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Bremerhaven, 17 October 2012

Micro-DICE networking program

Steering Committee

Report for Micro-DICE short visit travel grant

Introduction

Ice cores present the only archive containing the palaeo-atmosphere enclosed in air bubbles which have been entrapped during the densification of snow via firn into ice. As with the ice matrix itself, dating is a crucial point in order to interpret such records. To determine the age difference between the enclosed air and the surrounding ice (delta-age) the exact length of the firn column (delta-depth) is crucial. The layering and variability of the density of the firn represented in its porous microstructure is a critical factor when discussing the delta-age. According to this, it is important to characterize all factors influencing the deformation of microstructure resulting in densification of snow to ice.

Already in 1980 Herron and Langway described that the form of depth-density profiles depends on temperature and snow accumulation rate. Higher temperature and lower accumulation rates result in a faster densification with depth. Recent studies based on Hörhold et al. [2012] exhibit direct evidence for the influence of impurities on deformation in polar ice. This dependence of the deformation on the concentration of impurities of polar firn was shown using density as strain marker . As a proxy of the impurities Hörhold et al. [2012] considered the Ca^{2+}-concentration. In that study, it was shown that layers with higher concentrations of impurities densify faster, than layers with lower concentrations. It was also observed that the correlation between Ca^{2+}-concentration and the density increases with depth.

The aim of this study is to further examine the dependence of densification on the impurity concentration for three different sites in Greenland. Those sites were chosen for their different climatic conditions for the ice. By improving the understanding of the mechanism of firn densification, the interpretation of climate time series will be improved in the future.

Samples

The Alfred-Wegener-Institute has drilled 15 ice cores and 27 firn cores during the summer 1993-1995 along the North Greenland Traverse [Wilhelms, 1996]. In the presented study the density of the ice cores B19, B22 and B30 were measured

