

LAYER ECHOES IN POLAR ICE SHEETS

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ABSTRACT. A multitude of extensive layers have been observed by radio-echo soundings in Greenland. By comparison with the stable isotope profile from Camp Century it is found that layering in the top of the ice has been formed in the period since the last glaciation. Radio-echo layers observed at greater depths in central Greenland may have been created in the period of the interstadials and further down possibly in the period prior to the last glaciation. Further investigations are needed to prove this.

RÉSUMÉ. Niveau d'échos dans les calottes glaciaires polaires. Une multitude de larges niveaux de réflexion ont été observés lors de sondages par radio-écho au Groenland. Par comparaison avec le profil des isotopes stables provenant de Camp Century on trouve que la formation de niveaux dans le haut de la calotte date de la période écoulée depuis la dernière glaciation. Les niveaux d'échos radios observés à de plus grandes profondeurs dans le Groenland central peuvent s'être créés dans les périodes interstadias et plus bas encore ils peuvent dater de la période précédant la dernière glaciation. Il faudrait de nouvelles recherches pour apporter des preuves.

ZUSAMMENFASSUNG. Schichtechos in polaren Eisdecken. Eine Vielzahl ausgedehnter Schichten wurde durch Radar-Echolotung in Grönland beobachtet. Aus dem Vergleich mit dem Isotopen-Profil von Camp Century ergibt sich, dass die Schichtung im Scheitelbereich des Eises in der Zeit seit der letzten Eiszeit ausgebildet wurde. Schichten, die mit Radar-Lotung in grösseren Tiefen Zentral-Grönlands beobachtet wurden, können in der Zeit der Interstadias und noch tiefer unten möglicherweise vor der letzten Eiszeit entstanden sein. Ein Beweis hierfür erfordert weitere Untersuchungen.

1. INTRODUCTION

Radio-echo soundings have revealed stratifications in polar ice sheets. Thus Robin and others (1969) describe from soundings in 1964 intermittent echoes apparently returned from a single layer on a track south of Camp Century in north-west Greenland. Other soundings carried out by the Danmarks Tekniske Højskole in 1969 showed a multitude of extensive layers in central Greenland briefly reported by Gudmandsen (1970). Harrison (1973) shows the geographical distribution of layer echoes as obtained by the Scott Polar Research Institute in Antarctica between 1969 and 1971.

The one thing which may be said with certainty about the origin of the layer echoes is that they are caused by changes of the permittivity of the ice, but what the mechanism is that caused these changes is still an open question. Robin and others (1969) showed that a small change in ice density in an isolated thin layer relative to its surroundings gives a reflection coefficient of sufficient magnitude to explain the observed echo. Harrison (1973) finds that variations of ice crystal orientation best explain the changes in permittivity at large depths while density variations and refrozen melt associated with ash layers may account for permittivity changes in the top hundred metres. G. de Q. Robin (private communication in 1973) suggests that changes in the impurity level of the ice may cause changes in the permittivity (changes of the loss tangent).

The other thing which may be stated about the layer echoes is that they extend almost continuously over hundreds of kilometres and thus seem to establish time horizons of a mechanism as yet unknown which occurred when the layer in question was at the surface.

This paper gives a short account of some observations related to layer echoes recorded during Danmarks Tekniske Højskole Greenland soundings in 1969, 1971, 1972, and 1974.

2. LAYER ECHOES AND DRILL-HOLE CORE DATA

Correlation between radio-echo soundings and physical data for the ice as obtained from cores recovered from drillings may be difficult to establish for a number of reasons.

One reason is the difference in resolution in the two cases. The finest resolution of a sounder today is of the order of five metres (pulse width of 60 ns) whereas the core data have a

resolution of the order of centimetres. Thus, a layer echo may be the pulse response of a number of permittivity variations within the resolution distance of the sounder. Also, it appears very difficult to ascertain how permittivity variations of different magnitude and uneven separation combine to form a layer echo. For that reason Harrison (1973) has adopted a statistical approach for calculation of the order of magnitude of the reflection coefficient assuming a statistically stationary random variation of the permittivity with depth.

