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Chinese radioglaciological studies on the Antarctic ice sheet: progress and prospects

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Abstract Chinese radioglaciological studies on the Antarctic ice sheet (AIS) began in 2004/05 when the 21st Chinese National Antarctic Research Expedition (CHINARE 21) team arrived at Dome A for the first time and radio echo sounding (RES) was conducted along the inland traverse and in the Dome A region. Subsequently, more field surveys were conducted along the traverse and in the Dome A region using different radar systems targeting different scientific purposes, such as revealing the landscape of the Gamburtsev Subglacial Mountains by detailed grid RES, or locating a deep ice core drilling site by mapping and studying internal structures, bedrock topography and subglacial conditions in the Dome A region. Furthermore, the evolution of the AIS was inferred from the typical mountain glaciation topography beneath Dome A, and the age of the deep ice core at Kunlun Station was estimated through numerical modeling. Recently, the Snow Eagle 601 airplane was acquired and an airborne geophysical system was constructed to survey the AIS in Princess Elizabeth Land during CHINARE 32 (2015/16) and CHINARE 33 (2016/17) in order to fill the large data gap there. In this paper, we review both the recent progress of Chinese radioglaciological science in Antarctica and future proposed work.

Keywords **Antarctic ice sheet, radioglaciology, Snow Eagle, radio echo sounding, Chinese Antarctic Expedition**

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1 Introduction

Radioglaciology, or the radio echo sounding (RES) method, is a discipline using ice-penetrating radars (IPR) to measure internal structures, subglacial topography and bedrock properties of ice sheets, ice shelves and glaciers (Bogorodskiy et al., 1985). Radioglaciology has been used to study the Antarctic ice sheet (AIS) for more than 60 years, and significantly contributes to our understanding of the ice sheet geometry, basal environments and continental geomorphology (Drewry, 1983; Evans and Robin, 1966). In addition, this approach helps modeling ice dynamics and estimating mass balance (Lythe and Vaughan, 2001). The new Bedmap2 database compiles 25 million measurements to provide a much more detailed bedrock DEM of the ice sheet, with most of the data coming from RES results (Fretwell et al., 2013). Subglacial lakes and water systems, which have critical impact on ice sheet dynamics, can be identified from RES data due to their high reflectivity and the smooth character at the ice-bedrock interface. Up to 2012, ~379 subglacial lakes had been identified under the AIS (Wright and Siegert, 2012), including Lake Vostok, which is the largest subglacial lake in Antarctica (Kapitsa et al., 1996). Radioglaciology also contributes to characterising subglacial channels, canyons, and hydrological connectivity beneath the AIS and therefore plays a significant role in identifying controls on ice sheet stability and mass balance, and its potential response to sea level change (Young et al., 2016; Bell, 2008; Walder and Fowler, 1994). Radioglaciology has long been extensively used on the AIS, but more recent improvements in radar technology and data processing methods help to

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characterize the ice sheet more accurately and efficiently (Cui et al., 2009a).

Radioglaciological studies commenced relatively late in China, during the 21st Chinese National Antarctic Research Expedition (CHINARE 21, 2004/05). During CHINARE 21, Chinese glaciologists traversed to Dome A from the coastal Zhongshan Station for the first time and were able to survey the region on a detailed surface RES grid (Cui et al., 2010a). Since then, different kinds of radar systems have been deployed, including a multi-polarization radar system, a Chinese developed deep IPR system and a shallow frequency-modulated continuous wave (FMCW) radar system. These have been used for both fine-scale surveying networks in the Dome A and Grove Mountains regions and for repeated surveys along the traverse route (Cui et al., 2016, 2015, 2010a, 2010b; Tang et al., 2016; Li et al., 2015). While the initial data acquisition typically focuses on ice thickness and basal topography, there has been a broader study of internal layers and basal environments. Significant motivation for RES studies in the Dome A region has been to search for the oldest ice on Earth and to map the unknown bedrock topography of the Gamburtsev Subglacial Mountains (GSM) beneath Dome A, the largest subglacial mountains in Antarctica. Ice thickness, bedrock topography, internal layers and basal conditions interpreted from radar data were used to reconstruct past snow accumulation rate in the Dome A region (Wang et al., 2016). With a local maximum ice thickness, relatively flat internal layers and bedrock topography, the first deep ice core drilling site was located at Kunlun Station in the Dome A region at a site considered as the most likely place to obtain a climatic record of ~1.5 million years in ice (Cui et al., 2010a). The striking mountain-glaciated topography of the GSM, as first revealed in a high resolution three-dimensional DEM, was used to infer the early origin and evolution of the AIS and the GSM (Sun et al., 2009). In 2015, China deployed its first fixed-wing airplane named "Snow Eagle 601" for Antarctic expeditions, and an airborne geophysical system was configured to conduct scientific survey in the AIS. Princess Elizabeth Land (PEL), the large data gap in AIS ice thickness measurements, has been investigated during the past two austral seasons. The data from PEL have great implications for investigation of ice sheet expansion, stability and the subglacial geology of East Antarctica.

