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Subglacial topography and internal structure of central and western Dronning Maud Land, Antarctica, determined from airborne radio echo sounding

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Abstract

During five austral summers, from 1994/1995 until 1998/1999, the Alfred Wegener Institute (AWI) carried out a large airborne radio echo sounding (RES) survey in Dronning Maud Land (DML), Antarctica. These ice thickness measurements are part of the AWI contribution to the pre-site survey for a deep ice core drill site in DML within the European Project for Ice Coring in Antarctica (EPICA). The survey encompasses more than 90,000 km of RES profiles over DML and the adjacent coastal area, covering more than 1 million km^2. The lower boundary of the ice sheet could be determined area-wide. Internal horizons occurring in the upper two-thirds of the ice column can also be traced for several hundred kilometers. This work presents the latest maps of the subglacial topography of the investigated area as well as of an internal horizon.

Keywords: RES; Antarctica; Dronning Maud Land; EPICA; Internal structure; Subglacial topography

1. Introduction

Ice is an almost ideal climate archive. In addition to paleotemperatures, it also preserves chemical characteristics of the atmosphere as well as dust particles in the yearly snow accumulation. During the transition from snow to ice, small samples of the atmosphere are trapped inside the ice within small bubbles. From a deep ice core drilled at the Russian station Vostok in East Antarctica, a record has been obtained revealing a climatic history over the last 420,000 years (Petit et al., 1999). In order to contribute to the understanding of climate evolution, the European Project for Ice Coring in Antarctica (EPICA) has been established. Of major concern are two questions: (1) whether climatic changes occur in the northern and southern hemisphere in phase and (2) whether climatic fluctuations affect the whole Antarctic continent simultaneously or not (Jouzel et al., 1996). Therefore, two deep ice core drillings in Antarctica are being carried out, one at Dome Concordia south of the Indian Ocean, which was started in 1997, and another one at a place still to be determined in Dronning Maud Land (DML) in the Atlantic sector (see Fig. 1).

The first ice core drilling is expected to provide a record covering the last 500,000 years due to a low accumulation rate, whereas the latter in DML will be

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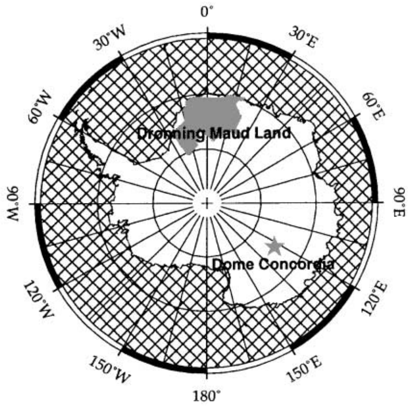

Fig. 1. Map of Antarctica with area of interest (grey shaded) and Dome Concordia.

in a relatively high accumulation area, which will allow a high temporal resolution. Due to its location in the Atlantic sector, this ice core should allow a direct correlation with the Greenland ice cores GRIP, GISP2 and NGRIP.

Knowledge of the ice thickness in DML is of great importance, not only for the obvious reason of knowing how deep to drill, but also because the lower part of deep ice cores can only be dated by modelling studies (Reeh et al., 1985). Such modelling studies require knowledge of the ice thickness distribution in the vicinity of the drill site as well as further upstream. Prior to the beginning of the radio echo sounding (RES) survey by the Alfred Wegener Institute (AWI) in 1994/1995, only the neighbouring areas of the investigated region in DML had been covered by glaciological and geophysical field work in the past, e.g. by the U.S. South Pole Queen Maud Land traverses between 1964 and 1968 (Beitzel, 1971; Clough et al., 1968), airborne RES by the Department of Geophysics of the Westfälische Wilhelms-Universität Münster, Germany, in 1985/1986 (Thyssen and Grosfeld, 1988) and airborne RES carried out by Soviet Antarctic Expeditions in the 1980s (Popov and Leitchenkov, 1997).

