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How old is the ice beneath Dome A, Antarctica?

B. Sun[1], J. C. Moore[2,3,4], T. Zwinger[2,5], Z. Liyun[2], D. Steinhage[6], X. Tang[1], D. Zhang[1], X. Cui[1], and C. Martín[7]

[1]Polar Research Institute of China, Shanghai 200129, China
[2]College of Global Change and Earth System Science, Beijing Normal University, China
[3]Arctic Centre, University of Lapland, P.O. Box 122, 96101 Rovaniemi, Finland
[4]Department of Earth Sciences, Uppsala University, Villavägen 16, Uppsala, 75236, Sweden
[5]CSC-IT Center for Science Ltd., Espoo, Finland
[6]Alfred Wegener Institute Helmholtz Centre for Polar and Marine Research, Bremerhaven, Germany
[7]British Antarctic Survey, Natural Environment Research Council, Cambridge, UK

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Correspondence to: J. C. Moore (john.moore.bnu@gmail.com)

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Abstract

Chinese scientists will start to drill a deep ice core at Kunlun station near Dome A in the near future. Recent work has predicted that Dome A is a location where ice older than 1 million years can be found. We model flow, temperature and the age of the ice by applying a three-dimensional, thermo-mechanically coupled full-Stokes model to a 70 km × 70 km domain around Kunlun station, using isotropic non-linear rheology and different prescribed anisotropic ice fabrics that vary the evolution from isotropic to single maximum at 1/3 or 2/3 depths. The variation in fabric is about as important as the uncertainties in geothermal heat flux in determining the vertical advection which in consequence controls both the basal temperature and the age profile. We find strongly variable basal ages across the domain since the ice varies greatly in thickness and any basal melting effectively removes very old ice in the deepest parts of the subglacial valleys. Comparison with dated radar isochrones in the upper one third of the ice sheet cannot sufficiently constrain the age of the deeper ice, with uncertainties as large as 500 000 yr in the basal age. We also assess basal age and thermal state sensitivities to geothermal heat flux and surface conditions. Despite expectations of modest changes in surface height over a glacial cycle at Dome A, even small variations in the evolution of surface conditions cause large variation in basal conditions which is consistent with basal accretion features seen in radar surveys.

1 Introduction

The search for ice older than 1.5 million years is active and key question for the Quaternary science community (e.g., Severinghaus, 2010; Van Liefferinge and Pattyn, 2013). The Gamburtsev subglacial mountains beneath Dome A were a major centre of ice-sheet nucleation during the Cenozoic (DeConto and Pollard, 2003; Sun et al., 2009), and hence potentially can provide ancient ice for paleoclimatic research. Kunlun station (80°25′01″ S, 77°06′58″ E, 4092 m a.s.l.) is located where the thickest ice (3090 m) oc-

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curs on the gently sloping summit region of Dome A (Fig. 1). Preliminary investigation has shown that the annual mean temperature (measured at 10 m below the surface) at Dome A is −58.5 °C, the lowest annual mean temperature ever recorded on the surface of the Earth (Hou et al., 2007). The average snow accumulation rate during the past several centuries (1260–2004 AD) is about 25 mm ice equivalent yr^{-1}, which is typical of other sites in the East Antarctic interior (e.g. Ritz et al., 2001).

In stark contrast with the nearly flat surface topography, radar mapping suggests that the Gamburtsev Mountains are very rugged Alpine style terrain (Bell et al., 2011; Fig. 1). This produces complex ice flow which, in some places may cause mixing of basal ice layers or localized basal melting and refreezing. When considering locations for deep ice coring in search of very ancient ice, ice thickness and geothermal heat flux has been recognized as of crucial importance. Modeling these parameters (Van Liefferinge and Pattyn, 2013) suggests that the best locations to search would not be where the ice is thickest, but where heat flux is low and ice thickness less than 3 km. This is because basal melting leads to loss of old ice at the bed and, in some places, deep layers of relatively young ice compared with locations where thinner ice is frozen to the bed. However these models rely on assumptions of isotropic ice and make use of Glen's flow law, whereas observations suggest that strong anisotropic fabric is commonplace in Antarctica even close to the surface (Svensson et al., 2007; Matsuoka et al., 2012).