Here, we introduce the progress of Chinese radioglaciological studies of the AIS including both the radar systems and current scientific achievements, and discuss future proposed work, especially that using the airborne geophysical platform.

2 Study areas

Study areas of Chinese radioglaciology are mainly focused on: (1) the inland traverse from coastal Zhongshan Station

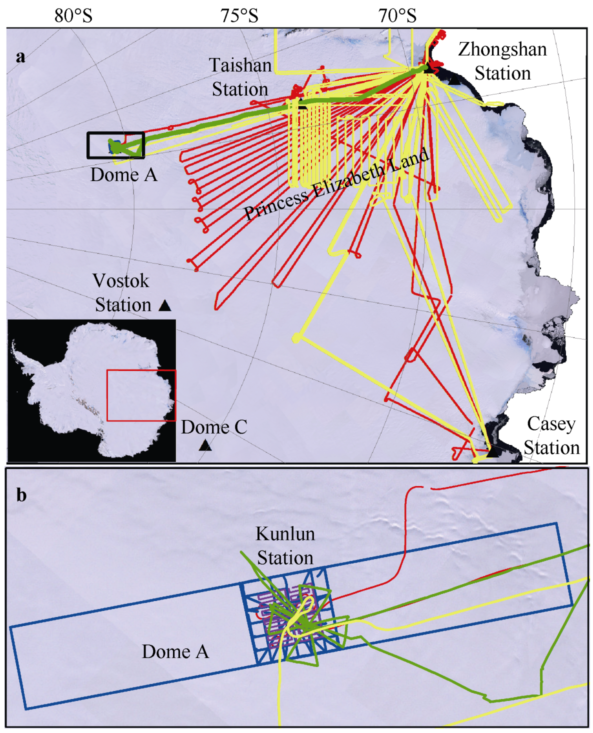

Figure 1 The coverage of Chinese radioglaciological studies. Background is the LIMA (Landsat Image Mosaic of Antarctica) mosaic, the black box in Figure 1a is shown in Figure 1b; green RES lines are from CHINARE 21, blue lines are from CHINARE 24, purple lines are from CHINARE 29, red lines are from CHINARE 32 and yellow lines are from CHINARE 33.

to Dome A, covering a distance of about 1300 km (green lines in Figure 1a, referred to as CHINARE traverse in this paper); (2) the Dome A region (Figure 1b); (3) the PEL area (the red and yellow lines in Figure 1a). During the initial period, ground-based RES survey of the AIS was the only method accessible for Chinese glaciologists, and the coverage is limited largely by logistic capability. We carried out several RES surveys along the CHINARE traverse and in the Dome A region, including during CHINARE 21 (green lines in Figure 1), CHINARE 24 (2007/08, blue lines in Figure 1), CHINARE 29 (2012/13, purple lines in Figure 1) and CHINARE 32 (along the same traverse line as CHINARE 21). The CHINARE traverse was surveyed repeatedly by different ground-based radar systems to acquire subglacial topography and ice thickness, distinguish ice fabrics and map both deep and shallow internal layers (Table 2). Also, the Dome A region was surveyed at a very high-resolution grid to characterize the unknown landscape of the GSM in as much detail as possible. Recently, using the new fixed-wing airplane, Snow Eagle 601, the study area has been extended to the PEL to fill the large data gap there and to investigate subglacial environments and geology in the region.

As a key transect of the ITASE (International Trans-Antarctic Scientific Expedition) project, the CHINARE traverse has been monitored continuously for 20 years. In addition to RES surveys (Cui et al., 2010b), atmospheric observations with automatic weather stations (Ding et al., 2015), snow surface elevation and ice-flow velocity monitoring with GPS (Zhang et al., 2008), shallow ice core drilling and snow accumulation measurement at 2-km spaced stakes were made along the traverse (Ding et al., 2011), and have provided very detailed multidisciplinary data from the coast to the interior of the AIS, which are significant to the study of the ice sheet and climate change.

The Dome A region, located in the center of the East Antarctica, is the highest dome of the AIS. Preliminary investigation at Dome A has shown that the annual mean temperature (measured at average depth of 10 m) is −58.5°C (Xiao et al., 2008), the mean surface velocity is 11.1 ± 2.4 cm·a^{-1} (Yang et al., 2014), the average accumulation rate (2005–2008) is 35 kg·m^{-2}·a^{-1} (water equivalent) (Wang et al., 2013). The GSM beneath Dome A are a major centre of ice-sheet nucleation during the Cenozoic (Xiao et al., 2008; DeConto and Pollard, 2003), and hence potentially can provide ice older than 1 million years and evidence of the AIS and GSM origin and evolution. The Chinese first deep ice-core drilling project DK-1 was initiated at Kunlun Station in the Dome A region in 2011 (Zhang et al., 2014).