2. The AWI RES system

The airborne RES system of AWI has been specially designed by the Department of Radio Technology of the Technische Universität Hamburg-Harburg and Aerodata Flugmeßtechnik, Braunschweig, under supervision of the AWI for use with the AWI owned fixed-wing polar aircraft Polar2, a Donier 228-101. It is theoretically capable of penetrating up to 4000 m of ice and to toggle between two different bursts of a duration of 600 and 60 ns, respectively, while recording 20 traces per second. The transmitting part of the system consists of a burst generator working at a center frequency of 150 MHz, a pulse generator (60/600 ns pulses), a power amplifier unit (1585 W) and a short backfire antenna. A second short backfire antenna is used on the receiving side together with an amplifier, 17/1.7 MHz bandpass filter, a logarithmic detector unit and A/D converter. The whole system is controlled by a central processing unit which allows the transmitted power and the burst length to be set. The data, approximately 1 GB h^{-1} including additional GPS and aircraft navigation data, are stored on 8 mm Exabyte tapes. Table 1 gives a summary of the technical data of the RES system. A more detailed description of the system is given by Nixdorf et al. (1999).

The ability to toggle between two pulse widths allows the system to record two profiles simultaneously on one flight track. The one with the long (600 ns) pulse is used for the ice thickness determination due to greater penetration depth, whereas the shorter (60 ns) pulse due to its higher resolution is used to trace internal horizons. In Fig. 2, the first 100 km of flight track 992136 is shown in order to demonstrate the difference in resolution and penetration depth of the two different pulses. The part on the left has been obtained using the long pulse and reveals clearly the ice/bed interface, whereas the right part reveals

Table 1
Technical data of the AWI RES system

Center frequency	150 MHz
Burst length	60/600 ns
Maximum transmitting power	1585 W
Dynamic range	193 dB
Antenna gain	14.2 dB each
Pulse repetition rate	20 kHz
Trace spacing ($v = 240$ km h^{-1})	3.35 m
Registration window	50 μs
Sample interval	13.33 ns

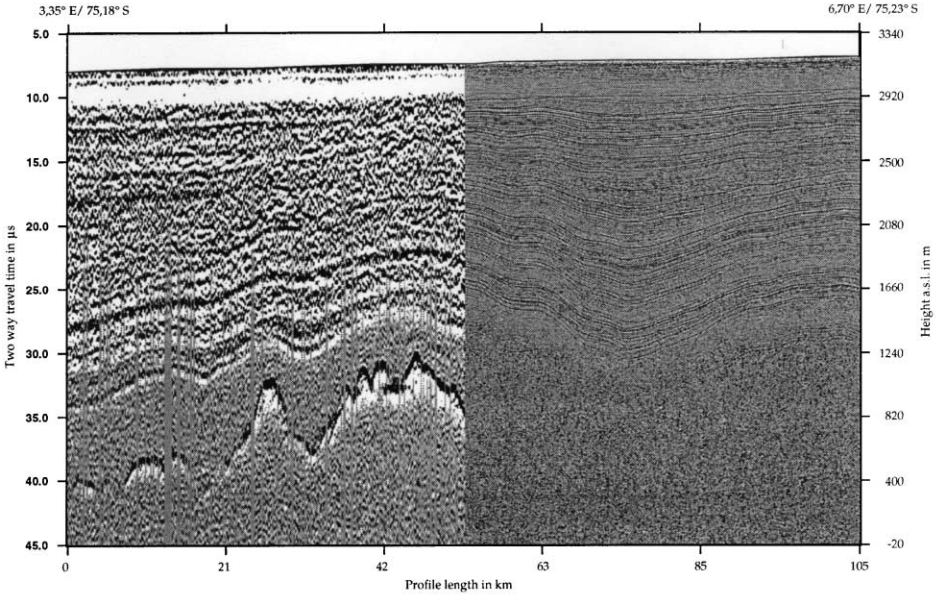

Fig. 2. Section of flight track 992136, processed, static corrections applied, left part 600 ns pulse, right part 60 ns pulse.

internal layering detected with the short pulse. Bandpass filtering and amplitude scaling have been applied in addition to horizontal stacking and a static correction to the section shown in Fig. 2.

