

## Dome Argus: Ideal site for deep ice drilling

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**Abstract** Located on the centre of ice drainage range, the highest Dome Argus (Dome A) of East Antarctic Ice Sheet (EAIS), could be represented as an ideal site for deep ice cores drilling containing oldest paleo-climate records. To select a suitable drilling site for deep ice core, it needs gather all information pertaining to the local meteorology, ice sheet landforms, ice thickness, subglacial topography of bed rocks, ice velocity, internal structures of ice sheet, etc. Based on the International Partnerships in Ice Core Sciences (IPICS), we present recent achievement of glaciological research and its perspective at Dome A in this paper. We systematically discussed the merits and possible ventures of potential drilling sites around Dome A. Among all the candidates, we find that the Chinese Antarctic Kunlun Station is the best site for carrying out the first deep ice core drilling campaign. We emphasize and assess further the possibility to obtain a replicate core for studying dynamics and evolution of climate change.

**Keywords** East Antarctic Ice Sheet, Dome Argus, glaciology, deep ice core

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### 0 Introduction

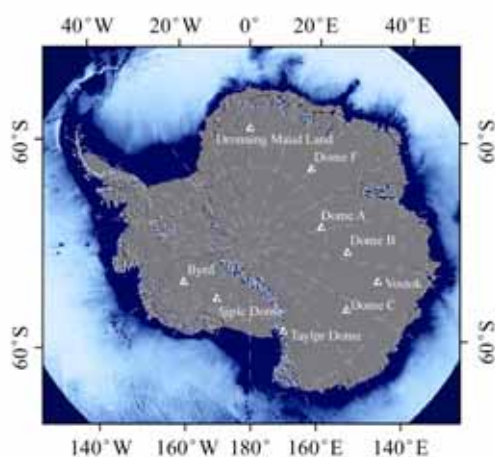
One of the hot issues on the Earth's climatic dynamics is whether the primary driving force of climate change comes from one hemisphere, or due to the coupling of both the northern and southern hemispheres. Deep sea drilling provided insight to resolve such problem. Marine sediment data covered millions of years of global climate change. Other sophisticated method to characterize the process of climatic change is deep ice core data. The ice core record of the northern hemisphere reaches back the past 150 000 a, while that of the southern hemisphere dates back over past 800 000 a. Vostok ice core data from the Antarctic continent extends back over 420 000 a and clearly shows the last 4 glacial-interglacial cycles<sup>[1]</sup>. Data from the European Project for Ice Coring in Antarctica (EPICA) in Dome Concord (Dome C), which is about 350 km from Vostok Station, covers the eight glacial cycles during the past 800 000 a<sup>[2-4]</sup>. At Dome Fuji (Dome F), Japan has drilled two ice cores; the first (1995—1996) contains climate records extending over the past 320 000 a<sup>[5]</sup>, the second (2003

—2007) dates back to 720 000 a BP<sup>[6]</sup>. The comparison of such ice core data from the East Antarctic Ice Sheet (EAIS) provided us abundant knowledge, coupled with the geochemistry and paleontology data of deep sea sediments, advanced effectively the new knowledge of the global climatic evolution.

The Taylor Dome ice core has strongly indicated the presence of a “Greenland type” of climate change, such as its rapid warming during the last glacial period, implying a non-synchronous climate change between the two hemispheres<sup>[7]</sup>. A comparison of ice cores from the Siple Dome and Taylor Dome suggests that climate change is not uniform even in the Antarctic continent. However, most ice core records from different locations show that there are similarities in climate information, for example, the comparison between the data from EPICA Dome C and that from the Vostok ice core. Based on the Dome F ice core record, Watanabe et al.<sup>[5]</sup> found that the EAIS experienced three continuous periods of glacier retreat, which is very similar with the classical record in Vostok. Taking into account that the distance between Dome F and Vostok station is about 1 500 km, this indicates that Vostok/Dome F ice core records seem to be a good representative of the surface temperature change in whole southern hemisphere scale. Regarding to the contradict data between Siple Dome and

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Taylor Dome, it could be either a glaciological illusion or a local phenomenon. In addition, the oxygen isotopic data of marine sediment indicated that the youngest climate cycles of 40 000 year appeared between only 1.3 Ma to 1.2 Ma ago. Given the facts, depending on the boundary conditions (such as greenhouse gas concentrations and ice volumes) as inputs, the numbers of digital climate models can easily simulate some characteristics of the present climate system, but they cannot obtain the multiple features if they use only the planet orbit factors. Humans are still unable to effectively simulate climate evolution, or even the mechanisms behind the corresponding climate change<sup>[8]</sup>. Specifically, it is still unclear why the 100 000 year climate cycles to become dominant during last 0.8 Ma, and why the earth still remains in the Holocene interglacial cycle. To better understand the details of the Earth's climatic behavior and its evolution, it is necessary to find an ice core record extending through over the past 1.5 Ma. According to the regular synthetic observations in the Dome Argus (Dome A) region by Chinese National Antarctic Research Expedition (CHINARE), the oldest ice core records might be located in the center of Dome A of the East Antarctic interior (Figure 1)<sup>[9-10]</sup>. Because the reconstruction (inversion) of paleoclimatological information should be influenced not only by temperature but also by precipitation, moisture transport, deposition, ice flow and other complex environmental factors, the discussion of the environmental conditions in the suggested ice core drilling locations before the drilling engineering is necessary. This article summarizes the results of glaciological research and discusses the developments in near future of the deep ice core plan at Dome A.