With the Snow Eagle 601 deployed in 2015, an international project called ICECAP (International Collaboration for Exploration of the Cryosphere through Aerogeophysical Profiling)—PEL was launched in 2015 to survey the PEL. The ICECAP-PEL project involves scientists from China, USA and UK, and the study area of Chinese radioglaciology was extended to the PEL. In the Bedmap2 dataset (Fretwell et al., 2013) the PEL is the largest unmeasured area of ice thickness in the AIS, and it may have extensive subglacial canyons that extend into the ice sheet interior and the second largest subglacial lake beneath the ice sheet (Jamieson et al., 2016). In addition, the PEL has great significance for subglacial geology, especially geological sutures related to the assembly of East Antarctica.

3 Radar systems

Different radar systems have been applied for ice sheet investigation in the past decades by Chinese glaciologists (Figure 2). Their characteristics are listed in Table 1, and the scientific objectives of the different missions are detailed in Table 2.

The Chinese and Japanese inland Antarctic expeditions have similar scientific objectives, including characterizing the crystal orientation fabric (COF) in ice. The first ground-based RES radars used by Chinese glaciologists were hence introduced from Japan. During CHINARE 21, China carried out its first RES survey using a set of dual-frequency pulse-modulated ice radars along the CHINARE traverse and in the Dome A region to survey subglacial topography and internal structure of the ice sheet (green lines in Figure 1a). During CHINARE 24, the second RES survey along the traverse and in the Dome A region was carried out with a multi-polarization (HH, HV, VV, VH) radar system to build a three-dimensional high-resolution DEM of subglacial topography around Dome A and to determine the COF of the ice along the survey lines. These two radar systems were developed by the National Institute of Polar Research (NIPR) in Japan. These RES data were expected to firstly reveal hidden landscape of the GSM beneath Dome A and the subglacial topography along the traverse, as well as provide a better understanding of COF within the ice sheet.

Meanwhile, China also made efforts to develop ground-based deep IPR and frequency-modulated continuous-wave (FMCW) radar for installation on the Chinese snow vehicles to meet the long-term need of Chinese radioglaciology, and to improve capability of mapping internal layers in both deep and shallow ice. The Chinese-developed deep IPR was tested in the field during CHINARE 28, and was then improved on the basis of the test results. The radar system (Figure 2c and table 1) was successfully applied to acquire subsurface properties in the Dome A region during CHINARE 29 and around Grove Mountains during CHINARE 30. The results show significant advantage of high vertical resolution when characterizing internal layers. During CHINARE 32, the FMCW radar system (Figure 2d and table 1) was used to measure shallow internal layers which are significant for reconstructing snow deposition history over past thousands of years, but were usually blanked in deep IPRs to improve depth-penetration.

Compared with ground-based RES, airborne RES is much more efficient in data acquisition and can reach most places in the AIS. The Snow Eagle 601 deployed by China is a BT-67 airplane modified from a DC-3 aircraft and has a relatively large payload that allows for more sophisticated suites of instruments, increased endurance that enables large coverage of scientific surveys and good performance in polar regions. The updated High Capability Airborne Radar System (HiCARS) was integrated into the Snow Eagle 601 airborne scientific system based on ICECAP international collaborations (Figure 2e and table 1). The HiCARS was developed and maintained by University of Texas, Institute for Geophysics (UTIG) in USA, and had been installed in another DC-3 aircraft and successfully used to survey ice sheets in both Greenland and Antarctica by UTIG in past decades. It is capable of mapping bedrock interfaces of deep valley floors, subglacial canyons, grounding zones and other complex features beneath very thick ice in the AIS. During CHINAREs 32 and 33, the HiCARS was installed in the Snow Eagle 601 to survey the PEL.

Figure 2 Radar systems used during CHINAREs. **a**, Dual-frequency radar system; **b**, multi-polarization radar system; **c**, Chinese developed deep IPR system; **d**, Chinese developed FMCW radar system; **e**, airborne HiCARS radar system.

