

## Towards an integrated study of subglacial conditions in Princess Elizabeth Land, East Antarctica

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During the 21st century, the contribution of the Antarctic Ice Sheet (AIS) to sea level rise has been increasing, affecting coastal regions and their large populations and economies (Moore et al., 2018). The ice loss from the AIS is driven primarily by increased melting of ice shelves by warm ocean waters and the subsequent acceleration, retreat and rapid thinning of the major outlet glaciers of the West Antarctic ice sheet (IPCC, 2019). However, subglacial conditions (thermodynamics and hydrology) of AIS remain poorly understood, despite recent advances in satellite and ground-based observations, and this makes it difficult to project the amount of future ice loss. To better understand the most compelling scientific issues addressing subglacial conditions, and following several recent technical and operational advances, the National Natural Science Foundation of China (NSFC) launched a special program named the “Polar Basic Science Frontier”. A scientific project focusing on Princess Elizabeth Land (PEL), East Antarctica, was initiated to study the subglacial environment and basal melting, to infer the geothermal heat flux and to establish high resolution subglacial topographic elevation by means of airborne remote sensing and numerical ice models. This project is based on the international ICECAP2 (International Collaborative Exploration of the Cryosphere through Airborne Profiling) project. The program in PEL has been led by the Polar Research Institute of China since 2015,

and involves international collaboration by many scientists from China, USA, Australia and UK (Cui et al., 2020b).

The ICECAP2 PEL sector lies between 64°56'S and 90°00'S in latitude and between 73°35'E and 87°43'E in longitude. It is bounded on the west by the Amery Ice Shelf, on the southwest by the Lambert Glacier, and on the east by Wilhelm II Land. The basal characteristics in PEL, which is potentially a critical region of ice sheet change, were considered to be the poorest known of any region in Antarctica (Cui et al., 2020b). Since 2015, large-scale subglacial features in PEL have been identified from satellite imagery (Jamieson et al., 2016), and further delineated by the Chinese National Antarctic Research Expedition (CHINARE) airborne ice radar sounding program (Cui et al., 2018). In the 32nd CHINARE (2015/2016) expedition, CHINARE introduced a Basler BT-67 fixed wing aircraft, named “Snow Eagle 601”, to carry out airborne geophysical exploration in the region. The aircraft is equipped with a variety of technologies including aerogeomagnetism, gravity instruments, laser altimeter and ice radar which jointly measure the subglacial conditions of the ice sheet. During five airborne operations from the 32nd CHINARE (2015/2016) to 36th CHINARE (2019/2020), CHINAREs have collected data along more than 175000 km of flight lines across PEL, extending to Lake Vostok and Ridge B (Cui et al., 2017, 2020a). The recently developed BedMachine method (Morlighem et al., 2020), which relies on fundamental physics-based mass conservation to estimate what lies between the radar sounding lines, was used to map the bed

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topography and ice thickness from the along-line radar data. A bed topographic digital elevation model (DEM) with a resolution of 500 m over an area of  $\sim 900000 \text{ km}^2$  was then generated (Cui et al., 2020b). This new bed DEM completes the final section of the first-order measurement of subglacial continental Antarctica.

The understanding of subglacial conditions in PEL resulting from this project will address two glaciological issues:

(1) The radar data profiles along the flight lines can be used to provide enhanced insight into the basal and englacial geometry and processes of the AIS. An important factor is subglacial water (e.g., a subglacial lake). The approach to identify subglacial lakes is relatively simple, and mainly depends on the quantification of basal reflection without significant attenuation from the ice. Judging the existence of subglacial lakes from radar data is mainly based on the echo from the ice-water boundary. The reflectivity is used to determine whether there are subglacial water bodies, or freeze-thaw conditions (Wright and Siegert, 2012). Subglacial water results in reflections brighter than surrounding bed echoes in the radar image. The reflection is defined by the logarithm (in dB) of the energy ratio between the echo and transmitted signals. The reflection from water is flatter and smoother in geometry than that from the surrounding bed, and the reflection energy is much stronger, usually exceeding about 10 dB. A basal reflectivity in the range of  $-5$  to 10 dB may correspond to subglacial water (Carter et al., 2007), and can be used to identify subglacial lakes that cannot be directly identified from the flat bright reflection of the radar image. An ice bottom reflectivity in the range of  $-15$  to  $-5$  dB usually corresponds to the intermittent existence of meltwater and water permeable sediment; reflectivity less than  $-30$  dB usually means that the bottom is frozen. These subglacial features are expected to delineate frozen and temperate beds, and can be used to calculate the water depth in any subglacial lakes. The derived subglacial parameters can provide necessary input to ice sheet modeling and also allow for the assessment of basal and englacial properties, including subglacial roughness, englacial stratigraphy, ice rheology, and anisotropy.

(2) Isochronous layers within the ice sheet can be identified within the radar images. These are a result of ice surface and basal topography, and past values of the surface accumulation, the ice flow field, and basal melting. Thus, they can be used to understand the evolution of the ice sheet. The layers can provide valuable information, such as change in mass balance, the distribution of subglacial water, basal melting, englacial temperature, age of the ice, past accumulation rate and ice flow. We focus on the description of structural deformation associated with these isochronous reflectors from the crystal orientation fabrics of the ice and their variability. To infer the englacial temperature and to determine the distribution

of basal water from bed-echo reflectivity, the ice crystal fabric tensor is parameterized. A three-dimensional anisotropic ice sheet model can be introduced to simulate the englacial temperature field, the subglacial water pathway, and to evaluate the geothermal flux and the subglacial hydrological processes.

In conclusion, the combination of airborne ice radar, remote sensing and ice sheet models is expected to improve the knowledge of subglacial conditions in PEL, and to reveal previously unknown deep features with major implications for the ice sheet response to climate change. It can also provide the data base for diagnosis of the subglacial environment in this area. However, it is still a great challenge to improve the spatial resolution of field-based airborne geophysical data to the sub-kilometer level. Obviously, due to the difficulty of aircraft logistical support on the AIS and the limited time for summer field work, the airborne profiling lines are usually radial networks with a large space-grid starting from stations near the Antarctic coast. The upcoming new CHINARE station near the Ross Sea and the scientific program (named “Probe-illuminating Ice Sheet”) covering the whole East Antarctic ice sheet, together with ongoing international collaboration, will gradually solve this problem.

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