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Deep Radio Echo Soundings in the Vicinity of GRIP and GISP2 Drill Sites, Greenland

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Summary: Surface based radio echo soundings with a specially designed burst system in the areas around the ice core drill sites GRIP and GISP2 in the central part of the Greenland ice sheet are presented. Digitally recorded and processed data sets show reflections from bedrock at ice thicknesses of more than 3 km and internal layerings in the ice sheet. The bedrock topography appears to be smoother in the close vicinity of the drill holes compared to more undulating bedrock in the south. The internal layerings show different behaviour above a bedrock trough between GRIP and GISP2 compared to most of the recorded data. The maximum ice thickness of 3400 m ±26 m is found 80 km south of GRIP.

Zusammenfassung: Boden-EMR-Messungen (Elektromagnetisches Reflexions-Verfahren) aus der Umgebung der Eiskernbohrungen GRIP und GISP2 im zentralen Teil Grönlands, die mit einer speziell entwickelten Burst-Apparatur durchgeführt wurden, werden vorgestellt. Digital aufgezeichnete und bearbeitete Datensätze zeigen Reflexionen vom Felsuntergrund bei Eisdicken von mehr als 3 km und interne Schichtungen im Eisschild. Die Topographie des Felsuntergrundes erscheint glatter in der näheren Umgebung der Bohrlöcher verglichen mit stärker gewelltem Felsuntergrund im Süden. Die internen Schichten zeigen unterschiedliches Verhalten über einem Felstrog zwischen GRIP und GISP2 verglichen mit dem größten Teil der aufgezeichneten Daten. Die maximale Eisdicke von 3400 m ±26 m wurde 80 km südlich von GRIP gefunden.

INTRODUCTION

In the years 1989 to 1992 a total of 4 expeditions to the ice cap in central Greenland were carried out for geophysical and geodetic investigations along the EGIG (Expedition Glaciologique Internationale au Groenland) line. This line was first set up in 1959 as a durable line across the Greenland ice cap to watch various glaciological parameters over a longer period of time (HOFFMANN 1973). A junction from the point T43 („Crête“, 71° 07.2' N, 37° 19.8' W) on the EGIG line to the ice core drill sites GRIP („Greenland Ice Core Project“, 72° 34.5' N, 37° 37.6' W) and GISP2 („Greenland Ice Sheet Program 2“, 72° 34.6' N, 38° 27.8' W) at the summit of the ice cap was established additionally to connect results from measurements on the EGIG line to data from the new ice cores. Airborne measurements along the EGIG line (GUDMANSEN 1975) and in the area of the summit of the ice cap (HODGE et al. 1990) were carried out in earlier years to find optimum drill locations. Now along these tracks and between the new drill sites (Fig. 1) several surface based radio echo soundings were performed to examine bedrock topography and internal layerings within the ice. Of special interest to drillers as well as to modelers are the areas around the drill sites. Therefore in this paper only data are presented that were recorded in the direct vicinity of GRIP and GISP2, on the track between the two drill sites and on the junction to the EGIG line.

EQUIPMENT

Two different radio echo sounding systems had to be run simultaneously for different aims. To get reflections from internal layerings with high resolution a 35 MHz single pulse radio echo sounder based on a modified sampling system and a digital audio PCM recorder were used. This allowed measurements of internal layerings down to about 1000 m below the ice surface. With reduced resolution it was possible to get reflections from down to 1500 m. The main results from these measurements will be presented in a different publication.

For the investigation of bedrock topography a system with higher energy to penetrate the ice sheet at thicknesses of more than 3000 m was necessary. A 35 MHz burst transmitter with a specially designed high gain antenna array mounted on skis was built for this purpose. On the receiver side amplifiers with logarithmic characteristics were used to detect bedrock reflections and deep internal layerings. Data acquisition was done by a computer based recorder with optical disk storage that operated on a sledge. Online up to 2048 traces were digitally averaged to reduce noise and enhance the dynamic range of the system. The depth resolution had to be reduced to $1/20^{th}$ of the resolution of the single pulse equipment. Due to recovery effects of the amplifiers there are no signals in the depth range between 0 and 1000 m below surface. However, this range is covered by the single pulse system. Both radio echo sounding devices were developed at the Forschungsstelle für physikalische Glaziologie, University of Münster and optimized in the field.