**Figure 1** Dome A and other deep ice core sites in Antarctic Ice Sheet (Datasets from BEDMAP and MODIS Mosaic of Antarctica Image Map).

## 1 Dome A and its environmental characteristics

Dome A, located at the top of the Gamburtsev mountains of

EAIS, is the ice divide that is highest and farthest away from the Antarctic coastline<sup>[11]</sup>. In glaciology, Dome A is considered to be a likely site for searching testimony of the origin and early evolution of the ice sheet, the history of ice flow, and for testing simulation results from ice sheet models.

Since the twenty-first Chinese National Antarctica Research Expedition (the 21st CHINARE) first reached Dome A by ground-based travel in the 2004/2005 season and conducted a systematic survey, China has carried out three surveys at Dome A, in 2007/2008 (the 24th CHINARE), 2008/2009 (the 25th CHINARE), and 2009/2010 (the 26th CHINARE), respectively. A number of data was obtained. In particular, during the 25th CHINARE, the Chinese established an Antarctic inland station—Chinese Antarctic Kunlun Station (80°25.02'S, 77°06.97'E), which further strengthened the ability to make direct observations in the Dome A region. By analyzing and researching the datasets, it has been found that Dome A, where many unique environmental characteristics exist, is likely to be an ideal location for deep ice core drilling. Satellite data show that around the center of Dome A, the strike of the region is northeast-southwest with a width of 10–15 km, length 60 km, and a total area of about 800 km<sup>2</sup>. In 2005, the 21st CHINARE found, using GPS, that the exact location of Dome A was located at coordinates (80°22'01.63"S, 77°22'22.90"E). The elevation is 4 092.46 m above sea level, about 1 228 km away from Zhongshan Station<sup>[12-14]</sup>.

In 2005–2006, a continuous temperature record at a depth of 10 m by an automated weather station shown that the annual mean air temperature of the region is about -58.3°C. The temperature measured is lower than that of the domes in the EAIS, such as Dome C, Dome F, Dome B, and also lower than that of the Vostok station. Therefore, this is the lowest annual mean air temperature that has been recorded on the surface of the planet<sup>[14]</sup>. With regards to precipitation patterns, based on the horizon of  $\beta$  activity and ice core density profiles, Hou et al.<sup>[15]</sup> calculated recent accumulation rates at Dome A over recent 40 years. They found that the average annual accumulation rate was 23 mm water equivalent. This value is comparable to that measured at the other inland sites of Antarctica, such as Dome C with 30 mm water equivalent, Vostok with 23 mm water equivalent, Dome B with 38 mm water equivalent, and Dome F with 32 mm water equivalent. They also confirmed that clear-sky precipitation is the dominant mechanism in the Dome A region. The results reported by Xiao et al.<sup>[14]</sup>, based on the changes in elevation of the snow surface in 2005 and 2006, showed that the total snow accumulation recorded was about 0.01–0.02 m in water equivalent per year. This implies that Dome A experienced extreme drought and the lowest snow accumulation rates in the East Antarctic Plateau. Model results also indicated that the surface energy balance at Dome A was compensated by negative net radiation and positive sensible fluxes, and that the sensible heat was, on average, transported from the atmosphere to the snow<sup>[16]</sup>.