3. Subglacial topography

The investigated region in DML covers an area of more than 1 million km^2 including ice shelves as well as mountains exhibiting bare rock at their summits. All RES profiles measured between 1994 and 1999 by AWI in DML and six additional flights carried out by the British Antarctic Survey (Walden and Corr, 1997) have been used to calculate an ice thickness grid with a cell size of 10 by 10 km using a minimum curvature algorithm (Smith and Wessel, 1990). A crossing point analysis of the ice thicknesses revealed that 50% of all misties are smaller than 10 m.

The two-way travel times have been converted into depth using a velocity of 168 m μs^{-1} (Bogorodsky et al., 1985) with an uncertainty of ± 20 m. The unconsolidated firn layer with its higher velocities of electromagnetic waves has been taken into account by adding a firn correction of 13 m (Steinhage, 2001) to the ice thicknesses. This firn correction has been derived from measurements of the complex permittivity on 5 up to 150 m long ice cores in DML (Wilhelms, 2000; Oerter et al., 1999; Karlöf et al., 2000). The locations of these ice cores drill sites can be seen in Fig. 3.

The subglacial topography has been derived by subtracting the ice thickness grid from the surface topography given by Bamber and Huybrechts (1996). Below the floating ice shelfs along the coast, the subglacial topography has been replaced by data of the "TerrainBase Global Terrain Model" of the National Geophysical Data Center and World Data Center-A for Solid Earth Geophysics, Boulder, CO, USA. The ice thickness data described above have been incorporated into the Bedmap project (Lythe et al., submitted). Bedmap has been set up in order to compile new data sets of ice thicknesses and bed topography covering Antarctica and to provide these data sets for further usage.

In order to make Fig. 3 less complex, just the three major ice streams and outlet glacier (Jutulstraumen, Bailey Ice Stream and Slessor Glacier) as well as the German wintering base Neumayer have been

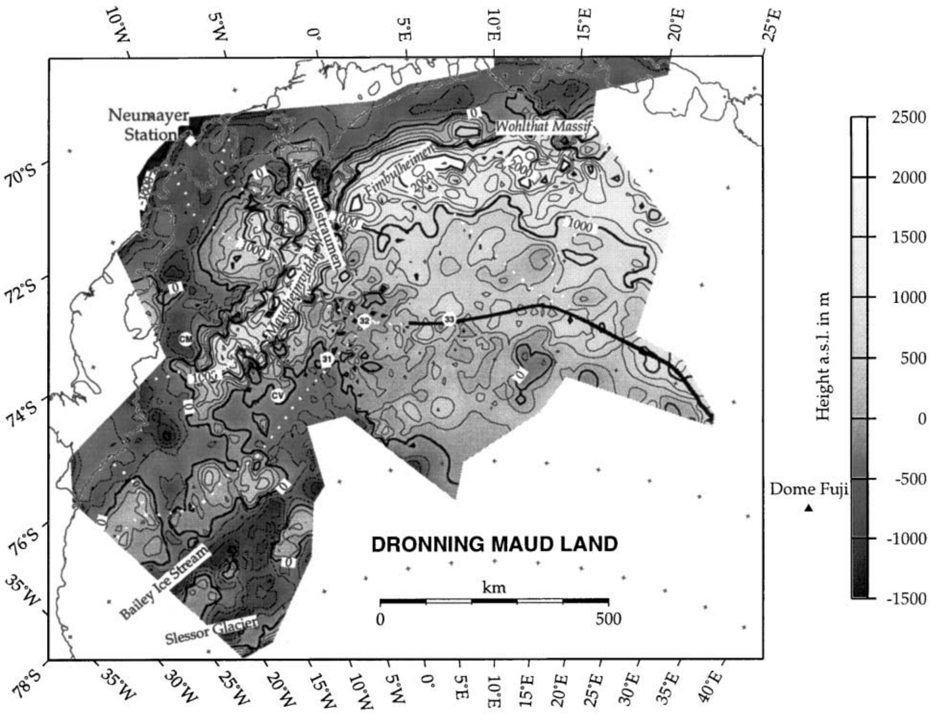

Fig. 3. Subglacial elevation of central and western Dronning Maud Land, contour line spacing 250 m. The ice free summits of the mountains are not especially marked. The bold black line between 3.5°E/75.2°S and 28.4°E/76.5° indicates the position of flight track 992136 shown below in Fig. 4 and the white dotted lines mark ice divides. The white circles indicate the location of ice core drill sites in DML.