These two systems were run parallel from sledges during movement on the ice. Traces were recorded at intervals of 10 m with the single pulse sounder. With the burst system the trace spacing was enlarged to 10-30 m. This depended on the desired trace length and the number of averages that were used for noise reduction. Navigation was done by GPS (Global Positioning System) which allowed measurements on the same tracks during different field seasons.

DATA PROCESSING

Except for one medium resolution profile this paper will deal

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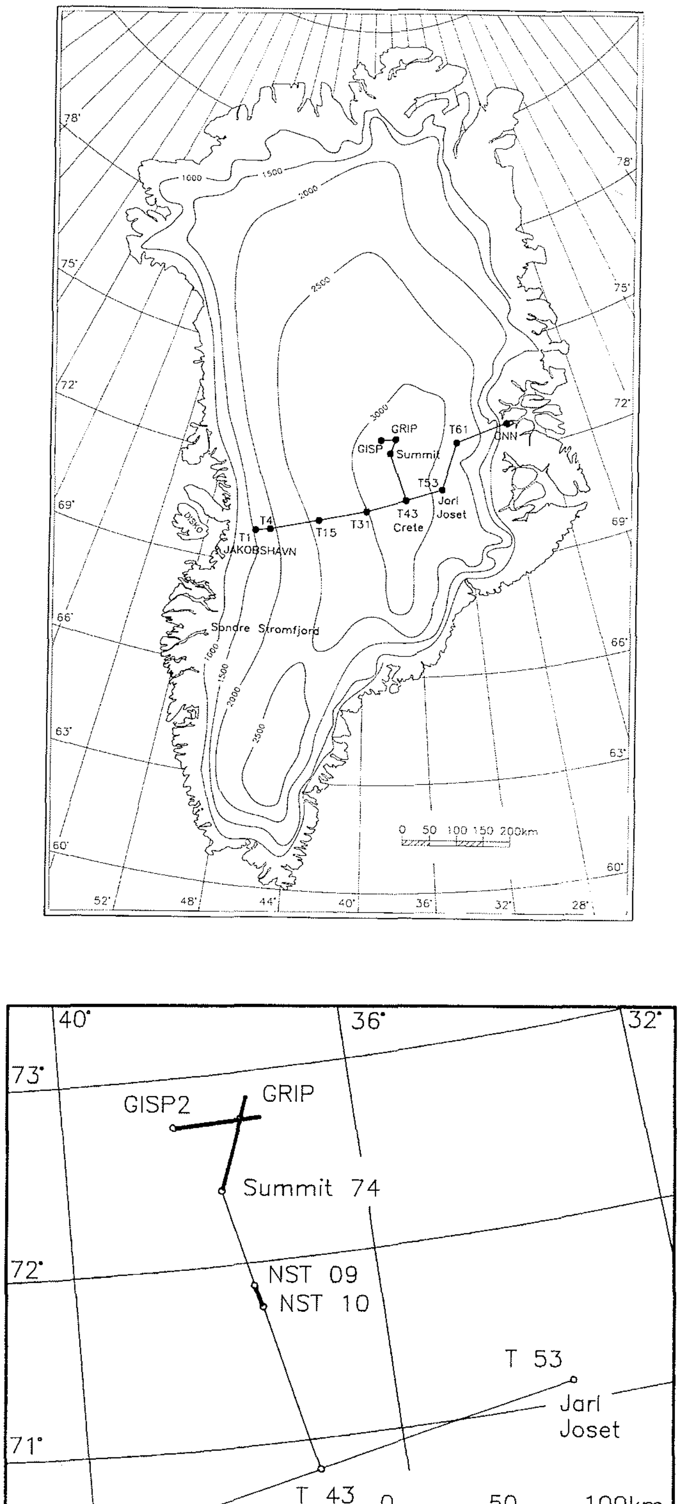

Fig. 1: Map of the central Greenland ice cap ((a) JONAS unpubl.). Lines mark the EGIG line and the junction to the two ice core drill sites GRIP and GISP2 along which radio echo soundings were performed. Bold lines in blow-up (b) mark the tracks where the presented data were obtained.

