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A stacked mixing sequence at the base of the Dye 3 core, Greenland

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Abstract. This paper documents, by a detailed isotopic and gas composition study of the basal ice from the Dye 3 core, a large degree of flow-induced mixing at the ice sheet base. This mixing results most probably from circular motion in troughs of bedrock undulations and flow separations with some entrainment of the underlying ice. The measured distribution of isotopes and gases in the basal ice is the consequence of successive mixing events having occurred upglacier from the site in an area of very rough bedrock topography. The deformation produced makes it possible for the basal part of the ice sheet to cross the subglacial valley existing in the Dye 3 area.

The Basal Silty Ice of the Dye 3 Core

The Dye 3 core was drilled in South Greenland about 200 km North-North-East from South Dome at 65°N 44°W by the GISP project (1979-1981). More than 25 m of silty ice was recovered at the bottom of the drill hole which reached a depth of 2037.8 m. The temperature at the bottom was about -12°C. The dispersed silty and sandy particles are evenly distributed in the silty ice at the boundaries of small ice crystals (mean diameter: 0.2 cm). Diffuse banding is present. The dirt content of the silty ice is relatively low (mean value: 0.03% by weight).

Despite numerous papers on this core, a comprehensive study of the basal silty ice has never been undertaken. Only the debris content and ice crystallography have been investigated in detail by Thorsteinsson (1990). The complete $\delta^{18}\text{O}$ profile of the 2000 m of glacier ice was published by Dansgaard et al. (1982). In the part of the core considered in this paper (2008.6-2037.8 m), two samples of ice (at 2011.7 m and 2030.2 m depth respectively) were studied previously in Bern for gas properties (Leuenberger, 1992). The results obtained for CO_2 are incorporated in this paper. A detailed isotopic and gas study is here described for the last 27 m of the core.

Stable Isotope Composition

The $\delta^{18}\text{O}$ profile shown in Fig. 1 includes the lowest part of debris-free ice, with nearly constant $\delta^{18}\text{O}$ values as reported Dansgaard et al. (1982), and the basal silty ice. The samples were analyzed in Copenhagen with a 2.5 cm continuous resolution. The data presented have been averaged over 10 cm intervals.

Figure 1 shows striking features. First, it displays the

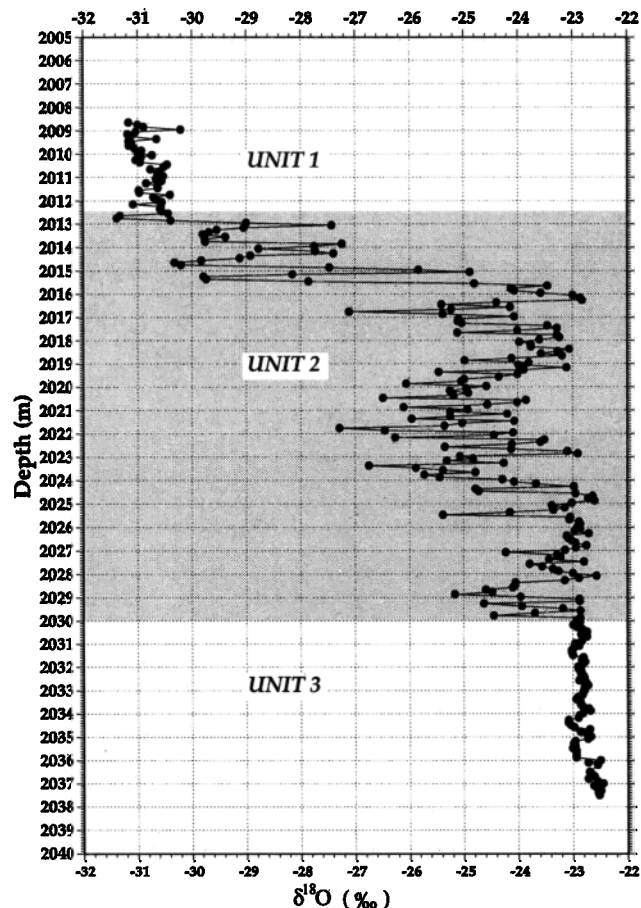


Figure 1. The $\delta^{18}\text{O}$ profile of the basal ice from the Dye 3 core.

