# Snow-accumulation rates and isotopic content ($^2$H, $^3$H) of near-surface firn from the Filchner–Ronne Ice Shelf, Antarctica

W. Graf, H. Moser,

*GSF-Forschungszentrum für Umwelt und Gesundheit, Neuherberg, Institut für Hydrologie, D-85758 Oberschleissheim, Germany*

O. Reinwarth,

*Kommission für Glaziologie der Bayerischen Akademie der Wissenschaften, D-80539 München 22, Germany*

J. Kipfstuhl, H. Oerter,

*Alfred-Wegener-Institut für Polar- und Meeresforschung, D-27515 Bremerhaven, Germany*

A. Minikin and D. Wagenbach

*Institut für Umweltphysik, Universität Heidelberg, D-69120 Heidelberg, Germany*

ABSTRACT. The accumulation and distribution of the $^2$H content of near-surface layers in the eastern part of the Ronne Ice Shelf were determined from 16 firn cores drilled to about 10 m depth during the Filchner IIIa and IV campaigns in 1990 and 1992, respectively. The cores were dated stratigraphically by seasonal $\delta^2$H variations in the firn. In addition, $^3$H and high-resolution chemical profiles were used to assist in dating. Both the accumulation rate and the stable-isotope content decrease with increasing distance from the ice edge: the $\delta^2$H values range from about −195‰ at the ice edge to −250‰ at BAS sites 5 and 6, south of Henry Ice Rise, and the accumulation rates from about 210 to 90 kg m$^{-2}$ a$^{-1}$. The $\delta^2$H values of the near-surface firn and the 10 m firn temperatures ($\Theta$) at individual sites are very well correlated: $d\delta^2$H$/d\Theta = (10.3 \pm 0.6)$‰ K$^{-1}$; $r = 0.97$.

The $\delta^2$H profiles of the two ice cores B13 and B15 drilled in 1990 and 1992 to 215 and 320 m depth, respectively, reflect the gradual depletion in $^2$H in the firn upstream of the drill sites. Comparison with the surface data indicates that the ice above 142 m in core B15 and above 137 m in core B13 was deposited on the ice shelf, whereas the deeper ice, down to 152.8 m depth, most probably originated from the margin of the Antarctic ice sheet.

## 1. INTRODUCTION

In the framework of the German Antarctic glaciological research program, accumulation rates and the isotopic content of the near-surface layers in the eastern part of the Ronne Ice Shelf have been determined. These investig-ations have been carried out in relation to mass-balance and ice-core studies. Sampling started during the pre-site survey for the German over-wintering base in 1979–80 (Reinwarth, 1981) and has continued during the 1983–84, 1985–86, 1989–90 and 1991–92 field seasons. Accumulation rates based on the evaluation of only one 10 m firn core at Filchner Station and ten snow pits were published by Reinwarth and others (1982, 1985) and Graf and others (1988). The $\delta^{18}$O temperature relationship, though still debatable, was used for the climatic interpretation of the $^{18}$O content of a 100 m ice core (Graf and others 1990a). A remarkable step forward was taken during the 1989 90 and 1991–92 field seasons by drilling 16 firn cores to 10 m depth and two ice cores to 215 and 320 m depth. The sampling locations cover much of the central part of the Ronne Ice Shelf. Also, the area of Berkner Island (Wagenbach and others, 1994), the Filchner Ice Shelf at the ice edge and the area south of Henry Ice Rise were sampled in 1990 with the help of the German Do-228 aircraft *Polar 2* and *Polar 4*. Great effort has been expended to date the firn cores as accurately as possible by combining several stratigraphical methods. Consequently, the distribution of the accumulation rates and of the stable-isotope content of the firn, as well as the δ-temperature relationship, can now be established more accurately. The results from the two cores from the southernmost part of the ice shelf are very helpful in estimating particle paths in the ice shelf and in interpreting the structural parameters of ice cores B13 and B15.

## 2. SAMPLING AND EXPERIMENTAL PROCEDURES

Figure 1 shows the area under investigation with the drilling sites of the 10 m firn cores and of the two deeper ice cores B13 and B15. The 10 m firn core at point D246 and ice core B15 were drilled in 1992 (Oerter and others, 1992a) and the other firn cores and ice core B13 in 1990 (Miller and Oerter, 1991). As part of the glaciological program, in all locations the temperature of the firn at approximately 10 m depth was measured. The drilling sites of eight firn cores are located at or close to the flowline through B15 and B13, four sites lie on the parallel flowline 50 km to the northwest, one at Filchner Station, one in a direction toward Berkner Island and the last two on the northern and southern domes of Berkner Island, Reinwarthhöhe and Thyssenhöhe, respectively (Institut für Angewandte Geodäsie, 1993).

The bulk d.c. conductivity (ECM method) of the firn was measured in the laboratory to obtain initial information on the annual layering (Minikin and others, 1994). To ensure a consistent depth scale for all high-resolution profiles, the cores were sub-sampled in the same way for isotopic and chemical analyses. Depth resolution was designed to get at least ten samples for each annual layer according to the signals in the ECM profiles. The samples were analyzed with respect to their stable-isotope content ($^2$H, $^{18}$O) and chemical constituents. Among the chemical profiles, only the non-sea-salt (nss) sulfate records were used for dating purposes in this paper (for further details, see Minikin and others (1994)). The $^3$H contents were measured on integrated samples over annual layers according to the $\delta^2$H stratigraphy.

The data on the deep ice cores reported here were measured on drill-chip samples for B13 (Oerter and others, 1992b) and core segments of approximately 20 cm length for B15 (Oerter and others 1992a). High-resolution profiles of ice core B13 in selected depth ranges have been given by Minikin and others (1991).

The $^2$H contents are expressed as $\delta$ values with respect to V-SMOW (Vienna Standard Mean Ocean Water) measured with a precision of 1.0‰. $^3$H contents are given in tritium units (TU) and referred to the measuring date, March 1992.