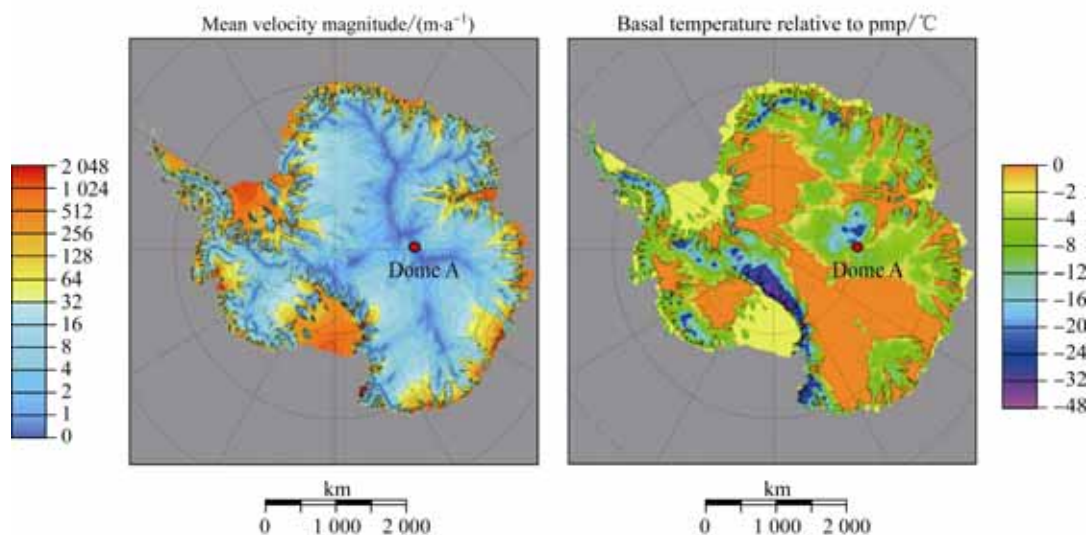
## 2 Shallow ice core

Drilling shallow ice cores would greatly improve the accuracy of site selection in the deep ice core plan. By using a 109.91 m long recovered ice core in 2004/2005, Hou et al.<sup>[17]</sup> found that the termination depth of the bubbles was about 102.0 m with an ice age of about 4 200 a. Their study also showed that Dome A is a highly significant hub for the Antarctic deuterium excess, with an increasing trend, which may reflect the overall migration effect of the moisture sources towards the equator during the late Holocene. Combining the information obtained from stable isotopes in the ice cores from the EAIS inland, it can be derived that the climatic conditions of the Late Holocene were more stable in the East Antarctic interior.

## 3 Ice flow

Understanding the state of ice flow around drilling site is particularly important in ice core drilling plans. Near the location of the ice dome, the horizontal component of ice

velocity is negligible when compared to the vertical component, in theory, and can be ignored. This is a critical reason for drilling deep ice cores in the vicinity of the ice domes<sup>[18]</sup>. According to recent observations by GPS, the horizontal velocity of the ice at distances from Dome A of 150 km and 230 km is  $1.3 \text{ m}\cdot\text{a}^{-1}$  and  $3 \text{ m}\cdot\text{a}^{-1}$  respectively, and within Dome A, the velocity is close to zero<sup>[19]</sup>. At a radius of 300 km from Dome A, the flow rate is less  $10 \text{ m}\cdot\text{a}^{-1}$ . Preliminary simulation results, obtained by Huybrechts from a three dimensional ice sheet dynamics model<sup>[20]</sup>, also showed that the mean velocity of the ice is close to zero within the Dome A region, where the temperature of the ice base is the lowest within the EAIS (Figure 2). In addition, Li et al.<sup>[21]</sup> constructed a two-parameter roughness index of the bedrock elevation to describe the subglacial landscape. Using the calculated results of the roughness index from the base of Dome A, they found that the features of the subglacial topography of Dome A corresponded to lower rates of deposition from erosion, indicating that the bottom has a colder and slower ice flow. These results reinforce the conclusion that the ice velocity at the bottom of Dome A is low.



**Figure 2** Vertical mean velocity and basal temperature of Antarctic Ice Sheet by a three dimensional ice model<sup>[20]</sup>.

An effective way of reconstructing the ice flow within the ice sheet is to combine all the information from the Crystal Orientation Fabric (COF) of ice. By analyzing the relationships between the characteristics of radar reflection and the COF types from the Dome A region, it can be shown that the COF type from this area is predominantly elongated single-pole, and there are remarkable differences among the various COF at the orientation of the principal axis. This may reveal the deviatory clockwise changes of the ice flow orientations at different depths within the ice sheet<sup>[22]</sup>.

## 4 Electromagnetic properties of ice

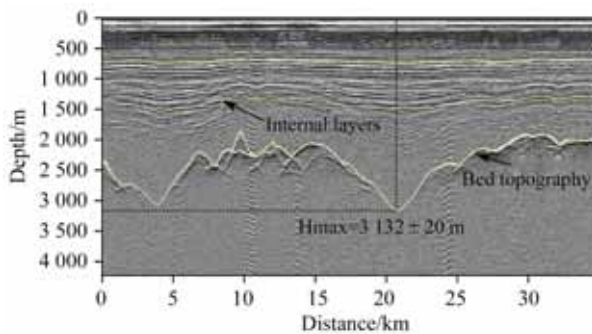
To understand the dynamics of the ice sheets and therefore

its current evolution, there are essential factors that need to be studied in order to obtain the temporal and spatial distribution of the stress and strain rates within the ice sheet. The differences among the stress and strain rates of the ice directly initiate the corresponding changes in the COF. Changes of COF can result in the presence of anisotropic dielectric conductivity, which is expressed by the dual-reflections and the anisotropic reflections of the electromagnetic waves within the ice sheet. Results from a three dimensional electromagnetic finite difference model simulation showed that the reflection power of the ice at different depths and different directions, at Dome A, are significantly different. Furthermore, at less than 800 m in depth, there also exist differences in the phase, which is derived from the change of dielectric constant and related

ice density variations in the shallow ice sheet. Above 800 m in depth, the reflection phases are similar<sup>[23]</sup>. Based on datasets from a dual-frequency radar (60 MHz and 179 MHz) echo detection along the Zhongshan Station—Dome A transect of the Antarctic ice sheet, Jiang et al.<sup>[24]</sup> found that the electromagnetic scattering characteristics of ice: radar echo energy attenuation of a 60 MHz antenna is faster than that of a 179 MHz antenna, at a depth of 100—700 m, and consequently, the radar-reflecting layer formed is due to variations in density of the ice.