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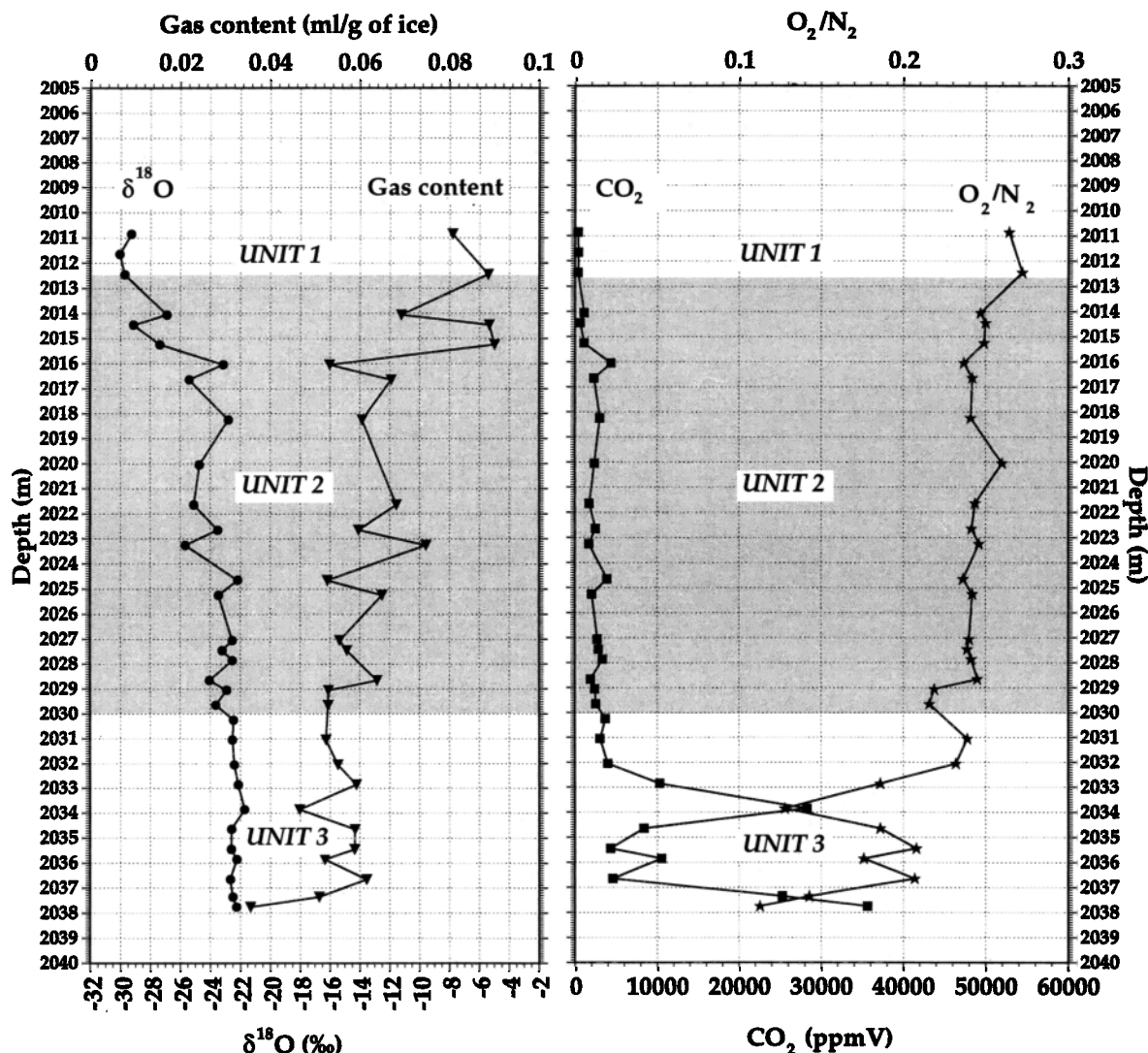