Abb. 1: Karte der Eiskappe in Zentralgrönland ((a) JONAS unpubl.). Die Linien markieren die EGIG-Linie und die Verbindung zu den beiden Eiskernbohrstellen GRIP und GISP2, entlang derer EMR-Messungen durchgeführt wurden. Die fetten Linien in (b) markieren die Strecken, auf denen die gezeigten Daten gewonnen wurden.

with data sets recorded with the the burst system showing the bedrock topography and low resolution internal layerings in more than 1000 m depth. All these records were processed digitally with a software package specially designed for the used radio echo sounders. The processing consisted roughly of the following steps: a differentiation filter to enhance details and to remove offsets that were produced by the logarithmic amplifier, a low pass filter to reduce high frequent noise and an automatic gain control to compress the dynamic range within the traces for the print out.

To calculate internal layer depths and ice thicknesses from the reflection times the velocity depth function of electromagnetic waves in ice had to be determined by CMP (Common Mid

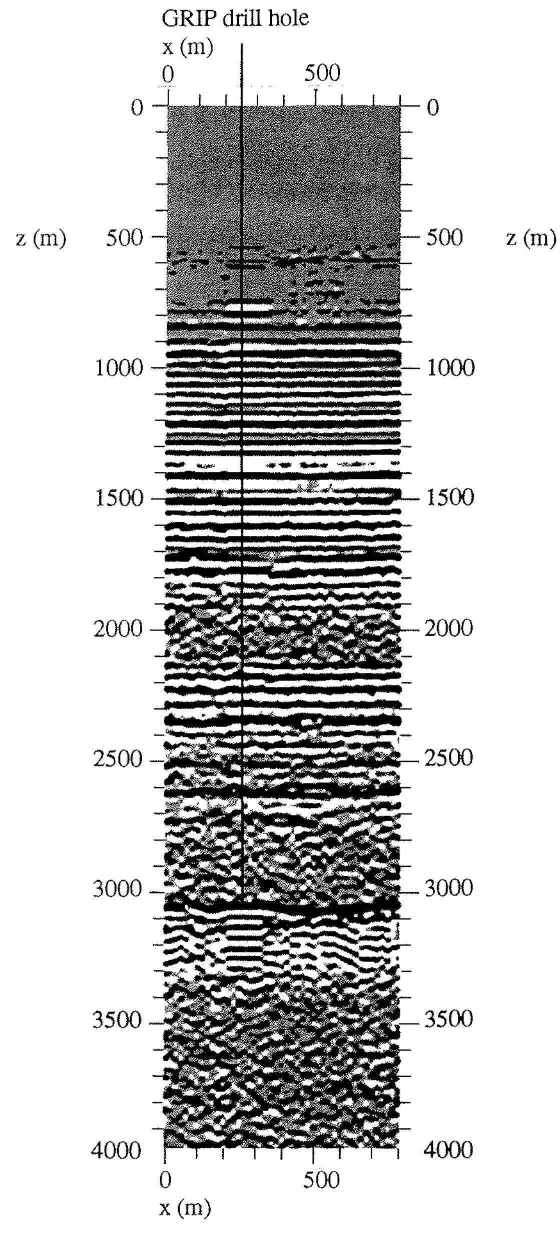

Fig. 2: Radio echo sounding at the GRIP drill hole where an ice thickness of 3050 m ±26 m was found.

Abb. 2: EMR-Messung am GRIP-Bohrloch, wo eine Eisdicke von 3050 m ±26 m gefunden wurde.

Point) measurements. These were carried out at certain points along the lines and at GRIP and GISP2. The precision of this velocity depth function was sufficent to identify certain strong reflections as acid layers within ice cores (HAMMER 1980). These deposits from volcanic eruptions were dated precisely in the GRIP ice core by JOHNSEN et al. (1992). The reflections can be traced with a precision of ±2 m along the whole track from the drill site GISP2 to GRIP, to the EGIG line and along the EGIG line itself to about 100 km from the west coast of Greenland. Because of the known age of these acid layers the reflections represent isochrones within the ice along these lines.