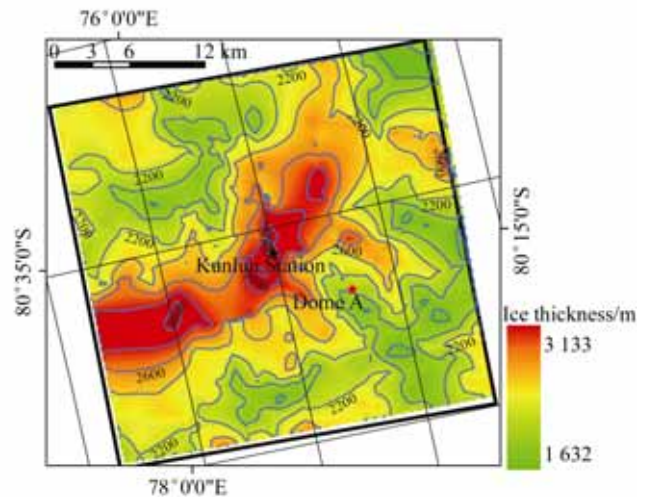
## 5 Ice thickness and surface elevation

Knowledge of ice thickness is of great importance, not only for knowing how deep to drill, but also for determining partly the dynamics of the ice flow by the ice thickness distribution in the vicinity of the observed area. The maximal ice thickness of Dome A, obtained by the radar survey during the 21st CHINARE, is more than 3 000 m (Figure 3).



**Figure 3** Internal layers and bed topography at Dome A from ice radargram.

BEDMAP provides a coarse, gridded dataset of the ice thickness of East Antarctic Plateau, including a low-resolution map of the ice thickness in the Dome region by interpolation methods<sup>[25]</sup>. Currently, a new and high-resolution digitized map of the ice thickness and subglacial topography, around the central region of Dome A, has been obtained. By mapping the data from the two ground-based ice radar surveys during the 21st CHINARE and the 24th CHINARE, Cui et al.<sup>[26]</sup> generated a three dimensional representation of the ice thickness distribution as well as a subglacial topography Digital Elevation Model (DEM), covering the central 30 km×30 km region at Dome A, with a 140.5 m × 140.5 m grid resolution. The map indicates that the average ice thickness in the Dome A central area is up to 2 200 m, with a minimum of 1 618 m and a maximum of 3 139 m around Kunlun Station (Figure 4). New research shows that 24% of the base in the Dome A region is frozen-on ice. The maximum thickness of frozen-on ice is 1 100 m. In some locations, up to 50% of the ice thickness has been contributed from basal<sup>[27]</sup>. The subglacial topography, with elevation from 949 to 2 445 m above sea level, is sharp, and the elevation of the relatively flat ice surface is between 4 070 m and 4 090 m.



**Figure 4** The distribution of ice thickness with a contour interval of 200 m in the central 30 km×30 km region at Dome A<sup>[12]</sup>.

## 6 Subglacial landscape

The Radar information from the 21st CHINARE revealed the subglacial landscape of the Gamburtsev mountains beneath Dome A. The landscape showed that, beneath the ice, there exists a U-shaped valley with a vertical drop of 432 m and an area of 562 km<sup>2</sup> (Figure 5). The geometry implies that the subglacial landscape is due to the superposition on and exploitation of the previous fluvial topography, and erosion from subsequent valley glaciations. The formation process of U-shaped valleys may undergo three phases of glaciations<sup>[28]</sup>. This landscape form has also been found in other places of the planet where there have been periods of glaciation. Figure 5 provides an example of U-shaped valley from Wales, which experienced glaciation when the region was covered by the Scandinavian ice sheet. The glacial landform suggests that the Gamburtsev mountains beneath Dome A are probably older than 34 Ma and is a main centre for ice sheet growth<sup>[28]</sup>.

Recently, the AGAP (Antarctica's Gamburstev Province Project) expedition imaged the internal structure of the entire Gamburtsev mountains range by airborne radar survey. The survey showed that there is complex structure at Dome A. Besides surface accumulation, another primary mechanism for growth of the ice sheet is a large amount of frozen-on ice accumulating from the base. This phenomenon can be explained by the mechanical processes of conductive cooling and glaciohydraulic supercooling of subglacial water<sup>[27]</sup>. Such results illustrate that the fundamental structure of the ice sheet has changed through basal accretion with freeze-on ice. This will damage the climate records contained in the ice and influence the future drilling.