Another reason for the difficulty of carrying out a proper correlation analysis is the rather small accuracy of the absolute position of a layer echo. Uncertainties are present due to factors such as the ice density variation in the upper part of the ice, the signal-to-noise ratio of the received signal, the pulse response of the layers and the time delay in the receiver. Due to the variability of signal strength it seems very difficult to overcome these uncertainties which may give an inaccuracy of a layer position of about 50 m in the worst case, e.g. when a long pulse of 1 μ s and a corresponding receiver bandwidth of 1 MHz is employed for instance. With a short pulse of 60 ns and a bandwidth of 14 MHz the corresponding figure is about 25 m.

Still another reason is that the majority of drill holes are not deeper than 400 m. Since the echo from the ice surface is very large it is normally not possible to observe layer echoes in the upper 200–300 m due to the receiver recovery phenomenon, so that a correlation with core data does not become meaningful when carried out over only 100–200 m of core.

However, the data from the deep core drilling at Camp Century (lat. $77^{\circ} 10' 53''$ N., long. $61^{\circ} 08' 33''$ W.) which reached the bedrock at 1 387 m (Hansen and Langway, 1966) is available for correlation with our soundings. Figure 1 shows the Z-scope display of the differentiated received signals at Camp Century. It is seen that layer echoes are observed in the depth interval 300–1 100 m. When this recording is compared with the core data it is observed that the deepest layer corresponds to the end of the last glaciation about 10 000 years before

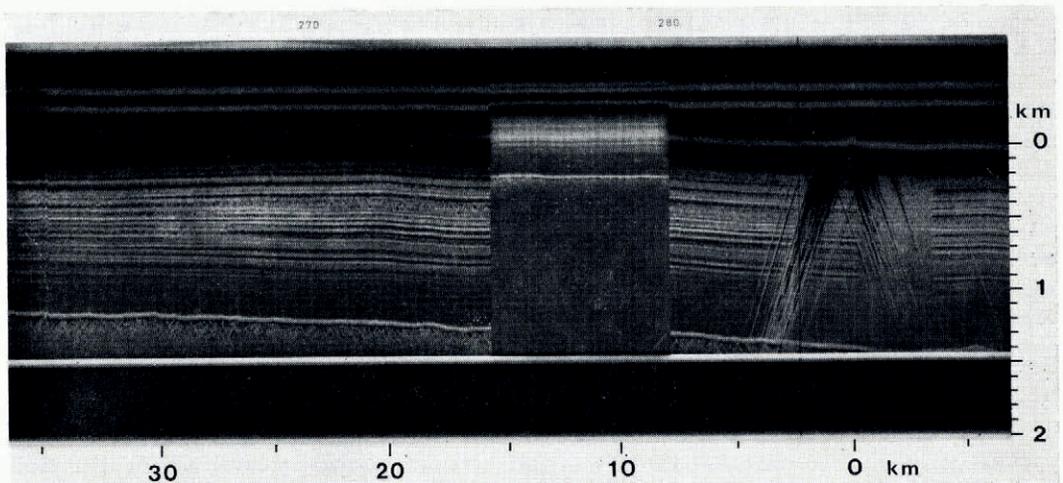


Fig. 1. Radio-echo sounding at Camp Century (lat. $77^{\circ} 10' 53''$ N., long. $61^{\circ} 08' 33''$ W.) on an approximately west-to-east track, 110 degrees true. Camp Century is situated at 0 km, where the elevation of the surface is 1 835 meters and the ice thickness is 1 387 meters.

It is seen that the ice thickness increases towards east and that the aircraft increases its altitude relative to the ice surface in the same direction.

The hyperbolic lines extending from the surface at Camp Century are caused by past camp construction activity. In the centre of the picture the sweep rate of the radar oscilloscope has been increased for a short time interval.