MEASUREMENTS AROUND GRIP AND GISP2

All presented data sets were measured around the GRIP and GISP2 drill sites and on the junction to the EGIG line. The short section in Fig. 2 was recorded on a track passing the GRIP drill hole in a distance of approximately 20 m. At this point an ice thickness of 3050 m ±26 m below the surface of 1991 can be calculated. Drill activity at GRIP was shut down at a depth of 3028.8 m below the 1990 surface. As the drill was not brought down to the bedrock itself but stopped in an area of silty ice above, it can be assumed that the calculated ice thickness is well within the error estimate. The grey zone between surface and about 1000 m depth results from amplifier recovery effects.

Fig. 3a shows data recorded between GISP2 and GRIP drill sites nearly in west to east direction. It turns out that the ice thickness at GISP2 of 3042 m ±26 m is only slightly less than that at GRIP. As the difference in surface elevation between the two drill sites is less than 30 m this figure can nearly be taken as an image of the rock basis. Bedrock topography appears to vary within a range of 200 m at a mean ice thickness of approximately 3050 m between GRIP and GISP2 except for a valley 2-7 km west of GRIP with an ice tnickness of approximately 3200 m.

The depth interval without reflections in 1900-2100 m below surface corresponds to the time interval of 20,000-30,000 B.P. (JOHNSEN et al. 1992) and the internal layerings below 2100 m depth to the time interval of 30,000-50,000 B.P. which both