Table 1 Technical characteristics of different radar systems used in radioglaciological studies by China in the AIS

Radar systems	CHINARE 21 dual-frequency radar	CHINARE 24 multi-polarization radar	CHINARE 29 and 30 Chinese developed deep IPR	CHINARE 29 Chinese developed FMCW radar	CHINARE 32 and 33 airborne HiCARS radar
Antenna	Three-element Yagi	Three/eight-element Yagi	Log-periodical	Vivaldi	Flat-plate dipole
Center frequency/MHz	60/179	179	150	1.25e3	60
Peak power/kW	1	1	0.5	0.002	8
Pulse width/ns	250/500/1000	60/500	2000/4000/8000	4e6	1000
Sampling time window/μs	50	60	50	4000	64
Sampling frequency/MHz	100	100	500	6.25	50
Noise/dB	<1	<1	<3	<3	<3
Dynamic range/dB	80	80	>110	70	120
Bandwidth/MHz	4	2/14	100	1.5e3	15
Antenna gain/dBi	7.2	7.2	9	55	18
Beam width/(°)	70	70	60	30	114 (along track) 50 (cross track)

Table 2 CHINARE RES missions: radar systems, study areas and scientific objectives

Mission(austral seasons)	Radar systems	Study areas	Scientific objectives
CHINARE 21 (2004/05)	Dual-frequency radar	CHINARE traverse; petal-like grid around Dome A	Subglacial topography, ice thickness, internal layers, and COF
CHINARE 24 (2007/08)	Multi-polarization radar	CHINARE traverse; 5-km space grid around Dome A	Subglacial topography, ice thickness and COF
CHINARE 28 (2011/12)	China developed deep IPR	CHINARE traverse	Radar system test
CHINARE 29 (2012/13)	China developed deep IPR and FMCW radar	CHINARE traverse; 1.5-km space square-wave lines around Dome A; Taishan Station	Internal layers, Subglacial topography around Dome A; FMCW radar test
CHINARE 30 (2013/14)	China developed deep IPR	Irregular lines in the Grove Mountains	Subglacial topography and lakes
CHINARE 32 (2015/16)	HiCARS airborne radar; China developed FMCW radar	Radial airborne lines in PEL with HiCARS; CHINARE traverse with FMCW radar	Subglacial topography, ice thickness, internal layers and basal conditions in PEL; Shallow internal layers along the traverse
CHINARE 33 (2016/17)	HiCARS airborne radar	Radial and orthogonal airborne lines in PEL	The subglacial lake and canyons, subglacial topography, ice thickness, internal layers and basal conditions

4 Main progresses

4.1 Subglacial topography, ice thickness and internal structure

Subglacial topography, ice thickness, and internal structure are all fundamental features of ice sheets. They are important controls in modelling ice-sheet dynamics and estimating global sea level rise. The recently released Bedmap2 dataset, a compilation of over 25 million AIS measurements, is available at 1-km grid resolution in many places. Nevertheless, large data gaps still exist and much of the ice sheet remains poorly surveyed, especially in places which are difficult to access.

The Dome A region is one of the most inaccessible places in the AIS because of its distance from the coast, high altitude and very low average temperature. A team of Chinese glaciologists first arrived at Dome A during CHINARE 21 in January in 2005 via a ground traverse from Zhongshan Station. A detailed RES survey was conducted to map subglacial topography along the CHINARE traverse, and to build a subglacial topography DEM with high resolution in the Dome A region (Table 2).

Cui et al. (2010a) analyzed RES data from CHINAREs 21 and 24 and interpolated the first three-dimensional distribution of ice thickness and a DEM of subglacial topography in the central 30×30 km^2 area of the Dome A region. The subglacial topography elevation ranges from 949 m to 2445 m, and ice thickness ranges from 1618 m to 3139 m in the area. The three-dimensional subglacial DEM revealed a typical mountain glaciation topography with pre-existing river valleys over-deepened by valley glaciers. The striking topography beneath the ice, namely the topography of the GSM, was dominated by a south-facing elongated deep valley with flanking mountains, steep trough sides, hanging tributary valleys and flat floors at the head of some tributary valleys. The valley geometry is dendritic.

Furthermore, RES data were used to infer the early origin and evolution of the AIS and GSM, and to locate a deep ice core drilling site in the Dome A region. Through analyzing quantitative information on the dendritic network and landform features, as well as Antarctic glacial history and glacial dynamics, scientists from Polar Research Institute of China (PRIC) and University of Edinburgh inferred that the ice sheet was likely to have developed during the initial phase of Antarctic glaciation around 34 million years ago when the mean summer surface temperature was no lower than ~3°C (Sun et al., 2009). The glaciation may have continued during several intervals until 14 million years ago when the present continental ice sheet formed, and the landscape of the GSM has most probably been preserved by cold-based ice beneath Dome A (Sun et al., 2009). As well as ice thickness and subglacial topography, internal stratigraphy is another factor that needs to be considered to locate a deep ice core drilling site in the Dome A region. Tang et al. (2011) traced and analyzed internal isochronous layers from a 200 km long RES profile obtained during CHINARE 21. The results demonstrated that internal isochronous layers varied with buried depth. The deep ice core drilling site was finally located at a position with minimum variation of internal layers, localized maximum ice thickness of over 3100 m and relatively flat subglacial topography in a subglacial valley floor. The Chinese inland station, Kunlun Station, was later constructed there to support the drilling campaign.