The recording was made in 1972 by means of a 60 MHz airborne radar with a transmitter power of 1.6 kW, a pulse width of 250 ns and a receiver bandwidth of 4 MHz.

present. This may be seen from Figure 2 which is a record of $\delta(^{18}\text{O})$ versus depth obtained from the Camp Century core by Dansgaard and others (1973). In this figure the observed layer echoes have been indicated by horizontal lines, the longer lines indicating "large" echoes (it should be recalled that a "large" echo represents a signal with a large rise time). The lowest horizontal line is shown in parentheses since it represents a layer observed about 30 km west of Camp Century which faded away before Camp Century, but was recovered east of Camp Century when the equipment sensitivity was increased (longer pulse width and correspondingly less band-width and resolution).

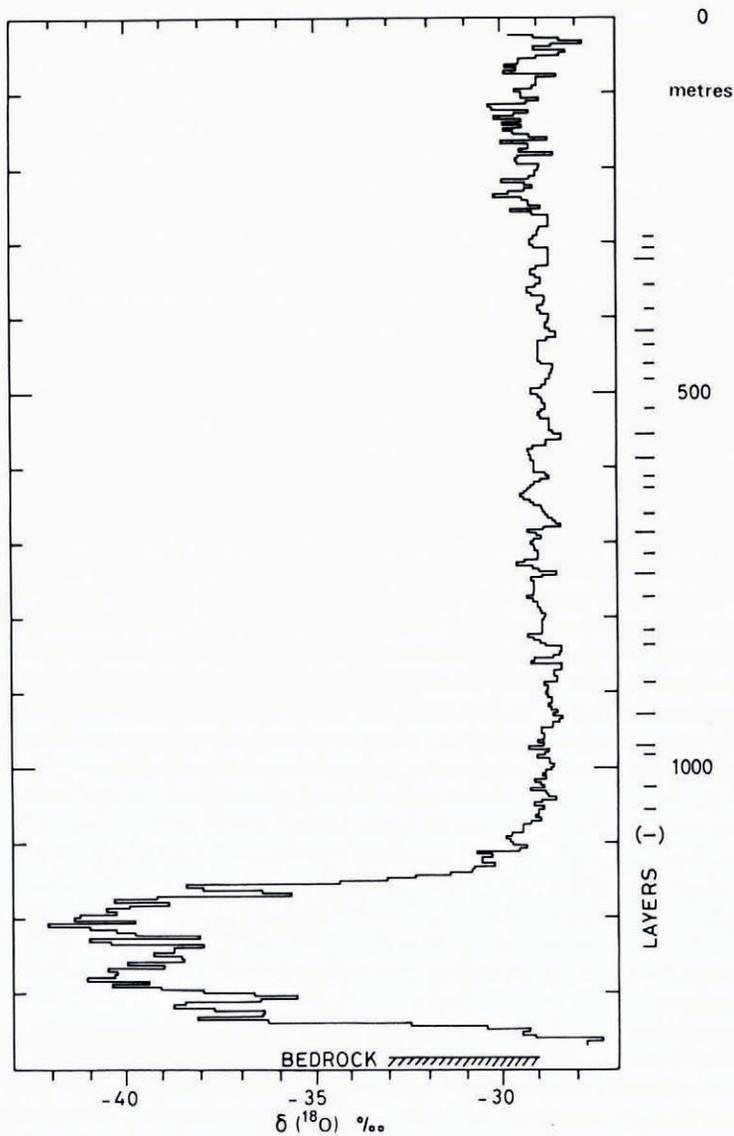


Fig. 2. Stable isotope profile from the deep core drilling at Camp Century, 1966. The $\delta(^{18}\text{O})$ data are given in four year increments. (Courtesy S. J. Johnsen, Geophysical Isotope Laboratory, Copenhagen University). Stratification as observed in Figure 1 is indicated at the depth scale; a long line represents a large echo.

The fact that the deepest observable layer coincides with the end of the glaciation leads us to believe that the layers were related to the climatic variations and thus correlated with the $\delta(^{18}\text{O})$ record. From Figure 2 it is seen that the correlation between the two sets of data is not very pronounced, but inaccuracies in the absolute position of the layer echo may account for part of the lack of correlation.