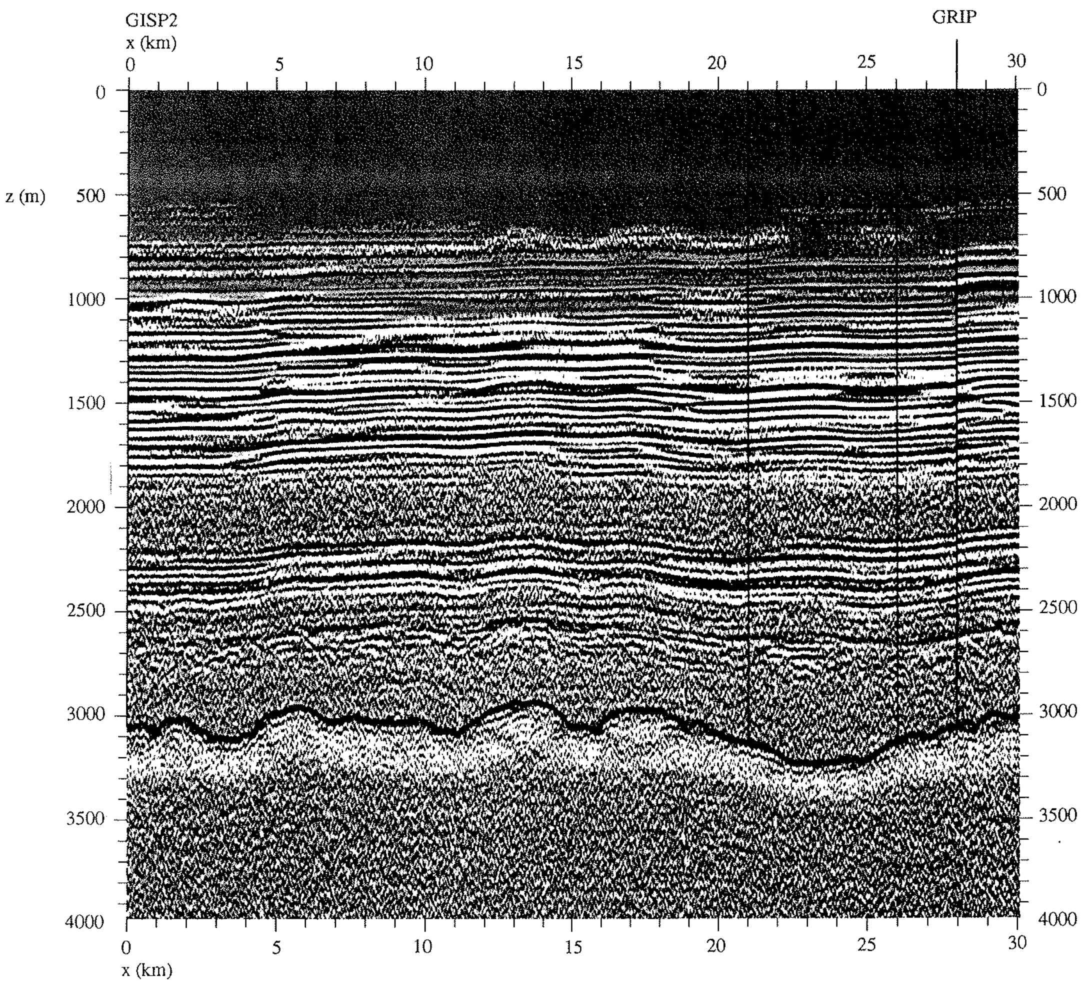

Fig. 3a: Radio echo sounding between the ice core drill sites GRIP and GISP2 in west to east direction. In the marked area, structures in the Wisconsin and in the Holocene ice rise above a valley at bedrock which might indicate a former icedevide.

Abb. 3a: EMR-Messung zwischen den Eiskernbohrstellen GRIP und GISP2 in West-Ost Richtung. In dem markierten Gebiet steigen die internen Strukturen im Wisconsin- und im holozänen Eis über einem Tal am Felsgrund an, was eine ehemalige Eisscheide andeuten könnte.

are in the Wisconsin ice age. Usually these layerings follow the bedrock topography with reduced amplitude of undulation on most of the track. However, GUNDESTRUP (pers. comm.) pointed out that in the area above the bedrock valley west of GRIP these layerings seem to take the opposite direction compared with the bedrock. Fig. 3b shows a magnification of this area with bedrock reflections and the lower internal layerings. Here it is obvious that despite the valley at bedrock all the internal layerings rise especially in the lower Wisconsin part with a slight shift of the peak position towards GRIP in the upper Holocene part. This effect can be found as well in high resolution measurements in layerings up to 400 m below ice surface. Fig. 3c shows data recorded on the same track with the single pulse system parallel to the burst system. For an easy comparison the lower part of the burst data including the bedrock reflection is shown with different vertical scale below the high resolution data. Here as well a slight trend of the peak elevation towards GRIP with decreasing depth is found. Assuming that there are no lateral bedrock structures which could have influenced the measurements this would mean that there was only snow accumulation and densification but hardly any ice flow in any particular direction to the sides in this area during the Wisconsin ice age. This might indicate that at least during the last glaciation the icedevide at the summit of the Greenland ice cap was shifted only about 5 km to the west of GRIP which is located at the present top of the ice sheet. This effect, however, may as well be due to some trough structures at bedrock with small transverse extensions. Such 3-dimensional bedrock structures