## 3. ISOTOPE PROFILES AND DATING OF THE FIRN CORES

The firn cores were dated using the $\delta^2$H and, to some extent, the $^3$H and chemical profiles (Table 1). Both the stable isotopes and the non-sea-salt (nss) sulfate profiles show seasonal variations. It is well known that the $^2$H content of precipitation is governed by the local temperature (Dansgaard, 1964). The nss sulfate concentration of the Antarctic troposphere appears to be controlled by the exhalation of dimethyl sulfide from the Southern Ocean and hence shows a pronounced summer maximum at coastal sites (Wagenbach and others, 1988; Savoie and others, 1992). Therefore, the seasonal concentration pattern is similar for both parameters. In the firn, these parameters provide highly valuable stratigraphic information depending on the build-up of the snow cover. To distinguish between layers accumulated in different years by stable-isotope profiles, at least parts of both the summer and winter precipitation have to be preserved in the snow cover, otherwise a quasi-periodic signal, necessary for reliable dating, is not detectable. To distinguish between nss sulfate peaks of different years, it is sufficient that the summer layers with their relatively high sulfate peaks are separated by some layers accumulated in autumn, winter or spring.

At some locations, or during years with low-accumulation rates, the stratigraphy may be seriously affected by the build-up of the snow cover, which depends primarily on the already-mentioned seasonal distribution of precipitation but also on the re-working of the snow surface by wind action, e.g. wind scouring (Fisher and others, 1983). Note that the stable isotopes are additionally smoothed by diffusion processes during the transformation of snow to firn and ice (Johnsen, 1977).

The $^3$H content in the troposphere also varies with the season (see e.g. Taylor, 1968). Since $^3$H measurements are very time-consuming, we measured only the $^3$H content of annual layers, which seems sufficient for dating purposes. According to investigations at the South Pole (Jouzel and others, 1979), $^3$H distributions in the Antarctic firn show distinctive features, which were used for the interpretation of the $^3$H profiles: a strong increase in the $^3$H content starting in 1963 after the nuclear weapons test series in the early 1960s, an absolute maximum in the years 1965–66 and a slow-down during the 1970s after the moratorium with a secondary maximum in 1973.

### 3.1. High-resolution $\delta^2$H and nss sulfate profiles

The $\delta^2$H depth profiles of four firn cores and the corresponding dating are shown in Figure 2. Obviously, the observed amplitudes of the seasonal $\delta^2$H variation depend on the accumulation rates and are lowest at sites in the southernmost part of the ice shelf. Annual-layer identification is based on the stable-isotope profiles but also on ECM, nss sulfate and $^3$H
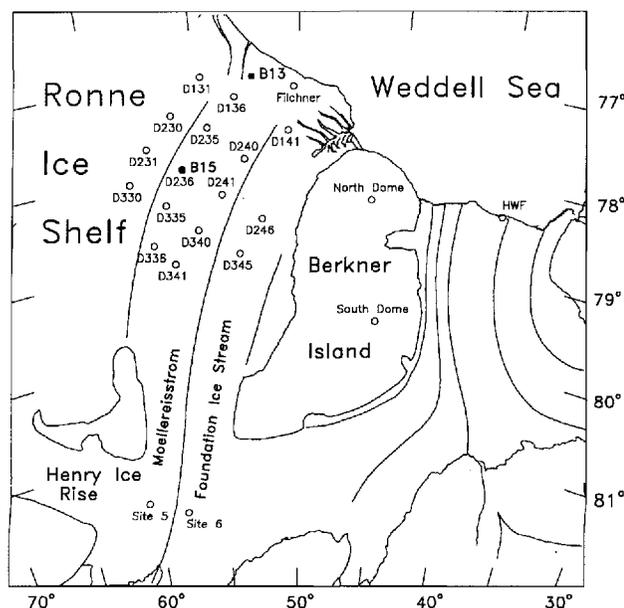


*Fig. 1. The drilling sites of the 10 m firn cores and of ice cores B13 and B15 on the Ronne Ice Shelf (map after Institut für Angewandte Geodäsie, 1993).*

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*Table 1. Mean annual values of $\delta^2 H$ and accumulation rates deduced from shallow firn cores drilled in 1990 and 1992 in the eastern part of the Ronne Ice Shelf and from snow pits dug in 1984 and 1986. The deviation ($1\sigma$) gives the scatter of the mean annual values*