There may be two reasons why there are no layer echoes below 1 100 m at Camp Century: (1) No layers were formed during the last glaciation, which occupies most of the lower part of the core, due to the lower temperatures in that period, for instance, and/or (2) the equipment is not sufficiently sensitive to detect layer echoes at these great depths.

The latter explanation seems plausible in view of the fade-observation referred to above and can be checked. A calculation shows that a layer at 1 100 m may be detected with the present equipment if its reflection coefficient is larger than about -80 dB. This calculation (Gudmandsen, 1971) is based on the equipment parameters and involves a computation of the two-way absorption in the ice down to the layer in question employing the measured temperature profile in the bore hole (Hansen and Langway, 1966) and the measurements by Westphal of the temperature variation of the dielectric loss in ice from the TUTO tunnel, Greenland.

A reflection coefficient of -80 dB is obtained from an isolated layer of about 4 cm thickness and a fractional permittivity deviation $\Delta\epsilon/\epsilon = 0.002$. This thickness is the layer thickness at 1 100 m as calculated following Dansgaard and Johnsen (1969) assuming that the initial layer thickness is equal to the yearly accumulation at present of 35 cm.

Further calculation shows that if the radar system sensitivity be increased by about 10 dB it should be possible to detect a layer with the same reflection coefficient near to the bedrock. However, the layers become very thin at this depth so a large fractional permittivity deviation will be needed to obtain that reflection coefficient.

3. LAYER ECHOES IN CENTRAL GREENLAND

It is interesting to note that the deepest layer at Camp Century can be traced along the ice divide over many hundred kilometres to the central part of Greenland. Figure 3 shows a Z-scope display obtained at Crête (lat. $71^{\circ} 07' 13''$ N., long. $37^{\circ} 18' 59''$ W.) in 1974 where the layer at about 1 900 m is a continuation of that at Camp Century at 1 100 m. This recording was obtained with an improved radar with an increase in sensitivity of 14 dB relative to that used in obtaining Figure 1.

Based on calculations similar to those outlined above but assuming that the temperature is constant in the ice column above the layer and equal to the 10 m temperature—in this case -30°C —it may be stated that a layer at 1 900 m may be detected if it has a reflection coefficient of -85 dB. The reflection coefficient is most certainly larger than that figure; from soundings in 1972 on approximately the same flight line with the original equipment a reflection coefficient of -70 dB is estimated (Gudmandsen, 1973). It should be mentioned that the layer at 1 900 m has a calculated age of 11 000 years assuming a mean yearly accumulation of 0.27 m (Dansgaard and Johnsen, 1969).

With the improved equipment, layers are detected further down in the ice at depths between 2 300 and 2 500 m as seen in Figure 3. A calculation shows that these layers may have a reflection coefficient of -70 to -75 dB. Furthermore there are traces of layers about 200 m above the bedrock.

These calculations are based on the assumption of a constant ice column temperature which is a good approximation for the upper 2 000 m at the centre of an ice sheet with a yearly accumulation of 0.27 m (Gudmandsen, 1971). Below that depth the temperature will increase appreciably causing increased losses. The observation of layers at great depths may therefore indicate that pronounced layers with a large reflection coefficient were formed during the last glaciation and/or that the ice at great depths is colder than calculated on the basis of Budd (1969).