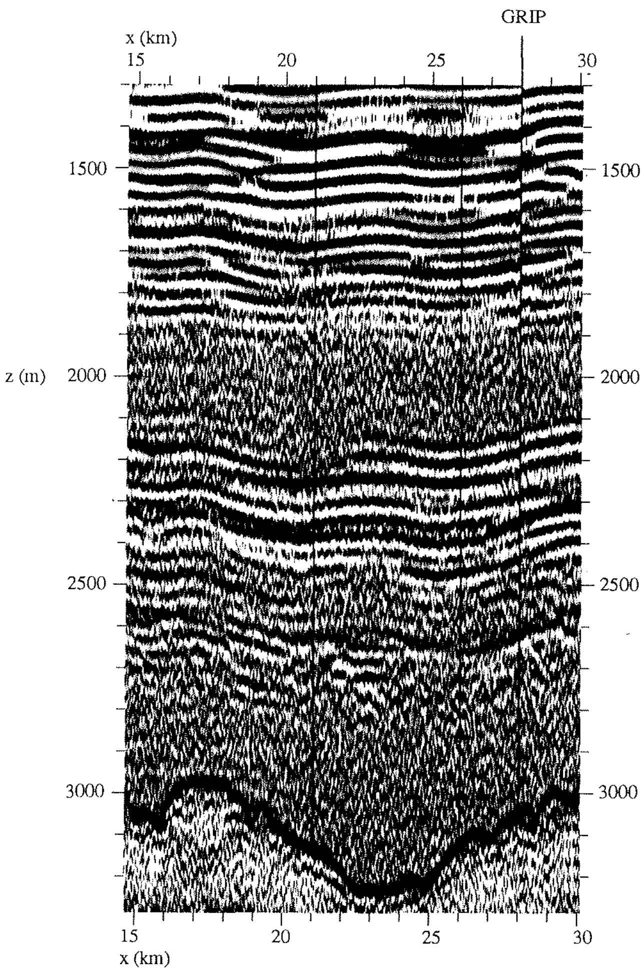

Fig. 3b: Blow-up of Fig. 3a showing the area west of GRIP. This shows the lower part of the Holocene ice, the Wisconsin ice and the bedrock.

Abb. 3b: Ausschnittvergrößerung der Abb. 3a westlich von GRIP. Sie zeigt den unteren Teil des holozänen Eises, das Wisconsin-Eis und den Felsgrund.

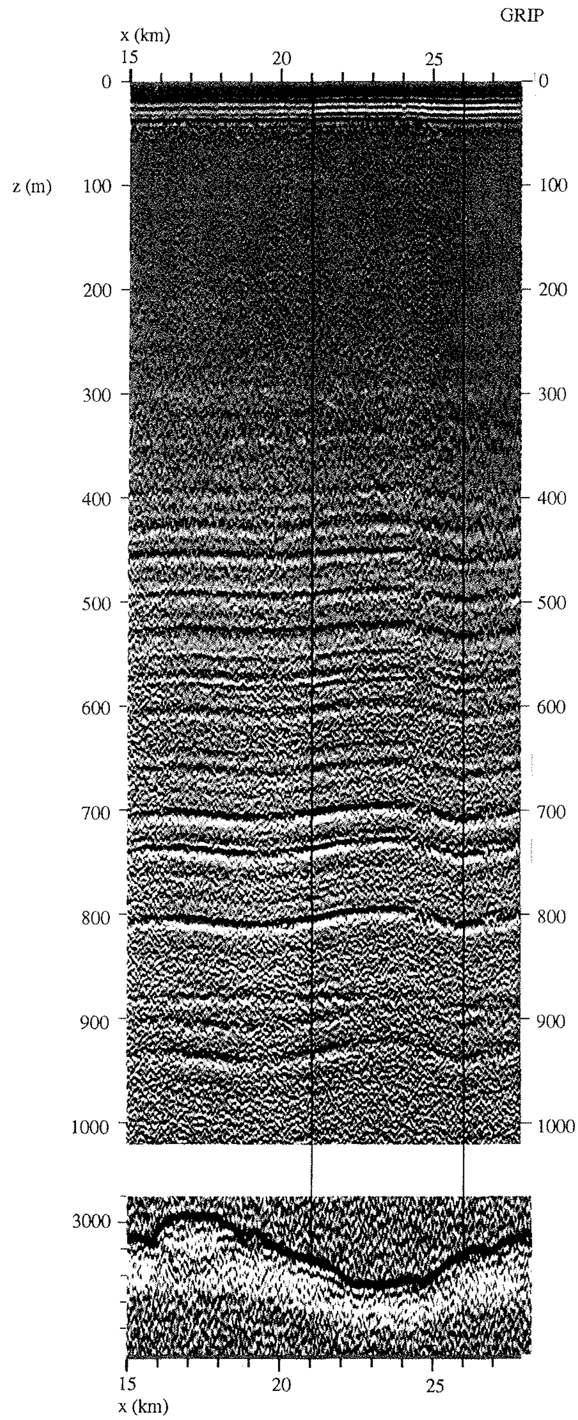

Fig. 3c: High resolution radio echo sounding between the ice core drill sites GRIP and GISP2. For a comparison with the internal structures of the Holocene ice the bedrock is shown below with different vertical scale.

Abb. 3c: Hochauflösende EMR-Messung zwischen den Eiskernbohrstellen GRIP und GISP2. Zum Vergleich mit den intemen Strukturen des holozänen Eises ist darunter der Felsgrund in unterschiedlichem vertikalen Maßstab abgebildet.

cannot be detected by the radio echo sounder because of the narrow beam radiated by the antenna array. Therefore there are nearly no refractions or reflections visible from the sides of the tracks.