| Site | Depth of the borehole | Dating method | | | Period covered by the core | $\delta^2 H$ | Accumulation rate | Firn temperature |
|------|------|------|------|------|------|------|------|------|
| | m | $^2$H | $^3$H | ch[1] | years | ‰ | kg m$^{-2}$ a$^{-1}$ | °C |
| *Firn cores drilled in 1990 and 1992 (firn temperatures measured in 1990 at the bottom of the borehole)* | | | | | | | | |
| BC90 | 11.0 | × | | | 1966–89 | 195.2 ± 10.0 | 207 ± 40 | 23.5 |
| D131 | 10.7 | × | | | 1966–89 | −201.9 ± 11.1 | 201 ± 38 | −23.3 |
| D136 | 11.0 | × | × | × | 1962–89 | −201.5 ± 11.9 | 189 ± 52 | −23.8 |
| D230 | 10.2 | × | × | | 1967–89 | −205.6 ± 12.3 | 199 ± 50 | 23.8 |
| D231 | 10.0 | × | | | 1965–89 | −209.3 ± 10.2 | 185 ± 45 | −24.4 |
| D235 | 9.7 | × | | × | 1968–89 | −206.3 ± 12.3 | 184 ± 40 | −24.3 |
| D236 | 9.5 | × | × | × | 1965–89 | −211.6 ± 11.3 | 166 ± 37 | 24.7 |
| D246 | 10.1 | × | | | 1979–86 | −209.4 ± 10.6 | 189 ± 50 | |
| D330 | 9.9 | × | × | | 1966–89 | −213.3 ± 11.2 | 176 ± 51 | 24.5 |
| D335 | 9.8 | × | | × | 1966–89 | −217.1 ± 9.5 | 170 ± 45 | −25.2 |
| D336 | 9.8 | × | × | × | 1964–89 | −224.0 ± 8.3 | 156 ± 43 | −26.1 |
| BAS site 5 | 10.1 | × | × | × | 1965–89[*] | −251.0 | 92 | −28.6 |
| BAS site 6 | 10.5 | × | × | | 1965–89[*] | −250.9 | 89 | −28.7 |
| Berkner north | 11.6 | × | × | × | 1970–89 | −184.2 ± 12.8 | 266 ± 65 | −22.5 |
| Berkner south | 11.1 | × | × | × | 1965–89 | −216.5 ± 15.3 | 174 ± 40 | −24.6 |
| HWF | 11.7 | × | | | 1965–88 | −200.1 ± 11.5 | 211 ± 49 | −24.4 |
| *Snow pits dug in 1984 and 1986 (firn temperatures measured in 1984[a] or 1986[b] at 10 m depth)* | | | | | | | | |
| D131 | | × | | | 1983–85 | −204.1 ± 5.8 | 202 ± 25 | |
| D140 | | × | | | 1979–83 | −186.4 ± 6.8 | 213 ± 33 | −24.7[a] −25.0[b] |
| D141 | | × | | | 1979–83 | −193.5 ± 10.8 | 189 ± 87 | −25.8[a] |
| D230 | | × | | | 1984–85 | −202.0 ± 10.5 | 230 ± 8 | −24.5[a] |
| D231 | | × | | | 1982–85 | 202.4 ± 14.6 | 203 ± 34 | |
| D240 | | × | | | 1979–85 | −207.6 ± 12.6 | 196 ± 46 | −25.9[a] |
| D241 | | × | | | 1979–85 | −212.4 ± 10.0 | 178 ± 38 | −26.3[a] |
| D330 | | × | | | 1983–85 | 209.3 ± 7.8 | 213 ± 33 | |
| D335 | | × | | | 1984–85 | −217.3 ± 2.2 | 195 ± 38 | |
| D340 | | × | | | 1979–85 | 218.3 ± 9.0 | 155 ± 30 | 26.9[a] −26.9[b] |
| D341 | | × | | | 1978–85 | −221.3 ± 16.3 | 137 ± 36 | −27.3[a] −27.4[b] |
| D345 | | × | | | 1981–85 | −226.9 ± 13.3 | 153 ± 16 | |

ch[1] Non-sea-salt (nss) sulfate and/or ECM profiling.

[*] Period which can be evaluated in the $^3$H profile.

profiles, which supplement each other. For example, at D335 (Fig. 3) the firn at a depth of 2.6 m contains two summer horizons according to nss sulfate, whereas the $\delta^2 H$ profile displays only one maximum, which is broadened by a shoulder. Obviously, the winter accumulation with its low $\delta^2 H$ value is missing here, similarly at D336 at the 3.1 m depth (Fig. 2).

At the sites with low-accumulation rates (BAS sites 5 and 6), none of the high-resolution profiles can be stratigraphically interpreted with confidence.

## 3.2. $^3$H profiles

The distributions of the $^3$H contents were determined at D136, D230, D236, D330, D336 and BAS sites 5 and 6.

The tritium fall-out at Berkner Island has been discussed by Wagenbach and others (1994). At D136 and D336, the appearance of the absolute maximum in 1966 strongly confirms the stratigraphical dating technique (Fig. 2). The temporal $^3$H change in the late 1960s and 1970s, less significant than the increase after 1963, is at least compatible with that at the South Pole and therefore supports the stratigraphic dating of the firn cores.