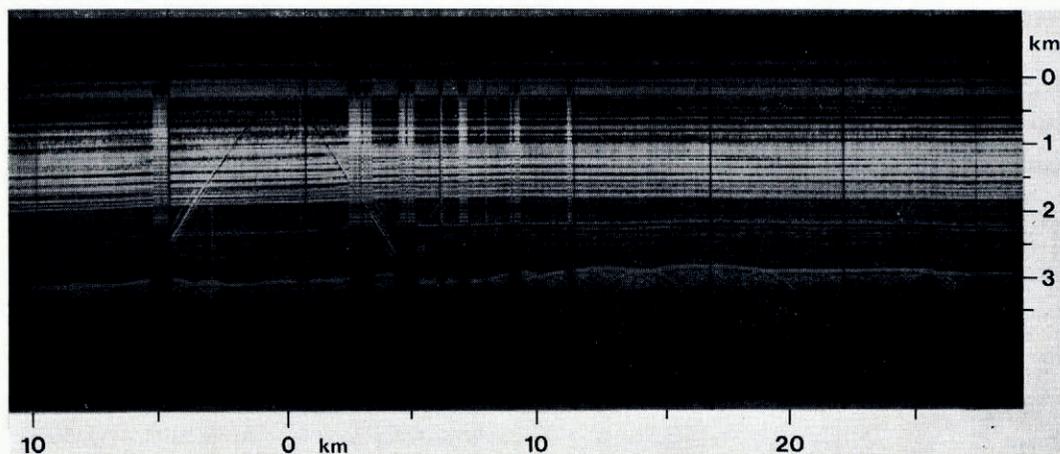


Fig. 3. Radio-echo sounding at Crête (lat. $71^{\circ} 07' 13''$ N., long. $37^{\circ} 18' 59''$ W.) on a west-to-east track along the EGIG track. Crête is situated at 0 km, where the elevation is 3 172 m and the ice thickness is 3 000 m.

The hyperbolic lines extending from the surface at Crête originate from the drilling activity in 1974. The vertical broad lines around Crête are caused by interference from the radio communication system on board the aircraft.

The recording was made in 1974 by means of a 60 MHz airborne radar with a transmitter power of 10 kW, a pulse width of 250 ns and a receiver bandwidth of 4 MHz.

It is tempting to suggest that the three layers observed at about 2 400 m were formed during the interstadials which may be seen in Figure 2 about 170 m above the bedrock. This suggestion is supported to some extent by the fact that these layer echoes can be traced over several hundred kilometres approaching the bedrock in the direction of Camp Century. Unfortunately, the 1974 soundings were discontinued due to antenna failure before arriving at Camp Century so a proof of this suggestion will have to wait for the soundings in 1975 or perhaps until a deep core drilling is carried out in central Greenland.

4. CONCLUSIONS

Radio-echo soundings in Greenland have revealed extensive layering in the northern part of the inland ice, roughly above lat. 69° N., forming almost continuous lines over many hundred kilometres. A multitude of layer echoes is observed in the upper part of the ice—at the centre of the inland ice down to about 2 000 m. A comparison with the $\delta(^{18}\text{O})$ record from the deep core drilling at Camp Century indicates that these upper layers were formed during the period from the end of the last glaciation until today. At greater depths three to four layer echoes are observed at the centre of the ice sheet which may have been formed during the interstadials. Correlation between layer echoes and the δ -record is not very pronounced possibly due to the limited accuracy in the determination of the absolute depth of a radar layer.

The data in this paper are part of more detailed reports in preparation of the radio-echo soundings carried out in Greenland. These soundings have been carried out under the auspices of Expédition Glaciologique Internationale au Groenland (EGIG) and Greenland Ice Sheet Program (GISP) by various teams from Danmarks Tekniske Højskole and were supported by Ministeriet for Grønland, Danish research foundations and the National Science Foundation, Washington, D.C., U.S.A.

Note added in proof: During soundings in Antarctica at Dome "C" (lat. $76^{\circ} 16.0' \text{ S.}$, long. $125^{\circ} 43.4' \text{ E.}$) with the same equipment and parameters as stated in Figure 3 a multitude of stratification echoes was observed down to 3 720 m with a total ice thickness of 4 220 m. The lowest layer is estimated to be more than 150 000 years old.