Currently, a deep ice core is being drilled in the Dome A region (Zhang et al., 2014). However, the possible ice age was challenged by recent findings of widespread basal melting and both refreezing and ice sheet thickening at the bottom in the Dome A region (Bell et al., 2011). Fischer et al. (2013) advised that a reduced ice thickness of ~2500 m can avoid basal melting and may be ideal for preserving old ice. During CHINARE 29, China conducted another RES survey in the central 20×20 km^2 area on a square grid (Figure 1). A more detailed and accurate ice thickness distribution and bedrock DEM was interpolated from this (Figure 3) (Cui et al., 2015). This has helped to capture the small scale topography in the area, which affects ice dynamics if channelised landscape guides ice flow and if fine-scale roughness impacts basal sliding (Graham et al., 2017). In addition, based on the RES survey during CHINARE 24, Cui et al. (2016) presented ice thickness and subglacial topography variations along the "Chinese Wall", a 200 km long and 30 km wide rectangular boundary across the ice divide in the Dome A region (Figure 1b). These datasets have the potential to play an important role in locating a new deep ice core drilling site in the Dome A region to obtain a climatic record approaching 1.5 million years old.

Ice thickness and subglacial topography along the CHINARE traverse was surveyed by IPR during CHINAREs 21 and 24 (Cui et al., 2010b). A high subglacial topography, with an average bedrock elevation of 728 m, was uncovered beneath the ice, and both ice thickness and bedrock elevation were found to vary with high frequency and magnitude. Bedrock interfaces were not detected in the segment from 700–900 km due to very thick ice and complex ice flow across the Lambert Glacier. In the Taishan Station region, Tang et al. (2016) presented ice thickness, subglacial topography and internal layers, mapped by IPR in a 2×2 km^2 area during CHINARE 29. The results show that ice thickness varies from 1856–1949 m, bedrock elevation varies from 662–770 m, and Taishan Station is located over a subglacial mountain peak with an elevation of 751 m. In the Grove Mountains region, Li et al. (2015) conducted RES using the China developed deep IPR system during CHINARE 30. Over 200 km of radar surveying lines were acquired in an austral season and ice thickness distribution and subglacial topography DEMs were interpolated.

China submitted most ice thickness and bedrock elevation data along the inland traverse and in the Dome A region to the Bedmap 2 project, and made its first contribution to the generation of this important dataset (Fretwell et al., 2013).

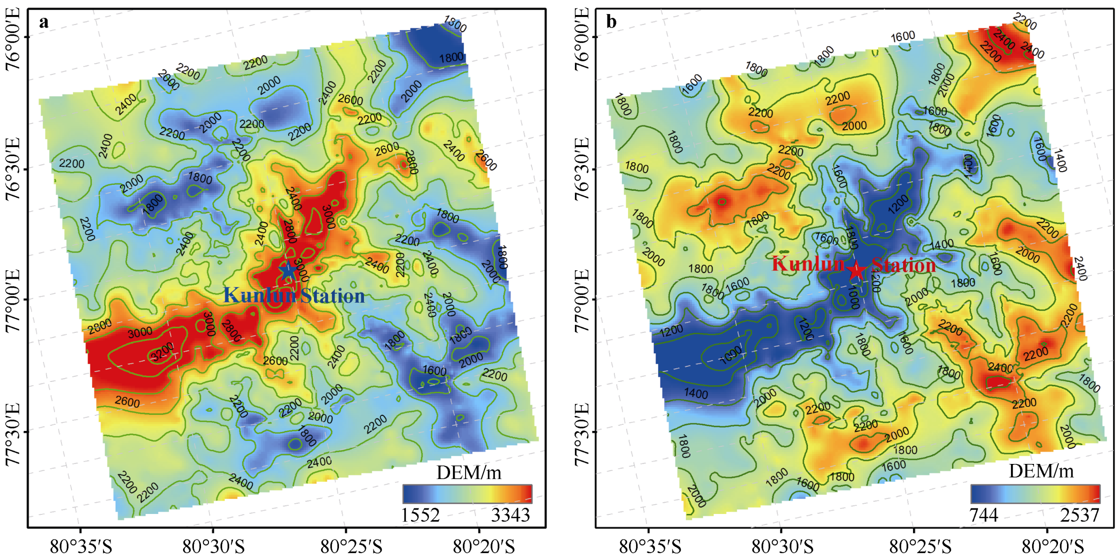

Figure 3 Ice thickness distribution (**a**) and subglacial topography (**b**) in the Dome A region based on RES results during CHINAREs 21, 24 and 29 (revised from Cui et al. (2015), green lines are contours).