The annual sub-sampling at BAS sites 5 and 6 was based on the first interpretation of the stable-isotope profiles (Graf and others, 1991). The measured $^3$H content made it evident that this initial dating was wrong. Therefore, the sampling error at BAS sites 5 and 6 is on the order of the thickness of an annual layer. Because
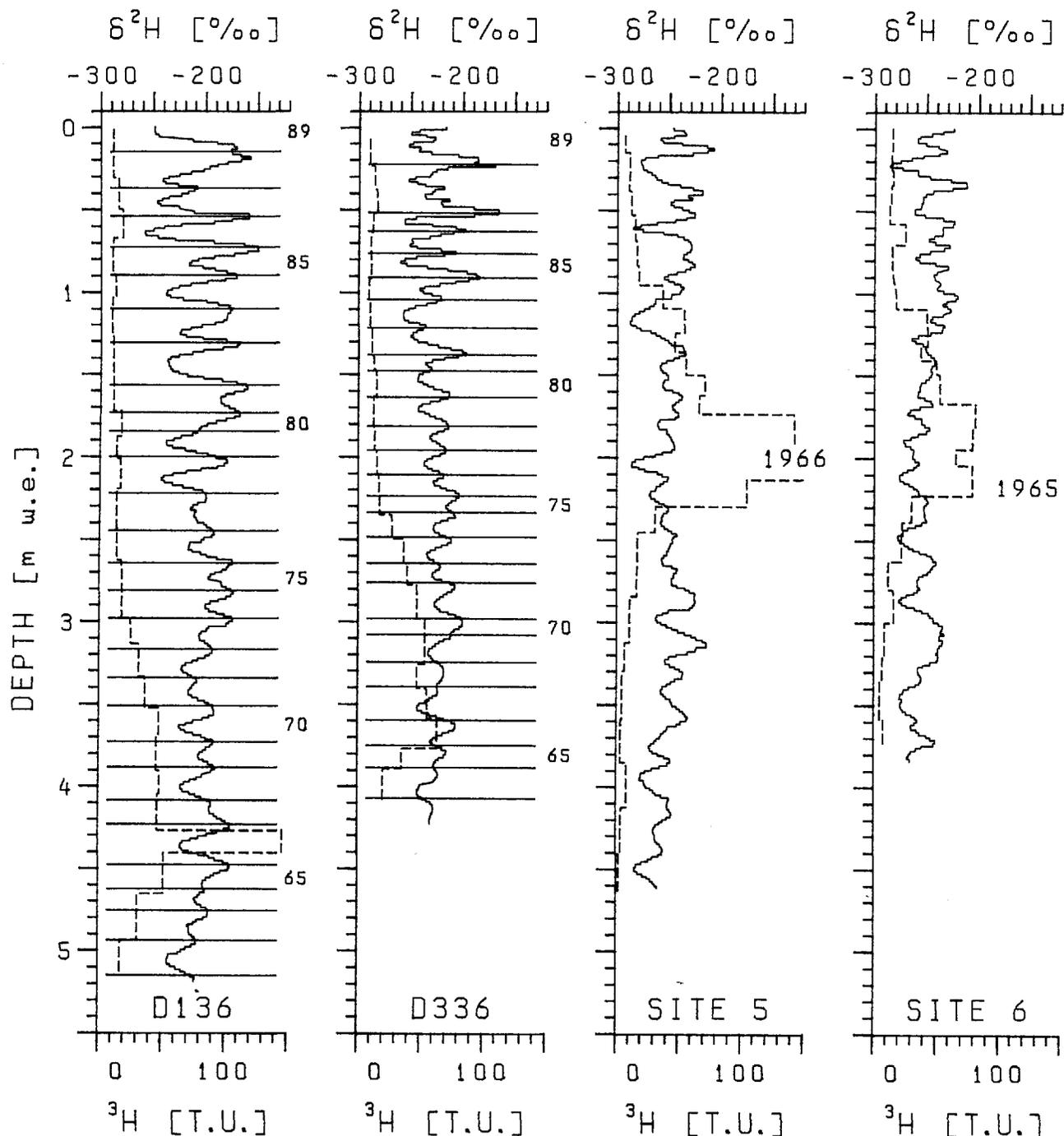
*Fig. 2. Profiles of the $\delta^2 H$ values (full lines) and $^3H$ contents (dashed lines) of the 10 m firn cores drilled at D136, D336, BAS site 5 and BAS site 6. The dating deduced from the profiles is indicated; the annual layering could be deduced from the $\delta^2 H$ profiles only at D136 and D336. $^3H$ contents are referred to the measurement date, March 1992.*

of this error and due to the much higher $^3H$ fall-out at these sites, the $^3H$ distribution is somewhat broader. At site 5, relatively high $^3H$ contents are found at 2 m depth; this horizon was assigned to 1966, according to the fall-out history at the South Pole. The very sharp increase of $^3H$ content at site 6 occurring at 2.2 m is most probably caused by the fall-out in 1965. At site 5, the high-resolution $\delta^2 H$ profile shows only 13 cycles down to 2 m depth and the nss-sulfate profile 18 of 25 layers, according to the $^3H$ dating. Accumulation rates, derived from the $^3H$ dating, are about $90 \, \text{kg m}^{-2} \text{a}^{-1}$ at both sites and therefore are lower by factors of 1.7 and 1.5, respectively, than hitherto assumed.

## 4. ACCUMULATION RATES AND THE $\delta^2 H$ VALUES OF SURFACE LAYERS

The accumulation rates and the mean $^2H$ values of the surface layers follow from the dating given in the previous section. They are given in Table 1 and their regional distribution is given in Figures 4 and 5. For completion, the results from the previous snow-pit studies are added. Generally, the accumulation rates and the $\delta^2 H$ values represent means of the mean annual values over the period covered by the cores or snow pits. Only annual layers, which encompass the entire deposition sequence for a year, are taken into account. The standard
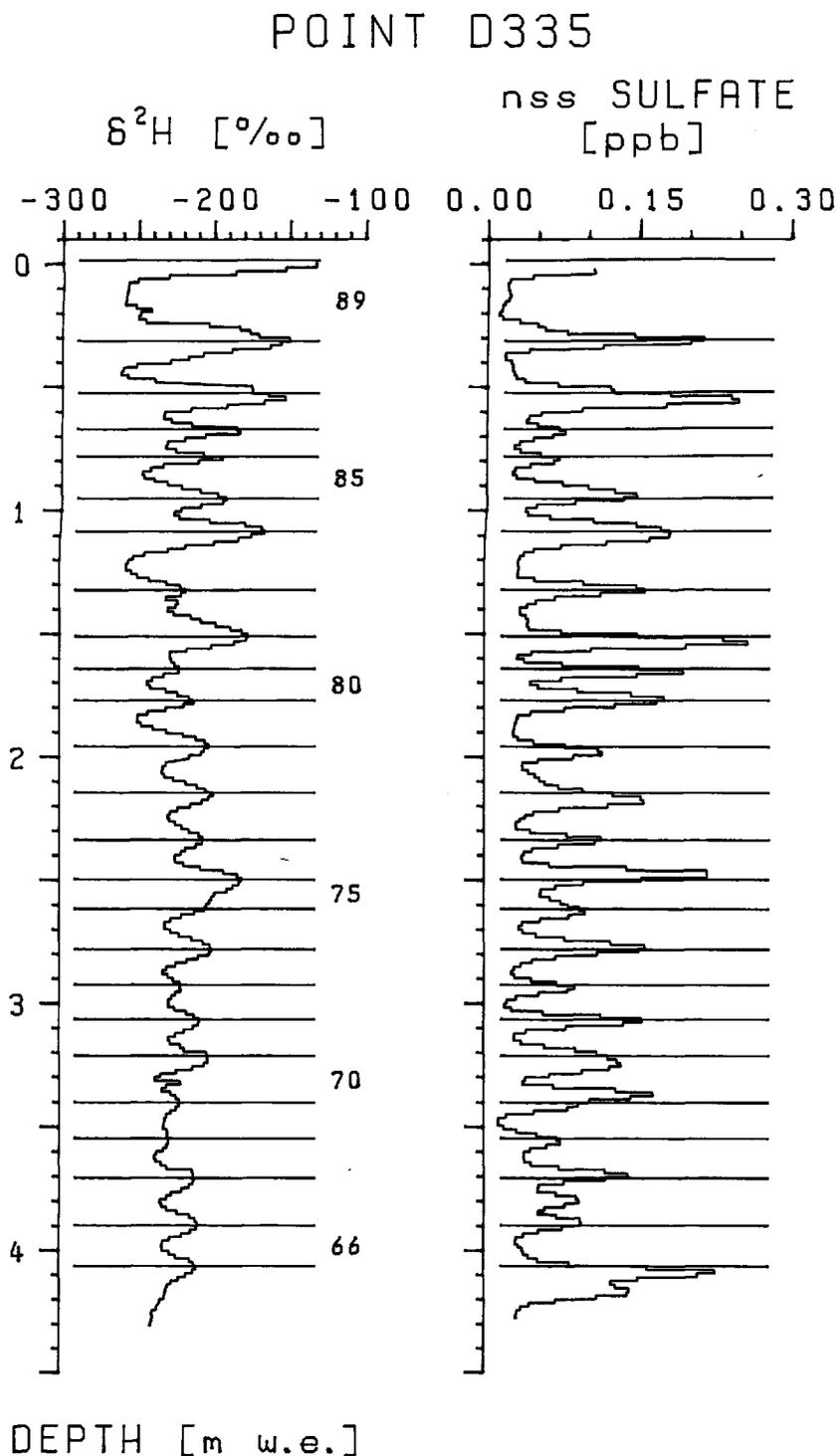
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# POINT D335