The cross section from the summit of the ice cap that was defined in 1974 („Summit 74", 72° 17.1' N., 37° 58.8' W.) to GRIP is shown in Figure 4. From Summit 74 to the north a mountainous area with rough bedrock relief and peak to trough amplitudes of up to 250 m is followed by a smooth bedrock plain with an ice thickness of about 3325 m. Behind a steep hill at bedrock of more than 300 m height above the plain and a slope of approximately 10% the GRIP drill site itself appears to be above the gentle slope of a flat hill with about 150 m elevation. In general the internal layerings follow the bedrock topography over this track although along the plain there is a trend upwards in the direction of GRIP of more than 100 m.

Fig. 5 shows the maximum ice thickness recorded along the whole track from GRIP to Crête and on the EGIG line. This was found about 80 km south of GRIP half way to the EGIG line between points NST10 (71° 42.3' N., 37° 43.1' W.) and NST08 (71° 52.2' N., 37° 46.1' W.). It could be evaluated to be 3400 m ±26 m at the deepest point of the valley which is located 2-5 km north of NST10. As the elevation of the ice surface at this point is 3188 m a.s.l. (KOCK, pers. comm.) this valley corresponds to a depression of 212 m below sea level. Internal layerings above this valley do not seem to follow bedrock topography in a small scale. Instead there is a slight uplift 3 km north of NST10 that might also be due to some 3-dimensional bedrock structures aside of this valley.

CONCLUSIONS

Surface based radio echo soundings in the vicinity of GRIP and GISP2 ice core drill sites and on the junction to the EGIG line show detailed bedrock reflections and internal layerings. Both drill sites appear to be above a relatively flat rock base which means that they are located on undisturbed ice layers. More rough terrain with slopes of more than 10% and peak to trough amplitudes of more than 300 m are found in the south of GRIP along the junction to the EGIG line. Internal layerings in general follow the bedrock topography except for small scale variations and an area only about 5 km west of GRIP. Here a contrary behaviour is found in all layers from the bottom to about 400 m below surface. However, it can not be decided whether this phenomenon shall be interpreted as a possible ice devide during the last glaciation or if this is caused by bedrock topography aside of the lines.

ACKNOWLEDGMENTS

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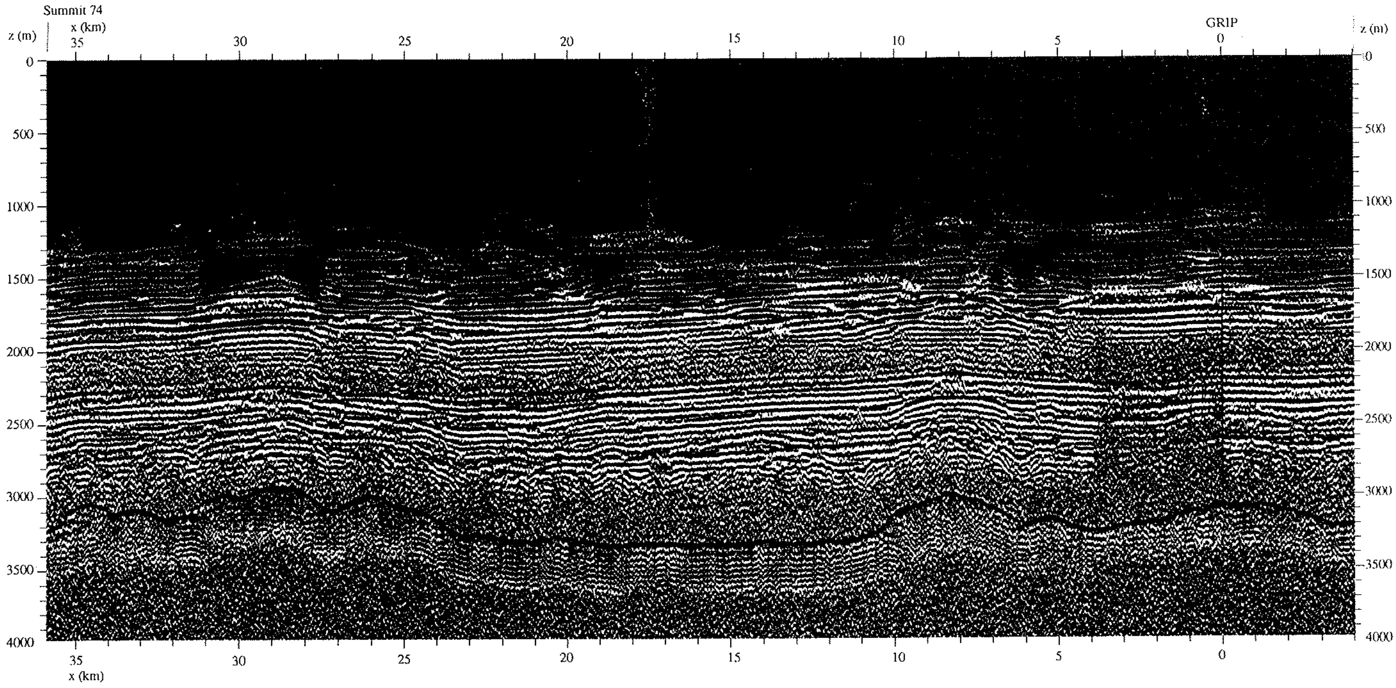