4.2 Subglacial conditions and processes

Important clues concerning subglacial conditions (distribution of subglacial water, lakes and sediment etc.), subglacial processes, and ice sheet dynamics can be found through quantitative studies of subglacial topography (Bingham and Siegert, 2009; Weertman, 1957). Bedrock roughness, defined as irregularity of ice-bedrock interface, was extensively used to characterize vertical variation of subglacial topography with horizontal distance along RES profile at all scales (Cui et al., 2009b; Siegert et al., 2005). In 2010, Li et al. (2010) developed a two-parameter roughness index method by additionally considering bedrock slopes (referred to as horizontal index) compared with the previous single index method (referred to as vertical index) which considered only the amplitude of the bedrock fluctuation. The two-parameter index takes account of both vertical and horizontal irregularities in subglacial surfaces, which can not only be used as a proxy for basal sliding velocity, but also can be used to distinguish erosional and depositional subglacial morphology, and can further distinguish continental and marine settings. Zhang (2013) applied the two-parameter index method to quantitatively study roughness of subglacial topography along the CHINARE traverse. Two patterns of subglacial topography are obvious: the vertical index and horizontal index are both small for subglacial topography with small fluctuation of bedrock elevation and large horizontal change; the vertical index and horizontal index are both large for subglacial topography with large fluctuation of bedrock elevation and small horizontal change (Zhang, 2013). This analysis identified that due to the existence of the GSM, vertical fluctuations of subglacial topography in the south side of the Lambert Glacier are generally larger than the north side of the traverse, and the slope of the high mountains along the south side is also larger (Zhang, 2013). Basal reflectivity is another parameter used to study subglacial conditions quantitatively, especially for characterizing the properties of the ice-bedrock interface. Although Yang et al. (2016) have summarized three primary methods to correct radio attenuation in ice when calculating basal reflectivity, these have not yet been applied to the analysis of the basal reflectivity and subglacial conditions in Chinese RES studies.

In the Dome A region, thick slabs of freeze-on ice at the bottom of the ice sheet were found during the 2011 AGAP (Antarctica's Gamburtsev Province) airborne RES by scientists from USA (Bell et al., 2011). Freeze-on ice can alter basal ice rheology, change basal ice layers, and destroy the climate record in a deep ice core. However, its structure and mechanism still need to be identified and studied. It is thus important to carry out detailed ground-based RES survey at places where freeze-on ice has been identified. During CHINARE 29, ground-based RES detected similar freeze-on ice structures in the Dome A region (Figure 4). Subglacial stratigraphy shows freeze-on ice zones with a length of ~10 km and an average thickness of ~300 m in the Dome A region (Tang et al., 2015). This was the first time that Chinese glaciologists found typical freeze-on ice in the Dome A region, and its impact on ice dynamics is critical to ice sheet stability and evolution (Wolovick et al., 2013; Bell et al., 2011).

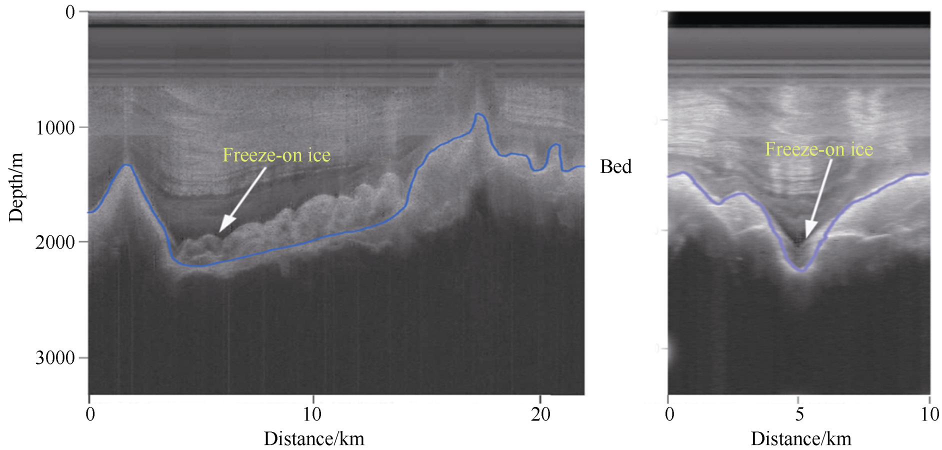

Figure 4 The freeze-on ice structure detected by Chinese glaciologists in the Dome A region (revised from Tang et al. (2015)).

4.3 Deep ice core age modeling

The age of the deep ice core being drilled in the Dome A region is of concern for glaciological and climatic scientists because it is likely to have an ice record which is more than 1 million years old (Van Liefferinge and Pattyn, 2013; Severinghaus et al., 2010). Before the ice core is drilled, it is thus important to estimate the ice age by numerical modeling. Several critical factors can influence modeling results, including the COF, past accumulation rate, and the geothermal heat flux.