Ice is a strongly anisotropic medium, and deep ice cores typically show that the initially random orientation of ice grains alters as the ice is buried and subjected to strain, leading to preferential orientation of the crystal c-axis (Shoji and Langway, 1985; Wang et al., 2003). This anisotropic ice may be an order of magnitude "softer" against deformation in certain directions than ice with random fabric, and has an important influence on the age of ice in the lower 1/3 of the ice thickness (Martín and Gudmundsson, 2012; Seddik et al., 2011). Deep ice cores from Vostok exhibit a girdle type fabric pattern (Lipenkov et al., 1989), whereas deep ice in Dome C and Greenland exhibit single maximum, i.e., the c-axes concentrate along the vertical direction (Thorsteins-

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son et al., 1997; Wang et al., 2003). At Dome F, which is perhaps the closest analogue to the Dome A region, a single maximum fabric dominated the bottom 1/3 of the ice core (Seddik et al., 2011).

2 Data and model

The open source, Finite Element Method package Elmer/Ice (http://elmerice.elmerfem.org) that has been used for the ice dynamical part of our simulations, solves the complete three-dimensional, thermo-mechanically coupled ice dynamics equations, a so-called "full-Stokes" model, (e.g., Zwinger and Moore, 2009; Seddik et al., 2011). Additionally we make use of relations between the strain rate tensor and the deviatoric stress tensor (e.g. Gillet-Chaulet et al., 2006; Martín and Gudmundsson, 2012) that employs the ice fabric orientation tensor and the ratios of the shear viscosity parallel to the basal plane to that in the basal plane, and the viscosity in compression or traction along the c-axis to that in the basal plane. If the local temperature is at the pressure melting point then a basal melting rate is calculated (Seddik et al., 2011), and as surface velocities are very low, basal sliding is not allowed.

A network of extensive ice penetrating radar (Cui et al., 2010; Sun et al., 2009; Bell et al., 2011; Tang et al., 2011), topographic (Zhang et al., 2007), and shallow ice core surveys (Jiang et al., 2012; Xiao et al., 2008) in the region surrounding the Kunlun field station provide input data for the model, and help to constrain the model results to meet observations. A 30 km × 30 km domain with an unstructured mesh of about 300 m horizontal resolution was embedded within a coarse (3 km) 70 km × 70 km unstructured mesh domain centered at Kunlun station (Fig. 1); this arrangement makes optimal use of the various airborne and ground based radar data. At the lateral domain boundaries (about 10 times the ice thickness away from the drill site), a zero-flux condition is applied to the temperature field while the velocity field was calculated using the hydrostatic approximation, hence results will become inaccurate towards the domain boundaries. Nevertheless, the distance to the inner domain should ensure that

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there is no influence on results around Kunlun station (Seddik et al., 2011). The domain was divided into 20 vertical layers with the lower 6 having logarithmic spacing with the bottom-most layer representing 0.3125 % of ice thickness. Geothermal heat flux is the most significant unknown boundary condition in determining the basal age of ice across Antarctica (e.g., Van Liefferinge and Pattyn, 2013). Van Liefferinge and Pattyn (2013) produce a map of the broad scale heat flux and its uncertainty based on 3 different estimates which gives about $50 \pm 25\,\mathrm{mW\,m^{-2}}$ in the Dome A region. The presence of both basal melt and freezing conditions in the Dome A region (Bell et al., 2011) helps limit geothermal heat flux values. Experiments show that below $45\,\mathrm{mW\,m^{-2}}$ very little basal melt occurs over the domain, while above $60\,\mathrm{mW\,m^{-2}}$ basal melt occurs even below ice 2400 m thick suggesting more widespread melt than Bell et al. (2011) observe. Hence we make our simulations with either 50 or $60\,\mathrm{mW\,m^{-2}}$ heat fluxes across the domain.

The present day temperature of −58.5 °C is likely about 10 °C warmer than that during the Last Glacial Maximum (LGM) over the east Antarctic plateau (Ritz et al., 2001), and accumulation rates during the LGM were perhaps half that of present day (e.g., Watanabe et al. (2003) found about 45 % for much of the glacial at Dome F). We examine the impact of changing surface temperatures using both a transient simulation through the last glacial cycle (starting from 130 kyr BP), forced by a temporal varying surface temperature (but on the fixed present day geometry), and steady state simulations using both glacial and modern surface temperatures.

The elevation of the Antarctic ice sheet has varied over glacial timescales as a result of changes in both surface accumulation rate and the grounding line at the ice margin. The effects of accumulation rate increase and grounding line retreat following the LGM would tend to cancel out, and modelling suggests that elevation changes of less than about 50 m occurred at Dome A (Saito and Abe-Ouchi, 2010; Ritz et al., 2001). Hence we keep geometry fixed in all (even transient) simulations, which implicitly determines accumulation rates.

