
• Inaccessible data with limited metadata available
•
Opportunities
• Learning from industry to address knowledge gaps or expand upon science ideas/techniques
• Focus on outreach & supporting future collaborations with non-participating/under represented institutions and universities
• Travel grants to specifically bring early career researchers*
• Deeper understanding of the connection between past glacier processes & geomorphology to Antarctica
• Consolidating datasets to be easily accessible to scientists
• Proactive projects
*as modeled in the volcanology group
Threats
• International geopolitical conflicts
fieldwork funding & budget cuts
• Loss of data, loss of knowledge from older cohort of scientists
• Inaccessibility + physical limitations/dangers in important locations


Strengths
Interdisciplinary projects.
DATA, CODE AVAILABILITY HAS IMPROVED (SHARING TOO!)
ECR Networks
NEW TECHNOLOGY (MANY OPTIONS, TESTED & TRIED)
Weaknesses
- Mismatch in data collections availability between Antartic & Greenland communities
- LACK OF EXPERIENCE in ATMOSPHERE - ICE INTERACTION.
- Opportunities to come together (as we are here)
- VOID IN COORDINATED LEADERSHIP IN EAIS
Opportunities
ARCTIC - ANTARCTIC CONNECTIONS (ARCTIFICATION, ANTARCTIFICATION)
ECRs to drive science more directly
Stronger links to NZ science community
Better integration accross nations
LEARN ACCROSS TIME SCALES (GEOLOGY - MODERN - FUTURE)
Threats
CAPABILITY LOSS (DEEP FIELD SUPPORT, DRILLING, LACK OF PROGRESS)
CAPACITY —"—
LOGISTICAL UNCERTAINTY
FUNDING MODELS

Outcomes and future directions

There were three main themes for future research needs that came out of the discussions:

1) **Additional in situ observations**
    a) (highlight Matt's point about instrumenting boreholes)
    b) Something about anisotropy? Felicity?
2) **Broad multi-geophysical coverage**
    a) The pending end to NSF support for the West Antarctic POLENET initiative highlights the need for national agencies to work together.
    b) Passive seismic, airborne seismic, gradiometry
    c) Inclusion of smaller instruments on fieldtrips, e.g., Gamma spectrometer, Susceptibility meter
    d) Multi-geophysical data assimilation techniques, integration of data with different spatial scales.
    e) Future work is needed to ensure that geophysical data products are FAIR.
3) **Model/data integration directions to better capture basal processes**
    a) Advances in subglacial and groundwater hydrological models, including models that account for ice/water/sediment interactions.
    b) Coupling of hydrological and ice sheet models.
    c) Integration of geophysical observations into ice-sheet model parameterization process.
    d) Sensitivity testing of ice sheet models to sliding laws and basal parameters (e.g. geostatistical simulation of subglacial topography) and comparison with process-scale models.

Based on these research priorities, we propose the following short-term and long-term actions:

Short-term actions

- Follow up mini workshop/zoom update in ~April 2024, try to include broader ABC community
- SCAR 2024 session on subglacial conditions (convened by Toby and Mickey)
- SCAR 2024 meetup/social event for sub-ice community
- WAIS 2024 (tentatively held in Florida) will include similar scientific themes
- Development of collaborative proposals
- Touch base with everyone in a year and make a newsletter on research updates and progress on science questions? Zoom meetup?

    - Include some sort of follow up survey to track number of papers, proposals, and new collaborations that come out of workshop
- Pursue visiting scholar opportunities for students to promote collaboration
- Small working group (action by Anya) to connect with POLENET advocates.
- ABC paper coming soon…

Long-term actions

- Establish international partnerships and connect funding agencies?
- Re-establish POLENET type system
- Airborne seismic (helicopter-deployed sensors for doing passive seismic)
- Gradiometry
- Some community driven product
- Strive for 2025 repeat of this workshop
- Create Jupyter Book of Bayesian/MCMC geophysical inversion workflows
    - Could be fun to have a coding retreat

We also note that supporting our ECRs is essential for maintaining a strong community. Possible future actions could include:

- Small catch-up gatherings at conferences
- Some sort of hackathon with some interested group
- Training or short course (ML for cryosphere, introduction to ice sheet modeling)
- Crash courses on different polar geophysical instruments and how they are deployed in the field

List of participants and contact information

The workshop benefitted from a strong international and early career presence. Researchers came from as close as Hobart to as far off as Colorado, Georgia, Poland, and South America. The participants covered a wide range of expertise including geophysics, geology, paleo studies, machine learning, and marine science.

The participants are listed below in the same order as they appear in the photo. PhD students are highlighted.

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Abstracts

The subglacial heat budget – a conceptual investigation

Tobias Stål, Anya M. Reading, Poul Christoffersen, Suze Nei Pereira Guimarães, Ian Kelly, Felicity McCormack

The nature of the subglacial landscape is, to a large extent, controlled by temperature and the transfer of thermal energy. Geothermal and frictional heat at the ice-bed interface and deformational heat within the ice, can raise the temperature to pressure-melting point and change its mechanical properties. Vertical and horizontal conduction and advection by the flow of ice and subglacial meltwater provide pathways for thermal energy removal and diffusion. Significant amounts of subglacial heat can be transferred through active hydrological systems, with the hydrostatic pressure acting as the driving force rather than the thermal gradient that controls the heat conduction. Changes in basal temperature or pressure can, in turn, facilitate meltwater refreezing that redistributes the free energy. The complexity of subglacial heat transfer illustrates the need for a holistic consideration of the coupled ice-bed system and associated hydrology and ice-sheet processes to map the distribution of subglacial heat reliably. With our ongoing investigations, we are building an analytical framework for the subglacial heat transfer mechanisms driving mechanisms that account for geothermal contributions from the solid Earth alongside hydrological and glacial processes and properties.