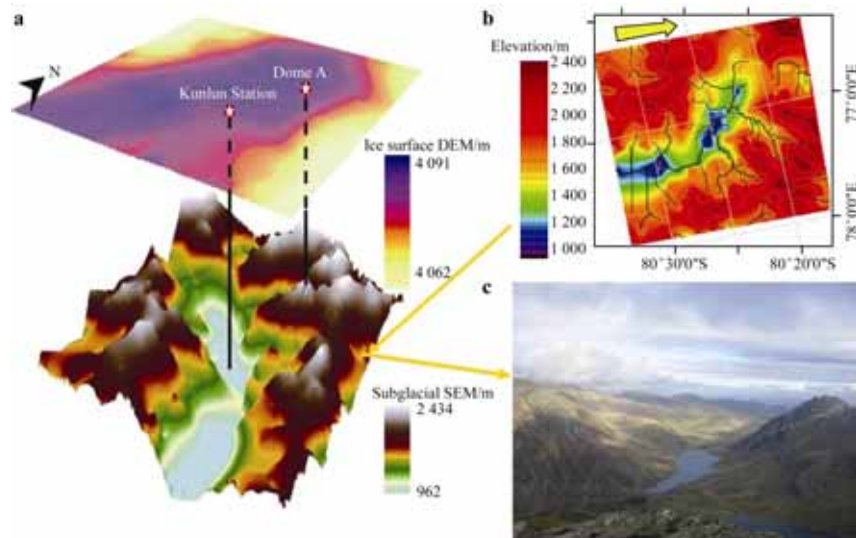
## 7 Internal layering structure

Radar profiles are used to image the internal layering ar-

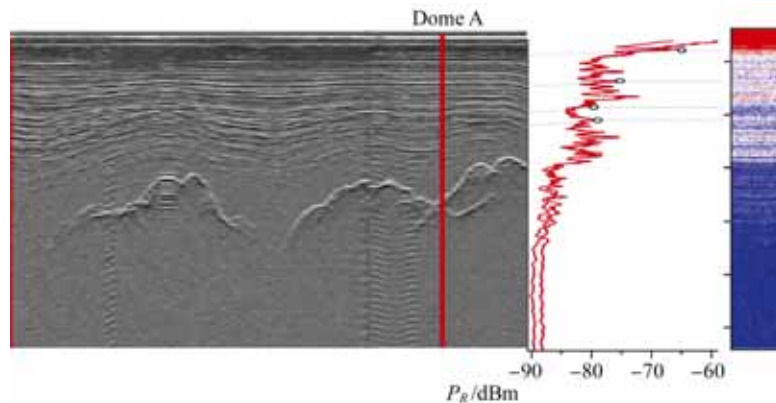
chitecture in ice sheets. The internal layers are known as “isochrones”<sup>[29]</sup>. It is believed to characterize the changes in dielectric permittivity of the ice. There are three mechanisms that lead to differences in the dielectric properties: changes in density of the shallower ice sheet, acidity, and COF of the deeper layers (>500 m)<sup>[30]</sup>. An important application of isochrones is to compare the sites with existing deep ice core drilling operations and potential candidate sites for drilling, and therefore the corresponding depth-age relationship of the candidate sites can be obtained. Further, through subsequent dating of ice, the past accumulation rates of ice can be estimated by numerical models<sup>[31-33]</sup>. There are other realistic applications for the internal isochrones: (1) to assess the ice deformation, and calculate the spatial distribution of the ice velocity field<sup>[34]</sup>; (2) to discuss the stability of the ice sheet<sup>[35]</sup>; (3) to investigate the processes of the ice flow disturbances by using the internal layers and subglacial topography<sup>[36]</sup>; (4) to analyze the correlation between COF of ice and echo-free zones<sup>[37]</sup>. For site

selection for deep ice core drilling, collecting all available data on the internal layering structure around the proposed site is a critical step. In general, to ensure that a continuous depth-age curve of the ice core record is obtained, the location of deep ice core drilling should be selected in the vicinity of a ridge or a dome, with flat and smooth isochrones shown in the relevant radar profiles<sup>[38-39]</sup>.

Based on the radar information from Dome A by the 21st CHINARE, Tang et al.<sup>[40]</sup> mapped the spatial distribution of the internal layers along a radar profile with length ~200 km, and analyzed the structure and the deformation of the layers (Figure 6). Several sites were selected as candidates to drill deep ice cores. Their main findings were that the shallower layers are compact and flat, and there exist some typical synclines and anticlines in local regions as well as some continuous bright layers in the middle ice sheet. The results also showed that the internal layers are asymptotic, parallel to the subglacial topography, if the basal topographic wavelengths are equivalent to the ice thi-



**Figure 5** Ice surface and subglacial topography at Dome A. **a**, Ice surface and three dimensional subglacial topography in the 30 km×30 km region with the center point Kunlun Station<sup>[12]</sup>. **b**, Two dimensional subglacial topography DEM<sup>[28]</sup>. **c**, A U-shape valley at Wales (This photo is provided by Siebert M J).



**Figure 6** A Z-scope and A-scope radargram with frequency 60 Hz at Dome A (left: Z-scope; right: A-scope corresponding to the vertical red line in Z-scope).

ckness. There exist also some discontinuous layers or echo-free zones in the bottom of the ice. Recently, Bell et al.<sup>[27]</sup> imaged the internal reflectors within the echo-free zones near the base. The imaging shown that there are two populations of reflectors in proximity to each other, one found adjacent to the high ridges of the Gamburtsev Mountains, and another found along the steep valley walls beneath the Kunlun Station.

## 8 Discussion

Based on the aforementioned summary of the environmental factors at Dome A, we have been able to initially identify that Dome A should represent a potential deep ice core drilling site. More detailed analysis should be carried out when we analyze the complexity of drilling preparation work.