Since we do not know the actual ice fabric at Kunlun, we illustrate a range of possibilities by prescribing 3 alternative scenarios in the central 30 km × 30 km area: isotropic,

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single maximum, and linear development of a "solid-cone" fabric where all the c-axes are uniformly and randomly distributed within a cone (or horizontal "girdle"), whose half angle we contract smoothly from 90° (equivalent to isotropic) at the ice surface to zero (single maximum) at 1/3 or 2/3 depth and thence to the ice base. Fabric variations in the Dome F, GRIP and EPICA Dome C ice cores showed isotropic ice in the upper parts with an evolution to a single maximum, which at Dome F persisted over most of the bottom 1/3 of the ice core (Seddik et al., 2011). Therefore the most likely dating for the upper parts of the ice column comes from integration of isotropic fabric layer thinning rates while those deeper would likely follow the thinning rates from the single maximum fabric. Hence we expect that, of the three alternatives, the girdle fabric would provide the most likely description of ice fabric for the whole core.

We compute steady-state and transient solutions with fixed present-day geometry. Firstly, we obtain a steady state solution for a linear (Newtonian fluid) rheology, in order to avoid the singularity of Glen's flow law at zero-shear initial condition. Secondly, restarting with this result, we compute for the isotropic steady state run with non-linear (Glen's flow law) rheology. Thirdly, we take the isotropic steady state solution as the initial guess from which we start to compute the anisotropic case. To calculate the age of the ice, A, would require velocity profiles over the full history of the ice sheet. Instead we solve the advection equation

$$\frac{\partial A}{\partial t} + \boldsymbol{u} \cdot \nabla A = 1$$

using a semi-Lagrangian method (Martín and Gudmundsson, 2012) and assuming a steady state velocity profile, $\boldsymbol{u}$, and a time non-varying geometry as the evolution of flow over glacial cycles is unknown. Hence, we cannot compute the age for the single glacial cycle transient simulation we perform.

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3 Results

3.1 Basal melt and temperatures

Basal melting rate is sensitive to surface accumulation rate and temperature, ice thickness and geothermal heat flux. As described in Sect. 2, we prescribe fixed geometry which implicitly determines accumulation rates. For 50 mW m^{-2} heat flux only a small fraction of the basal ice in the 30 km × 30 km domain is at the pressure melting point, including Kunlun station drill site (Fig. 2). Basal melting is considerably stronger for 60 mW m^{-2} heat flux (Fig. 2), and the spatial extent of melting is also greatly increased despite the steep topography.

3.2 Vertical velocity and age profile

The geothermal heat flux does not greatly affect internal temperatures in the ice sheet (Fig. 2), but it does impact vertical velocity in the ice sheet (Fig. 3) when basal melting occurs. This is particularly important in determining the age profile of the ice (Fig. 3). Simulations with the same fabric but higher geothermal heat flux or warmer surface temperatures produce larger vertical velocities than cooler ones as the ice tends to be softer and has more melt. However the order of the profiles in Fig. 3 by fabric is not entirely intuitive, while generally isotropic ice has higher vertical velocity than girdle and single maximum fabrics, the curves often cross each other at depth. The modelled age profile can be compared with ages in the upper part of the ice sheet from dated radar internal reflection horizons tracked from the Vostok ice core site. The dated radar isochrones do not extend further backwards than 160 kyr BP, or about the upper 1/3 of the ice depth at Kunlun station.

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4 Discussion

The age of the ice depends on the vertical velocity profile in the ice, which depends on the basal melt rate, governed entirely in our model by the geothermal heat flux, surface temperature and the ice fabric (see Fig. 3). The normal velocity at the surface, w_s, in all simulations is the accumulation rate since we specify a fixed geometry in the simulations. Both the transient simulation and the steady state simulations with glacial surface temperature produce w_s notably too low even with a geothermal heat flux of $60\,\mathrm{mW\,m^{-2}}$. Present day accumulation rates are about $25\,\mathrm{mm\,ice\,equivalent\,yr^{-1}}$, and those in the glacial periods about half that, hence reasonable simulations should produce w_s of about $14\,\mathrm{mm\,ice\,equivalent\,yr^{-1}}$. The discrepancies in the modelled ages of the radar isochrones are smaller when the simulation produces reasonable w_s (Fig. 4). However, as isochrones are only available for the upper 1/3 of the ice sheet thickness they cannot constrain the age near the bed as different, but reasonable combinations of fabrics, geothermal heat flux and surface temperature can produce essentially identical behaviour in the upper 1/3 of the ice sheet that diverge dramatically in the deeper parts (Fig. 3). Hence, with the observations available now, we cannot well constrain the age of the basal ice.