*Fig. 3. High-resolution profiles of the $\delta^2H$ values and of the non-sea-salt (nss) sulfate concentrations of the firn core drilled at D335. The annual layering deduced from the profile is indicated.*

deviations indicate the year-to-year variability, which is caused by the build-up of the snow cover. However, averaging over several years results in rather representative mean values. Assuming a possible dating error of 1 year, the accumulation rates are accurate to about 5%. The inaccuracy of the density values introduces an error of the same order.

The $\delta^2H$ value in the near-surface firn decreases from −195‰ at the drilling site of B13 (BC90), 30 km distant from the ice edge, to −251‰ at BAS sites 5 and 6 south of Henry Ice Rise. Along the flowline through B13 and B15, $\delta^2H$ decreases by 9.1‰ per 100 km to the south. The

accumulation rates decrease accordingly from 200 to 90 kg m$^{-2}$ a$^{-1}$.

## 5. THE $\delta^2$H–TEMPERATURE RELATIONSHIP

The areal analysis of the stable-isotope content of near-surface firn and the 10 m firn temperature provides information on the sensitivity of the isotopic content to temperature changes (Robin, 1983). The $\delta^2H$ values of the near-surface layers in the eastern part of the Ronne Ice Shelf (Table 1) are closely correlated to the 10 m firn
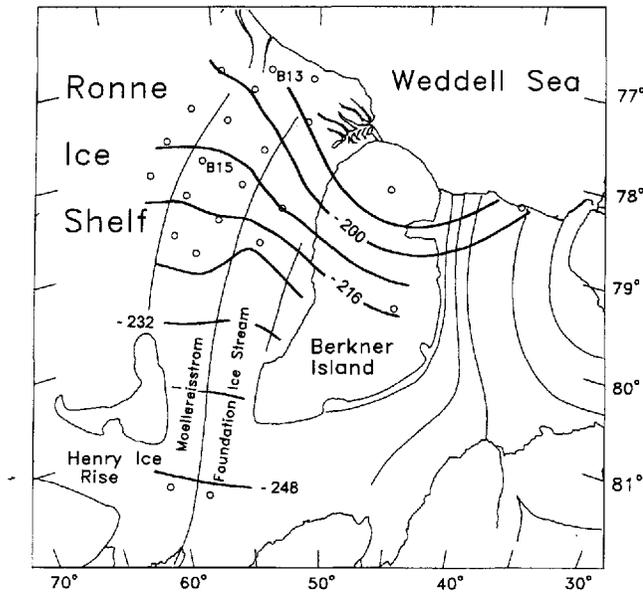
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*Fig. 4. Distribution of the $\delta^2 H$ values of the near-surface layers in the eastern part of the Ronne Ice Shelf. Isolines of $\delta^2 H$ values are plotted at intervals of 8‰.*
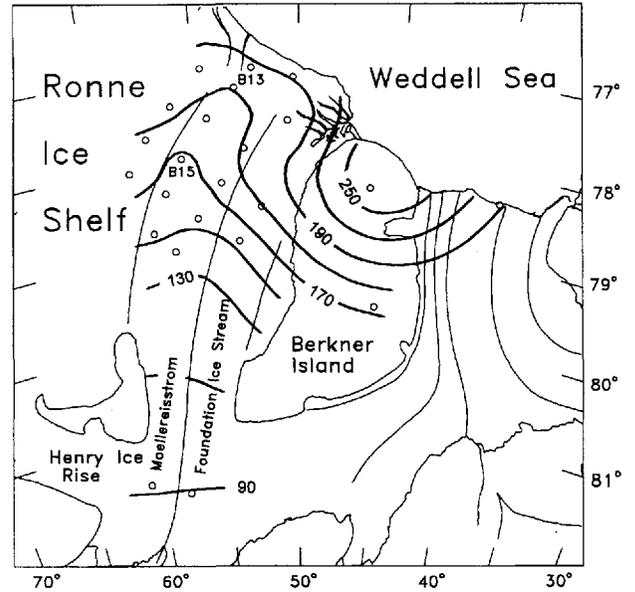
*Fig. 5. Distribution of the accumulation rates in the eastern part of the Ronne Ice Shelf. Isolines of accumulation rates are plotted at intervals of $10\,kg\,m^{-2}\,a^{-1}$.*