REFERENCES

- Budd, W. F. 1969. The dynamics of ice masses. *ANARE Scientific Reports*. Ser. A(IV). Glaciology. Publication No. 108.
- Dansgaard, W., and Johnsen, S. J. 1969. A flow model and a time scale for the ice core from Camp Century, Greenland. *Journal of Glaciology*, Vol. 8, No. 53, p. 215-23.
- Dansgaard, W., and others. 1973. Stable isotope glaciology, by W. Dansgaard, S. J. Johnsen, H. B. Clausen and N. Gundestrup. *Meddelelser om Grønland*, Bd. 197, Nr. 2.
- Gudmandsen, P. 1970. Notes on radar sounding of the Greenland ice sheet. (In Gudmandsen, P., ed. *Proceedings of the international meeting on radioglaciology, Lyngby, May 1970*. Lyngby, Technical University of Denmark, Laboratory of Electromagnetic Theory, p. 124-33.)
- Gudmandsen, P. 1971. Electromagnetic probing of ice. (In Wait, J. R., ed. *Electromagnetic probing in geophysics*. Boulder, Colorado, Golem Press, p. 321-48.)
- Gudmandsen, P. 1973. Radioglaciology—soundings at proposed drill sites. Lyngby, Technical University of Denmark, Laboratory of Electromagnetic Theory. (Report for GISP No. D 185.)
- Hansen, B. L., and Langway, C. C., jr. 1966. Deep core drilling in ice and core analysis at Camp Century, Greenland, 1961-66. *Antarctic Journal of the United States*, Vol. 1, No. 5, p. 207-08.
- Harrison, C. H. 1973. Radio echo sounding of horizontal layers in ice. *Journal of Glaciology*, Vol. 12, No. 66, p. 383-97.
- Robin, G. de Q., and others. 1969. Interpretation of radio echo sounding in polar ice sheets, by G. de Q. Robin, S. Evans and J. T. Bailey. *Philosophical Transactions of the Royal Society of London*, Ser. A, Vol. 265, No. 1166, p. 437-505.

DISCUSSION

W. F. BUDD: Why do you suppose subsurface echoes are related to the changes in the isotope ratios with depth? Is it known whether the changes in the isotope ratios affect the dielectric behaviour, or is the association indirect?

P. GUDMANDSEN: We do not expect the isotope ratio to have a direct influence on the permittivity of the ice. What I showed was an early attempt to correlate the stratification with climatic variations as observed by variations in the isotope ratio without any regard to the effect on the permittivity caused by these variations. In the present context the figures show clearly that the deepest layer observed corresponds to the end of the last ice age. Also, it shows the interstadials near to the bedrock.

W. S. B. PATERSON: As a comment on Dr Budd's question, I would point out that Langway and his associates have shown that in the Camp Century core the concentrations of particles and soluble impurities are much greater in the Wisconsin ice than in the past-Wisconsin ice.

G. DE Q. ROBIN: In my paper yesterday I suggested that the change in permittivity at great depths was due to changes in the conductivity which changes the loss tangent of the ice. On this model one is likely to see internal reflections close to bedrock more easily when the bedrock temperature is well below the freezing point while at higher basal temperatures absorption will prevent such reflections. It may also be possible to estimate temperature gradients at great depths from the variation of internal echo strengths with depth.

GUDMANDSEN: This last suggestion will require that the reflection coefficient of the stratification is the same from layer to layer. The layers in the upper part of the ice do show a large variability in reflection coefficient.

J. F. NYE: Some of us are hoping that it may be possible to measure the velocity of the top surface of the ice relative to an internal layer by using the fading pattern of the internal layer as a reference: this would be an extension of the technique discussed yesterday for measuring velocity relative to the rock bed or a basal moraine. Does the reflection from an internal layer have a horizontal variation that might be used for this purpose, and does it have a perceptible tail?

GUDMANDSEN: Unfortunately this seems not to be the case. Most of the echoes from internal layers are superimposed on the surface reflection pulse and are therefore difficult to analyse as to pulse shape. The stratification echoes observed "below" the surface pulse are all so small that they exhibit no tail. I should like to add that the differentiated signals recorded in the Z-presentation show no appreciable difference at the two frequencies—60 MHz and 300 MHz operated simultaneously—so the layers seem to be rather smooth.