shown. In the west, one can clearly recognize the channels below sea level of Slessor Glacier and Bailey Ice Stream. Close to the center, around 3°W, the Jutulstraumen cuts through the coastal mountains, separating Maudheimvidda in the west from Fimbulheimen in the east. Another interesting feature is the large basin slightly below sea level southwest of the Jutulstraumen as well as the smaller basin around 12°E and 76.25°S.

4. Internal structure

Internal layers can be detected and traced for several hundred kilometers by using the short (60 ns) burst with its 5 m vertical resolution. They are caused by density variations within ice sheets, mainly in the upper few 100 m, and by enclosure of volcanic ashes and acids (Harrison, 1973; Fujita et al., 1999; Robin et al., 1969). Internal layers are regarded as isochrones although they generally result not from a single snow fall but by a series of snowing events throughout a longer period, up to several years (Vaughan et al., 1999). Fig. 4(b) shows eight arbitrarily chosen internal horizons as well as subglacial and surface topography. See Fig. 3 for exact position of the profile 992136, which follows the ice divide in that region. The highest and lowest internal horizons have been chosen to be traceable as far as possible on most profiles within the sub data set. The location of bed reflections are indicated by segments of the bold black line on top of the grey shaded subglacial bed. The latter has been obtained by sampling the map shown in Fig. 3 along the profile. The figure shows clearly a decrease in amplitude of the internal layers with increasing height above the bed. As a consequence, the distance between the layers is larger above depressions than above crests of the bed. The general dipping of the layers of about 120 m from southeast towards northwest is caused by a general increase of the accumulation rate from approxi-

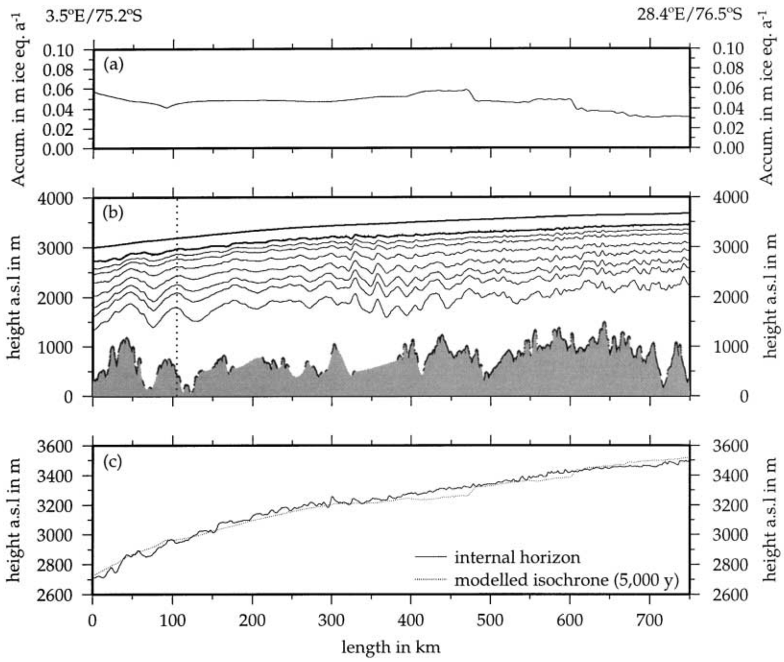

Fig. 4. (a) Accumulation rate along the profile 992136 (Ühlein, personal communication, 1999). (b) Several picked internal layers of profile 992136. The first 105 km up to the dotted line mark the section shown in Fig. 2. (c) Comparison of the calculated 5000 year isochrone using the Nye time scale (Paterson, 1994) and the accumulation rate presented in (a) with the highest picked internal layer, bold line in (b).