On East Antarctic Subglacial Boundary Conditions

Mareen Lösing

Direct geothermal heat flow measurements and geological samples are sparse and highly clustered in Antarctica and indirect estimations and interpretations from geophysical data are needed to understand the impact of heat flow on the ice sheet base. Methods are usually based on a simplified and compositionally homogenous lithosphere resulting in weakly constrained and inconsistent models. From denser sampled continents, such as Australia, we know that thermal parameters and heat flow can exhibit large spatial variations depending on geology and tectonic history. We infer information about the crustal structure and possible geological features in southern Australia and East Antarctica by jointly inverting gravity and magnetic data to recover a coupled density and magnetic susceptibility distribution. Subsequent clustering of the density and susceptibility parameters indicates structural similarities to lithological units in southern Australia. The former connection of both continents in Gondwana allows for the better-known geology in Australia and identification of coherent structures along the adjacent margins to be used to understand East Antarctica. The parameter relationship between susceptibility and density, and the defined clusters, can be input to machine learning techniques to define a spatially variable heat production map, which in turn leads to improved heat flow estimates: For this, we use petrophysical and geochemical sample databases to correlate and confine thermal parameters with our density-susceptibility results. Finally, we present a preliminary heat production/flow map and geological clusters for East Antarctica providing crucial boundary conditions for ice sheet modelling.

Surface and Bed Topography Mapping of Foxfonna & Rieperbreen Glacier, Svalbard, 1936-2020

Wai Yin Cheung

Arctic small-size glaciers and icecaps are valuable indicators of climate conditions in remote areas. A study conducted on Foxfonna and Rieperbreen glaciers in Svalbard used Unmanned Aerial Vehicles (UAVs) and Ground-Penetrating Radar (GPR) to collect data. The findings reveal that since 1936, about 55.08% of the glacier area (6.46 km2) has been lost. Elevation data from historical aerial photography shows a mean surface elevation change of -20.50 ± 11.31m from 1961 to 2020, with an accelerating negative change each year. Additionally, over a 60-year period between 1961 and 2020, 56.68% of the ice volume was lost. The GPR results identified a temperate ice area, up to 20m thick and buried beneath approximately 100m of ice, suggesting recent formation likely due to surface meltwater introduction during an extreme melt year. The coal mine located under the ice on Foxfonna experiences constant flooding from surface meltwater. The GPR analysis of Rieperbreen indicated thrusting features, suggesting a historical surge verified by surrounding landforms and elevation changes. Both glaciers' accumulation areas are too low to benefit from the ongoing increase in precipitation. Extrapolating the estimated ice volume loss per year suggests that by the 2050s, Foxfonna and Rieperbreen will nearly cease to exist, posing a threat to the coal mine due to increased flooding. This study's findings are crucial for predicting the future of high Arctic small-size glaciers, which may disappear in the near future and how will impact the local community.

Ice penetrating radar survey of a super-buoyant terminus of San Quintin Glacier, Northern Patagonia Icefield

Michal Petlicki

The piedmont lobe of San Quintín, the largest glacier of the Northern Patagonia Icefield, in southern Chile, has lately entered a phase of frontal retreat, where its terminus is rapidly disintegrating into large tabular icebergs calving into a recently formed proglacial lake. We present results from a 2019 airborne ice penetrating radar survey conducted at the terminus of this large Patagonian glacier (763 km2 in 2017). This survey, complemented with remote sensing data, reveals that the current retreat can be attributed to the recent detachment of a floating terminus from the glacier bed, manifesting in a strong reflection of the radar signal from the ice-water interface. Consequently, it is imminent that the last remaining piedmont lobe in Patagonia may vanish in the coming decade.

Passive Seismic Monitoring of Hydrological Processes at Sørsdal Glacier, East Antarctica Using Unsupervised Learning and Hydrodynamic Modelling

JC Magyar, AM Reading, RJ Turner, S Cook, SS Thompson, B Kulessa, Kelly, C Schoof

Cryoseismology has seen rapid recent development, in part driven by the capability to monitor intermittent or hidden glacier processes continuously and remotely. Flowing water in glacier hydrological systems constitute an import class of events of particular focus in this work. Understanding meltwater production and routing is integral to assessing future stability of outlet glaciers due to its role in ice sheet mass balance, hydrofracturing and basal lubrication. The semi-automated detection and classification of cryoseismic signals through unsupervised learning offers an attractive monitoring tool to provide precursive indicators for changes in glacier dynamics.