Matsuoka et al. (2003) proposed a multi-polarization RES method to distinguish vertical girdle COF and single pole COF by periodical variations of echo power. In order to examine the COF in the Dome A region, multi-polarization point measurements were made using a dual-frequency IPR by rotating a snow vehicle platform clockwise at angular intervals of 22.5º during CHINARE 21. Wang et al. (2008) analyzed the relationship between echo signal features and COF types based on multi-polarization measurements. The results indicate that at the summit of Dome A the COF type is not a perfect circular single pole, but an elongated single pole. Moreover, the COF principal-axis-azimuth differences change with time revealed that ice flow orientations were not constant but deviated clockwise with increasing buried depth.

Spatial-temporal variations of past accumulation rates in the Dome A region were reconstructed from isochronous layers traced from ground-based RES profile during CHINARE 21 and airborne RES profile collected by the Dome Connection (DoCo) project launched by Alfred-Wegener-Institute (AWI) in Germany. The depth-age relationship of the layers was dated from Vostok deep ice core data (Petit et al., 1999). Six layers were traced and accumulation rates of the past ~161 ka were calculated using the Dansgaard-Johnsen model (Dansgaard and Johnsen, 1969). The ages of the six isochronous layers from ice sheet top to bottom are 34.3±1.3, 39.6±0.1, 47.5±1.7, 93.3±0.4, 123.5±1.5, and 161.4±1.0 ka, which corresponds to mean past accumulation rates of 2.21, 2.44, 2.62, 1.95, 2.46, and 2.07 $cm \cdot a^{-1}$ (ice equivalent) respectively (Wang et al., 2016). Past accumulation rates increased slightly from the southern Dome A summit to the northern end along the 216 km long radar profile (Wang et al., 2016).

A three-dimensional, thermo-mechanically coupled full-Stokes model was applied to estimate ice age with different parameter schemes in the 70×70 km^2 domain around Kunlun Station (Figure 5) (Sun et al., 2014). The modelled ice age varies intensely with uncertainties as large as 0.5 million years (Sun et al., 2014). The greatly varying ice thickness across the domain and possible basal melting can effectively reduce the ice record by melting the deepest part of ice. Sun et al. (2014) suggest that it is very likely to obtain a deep ice core of 0.7 million years old at the Kunlun Station drilling site, but basal conditions in the Dome A region are sensitive to small changes in surface forcing, such as ice thickness, surface temperature, and accumulation rate. Also this result significantly depends on the unknown geothermal heat flux (Van Liefferinge and Pattyn, 2013). Similarly, suggestions from Fischer et al. (2013), Van Liefferinge and Pattyn (2013) also suggest that the best locations would not be where the ice is thickest, but where geothermal heat flux is low and ice thickness less than 3 km because too thick ice may lead to temperate basal conditions in the Dome A region. Therefore, selecting reduced ice thickness and modeling basal melting rate using more accurate geothermal heat flux and ice fabric, it may be possible to locate a drilling site with ice which holds a climatic record approaching 1.5 million years old in the Dome A region.

4.4 Airborne radio echo sounding

During CHINARE 32, the ICECAP-PEL international campaign was launched to survey the PEL so as to fill a large data gap in Bedmap2 (Fretwell et al., 2013), as well as to identify any large subglacial lake and canyon systems

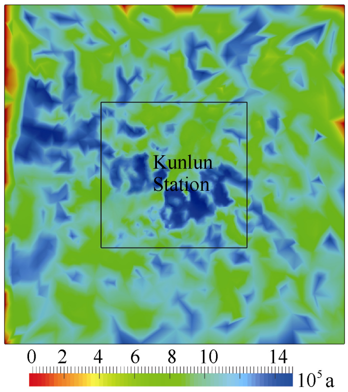

Figure 5 Deep ice age at 95% depth around Kunlun Station in the 70×70 km^2 area from numerical modeling using 60 $mW \cdot m^{-2}$ heat flux and −58.5°C surface temperature (the central 30×30 km^2 region is within the black box). The parts with no basal melt are limited to an age of 1.5 million years (revised from Sun et al. (2014)).

proposed by an international team involves scientists from Chinese, USA, UK, and Australia in the region (Jamieson et al., 2016). Two austral seasons of field aerogeophysical survey have now been finished, and the flight lines of CHINAREs 32 and 33 are shown in Figure 1. A survey grid of radial lines was designed to quantify subglacial topography and ice thickness in PEL as extensively as possible in the first season, while a grid of mainly parallel lines was designed to focus on the subglacial lake and canyon systems (Table 2). The capabilities of the Snow Eagle 601 and its airborne geophysical system were also tested and proven by the aerogeophysical investigations during the two austral seasons (the Snow Eagle 601 with airborne geophysical instruments are shown in Figure 6). In future, the Snow Eagle 601, which has stable funding from the Chinese government, will continue to carry out airborne geophysical investigation of the AIS.