The deep ice core drilling program is expected to obtain an Antarctic ice core record covering at least the past 1.3 Ma (the ideal situation is that of 1.5 Ma) and containing several 40 000 year climate cycles. The main reason is that the transition of the climate cycles from the 40 000 year periodicity to 100 000 year periodicity occurred in the last 1.3 to 1.2 Ma ago<sup>[8]</sup>. A convenient way of selecting drilling locations is to compare the drilled site of deep ice cores and Dome A by tracing the radar profiles. The current view is that the best way of obtaining a reliable and continuous ice core record is to obtain ice samples with larger geometric lengths. Of interest in the site selection is the number of the continuous internal layers traced. Obviously, the older ice core records will be at the bottom of the ice sheet, where there is lower accumulation at its ice surface. However, the lower accumulation rate is always involved in the risk of flow disturbance and layer distortion. Layer distortion may lead to the failure of restoring climate records in the ice. The most effective method of assuring the integrity of the deep ice core record is to obtain at least two deep ice cores around similar sites, such as that of GRIP, Dome F and Dome C. Therefore, we suggest that the goal of the drilling program should be to obtain at least two ice cores in different locations around Dome A.

From the environmental information about Dome A in the preceding discussion, it is known that there exist some sites, with high ice thickness, lower ice accumulation rates, small flow velocity, and flat and smooth internal layers, satisfying the preconditions for drilling for older ice cores. To limit the site selection, it is essential to search for those sites with small flow disturbances, relatively flat ice bases, and low ablation. In addition, according to the conclusions by Bell et al.<sup>[27]</sup>, widespread freeze-on ice area was found at the base of Dome A, which will likely change the ice rheology and the ice flow. Thus, the freeze-on ice area should be first identified and eliminated. Radar images can be used to discriminate areas with obvious rough bedrock and basal freeze-on ice. However, Dome A, because of the possible presence of complex basal processes, it might not be one of the locations with the oldest ice in Antarctica.

To comprehend all the information from the interior of the ice sheet and the ice flow of the subglacial ice/rock interface, numerical ice models should be developed. Although accurate ice flow models for depicting Dome A have not yet been completed, there have been favorable conditions for supporting model development. First, the ice thickness, the elevation, and the subglacial topography of Dome A have been obtained. Second, the data from recent ice surface velocities and surface accumulation rates have also been collected (primarily in some sparse observational positions). Third, the internal layers revealed in radar profiles were recently traced by comparing the Vostok ice core with Dome A; this will be used to date the shallow and intermediate layers of the ice sheet (another important aspect of the simulation work is to estimate that age of deep internal layers and the temperature of the base, as well as to infer the dynamics history of ice flow).

There are two major applications in the plans for future ice cores: (1) establishing a chronology of the deep ice cores at any depth; (2) designing algorithms for the paleoclimatic proxies contained in the ice cores in order to infer temperature, ice accumulation rates, and other climate factors. Because many uncertain elements are involved in the process of dating ice cores, it is necessary to additionally discuss such issues in the planned deep ice core program at Dome A. Historically, the accuracy of ice core dating has been gradually improved through the high-resolution identification of annual ice layers. Greenland ice core dating reaches back to over the past 100 000 a. However, the resolution of ice core dating, by visually counting annual ice layers, is low in the EAIS because of its lower precipitation. Parrenin et al.<sup>[41]</sup> estimated the uncertainty of the Vostok timescale to be  $\pm 15\ 000$  a. The dating procedures for Antarctic ice cores are so complex that it is difficult to clarify what conjectures should be used. The dating of ice cores from Dome F was also determined by the method of Parrenin et al.<sup>[41]</sup>, which involved the use of orbital tuning such that it can be used to determine the conjunction points of the curves of the Dome F proxies and Vostok proxies. Parrenin et al.<sup>[42]</sup> established a new chronology for Dome C by using a combination of various age markers and an ice flow model, which involved the use of independent age markers, inverse methods, synchronization, and correlation methods. Based on a stratigraphic link between Dronning Maud Land (DML) and Dome C that consists of 322 volcanic match points, and a transfer of data using the link between the two cores through the information from a glaciological model at Dome C, a chronology for the deep ice core from DML was developed by Ruth et al.<sup>[43]</sup>. Their results implied a complex ice flow history for the entire depth of the DML ice core. However, all dating methods have advantages and shortcomings<sup>[41]</sup>. We can predict that similar problems to those already mentioned will appear in the chronological study at Dome A in different degrees. For this reason, special measures should be aimed at rectifying these problems before the drilling commences.

Before selecting the drilling sites, detailed ground-

based and airborne radar investigations would be required. At present, the Chinese Inland Traverse Expedition (CITE) has obtained a ground-based gridded radar profile with an area of 900 km<sup>2</sup> around Dome A. Other inland traverse projects using airborne radar surveys were also carried out to cover the Dome A region, such as IPY TASTE-IDEA (International Polar Year, Trans-Antarctic Scientific Traverses Expeditions—Ice Divide of East Antarctica)<sup>[44]</sup>, DOCO (Dome Connection East Antarctica) plans of Alfred Wegener Institute<sup>[45]</sup>, and AGAP project<sup>[27]</sup>. These surveys will greatly improve the ability to acquire suitable drilling sites.