We use data collected in the 2017-18 austral summer at Sørsdal Glacier, East Antarctica, and explore automatic detection, characterisation, and classification of the seismic signals. A range of complementary glaciology work informs the context of the seismological study. Event detection algorithms such as multi-STA/LTA (Latto et al. 2023) are used to construct catalogues of events occurring on timescales across multiple orders of magnitude. Such flexibility is necessary for monitoring glacier hydrology, where events could vary from violent drainages of meltwater to prolonged transitions in channelised flow.
The catalogued events are clustered in feature-space to aid in separation according to generative mechanism (Provost et al. 2017; Turner et al. 2021). Appraisal of the clusters uses a workflow that includes manual inspection of event character, analysis of coincident weather and tidal data, characterisation of surrounding seismic noise, and comparison with catalogues of known cryoseismic and teleseismic events. Due to uncertainty on the characteristics of seismic waves generated by bursts of meltwater and flow within complex conduit geometries, synthetic waveforms are produced for comparison in these cases. These are generated by coupling a numerical simulation of flowing glacial water with seismic wave propagation methods. We find several groups of seismic signals with waveform characteristics suggesting dynamic glacier activity and variable hydrological systems, supporting the use of passive seismology for remotely monitoring change in East Antarctica.

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Extracting Ice Thickness Measurements from the Digitized Historical SPRI-NSF-TUD Airborne Radar Echo Sounding at Ross Ice Shelf, Antarctica through Computer Vision Algorithms
A. Tarzona, W. Chu, H. Verboncoeur, M. Siegfried, D. M. Schroeder, A. Altaweel, B.Amaro, K. Tran

During the 1960s – 1970s, the collaborative efforts of the Scott Polar Research Institute (SPRI), National Science Foundation (NSF), and the Technical University of Denmark (TUD) also known as the SPRI-NSF-TUD, collected valuable airborne radar echo sounding dataset containing ice shelf thickness observations at Ross Ice Shelf (RIS). This archival dataset presents an opportunity to expand our understanding of RIS evolution on a multi-decadal timescale. However, in contrast to modern airborne radar echo sounding data, the digitized Z-scope records did not have vertical scale information, which makes it difficult to extract ice thickness information. To tackle this hurdle, we introduce semi-automatic and automatic computer vision picking algorithms designed to extract surface and base features within the digitized Z-scope records. This enable us to show historical ice shelf thickness at RIS and compare these measurements with modern airborne radar echo sounding data at glaciologically important locations at RIS such as Roosevelt Island and Crary Ice Rise. In essence, our digitization and thorough examination of this historical dataset empower us to fully exploit the potential of this archival dataset to examine multi-decadal changes at Ross Ice Shelf.

Probing anisotropic stratification and interannual variations of the Greenland ice sheet by teleseismic P-wave coda autocorrelation
T.-S. Phạm, A. Sanjayan, H. Tkalčić, and B. Tauzin

Seismic body waves from distant earthquakes travel steeply to a seismic station and carry rich information about subsurface structures. In an ice sheet environment, the sharp seismic discontinuity at the ice-bedrock interface effectively reflects the energy bounced from the free surface. Thus, the ice sheet acts as a waveguide to trap a large portion of incident seismic energy, resulting in repetitive ground motions recorded by over-ice seismometers. The weak self-similar signals can be amplified by cross-correlating the earthquake seismograms with themselves (i.e., autocorrelation) before stacking over multiple events.

Here, we apply this autocorrelation technique to the records of P-wave arrivals and following reverberations (i.e., the P-wave coda) of stations deployed over the central region of the Greenland ice sheet (GrIS), the second-largest ice sheet on Earth. Firstly, we estimate the ice sheet's thickness and P- over S- wave speed ratio beneath several recording sites. It is demonstrated that the in-situ measurements provide fresh constraints for the anisotropic fabrication models of temperate ice in the bulk ice columns. Furthermore, we observe seasonal fluctuation in amplitudes of signals reverberating within the ice sheets at the Greenland summit, with more substantial reflection peaks in summers and weaker in winters. With the availability of co-located atmospheric observatories, we identify the correlation between the interannual variation and the annual snowfall cycle. Our findings provide new insights into the interaction of the ice sheet with atmospheric forcing, which will become increasingly important in the current context of global warming.

Glacial deposits and landforms in the upper Mersey and Forth river valleys
Nicholas J. Roberts and Grace V. Cumming

Recurrent Pleistocene ice caps on Tasmania's Central Plateau fed valley glaciers that descended upper reaches of the Forth and Mersey basins, producing diverse valley-bottom deposits and landforms. Previous studies document many such sites, but their interpretations are complicated by incomplete stratigraphy, muted surface morphology, and limited age constraints. New mapping and Quaternary investigations are improving characterisation and understanding of this area's glacial geology, geomorphology, and geochronology. Critically, LiDAR has helped identify subtle landforms predating the Last Glacial Maximum (LGM) and improve associations between sites. In Mersey Valley, muted ridges beyond LGM terminal moraines record progressively more restricted glaciers as thick as 400 m during Middle and possibly Early Pleistocene glaciations. Exposures along Mersey River's largest tributaries comprise last glacial (Little Fisher River) and earlier (Arm River) interbedded glacial, glaciofluvial, and glaciolacustrine sediments with localised evidence of glacial tectonism. In Forth Valley, deposits and landforms near Lemonthyme Creek record proglacial and subglacial processes of likely Early Pleistocene age. Quartzite roches moutonnées provide Tasmania's best examples of glacially streamlined bedrock. For 3 km farther down Forth Valley, isolated, topographically concordant surfaces are underlain by till eroded into a >15-m-thick glaciolacustrine sequence that together record valley-glacier ice that advanced over a proglacial lakebed and, likely, the up-valley bedrock highs. Sedimentologic features and new $^{40}Ar/^{39}Ar$ ages refute the previous suggestion that diamicton in nearby boreholes records the onset of icehouse conditions at the Eocene-Oligocene transition. Beyond constraining local glacial histories and landscape evolution, the Mersey-Forth records are helping to improve Tasmania's late-Cenozoic chronostratigraphic framework.