Figure 2. The CO_2 concentration, the O_2/N_2 ratio, the total gas content profiles of the basal ice from the Dye 3 core. For comparison, a $\delta^{18}\text{O}$ profile is shown with the same resolution as for the gas samples.

near constant $\delta^{18}\text{O}$ values for the lowest part of the debris-free ice (the first 4 m of the profile) followed by a major shift in δ -values in the three uppermost meters of the basal silty ice. $\delta^{18}\text{O}$ values increase from -30‰ to -23‰. The basal silty ice then exhibits fluctuating δ -values followed downcore by a section of nearly constant δ -values along the 7 last meters of the core. The $\delta^{18}\text{O}$ values in this last section are about -22.5‰ while Holocene ice in the core has a mean value of about -28‰ (Dansgaard et al., 1982). Only summer layers close to the surface reach such high $\delta^{18}\text{O}$ values in the entire 2037.7 m core. The contrast between Holocene and these bottom $\delta^{18}\text{O}$ values is however not sufficient to conclude, as has been done for the basal ice of the GRIP core (Souchez et al., 1994), that ice formed in the absence of an ice sheet also contributed to the basal silty ice, although such a possibility cannot be excluded.

Samples of ice were also measured in Saclay every odd 10 cm for δD and $\delta^{18}\text{O}$ to obtain the δD - $\delta^{18}\text{O}$ relationship. This relationship is $\delta\text{D} = 8.07 \delta^{18}\text{O} + 10.58$ ($r^2 = 0.991$; 153 samples). This can be considered as a local Meteoric Water Line (MWL). Deuterium excess ($\delta\text{D} - 8$

$\delta^{18}\text{O}$) was calculated for each sample. The values (around 9‰) are slightly higher than those obtained in the sections of the Dye 3 core already analyzed (a maximum of 8‰ during cold phases, as reported in Johnsen et al., 1989).

The alignment of the samples on a MWL together with the absence of any large scale trend in the deuterium excess profile are arguments for isotopically unmodified solid precipitation. This result implies that no significant meltwater was lost from the silty ice during or after its formation, which situation does not agree with a superimposed ice origin as suggested by Koerner (1989).

The basal silty ice from the Dye 3 core cannot be the result of adfreezing. No freezing slope was developed in the $\delta\text{D} - \delta^{18}\text{O}$ diagram (Souchez and Jouzel, 1984). Moreover, the few total gas content measurements performed by Stauffer et al. (1985), reported by Koerner (1989) and confirmed in the next section, give values which are too high for ice formed by refreezing of meltwater (Gow et al., 1979). Ice intrusion of a subglacial sediment by pressure-induced regelation past grains is also precluded since the isotopic signature of such a process would have been different (Iverson and Souchez, 1996).

Gas Content and Gas Composition Profiles

Gas composition analyses were performed using a dry extraction technique in a cold room at -20°C (80% recovering efficiency) and a Varian 3300 gas chromatograph. A molecular sieve column and a thermal conductivity detector were used for O_2 and N_2 , an Haysep column and a flame ionization detector were used for CO_2 after it has been catalytically transformed into methane. Different standard mixtures (prepared by the company Messer International) were used to frame each sample in area counts because of the large concentration ranges. The precision of the measurements (r.s.d.) is 2.5% for CO_2 and 0.4% for O_2 and N_2 . Total gas content measurements were performed with a Toepler pump with a relative precision of 5% (Martinerie et al., 1994). The reliability of the procedure used in Brussels for CO_2 and total gas content was tested through cross-calibration with the LGGE in Grenoble on GRIP basal ice samples (Souchez et al., 1995).

Results of gas analyses are shown in figure 2. CO_2 concentrations reach values as high as 36000 ppmv while the O_2/N_2 ratio goes down to about 0.11 compared with the atmospheric value of 0.27. In glacier ice just above the silty basal ice, total gas contents are around 0.09 ml/g ice, a normal value for glacier ice, while they cluster around 0.06 in the major part of the silty basal ice, reaching a minimum of 0.036 in the bottom of the core.