Fig. 4: Cross section of Fig. 3 in south to north direction from Summit 74 to the GRIP ice core drill site.

Abb. 4: Querprofil zu Abb. 3 in Süd-Nord-Richtung von Summit 74 zur GRIP Eiskernbohrung.

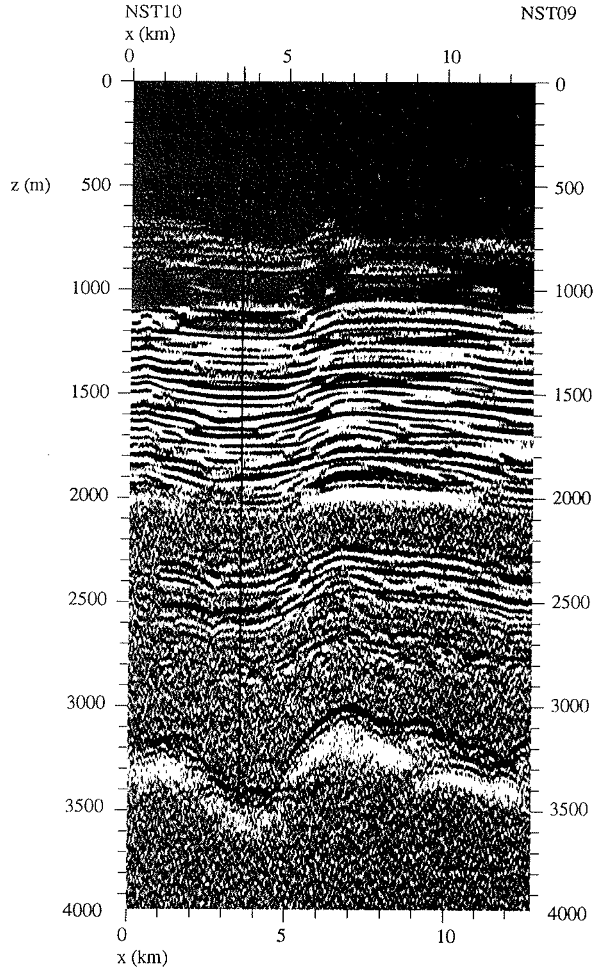

Fig. 5: Radio echo sounding 80 km south of GRIP on the junction from GRIP to the EGIG line in south to north direction. The arrow points to the maximum ice thickness measured on the whole track of 3400 m ±26 m.

Abb. 5: EMR-Messung 80 km südlich von GRIP auf der Verbindung von GRIP zur EGIG-Linie in Süd-Nord-Richtung. Der Pfeil zeigt auf die größte Eisdicke von 3400 m ±26 m, die auf der gesamten Strecke gemessen wurde.

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