Basal hydrology and mechanics captured seismically on a fast-moving glacier in Greenland

Poul Christoffersen, Charlie Schoonman, Samuel Doyle, Bryn Hubbard, Robert Law, Thomas Chudley, Tun Jan Young, Coen Hofstede

The Greenland ice sheet is losing mass and contributing to global sea level rise at a growing rate. The net ice loss, which currently raises global sea levels by nearly 1 mm annually, is caused by more ice discharged from glaciers terminating in fjords as well as higher surface meltwater production. It is crucial to understand how this meltwater is accommodated when it reaches the bed because subglacial hydrological systems exert control on ice sheet motion through feedback mechanisms that is either positive (if the water is widely distributed) or negative (if it is concentrated in large channels). Here, we report the seasonal evolution of subglacial drainage from seismic noise and stick-slip events recorded with a seismic network installed on Sermeq Kujalleq (Store Glacier). The data reveal day-to-day variations as well as seasonal evolution of hydrology and basal mechanics of a major marine-terminating glacier in Greenland.

With seismic stations installed in a deep borehole as well as on the surface of the glacier, we show meltwater produced on the first day of the melt season reached the bed beneath thick (>1 km) and cold (-20C) ice. A sudden increase in seismic noise is interpreted to stem from previously isolated cavities becoming connected and turbulent flows setting in. We also detect a marked reduction in basally produced icequakes, which suggest basal friction was reduced. Later in the melt season, the network captured episodic subglacial flooding associated with a supraglacial lake drainages, which caused short-lived glacier acceleration events detected with Global Positioning System (GPS) systems. With glacier velocities returning to pre-event values, we interpret subglacial lake water was accommodated in sliding-induced cavity expansion that was widely distributed rather than concentrated.

The most significant meltwater input was associated with atmospheric blocking, which brought rainfall and warm and moist maritime air onto the ice sheet from Baffin Bay. At this summer peak of meltwater production GPS records of glacier velocity show marked deceleration consistent with a transformation of the basal drainage system from widely distributed to concentration in a channel. Atmospheric blocking towards the end of the melt season provide insight to the forcing of this channel, which was unable to grow fast enough to accommodate the additional inputs of surface meltwater during these events. When surface meltwater production finally ceased, we observed a gradual decrease in seismic tremor as well as a gradual return of basal icequakes.

Analytical framework to model seismic signals from fluid particle collisions in hydrodynamic simulations of glacier melt water
Ross J. Turner, Jared Magyar, Sue Cook, Anya M. Reading

We present an analytic framework to model seismic body waves due to supraglacial, englacial or subglacial flows in solid ice based on a smoothed particle hydrodynamic (SPH) simulation. Consisting of two parts, i) hydrodynamic modelling and ii) seismic wave propagation, the flexible framework allows for a pre-existing fluid simulation to be supplied to generate synthetic seismic signals. The field of glacier-related seismology has seen rapid development in recent years, with an expanded availability of passive seismic datasets that contain records of seismic disturbances generated by glacier processes. Some of these processes, such as basal slip and crevasse propagation, have mechanisms with plate tectonic deformation counterparts, however, many glacier signals are generated by moving melt water. This contribution aims to inform the interpretation of such signals.

Our approach tracks the trajectories of fluid particles near the water-ice interface, as recorded in standard simulation outputs, to create a catalogue describing the energetics of each collision. We illustrate the capability of this framework using four end-member cases of water flow along surface channels with different geometries. Seismic signals are simulated at a variety of locations around the channel based on the impulse of the database of simulated collisions. We consider the change in character of the seismic waveforms by modelling frequency-dependent attenuation and weak dispersion in the glacial ice, in addition to the standard geometric spreading. The acceleration time series produced in this work are invariant to the temporal and spatial resolution of the hydrodynamic simulation, provided more than some minimum resolution is used. These time series may be converted to velocity or displacement for comparison with observed seismic signals.

Investigating the seismic waves generated for our four channel geometries, we find distinct waveform envelope shapes with different first and later amplitude peaks matching initial and subsequent collisions of the melt water surge with the supraglacial channel walls. The change in waveform character with distance is also captured such that the character attributes due to the process and the those due to the propagation effects may be understood. The flexibility inherent in the model framework will allow for the generation of the seismic signals from simulations of a variety of different water flow geometries including simple 3D channels into and through a glacier. We make the code available as an open source resource for the polar geophysics community with the aim of adding to the toolbox of available approaches to inform the potential future seismic monitoring of melt water movement and related glacier processes.