Such gas properties preclude a direct atmospheric origin. The gas composition and the significantly lower gas content of the silty ice (0.06 ml/g), compared to that of the overlying glacier ice (0.09 ml/g), cannot result from a normal process of atmospheric air trapping in the ice.

Discussion

Figure 3 (a, b and c) shows respectively the $\delta^{18}\text{O}-\text{CO}_2$, total gas content- CO_2 and total gas content- O_2/N_2 in the basal part of the Dye 3 core. In order to get the same resolution for both parameters, δ -values in Fig. 3 have been averaged over the distance representing the length of a gas sample.

Three units have been defined from the behavior of the δ -profiles with depth. In both unit 1 (2008.6-2012.6 m) and unit 3 (2030-2037.8 m) the δ -values are remarkably stable while, in unit 2, the record is much more variable. It is clear from figures 2 and 3 that these units also correspond to contrasted co-variation patterns between the variables considered.

Unit 1 is composed of debris-free samples of glacier ice directly above the silty ice (open squares in Fig. 3). These samples have $\delta^{18}\text{O}$ values of about -29.5‰ and CO_2 concentrations only slightly higher than atmospheric ones (from 336 to 375 ppmv).

Unit 2 (half black squares in Fig. 3) corresponds to the upper part of the silty ice from 2012.6 m to 2030 m depth and shows major shifts in δ -values. There is a positive correlation between $\delta^{18}\text{O}$ and CO_2 in this unit, with CO_2 concentrations considerably higher than atmospheric ones. This similarity between gas parameters (CO_2 but also O_2/N_2 ratios and total gas contents) and ice parameters ($\delta^{18}\text{O}$ but also δD) is a strong argument in favor of a mixing process between two end-members. It is further sup-

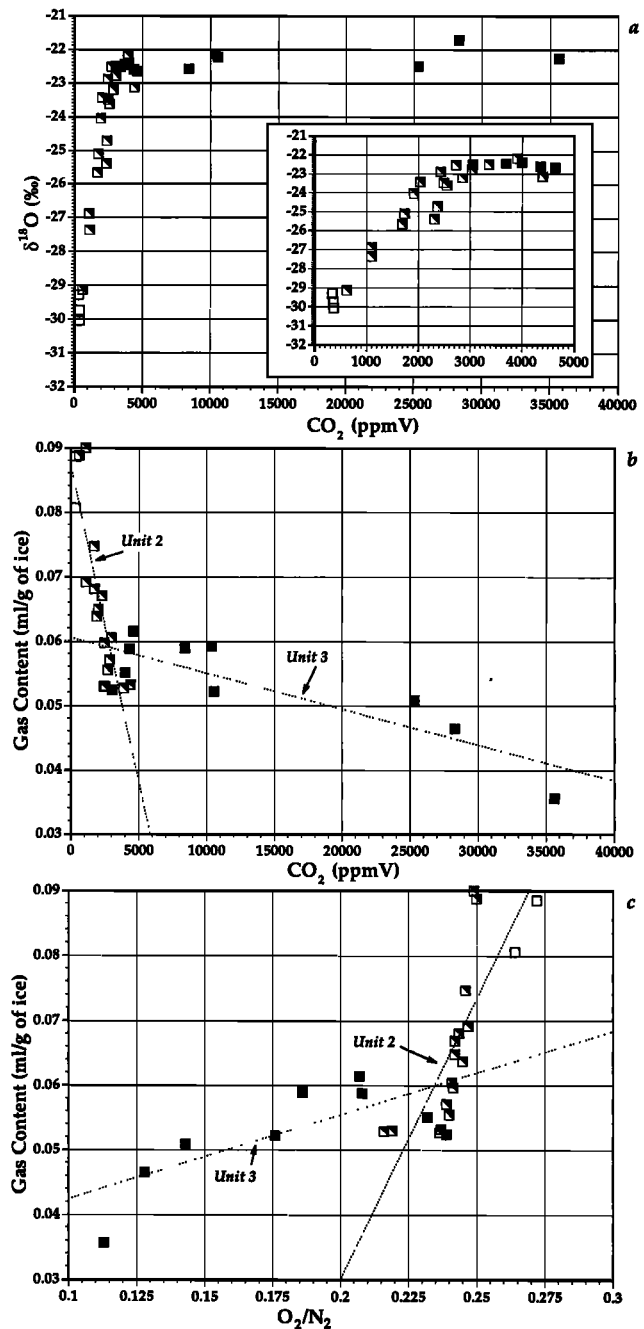


Figure 3. The $\delta^{18}\text{O}-\text{CO}_2$ (a), total gas content- CO_2 (b) and total gas content- O_2/N_2 (c) relationships in the basal part of the Dye 3 core.