temperatures, representing the mean ambient temperatures at the measuring sites (Fig. 6). The best correlation is found between $\delta^2 H$ values of firn cores drilled in 1990 and firn temperatures $\Theta$ measured in the same year, which is described by the regression line $\delta^2 H = 42 + 10.3$ ($\pm 0.6)\Theta$, $r = 0.97$ (line 1 in Fig. 6). The values from snow-pit samples taken in 1984 and 1986 do not fit this line and change abruptly between points D141 and D240. They may, however, be correlated by two separate regression lines for the sites close to and away from the ice edge,

respectively, which are nearly parallel to line 1. The data set of the near-coast stations was complemented by values from the coastal station Druzhnaya I (Graf and others, 1990b).

The shift between the regression lines may reflect calibration errors of the thermocouple used for measuring the 10 m firn temperature. However, shifts of the regression lines parallel to each other are of no importance for the calibration of isotope climatic records because only the gradients $(d\delta^2 H/d\Theta)$ are of interest.

The temperature gradient of the $\delta^2 H$ values $(d\delta^2 H/d\Theta)$
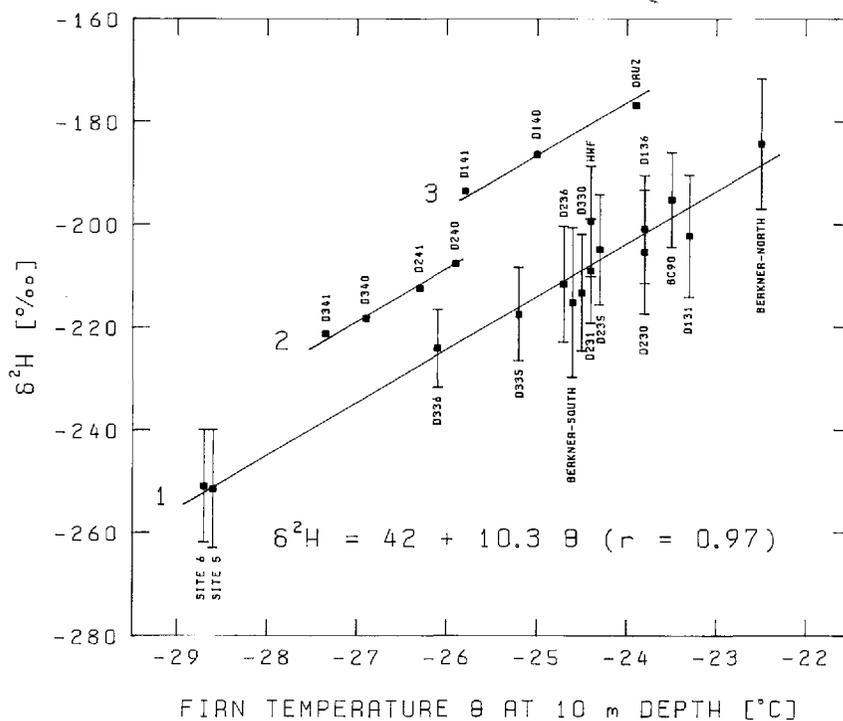


$$\delta^2 H = 42 + 10.3\ \Theta\ (r = 0.97)$$

*Fig. 6. Relationship between the $\delta^2 H$ values of near-surface layers and the firn temperature at 10 m depth in the eastern part of the Ronne Ice Shelf. See text for the explanation of the different regression lines 1, 2 and 3.*
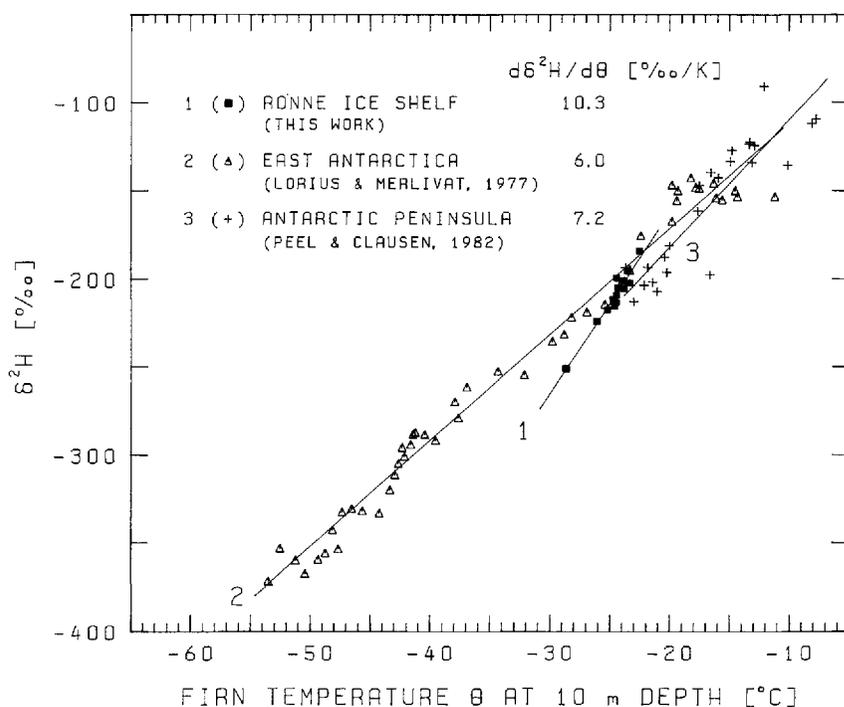
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*Fig. 7. Relationship between the $\delta^2 H$ values of near-surface layers and the firn temperature at 10 m depth in three areas of Antarctica.*