**Characterizing the subglacial hydrology of the South Pole Basin, Antarctica using COLDEX
airborne geophysics**

Megan Kerr, Duncan Young, Shuai Yan, TJ Fudge, Donald Blankenship, Shivangini Singh

The South Pole Subglacial Basin, situated between the Transantarctic Mountains and the Gamburtsev Subglacial Mountains, remains one of the least-studied regions of Antarctica. Over 20,000 line-km of new airborne radar, magnetics and gravity data collected through the NSF Center for Oldest Ice Exploration (COLDEX) offer new insights into the geophysical characteristics of this province. Here we present an updated map of water flow routes and subglacial lake candidates in and around the South Pole Basin, identified using a hydraulic potential model and bed reflection characteristics derived from ice penetrating radar. In addition, using 2D forward modeling of gravity and magnetic data, we estimate the thickness of water and sediment within the largest of the lake candidates. We discuss our results in the context of the crustal hypothesis for this region and discuss the implications for geothermal heat flux, old ice preservation in the broader Dome A region, and plans for the second COLDEX field season.

Atmospheric effect over sea ice in Larsen B Embayment, NE Antarctica Peninsula, and its consequences on the glacial environment

Liliana Sofía Margonari

From 2002, after the collapse of the Larsen B ice shelf, north-Easter Antarctic Peninsula, until 2012, the landfast sea ice in Larsen B embayment (LBE) has been variable. In the summers of 2004 to 2007, 2009 and 2011, sea ice formed during the previous winters, fragmented and almost completely disappeared, while in the summers 2003, 2008 and 2010 sea ice remained stable and in contact with the shore. During the austral summers of 2012 to 2021 inclusive, the landfast sea ice remained stable, although in the summer of 2016 the lasdfast sea ice was partially melted and ponds were formed. In January 2022, after a decade with old sea ice, this broke. Although it was regenerated in April 2022, the sea ice was very unstable throughout 2022, and during whole 2023 summer, the embayment was devoid of sea ice and this was not regenerated again until the end of April 2023. We analysed the surface atmosphere conditions (winds, humidity and teperature) from climate reanalysis ERA-5 developed by European Centre for Medium-Range Weather Forecasts, and we found a correlation between the presence of dry

westerly winds and temperature increase in the eastern Antarctic Peninsula. Likewise, a a direct relationship was found between relatively warm years and the sea ice fragmentation. As a consequence of the landfast sea ice break up and new exposure to sea waves, the outlet glaciers have become more unstable and have had an accelerated retreat by calving. These sea ice conditions are expected to continue in this context of climate change, leading to more instability of the outlet glaciers and with the possibility of similar events around Antarctica occur, and that could imply a significant impact on the sea level rise and fresh-water budgets in the ocean.

Approaches to constraining East Antarctic rheology using seismic measurements from isolated stations
Niam Askey-Doran, Ross J. Turner, Tobias Stål, Anya M. Reading

Glacial Isostatic Adjustment (GIA) plays a key role in the evolution of the Antarctic ice sheets and the pattern of global sea level change. The pattern and magnitude of the solid Earth response to changes in ice load is influenced by the structure of the lithosphere and mantle. For example, low viscosity regions in the mantle can lead to greater rates of isostatic adjustment, whereas a thicker lithosphere can act to decrease sensitivity to spatial variations in mantle viscosity. Such lateral variations can have a significant effect on the output of GIA models. A greater understanding of regional scale mantle and lithospheric structure, particularly in East Antarctica, is needed in order to constrain the outputs of GIA models.

Detailed studies of 3D rheology in East Antarctica are challenging due to the sparsity of seismic stations across this region. Stochastic Bayesian approaches to inversion naturally provide information on uncertainties and can be a powerful technique when data is sparse. The utility of such approaches has been demonstrated by the recent results of the Mars InSight mission.

My project employs stochastic Bayesian approaches recently used on Mars to constrain the rheology of the lithosphere and asthenosphere in East Antarctica. Methodologies will be developed that can be used on data recorded at isolated stations to constrain possible bounds for rheology on a regional scale. In future work, seismic measurements may be used in combination with other techniques such as magnetotelluric measurements to provide additional constraints on solid Earth rheology.

A multi-decadal study of changes in the Denman Glacier region, East Antarctica, using historical aerial photography and computational approaches
Shyla Kupis, Tobias Staal, Emiliano Cimoli, Sarah S. Thompson, Duanne A. White, and Anya Reading

The East Antarctic Ice Sheet contains about 90% of the total ice mass of the Antarctic, and it is experiencing ice mass loss that is almost equivalent to the West Antarctic Ice Sheet (Rignot et al., 2019). An area of particular concern, Denman Glacier, poses a risk to global sea level rise from accelerated grounding line retreat (Thompson et al., 2023; Miles et al., 2021). Long-term records are needed to quantify multi-decadal ice mass changes in Antarctica and its future contributions to global sea level rise; however, satellite altimetry has only measured elevation changes for the last 40 years (Zwally et al., 2021; Miles et al., 2021). Altimeter-derived observations are, therefore, unable to fully capture long-term ice mass trends.

Historical aerial photography can extend the temporal study of glaciers and serve as a benchmark in the ice sheet mass balance approach. Operation Highjump (1946-1948), provided the first comprehensive dataset of aerial surveys along the Antarctic coastline (Brolsma, 1999). However, traditional photogrammetry methods cannot be applied to such historical analog imagery. The Highjump archive is particularly challenging to georeference because the imagery lacks distinct, fixed features that can serve as ground control points.

Archives of historical nadir and oblique imagery are georeferenced and orthorectified in this work using limited flight and camera metadata. We are implementing deep neural networks into a Structure from Motion (SfM) photogrammetry workflow to systematically process oblique aerial imagery in the Shackleton-Denman system. The SfM workflow will georeference the Highjump imagery to a high-resolution digital elevation model. Our contribution will extend the temporal coverage of ice mass trends in the Shackleton-Denman system, thereby providing an extended record of the dynamic glacier behavior.