The large sensitivities and discrepancies from radar isochrone dates produced by different simulations question the assumptions made in the model, particularly the fixed surface geometry. This implies that Dome A is a dynamic region where basal conditions are sensitive to small changes in surface forcing, such as thickness changes of tens of metres, which can switch bedrock locally from melting to freeze-on, driving changes in hydrology and latent heat distribution, and perhaps the unusual basal accretion noted in the radar surveys (Bell et al., 2011).

Another open question is the lateral distribution of fabric, induced by the – in comparison to other large ice-core drilling sites – uniquely steep and rough bedrock topography of the Gamburtsev mountain range. The kinematic constraints imposed by the bedrock (including local sliding at temperate base) may lead to locally strong variations of verti-

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cal shearing and, in consequence, of the fabric perhaps with even a dynamic feedback on the flow.

As the drill site is located at one of the deepest parts of the steep valley under Kunlun station (Fig. 5), much older ice may be expected within a few hundred metres (Fig. 6). The general layout of valley troughs in Fig. 1 is suggested in Fig. 6 as the troughs tend to exhibit basal melting. However, there is clearly not a perfect correlation with ice thickness even though surface slope is gentle and geothermal heat flux is constant. Hence the three-dimensional flow is also relevant to the age distribution. Exploring such phenomena could be done by off-nadir drilling in order to examine lateral fabric distributions. We expect a significant improvement of the model, once the input of a measured fabric distribution has been incorporated. It is therefore possible that the Kunlun site would provide both a highly resolved record of the past 6–700 000 yr from vertical drilling, and a longer but lower resolution record from off-nadir drilling. Indeed exploration of the basal valley features may well also lead to knowledge of the sub-basal hydrology and accretion processes observed by radar surveys of the area.

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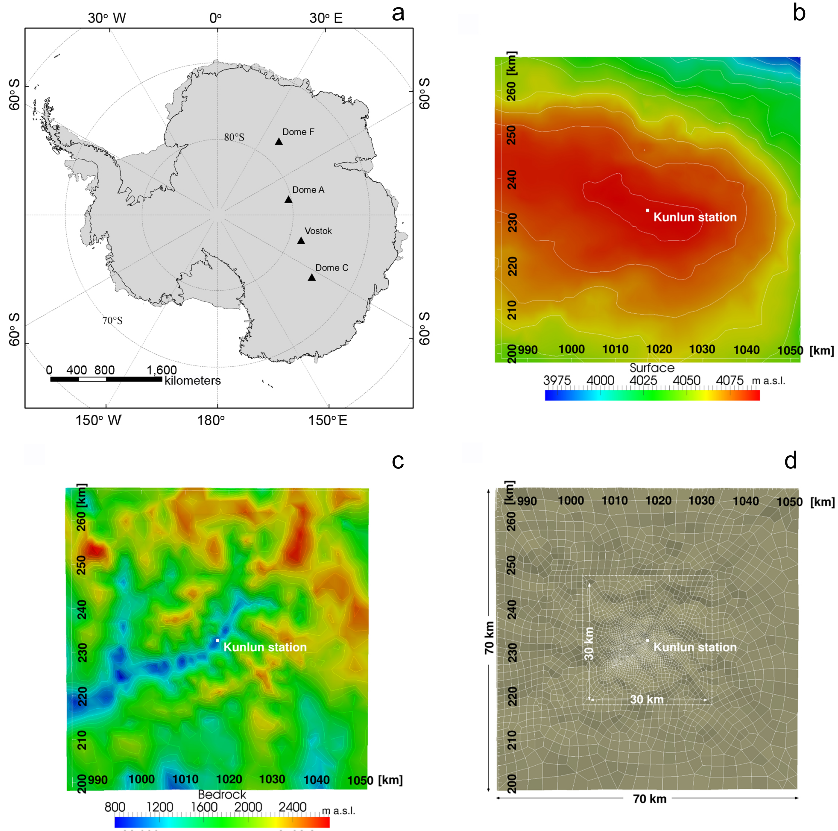

Fig. 1. (a) Map of Antarctica with locations of Dome A, Dome C, Dome F and Vostok; **(b)** surface topography in the vicinity of Dome A and Kunlun Station (contour spacing 10 m); **(c)** bedrock topography (contour spacing 200 m); and **(d)** the finite element mesh in the 70 km × 70 km domain, with higher resolution in the central 30 km × 30 km region. The coordinate system is WGS 1984 plotted using Antarctic Polar Stereographic with standard parallel at 71° S and central meridian at 0° E.