## 9 Summary

Integrating the climatic and environmental information in the Dome A region, at the location of Kunlun Station (80°25.02'S, 77°06.97'E), there is higher ice thickness, low estimated basal temperature and basal ice velocity, low surface ice velocity and surface temperature, flat bed and smooth internal layers, and low snow accumulation rates, satisfying the necessary conditions of finding older ice and investigating the past and future stability of the Antarctic Ice Sheet. Thickness of the ice samples from the Kunlun Station might contain long and highly detailed climate records as well as speleothems, environmental records. For contributing to understand the mechanisms behind the initiation of deglaciation, the freeze-on ice accumulating process and the subglacial environmental conditions, the first deep ice core drilling campaign should be made, even though its core record is unlikely to be longer than the records from Dome C, DML, Vostok and Dome F. In order to obtain the best possible climate record, ice core information that includes water isotopes, COF, volcanic eruptions, precipitation patterns, trapped gases (carbon dioxide, methane), and biological materials should be satisfied. A replicate coring program will be necessary after the first drilling campaign near the Kunlun Station.

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## References

- Petit J, Jouzel J, Raynaud D, et al. Climate and atmospheric history of the past 420,000 years from the Vostok ice core, Antarctica. *Nature*, 1999, 399: 429-436.
- EPICA Community Members. Eight glacial cycles from an Antarctic ice core. *Nature*, 2004, 429: 623-628.
- EPICA Community Members. One-to-one hemispheric coupling of millennial polar climate variability during the last glacial. *Nature*, 2006, 444: 195-198.
- Jouzel J, Masson-Delmotte V, Cattani O, et al. Orbital and millennial Antarctic climate variability over the last 800 000 years. *Science*, 2007, 317: 793-796.
- Watanabe O, Jouzel J, Johnsen S, et al. Homogeneous climate variability across East Antarctica over the past three glacial cycles. *Nature*, 2003, 422: 509-512.
- Motoyama H. The second deep ice coring project at Dome F, Antarctica. *Scientific Drilling*, 2007, 5: 41-43.
- Steig E J, Morse D L, Waddington E D, et al. Wisconsinan and Holocene climate history from an ice core at Taylor Dome, western Ross Sea embayment, Antarctica. *Geografisker Annaler*, 2000, 82A: 213-235.
- International Partnerships in Ice Core Sciences (IPICS) 2008 Steering Committee meeting. 2008, <http://pages-142.unibe.ch/ipics/data/>.
- Ren J W, Xiao C D, Hou S G, et al. New focuses of polar ice-core study: NEEM and Dome A. *Chinese Science Bulletin*, 2009, 54: 1009-1011.
- Tang X Y, Sun B, Li Y S, et al. Some Recent Progress of Antarctic Ice Sheet Research. *Advances in Earth Science*, 2009, 24(11): 1210-1218 (in Chinese).
- Sun B, Cui X B. Progress on Chinese Expedition of Antarctic Dome Argus in 2007/2008. *Chinese Journal of Polar Research*, 2008, 20(4): 371-378 (in Chinese).
- Cui X B, Sun B, Tian G, et al. Ice radar investigation at Dome A, East Antarctica: Ice thickness and subglacial topography. *Chinese Science Bulletin*, 2010, 55(4-5): 425-431.
- Zhang S K, E D C, Wang Z M, et al. Surface topography around the summit of Dome A, Antarctica, from real-time kinematic GPS. *Journal of Glaciology*, 2006, 177: 159-160.
- Xiao C D, Li Y S, Hou S G, et al. Preliminary evidence indicating Dome A (Antarctica) satisfying preconditions for drilling the oldest ice core. *Chinese Science Bulletin*, 2008, 53: 102-106.
- Hou S G, Li Y S, Xiao C D, et al. Recent accumulation rate at Dome A, Antarctica. *Chinese Science Bulletin*, 2007, 52: 428-431.
- Chen B L, Zhang R H, Sun S F, et al. A one-dimensional heat transfer model on Antarctic Ice Sheet and modeling of near-surface temperatures at Dome A, the summit of Antarctic Plateau. *Science in China Series D: Earth Sciences*, 2010, doi: 10.1007/s11430-010-0017-z.
- Hou S G, Li Y S, Xiao C D, et al. Preliminary results of the close-off depth and the stable isotopic records along a 109.91 m ice core from Dome A, Antarctica. *Science in China Series D: Earth Sciences*, 2009, 52(10): 1502-1509.
- Tang X Y, Zhang Z H, Sun B, et al. Antarctic ice sheet GLIMMER model test and its simplified model on 2-dimensional ice flow. *Progress in Natural Science*, 2008, 18(2): 173-180.
- Zhang S K, E D C, Wang Z M, et al. Ice velocity from static GPS observations along the transect from Zhongshan station to Dome A, East Antarctica. *Annals of Glaciology*, 2008, 48(1): 113-118.
- Huybrechts P. Numerical modeling of ice sheets through time//Knight P G. *Glacier Science and Environmental Change*. Oxford: Blackwell Publishing, 2006: 406-412.
- Li X, Sun B, Siegert M J, et al. Characterization of subglacial landscapes by a two-parameter roughness index. *Journal of Glaciology*, 2010, 56(199): 831-836.
- Wang B B, Tian G, Cui X B, et al. The internal COF features in Dome A of Antarctica revealed by multi-polarization-plane RES. *Applied Geophysics*, 2008, 5(3):230-237.
- Wang B B, Tian G, Sun B, et al. The study of the COF feature in the Antarctic ice sheet based on 3-D anisotropy FDTD method. *Chinese Journal of Geophysics*, 2009, 52 (4): 966-975 (in Chinese).
- Jiang Y Y, Sun B, Ke C Q, et al. Scattering features analyses of the shallow Antarctic ice sheet based on ice-penetrating radar method: A case-study along the Zhongshan station-Dome A transect. *Chinese Journal of Polar Research*, 2009, 21(1): 48-59 (in Chinese).
- Lythe M B, Vaughan D G. BEDMAP: A new ice thickness and subglacial