on the Ronne Ice Shelf is surprisingly large compared to $\delta^2 H$–$\Theta$ relationships found in other areas of Antarctica (Robin, 1983; Fig. 7). The gradients may reflect the conditions of the snow-forming processes during moist-air advection, governed mainly by the isobaric cooling of air masses over the Ronne Ice Shelf, whereas adiabatic cooling prevails on the Antarctic Peninsula (Peel and Clausen, 1982) and along the traverse from Durmont d'Urville to Dome C (Lorius and Merlivat, 1977), leading to lower temperature gradients of $d\delta^2 H/d\Theta = 7.2$ and $6.0‰ K^{-1}$, respectively. In addition, in the interior of Antarctica the difference between the surface temperature and the temperature above the inversion affects the $\delta^2 H$–$\Theta$ relationship. Though the gradients are different, all values follow

roughly a common regression line. This suggests a similar history of the advected moist-air masses reaching Antarctica.

## 6. THE RELATION OF THE $\delta^2 H$ VALUES OF ICE CORES B13 AND B15 TO THE SURFACE DATA

Ice core B13 contains ice of meteoric origin down to 152.8 m, followed by the so-called marine ice accumul-ated from the water column (Oerter and others, 1992b). At B15, 140 km south of B13, the boundary between the ice of different origins is found at the same depth. In this section, we will give three examples of the application of surface data in interpreting the $\delta^2 H$ profile of the meteoric ice.



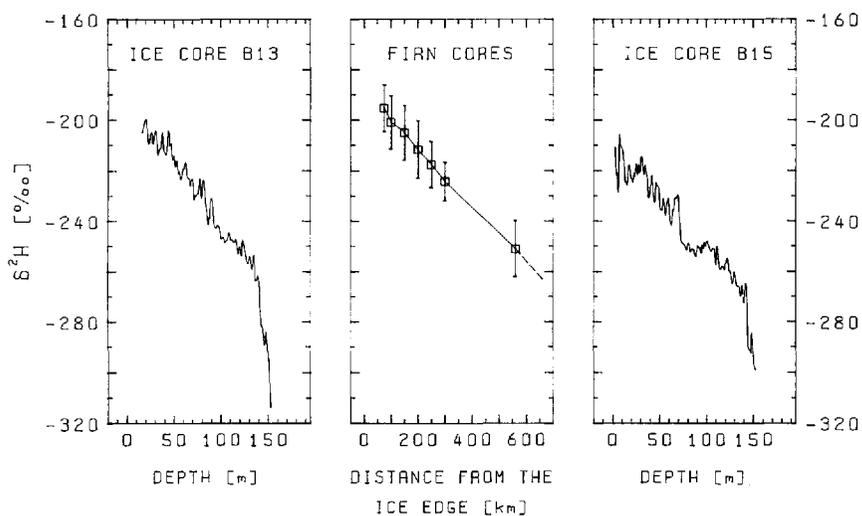*Fig. 8. The $\delta^2 H$ values of cores B13 and B15 in comparison to the values of the near-surface layers on the Ronne Ice Shelf at locations along the flowline through B13 and B15. The ice below 137 m in core B13 and below 142 m depth in core B15 originated from the inland ice.*

Further information on the structural parameters of the two ice cores have been given by Eicken and others (1994).

The relatively high flow velocities of the Ronne Ice Shelf mean that the deepest ice of meteoric origin recovered from the cores was deposited far upstream of the drilling site. The $\delta^2$H values of ice cores B13 and B15 reflect the progressive depletion of the snow in the heavier isotope $^2$H along the flowline to the south (Fig. 8). $\delta^2$H variations caused by climatic changes are superimposed and can only be separated by knowing both the origin of the ice by ice-flow modeling, e.g. using the simple model of Thomas (1973) and the $\delta^2$H distribution along the principal surface flowline.

On the other hand, because the expected climatically induced $\delta^2$H variations are small compared to the spatial changes upstream from the drilling site of the cores, the origin of the ice may be estimated at least qualitatively from a comparison of the ice core and surface-snow isotope data (Fig. 8). For example, the $\delta^2$H value suggests that the ice at a 100 m depth originates from the region south of Henry Ice Rise.

The $\delta^2$H values decrease rapidly below 137 m in B13 and below 142 m in B15 to about –300‰. It is unlikely that such low values would be encountered at the surface of the Ronne Ice Shelf, even in the region of the grounding line as indicated by the broken line in Figure 8. We conclude, therefore, that the ice in these deepest layers was deposited on the ice sheet at higher elevations. Only in the improbable case that the $\delta^2$H values in the surface snow decrease between BAS site 5 and the grounding line by 50‰ within a distance of only 100 km (about five times faster than between the ice edge and BAS site 5) could the ice originate from precipitation on the ice shelf. From the rather small thickness of the layer in B13 originating from the inland ice, strong basal melting is inferred between the grounding line and the area where basal accumulation starts (Oerter and others, 1992b).

## ACKNOWLEDGEMENTS

## REFERENCES

Dansgaard, W. 1964. Stable isotopes in precipitation. *Tellus*, **16**(4), 436–468.

Eicken, H., H. Oerter, H. Miller, W. Graf and J. Kipfstuhl. 1994. Textural characteristics and impurity content of meteoric and marine ice in the Ronne Ice Shelf, Antarctica. *J. Glaciol.*, **40**(135), 386–398.