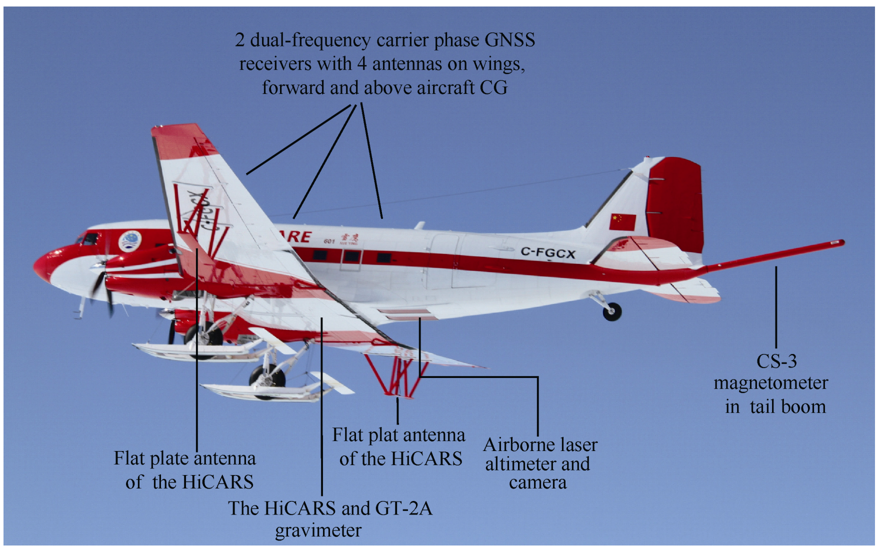

Figure 6 The first fixed-wing airplane Snow Eagle 601 deployed by China for Antarctic survey with airborne geophysical instruments.

5 Prospects

It has been over ten years since Chinese glaciologists first carried out radioglaciological studies on the AIS during CHINARE 21 (2004/05). Along the CHINARE traverse and in the Dome A region, ice sheet internal structure and ice-bedrock interfaces were measured by different ground-based RES systems for multiple scientific purposes, such as mapping subglacial conditions, distinguishing COF types, measuring internal layers and freeze-on ice. From ground-based surveys, we obtained detailed subglacial topography with high spatial resolution in the Dome A region and uncovered the typical mountain glaciation topography of the GSM. Although significant advances in our understanding of the AIS and its bed were made early on, due to logistical limitations, studies had largely focused on the inland traverse and Dome A region. The deployment of the first fixed-wing airplane (Snow Eagle 601) with an airborne geophysical system, including the HiCARS IPR, gravimeter, and magnetometer provides a step change in the potential for data collection and science capabilities. The two seasons of aerogeophysical investigations in PEL during CHINARE 32 (2015/16) and CHINARE 33 (2016/17) provided very high quality data over a wide area.

We propose the following future Chinese radioglaciological studies:

(1) Due to limitations of data coverage, many important aspects of radioglaciology of the AIS, such as subglacial water and lakes, subglacial canyons and channels and the subglacial hydrological system, basal processes across grounding zones, bathymetry under ice shelves, etc., have not yet been studied by China. These all have critical impact on the dynamics of the ice sheet and relate to significant science issues. Now, relying on the Snow Eagle

601 and its airborne scientific system, we can engage in and make Chinese contributions to these science issues.

(2) Radioglaciology investigations by China have been ongoing for only a short time. We have not yet accumulated enough experience both in management of field campaigns and knowledge of radioglaciology, especially airborne geophysical research. Now, the volume and quality of data from China, especially from airborne measurements, will increase, and new cooperation with data users is anticipated and welcomed.

(3) Antarctica is a large continent with extremely harsh conditions, and little can be achieved by a single nation. Rather, extensive and deep international collaborations should be developed to help Chinese glaciologists to pursue science frontiers, and to improve the Chinese contribution to Antarctic science. In addition, based on wide international collaboration, it is very important to look for additional logistical bases for operations of the Snow Eagle 601, so as to access more regions in the AIS. Gaps in our knowledge of the AIS is an issue because the spatial and temporal resolution of boundary conditions and critical parameters of the ice sheet are not sampled well enough to satisfy ice sheet and climate modeling. By improving our understanding of the bed and ice conditions, we will reduce uncertainties relating to the dynamic behaviour of, and controls upon, the AIS. It is important to have international programs because these provide the links required between science objectives, logistics and investment, enabling Snow Eagle 601 to continue operating in the AIS with stable funding into the future.

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