- topographic model of Antarctica. *Journal of Geophysical Research*, 2001, 106: 11335-11351.
- 26 Cui X B, Sun B, Tian G, et al. Ice radar investigation at Dome A, East Antarctica: Ice thickness and subglacial topography. *Chinese Science Bulletin*, 2010, 55(4-5) 425-431.
- 27 Bell R E, Ferraccioli F, Creyts T T, et al. Widespread Persistent Thickening of the East Antarctic Ice Sheet by Freezing from the Base. *Science*, 2011, 331(6024): 1592-1595.
- 28 Sun B, Siegert M J, Mudd S M, et al. The Gamburtsev Mountains and the origin and early evolution of the Antarctic Ice Sheet. *Nature*, 2009, 459: 690-693.
- 29 Eisen O, Nixdorf U, Wilhelms F, et al. Age estimates of isochronous reflection horizons by combining ice core, survey, and synthetic radar data. *Journal of Geophysical Research*, 2004, 109(B04106), doi:10.1029/2003JB002858.
- 30 Fujita S, Maeno H, Uratsuka S, et al. Nature of radio echo layering in the Antarctic ice sheet detected by a two-frequency experiment. *Journal of Geophysical Research*, 1999, 104(B6): 13013-13024.
- 31 Siegert M J, Hodgkins R, Dowdeswell J A. A chronology for the Dome C deep ice-core site through radio-echo layer correlation with the Vostok ice core, Antarctica. *Geophysical Research Letters*, 1998, 25:1019-1022.
- 32 Siegert M J, Payne A J. Past rates of accumulation in central West Antarctica. *Geophys Res Lett*, 2004, 31(L12403), doi:10.1029/2004GL020290.
- 33 Steinhage D, Nixdorf U, Meyer U, et al. Subglacial topography and internal structure of central and western Dronning Maud Land, Antarctica, determined from airborne radio echo sounding. *Journal of Applied Geophysics*, 2001, 47:183-189.
- 34 Cui X B, Sun B, Tian G. Progress and Prospect of Ice Radar in Investigating and Researching Antarctic Ice Sheet. *Advances in Earth Science*, 2009, 24(4): 392-402 (in Chinese).
- 35 Neumann T A, Conway H, Price S F, et al. Holocene accumulation and ice sheet dynamics in central West Antarctica. *Journal of Geophysical Research*, 2008, 113, F02018, doi:10.1029/2007JF000764.
- 36 Hindmarsh R C, Leysinger V J M, Raymond M J, et al. Draping or overriding: The effect of horizontal stress gradients on internal layer architecture in ice sheets. *Journal of Geophysical Research*, 2006, 111(F02018), doi:10.1029/2005JF000309.
- 37 Drewry D J, Meldrum D T. Antarctic airborne radio echo sounding, 1977-78. *Polar Record*, 1978, 19: 267-273.
- 38 Frezzotti M, Bitelli G, De M P, et al. Geophysical survey at Talos Dome, East Antarctica: the search for a new deep-drilling site. *Annals of Glaciology*, 2004, 39: 423-432.
- 39 Jacobel R W, Welch B C, Steig E J. Glaciological and climatic significance of Hercules Dome, Antarctica: An optimal site for deep ice core drilling. *Journal of Geophysical Research*, 2005, 110( F01015).
- 40 Tang X Y, Sun B, Zhang Z H, et al. Structure of the internal isochronous layers at Dome A, East Antarctica. *Science in China Series D: Earth Sciences*, 2010, doi: 10.1007/s11430-010-4065-1.
- 41 Parrenin F, Jouzel J, Waelbroeck C, et al. Dating the Vostok ice core by an inverse method. *Journal of Geophysical Research*, 2001, 106(D23): 31837-31851.
- 42 Parrenin F, Barnola J M, Beer J, et al. The EDC3 chronology for the EPICA Dome C ice core. *Climate of the Past*, 2007, 3: 485-497.
- 43 Ruth U, Barnola J M, Beer J, et al. "EDML1" : A chronology for the EPICA deep ice core from Dronning Maud Land, Antarctica, over the last 150 000 years. *Climate of the Past*, 2007, 3: 475-484.
- 44 Goldman H V. From the editor: halfway through the IPY-halfway for an Antarctic traverse. *Polar Research*, 2008, 27: 1-6.
- 45 Steinhage D. Dome Connection East Antarctica (DoCo)—internal structure of the ice sheet between deep ice core drill sites in East Antarctica revealed by airborne RES//Symposium on Glaciology in the International Polar Year. UK: Northumbria University, 2009: 27-31.