Our preliminary study uses historical aerial imagery and computational approaches to evaluate changes in ice
sheet extent and glacial geogeomorphology at Bunger Hills. We are providing robust geolocations and flight lines for the images from ground control points. Our locations show significant improvements when compared with the provided metadata. We also investigated dynamic changes in the landscape, where it is presumably less driven by seasonal variability. Initial findings from the pilot study show an increased presence of glacial lakes and ice extent changes around the exposed rock outcrops. We are extending this pilot study to the remaining Highjump archivein the Shackleton-Denman system. A deeper investigation will address multi-decadal changes in the glaciers, ice
shelf, and continental ice sheet. The aim is to calculate historical ice mass changes to constrain the long-term East Antarctic ice sheet mass balance.

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Workshop in Subglacial Hydrology and Geology
Katharina Hochmuth

"Well, there used to be ice here…"
- combining the continental shelf and subglacial observations

The upcoming marine voyages to the Shackleton/Denman region of East Antarctica on RV Polarstern (summer 2024) and the RV Nuyina (summer 2025) will collect geological and geophysical data on the continental shelf. Whereas the West Antarctic continental shelves are comparably well studied, the substantial datasets on the continental shelves of East Antarctica are very limited and concentrate in the Prydz Bay and Sabrina Coast area. The newly acquired as well as the legacy datasets reveal previously subglacial landscapes of e.g. the last glacial maximum (multibeam-echosounder, sediment echosounder, gravity coring) and earlier glacial advances (sediment echosounder, reflection seismic data, gravity coring). Unfortunately for most projects in the marine realm, the investigation stops at the current ice edge and very limited connections are made to today's subglacial hydrology and geology in the hinterland. I am interested in exploring how we can use marine and terrestrial datasets to work on a better understanding of icesheet dynamics as well as its interaction with the solid earth and the ocean.

Subglacial geology "fingerprinting" for deciphering past ice sheet behaviour in the Denman Glacier region, East Antarctica
Jacqueline Halpin, Nathan Daczko, Jack Mulder, Alessandro Maritati, Jo Whittaker, Alan Aitken, Tobias Stäl, Katharina Hochmuth, Tom Williams, Taryn, Noble, Naomi Tucker

The Denman Glacier is currently one of the fastest retreating glacial systems in East Antarctica. It is estimated to hold an ice mass equivalent of some 1.5m of sea level rise, and overlies one of the deepest trenches on Earth, potentially plunging to >3,500m below sea level (Morlighem et al., 2020). Our knowledge of the subglacial geology is provided through remotely sensed and airborne geophysical datasets together with sparse but crucial direct observations from geological sampling. Geological data are mostly concentrated in the largest ice-free area of the Bunger Hills, whereas isolated nunataks to the west of the Denman Glacier, and southward along the glacier flanks, are more sparsely sampled and poorly understood.

Geological-geophysical datasets suggests the deep Knox Rift exerts a key influence

on the regional topography, focussing erosion from the Denman and Scott glaciers. This rift likely hosts two sedimentary basin systems; (1) older (1000-600 Ma) basin inliers exposed as the Mt Sandow and Amundsen nunataks, possibly related to parts of the Aurora Subglacial Basin to the east, and (2) a younger (300-200 Ma) basin previously solely characterised from geophysical data, but recently sampled via sedimentary moraines collected from the SW Bunger Hills. This younger Knox Basin is correlated with the Perth Basin of Western Australia, having formed in response to intracontinental extension of Pangea. These sedimentary strata overly ancient Archean (2.7-3.0+ Ga) and Proterozoic (1.1 – 1.8 Ga, 550 Ma) metamorphic-igneous crystalline basement, that define several geological terranes/provinces recording tectonic processes across three supercontinent cycles.
Here we describe how the isotopic "fingerprint" of the various terranes may be advantageous to deciphering past ice sheet change in the Denman region through integrating with the provenance record in marine sediment. Our reconnaissance analysis of the continental shelf seismic structures coupled with legacy marine core material from nearby Deep Sea Drilling Project Leg 28 Site 268 suggests we can explore the imprint of changing ice sheet dynamics through past climatic fluctuations. The Denman Glacier is one of many showing signals of accelerating rates of ice loss in East Antarctica. Our goal is to help understand what this vulnerability could mean for our future, by exploiting the long-term geological record of ice sheet/ocean behaviour in this poorly understood region.

Towards understanding basal condition from geophysical and geological information
Lu Li, Alan Aitken, Mareen Losing, Emma MacKie

In recent years, advancements have been made in understanding ice sheet bed conditions through geophysical observations and geological classifications, which span scales from catchment to continent. These products offer a qualitative interpretation linking ice sheet dynamics to subglacial geology. However, there is a significant knowledge gap regarding how to incorporate this heterogeneity into numerical models to quantify the geological impact. Another knowledge gap pertains to changes in basal conditions due to processes related to the geological conditions.