Fisher, D. A., R. M. Koerner, W. S. B. Paterson, W. Dansgaard, N. Gundestrup and N. Reeh. 1983. Effect of wind scouring on climatic records from ice-core oxygen-isotope profiles. *Nature*, **301**(5897), 205–209.

Graf, W., H. Moser, H. Oerter, O. Reinwarth and W. Stichler. 1988. Accumulation and ice-core studies on Filchner–Ronne Ice Shelf, Antarctica. *Ann. Glaciol.*, **11**, 23–31.

Graf, W., O. Reinwarth and H. Moser. 1990a. The 520-year temperature record of a 100 m core from the Ronne Ice Shelf, Antarctica. *Ann. Glaciol.*, **14**, 90–93.

Graf, W., O. Reinwarth and H. Oerter. 1990b. Isotopic and stratigraphical interpretation of a 16 m firn core nearby Druzhnaya I. *In* Miller, H., ed. *Filchner–Ronne-Ice-Shelf-Programme, Report No. 4*. Bremerhaven, Alfred Wegener Institute, 46–49.

Graf, W. and 6 others. 1991. Isotopic and chemical investigations of 10 m firn cores from the eastern part of the Ronne Ice Shelf, Antarctica. *In* Miller, H. and H. Oerter, eds. *Filchner–Ronne-Ice-Shelf-Programme, Report No. 5*. Bremerhaven, Alfred Wegener Institute, 45–53.

Institut für Angewandte Geodäsie. 1993. *Filchner Ronne-Schelfeis, Antarktis. Satellite image map 1 : 2 000 000*. Frankfurt am Main, Institut für Angewandte Geodäsie.

Johnsen, S. J. 1977. Stable isotope homogenization of polar firn and ice. *International Association of Hydrological Science Publication* 118, 210–219.

Jouzel, J., L. Merlivat, M. Pourchet and C. Lorius. 1979. A continuous record of artificial tritium fallout at the South Pole (1954–1978). *Earth Planet. Sci. Lett.*, **45**, 188–200.

Lorius, C. and L. Merlivat. 1977. Distribution of mean surface stable isotope values in East Antarctica: observed changes with depth in the coastal area. *International Association of Hydrological Sciences Publication* 118 (Symposium at Grenoble 1975 — *Isotopes and Impurities in Snow and Ice*), 127–137.

Miller, H. and H. Oerter, eds. 1991. Die Expedition ANTARKTIS-VIII mit FS Polarstern 1989/90. Bericht vom Fahrtabschnitt ANT VII/5. *Ber. Polarforsch.*, **86**, 69–71.

Minikin, A., D. Wagenbach, W. Graf, O. Reinwarth and H. Oerter. 1991. Preliminary results of the isotopic and chemical investigations of the 214 m ice core from the Ronne Ice Shelf, Antarctica. *In* Miller, H. and H. Oerter, eds. *Filchner–Ronne-Ice-Shelf-Programme, Report No. 5*. Bremerhaven, Alfred Wegener Institute, 19–24.

Minikin, A., D. Wagenbach, W. Graf and J. Kipfstuhl. 1994. Spatial and seasonal variations of the snow chemistry at the central Filchner–Ronne Ice Shelf, Antarctica. *Ann. Glaciol.*, **20** (see paper in this volume).

Oerter, H., C. Drücker, J. Kipfstuhl, U. Nixdorf and W. Graf. 1992a. The Filchner IV campaign and the 320 m deep ice core B15. *In* Oerter, H., ed. *Filchner Ronne-Ice-Shelf-Programme, Report No 6*. Bremerhaven, Alfred Wegener Institute, 47–53.

Oerter, H. and 6 others. 1992b. Evidence for basal marine ice in the Filchner–Ronne ice shelf. *Nature*, **358**(6385), 399–401.

Peel, D. A. and H. B. Clausen. 1982. Oxygen-isotope and total beta-radioactivity measurements on 10 m ice cores from the Antarctic Peninsula. *J. Glaciol.*, **28**(98), 43–45.

Reinwarth, O. 1981. Glacial meteorological investigations on the Filchner–Ronne Ice Shelf during the station site survey 1979/80. *Polarforschung*, **51**(1), 61–75.

Reinwarth, O., W. Rauert, W. Stichler and H. Moser. 1982. Preliminary investigations on accumulation at the Filchner/Ronne Ice Shelves and Atka Bay. *Ann. Glaciol.*, **3**, 274–278.

Reinwarth, O., W. Graf, W. Stichler, H. Moser and H. Oerter. 1985. Investigations of the oxygen-18 content of samples from snow pits and ice cores from the Filchner–Ronne and Ekström Ice Shelves. *Ann. Glaciol.*, **7**, 49–53.

Robin, G. de Q. 1983. The climatic record from ice cores. *In* Robin, G. de Q., ed. *The climatic record in polar ice sheets*. Cambridge, Cambridge University Press, 180–195.

Savoie, D. L., J. M. Prospero, R. J. Larsen and E. S. Saltzman. 1992. Nitrogen and sulfur species in aerosols at Mawson, Antarctica, and their relationship to natural radionuclides. *J. Atmos. Chem.*, **14**, 181–204.

Taylor, C. B. 1968. A comparison of tritium and strontium-90 fallout in the Southern Hemisphere. *Tellus*, **20**, 559–576.

Thomas, R. H. 1973. The dynamics of the Brunt Ice Shelf, Coats Land, Antarctica. *Br. Antarct. Surv. Sci. Rep.* 79.

Wagenbach, D., U. Görlach, K. Moser and K. O. Münnich. 1988. Coastal Antarctic aerosol: the seasonal pattern of its chemical composition and radionuclide content. *Tellus*, **40B**, 426–436.

Wagenbach, D. and 6 others. 1994. Reconnaissance of chemical and isotopic firn properties on top of Berkner Island, Antarctica. *Ann. Glaciol.*, **20** (see paper in this volume).

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