mately 0.033 to 0.063 m a^{-1} (Watanabe et al., 1999; Oerter et al., 2000). The variation of the accumulation shown in Fig. 4(a) has been taken from an accumulation map by Ühlein (personal communication, 1999). Using the Nye time scale (Paterson, 1994), it is possible to calculate the age at a certain depth based on a knowledge of the ice thickness, the accumulation rate and the precondition of the absence of basal melting and horizontal advection within the ice. Because the profile is flown along the ice divide where the horizontal movement of the ice is negligible, the Nye time scale can be used. Fig. 4(c) shows the depth of the highest internal horizon of Fig. 4(b) together with the modelled 5000 year isochrone. The good agreement of the two graphs indicates that, indeed, internal layers can be considered as isochrones. Yet it is not possible to determine the age of the internal layers with the simple Nye time scale with an adequate precision due to the logarithmic term within the Nye time scale and the interpolation of the accumulation rate along the discussed profile.

Fig. 5 shows a contour map of the lowest internal horizon, ranging from about 1000 m a.s.l. in the east to approximately 2300 m in the west. Because the

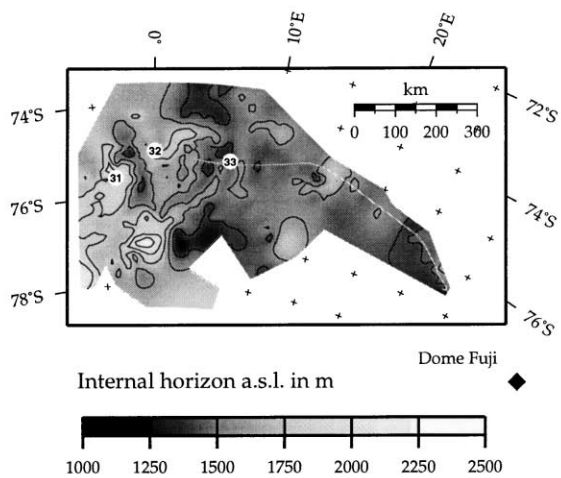

Fig. 5. Map of the deepest internal horizon of Fig. 4, contour interval 200 m. The white line indicates the position of the profile 992136.

toggle mode was not available from the beginning of the RES survey, the area covered by this map is much smaller than the investigated region. The extent is also limited by the coastal mountains of Maudheimvidda and Fimbulheimen where subglacial topography and ice dynamics make it impossible to follow this deep horizon.

If the investigated area could be extended further east or if there would be a flight up to Dome Fuji, it would be possible to transfer a depth age scale from the ice core drilling there to the planned drilling in DML. This has been shown by Siegert et al. (1998) for the deep ice core drillings at Dome Concordia and Vostok.

5. Conclusions

Results of the extensive airborne RES survey of AWI in DML, here summarized as a map of the subglacial topography and of an internal layer, are substantial contributions in the discussion within the EPICA community for a deep ice core drill site in the Atlantic sector of Antarctica. The newly derived subglacial topography as well as the ice thickness data set are a necessary base for all involved to decide where to locate the hole. Due to the ability to toggle between a long pulse with large penetration depth and a short one with high resolution, it is possible to gain a more detailed understanding of the ice sheet. The latter shows the layering within the ice sheet and will provide important information for ice dynamic modelling studies.

The map of the subglacial topography (Fig. 3) reveals the extent of the coastal mountain chains of Maudheimvidda and Fimbulheimen to the south, and deep valleys intersecting them. It also clearly shows the deep bed of Jutulstraumen, Bailey Ice Stream and Slessor Glacier, the major outlets of the ice sheet in this sector, as well as a bumpy region towards the interior of Antarctica, south of the coastal mountains. Since the austral summer 1996/1997, it has been possible to map internal layering at high resolution concurrently with the ice thicknesses. This is shown in detail in the right part of the section in Fig. 2 and for the whole profile in Fig. 4.

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