Here, we address this issue by examining basal conditions in Antarctica, which include the basal friction coefficient, basal temperature, bed topography, variations in bed topography, and geological classification (sedimentary basin likelihood). Using principal component analysis, we observe considerable variations in basal conditions both at the continental and individual catchment scales. In a continental scale analysis, geological conditions and basal temperature are positively correlated, while the basal friction coefficient shows a weak positive correlation with bed topography and a negative correlation with the likelihood of sedimentary basins. However, for Thwaites Glacier, the basal friction coefficient is orthogonal to bed topography and basin likelihood, suggesting no correlation with these variables in the major principal component. It is, however, weakly positively correlated with bed roughness and negatively correlated with basal temperature.

Furthermore, we will briefly discuss processes that could potentially alter basal conditions and ways to incorporate these changes into numerical models.

What's really going on at the base of the Aurora Subglacial Basin?

Felicity S. McCormack, Jason L. Roberts, Christine F. Dow, Tyler Pelle, Bernd Kulessa, Alan Aitken, Lawrence A. Bird, Katharina Hochmuth

The Aurora Subglacial Basin (ASB) is the fastest thinning sector of East Antarctica, and contains a greater volume of ice than both the West Antarctic Ice Sheet and the whole of Greenland. Recent studies show that the primary outlet glaciers in this region – the Totten and Vanderford Glaciers – are thinning and retreating, most likely due to similar ocean-driven melt processes that are operating in the Amundsen Sea Sector. Evidence from offshore sediment cores and ice sheet model experiments suggest that complex, nonlinear dynamics could play a role in causing ice flow piracy from the Totten Glacier to the Vanderford Glacier. This potential for nonlinear ice sheet dynamics has significant implications for our capacity to predict the onset and duration of rapid retreat events, or even tipping points, in the ASB. The subglacial environment of the ASB is key to understanding the evolution of the system, and yet it is highly complex and variable – incorporating hard, crystalline bedrock that supports little sediment; sedimentary basins that support hydrogeology and fluid exchange with the groundwater system; and both distributed and channelised subglacial hydrology systems – and sparsely observed. This spatial variability in subglacial conditions influences how basal shear stress is distributed across the region and hence the flow processes that operate. In this speculative abstract, I consider what evidence we have of the conditions in the subglacial environment of the ASB, how they might impact ice flow processes, and ask what role they could play in the evolution of the ASB as the climate changes.

The Integrated Digital East Antarctica program

Lenneke Jong

The Integrated Digital East Antarctica program aims to deliver an authoritative digital representation of East Antarctica and the Southern Ocean, integrating data from across research disciplines and providing access to data, tools and data products to underpin science and inform decision making.

Climate and geophysical modelling efforts form an important part of this program, through improvements the integration of data to provide the most up-to-date input available for model input, and by developing tools to improve the utility of modelling outputs for further research and end-users. The success of IDEA is reliant on connection and collaborations across the Australian Antarctic Science Program.I will provide an introduction to IDEA and an invitation for discussion on where we can focus our efforts to make data more accessible and inter-operable. By way of an example I will discuss a very loose idea around tools to develop to better integrate radar and gravity data from airborne surveys into input for ice sheet models and conversely, how to use modelling and statistical methods to better inform where to target our future data collection efforts.

Advancing ice sheet models with machine-learning and data science
Matthias Scheiter, Poul Christoffersen, Anja Reading and Tobias Staal

The East Antarctic Ice Sheet is one of the most significant potential contributors to global sea-level rise in the future. Numerical ice flow simulations combined with future climate scenarios can help to quantify processes leading to ice mass loss from the ice sheet, but resulting projections are subject to large uncertainties. Some of the main challenges surrounding these uncertainties are: a) insufficient spatio-temporal resolution due to computational constraints; b) sparse observations due to the remoteness and continental scale of the ice sheet; and c) the inability to include detailed processes into the model, in particular at the ice base where very few direct observations have been made. It is desirable to find novel ways to overcome these challenges to improve future ice sheet projections and better-constrain their uncertainties.

In recent years, the use of machine learning techniques has seen a steep rise in many fields of the natural sciences, including in the glaciology community. Machine learning algorithms offer a variety of potential ways to aid ice-sheet modelling efforts, including better exploration of vast datasets, more meaningful ways to fill in missing data, and the acceleration of numerical models by including physical laws into the machine learning algorithm. This project, which is in its initial stages, will bring together these approaches into a unified framework. For instance, machine-learning techniques will be used for geophysical inversions that data-driven and better equipped to deal with uncertainties compared to the inversion practice used currently to initialise ice sheet models. The project will, ultimately, produce a Variational Physics-Informed Neural Network (VPINN) for the investigation of ice flow and the subglacial properties in East Antarctic drainage basins, with the emulator verified by physical simulations before making projections. The work forms a part of the Australian Centre for Excellence in Antarctic Science and we present ideas that may be further developed in the future.

The known unknowns: assimilating sparse datasets to uncover sub-ice heat flow
Ben Mather

Geophysical inversions often suffer from non-uniqueness — the plausibility of multiple models to adequately fit the available data. Antarctica takes this to the extreme. With glaciers obscuring most of its surface geology, the number of surface heat flow measurements to constrain sub-ice heat flow is incredibly sparse. However, other geophysical datasets now exist in Antarctica which are sensitive to temperature. From bottom to top: seismic velocities can constrain the temperature of the mantle, topography can constrain the thickness of the lithosphere (assuming isostatic equilibrium), the Curie depth can constrain the 580°C isotherm, and the heat generation of basement rocks can be inferred from tectonic reconstructions of adjacent terranes. Integrating these within a Bayesian framework provides a path to constrain regions with low data coverage. In this talk I will discuss how probabilistic hydrothermal models which assimilate multiple datasets could uncover sub-ice heat flow in Antarctica.