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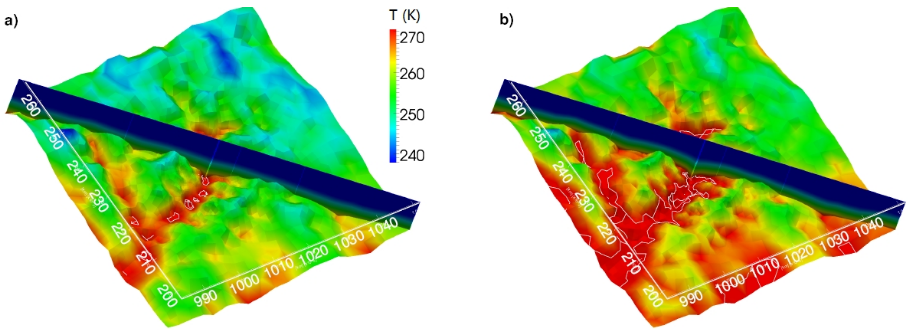

Fig. 2. Basal temperature distribution for 50 mW m^{-2} **(a)** and 60 mW m^{-2} **(b)** geothermal heat flux over the 70 km × 70 km domain for the solid-cone or horizontal girdle with 1/3 transition depth fabric simulations. The vertical temperature distribution is shown in a transect across the domain cutting through the Kunlun drill sit at the centre. The vertical coordinate is stretched by a factor of 5. The temperate areas at the bedrock are surrounded by a white contour.

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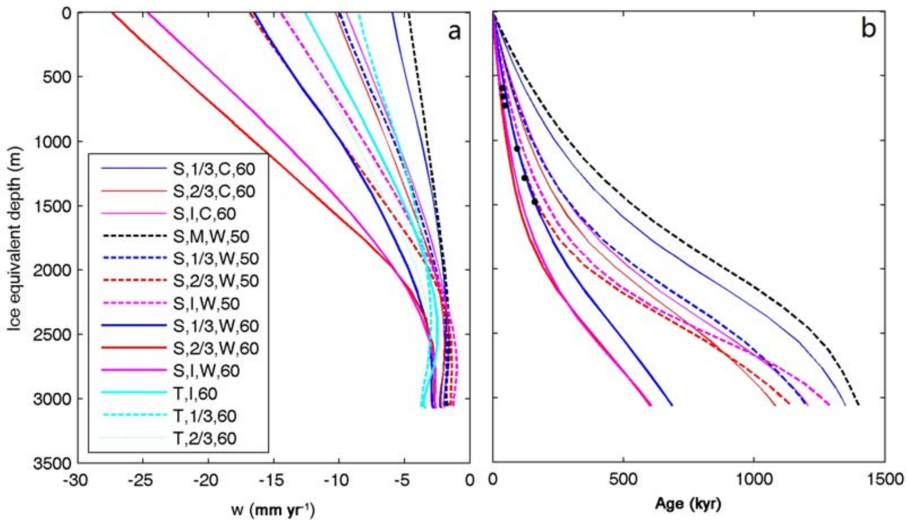

Fig. 3. (a) Vertical velocity, w, as a function of depth from the surface to bedrock for different fabrics and geothermal heat flux at Kunlun station. Simulations at steady state (S) using isotropic (I, magenta) and girdle 1/3 transition depth (1/3, blue), 2/3 transition depth (2/3, red) and single maximum (M, black) fabrics; with 50 mW m^{-2} heat flux (dashed), and 60 mW m^{-2} (solid); and for cold (C) glacial period surface temperatures (thin lines) and warm (W) interglacial temperatures (thick lines). Transient runs (T) from 130 kyr BP with a 200 yr time step size spun up from steady state of glacial conditions and 60 mW m^{-2} heat flux with isotropic fabric (cyan solid), girdle 1/3 (cyan dashed) and 2/3 (cyan dotted). **(b)** Age-depth profile at Kunlun station. The black points denote the age-depth data from dated radar internal reflection horizons tracked from the Vostok ice core site, a 46 m firn correction is subtracted from the radar depths to convert to the ice equivalent model scale. The two best fits are from steady state simulations with present day surface temperature, using girdle fabric 1/3 and 60 mW m^{-2} heat flux (thick solid blue), and using girdle fabric 2/3 and 50 mW m^{-2} heat flux (thick dashed red).