ported by the co-variation amongst gas parameters (Fig. 3b and 3c), especially if one considers that these might be blurred by post-mixing small scale diffusion processes. One end-member could be glacier ice as in unit 1 and the other having properties similar to the top of unit 3. Such a flow-induced mixing was first demonstrated for the basal silty ice of the GRIP core (Souchez et al., 1995).

Unit 3 (black squares in Fig. 3), corresponding to the lowest part of the basal silty ice below 2030 m depth, shows nearly constant $\delta^{18}\text{O}$ values of about -22.5‰ and large fluctuations in CO_2 concentrations going up to 36000 ppmv. It also differentiates itself from the other units by a contrasting co-variation pattern amongst gas pa-

rameters (Fig. 3b and 3c). Such properties can also be explained by flow-induced mixing if the isotopic composition of the ice of the two end-members is not very different while the CO₂ concentrations would respectively be about 4000 ppmv and above 36000 ppmv (for the ice in contact with the subglacial bed). Such a mixing process could be responsible for the presence of an interval with nearly constant δ -values.

Dansgaard et al. (1982) pointed out the possibility that the nearly constant δ -level in the last 28 m of glacier ice above the silty ice is the result of the drill penetrating in parallel with the isochrones. This implies folding of the deepest layers. An alternative interpretation based on this study is that flow-induced mixing will also facilitate the homogenizing of the isotopic composition, leading to stable δ -values with depth. The three samples of unit 1 just above the basal silty ice are an integral part of this entity.

To summarize, our data sets suggest that the whole basal ice sequence at Dye 3 can be seen as the stacking of three different mixing units. Unit 1 most probably reflects isotopic homogenization of glacier ice with near constant gas properties and unit 3 results from the mixing of two end-terms with strongly contrasted gas properties and weakly contrasted isotopic signatures. Moreover, unit 2 is the consequence of mixing between the bottom of unit 1 and the top of unit 3. Gudmundsson (1997) has studied glacier sliding over sinusoidal bed and the characteristics of creeping flow over bedrock undulations. His model shows that the ice within a trough rotates slowly with the upper part of this circular motion in the general flow direction of the ice. There is a flow separation such that the ice in the trough will, theoretically, never leave it. A calculation has been conducted for a perfectly lubricated bed and repeated for no-slip boundary conditions. In both situations a flow separation of this type was found. It is possible to understand the properties of the Dye 3 basal ice using results of this study and allowing part of the ice in the circular motion to be entrained by the general flow. As shown by Overgaard and Gundestrup (1985), the bedrock topography in the vicinity of the Dye 3 station is very rough with a subglacial valley about 400 m deep situated at right angle to the ice flow. The resolution of the radio-echo-sounding is however clearly not sufficient to compare a known roughness near Dye 3 to that required to cause flow separation at a metric scale. The variable bedrock roughness could induce circular motion in troughs and flow separations at different scales accompanied by some entrainment of the underlying ice. We interpret profile properties in the basal silty ice of the Dye 3 core as the result of successive mixing events that have occurred upglacier from the site.

Conclusion

A detailed study of isotopic composition and gas properties of the Dye 3 basal ice shows that flow-induced mixing at different scales best explains the observed profiles. This helps to understand the deformation produced at the base of the Greenland Ice Sheet. By such a process, the basal part of the ice sheet is able to cross a subglacial valley.

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saw of the basal 29 m of ice from the Dye 3 core. Thanks are also due to Dr. M. Stievenard from Saclay for isotopic measurements and to Dr. J.-L. Tison for improving an early draft of the manuscript.

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