"Developing ground-based passive geophysics as an efficient tool to map and monitor the Antarctic ice-bed interface zone (IBIZ)"

Ian D. Kelly, Anya M. Reading, Tobias Staal, Maria Manassero, Alan Aitken, Andrew Bassom

The coupled system between the Antarctic Ice Sheet (AIS) and underlying solid Earth encompasses numerous processes and interactions crucial to our understanding of past and future ice-sheet dynamics, tectonic evolution and geomorphological history. The critical junction between the two components, defined here as the Antarctic ice-bed interface zone (IBIZ), supports structural composites of ice, water, sediments and rocks that both respond to and influence changes in basal ice-sheet conditions, forming a distinctly complex and dynamic subsurface environment. Existing insights into the IBIZ have been provided primarily by airborne geophysics and active seismic surveys; however, logistical feasibility has skewed observational coverage towards the ice-sheet margins and restricts the capacity to monitor these subsurface features over short timescales. Our limited knowledge of the Antarctic IBIZ remains a major hurdle for ice-sheet modeling and improved estimations of future sea-level rise from Antarctica.

Passive-source, ground-based geophysics has been rapidly adopted as an attractive solution to these challenges, encouraged by milestone improvements in polar-rated sensor technology, autonomous power and telemetry systems, as well as in-field deployment tactics. Seismic studies have widely demonstrated the strengths of receiver function analysis and seismic tomography for complementary interface and velocity information, whilst the magnetotelluric (MT) method has recently indicated the potential to infer subglacial water systems from their effective electrical conductivity.

In this presentation, we present ongoing developments in passive seismic and MT approaches, informed by preliminary forward modeling and example cases, that aim to expand the toolkit available for mapping and monitoring the IBIZ and promote future temporary deployments in the Antarctic region. We particularly focus on underexplored techniques exploiting ambient seismic noise, such as the horizontal-to-spectral ratio (HVSR) and spatial autocorrelation (SPAC) methods, which may facilitate structural characterisations on monthly or even weekly timescales and transform monitoring capabilities compared to earthquake catalogs. We also clarify present knowledge and outline outstanding uncertainties surrounding the Antarctic IBIZ to inform discussions on future efforts in data acquisition and analysis.

Tasmania's glacial records and their Southern Hemisphere context
Nicholas J. Roberts

Tasmania's diverse evidence of Palaeozoic and late-Cenozoic glaciation includes subglacial, ice-marginal, and proglacial features. Since their first recognition in the 1800s, such records have been expanded, refined, and correlated, substantively through advancements in geochronology and remote sensing. Purported evidence of Mid-Cenozoic glaciers is dubious, hinging on features of questionable age or origin.

Lowermost units of the Parmeener Supergroup record late-Carboniferous to Permian (ca. 300 Ma) ice flowing into the marine Tasmania Basin, then poleward of 60° S. These rocks areexposed in Tasmania's lowlands and mid-elevation escarpments. They broadly correspond toPermo-Carboniferous glacial deposits from other Gondwanan fragments scattered across the Southern Hemisphere and Himalaya. Fjord to deep-water glaciomarine environmentsdominated basal Parmeener depocenters, although mudstone rhythmites and massive tillitesindicate localised glaciolacustrine and truly glacial environments. Stratigraphic and facies analyses suggest several glacier advances, probably spanning multiple glaciations over millions of years. However, globally fragmented deposits, low-resolution chronostratigraphy, and absent geomorphology hinder determination of the number, ages, and extents of Gondwanan glaciations.

Tasmanian's high country records multiple Pleistocene, and possibly late-Pliocene,glaciations. Their youth facilitates more detailed reconstructions of glacier ages, extents,spatial-temporal correlations, and precise environmental conditions. Importantly, well preserved landforms bolster insights on glacial and hydro-glacial processes. Widespread late-Cenozoic surficial deposits record extensive glacier influence – including truly glacialsediments (tills) and isolated glaciolacustrine sediments – but are generally thin and poorly exposed. Glaciofluvial features are harder to recognise because of their similarity to somepost-glacial alluvium, whereas glaciomarine features are absent because Cenozoic glaciers did not reach tidewater. Many large mass movements beyond glacier limits are of presumedpreglacial origin but remain poorly understood.

Landforms and deposits record at least five Pleistocene glaciations since ~1 Ma, although evidence of others likely exists. Glaciers were successively more restricted, enabling study of multiple glaciations. This pattern parallels other Southern Hemisphere records, particularly in the Andes, but contrasts most Northern Hemisphere records in which Last Glacial Maximum (LGM) glaciers were the most extensive and obscured older glacial features. Tasmania's LGM occurred ca. 20-18 ka with glaciers gone by ca. 15 ka; earlier Pleistocene glaciationsprobably also terminated rapidly. Cryosphere-affected landscapes likely experienced accelerated sedimentologic and geomorphic change following each deglaciation, though 'paraglacial' terminology used elsewhere to describe this repose has not historically been applied. Although better understood than Permo-Carboniferous glaciations, Tasmania's Pleistocene glacial history remains fragmentary, hampering detailed comparison with better established chronologies in Antarctica, the Andes, and the Northern Hemisphere.