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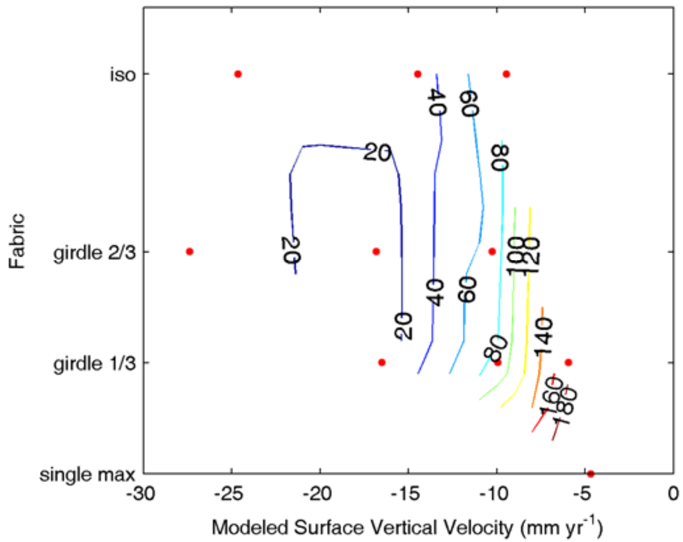

Fig. 4. Contoured RMS (root mean square in kyr) for the mismatch in ages (red dots) of the radar isochrones for various fabrics as a function of the surface velocity w_s from the simulations shown in Fig. 3. There is a minimum in RMS between w_s of 15 and 20 mm yr^{-1} whereas simplistic expectations would suggest a long term steady state surface mass balance and w_s of about 14 mm yr^{-1}.

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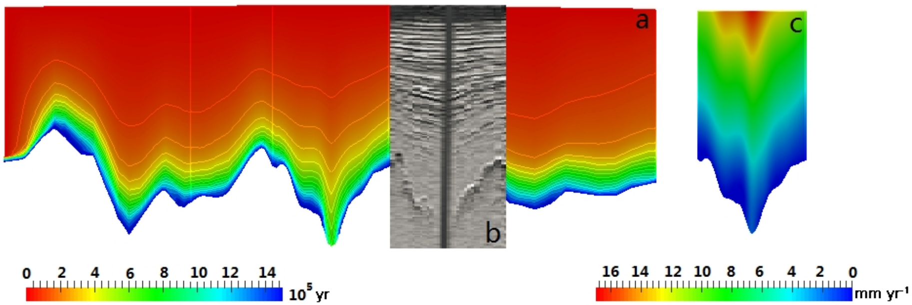

Fig. 5. (a) Transect across the same line passing through Kunlun station in the 70 km × 70 km domain as in of the age of the ice sheet with the best fit simulation from Fig. 3 (girdle 1/3 transition depth, 60 mW m^{-2} heat flux and surface temperature of −58.5 °C). The vertical coordinate is stretched by a factor of 10. **(b)** Radar observations with the same horizontal and depth scales are shown as a greyscale image (Tang et al., 2011) for the central Kunlun valley (the part immediately to the left of the radar image). **(c)** The vertical velocity in the Kunlun valley section. The age simulation was run for 1.5 Myr and the age at the basal layer where frozen is the same as simulation time.

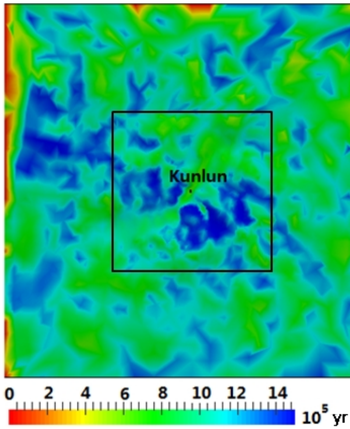

Fig. 6. Age of the ice at 95 % depth in the 70 km × 70 km domain (central 30 km × 30 km region is boxed) using the same simulation parameters as for Fig. 5. The parts where with no basal melt are limited to an age of 1.5 Myr.

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