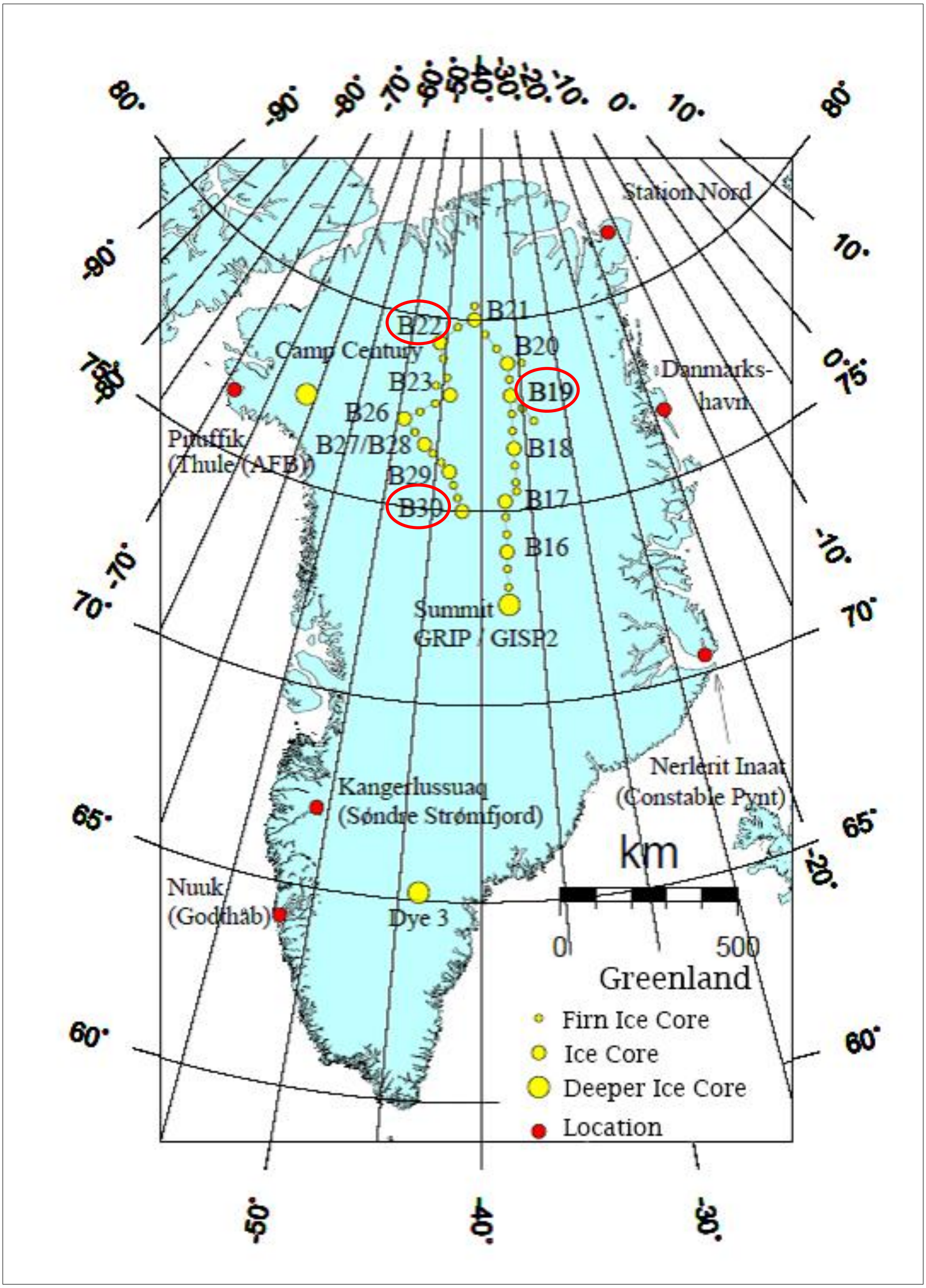


Figure 1. The North Greenland Traverse [Wilhelms, 1996]. The ice cores B19, B22 and B30 investigated in this study are highlighted with red circles.

Table 1. Coordinates, length, age and accumulation rate of the ice cores B19, B22 and B30 [Wilhelms, 1996]

Ice core	Latitude	Longitude	Length [m]	Age [AD]	Accumulationrate [mm w.eq.]
B19	78,001 °N	36,398 °W	150,4	934	97,18 ± 1,64
B22	79,341 °N	45.912 °W	120,6	1479	148,70 ± 1,82
B30	75,000 °N	42,000 °W	160,8	1259	171,28 ± 1,87

and the calcium concentration quantified. The position of the ice cores is given in the Figure 1. Table 1 gives additionally to the location and the length of the individual ice cores an overview of the accumulation rate and the ages, which were analysed by Wilhelms [1996]

Densification

The transformation of polar snow to firn and finally to ice depends on many processes which results in densification of the material with the depth. The densification process can be divided into three stages with two different critical densities [Freitag et al, 2004].

During the first stage the main processes for the densification are the grain settling and packing [Herron and Langway, 1980]. Transport mechanism and surface diffusion are rounding the grains [Arnaud et al., 2000]. Paterson [1981] describes the estimation that a rhombohedral arrangement of grains of the same size lead to a porosity of 26 %, which represent the closest packing of the sphere. Experiments result in porosity, which never reduce below 40 %. For ice with a density of 0.91 g/cm³ follows for a porosity of 40 % a density of 0.55 g/cm³ for this stage. The density of 0.55 g/cm³ is in the literature described as the first critical density [Herron and Langway, 1980].

In the second stage the densification occurs isothermal [Arnaud et al., 2000] with the main processes of recrystallization [Wilhelms, 1996] and plastic deformation Arnaud et al., 2000]. The recrystallisation changes the shape and size of the grain and also leads to form and growth of grain bonds [Alley et al., 1982].At a density of 0.73 g/cm³ the maximal area of the contact between the grains is attained [Wilhelms, 1996] and thus, the pore volume is minimized and therefore the air is enclosed in tubes. Further densification then only occurs in form of plastic deformation up to a density of 0.83 g/cm³, which is the second critical density.

The air in the subsequent third stage is trapped in isolated air bubbles at the close off depth, which is the firn-ice transition. The close off depth usually is located between 50 and 100 m [Landais et al., 2006]. Below this depth the density still increases up to 0.91 g/cm³ due to the compression of the air bubbles [Wilhelms, 1996].

Dust

Dust particles entrapped in the ice matrix give information about climatic conditions of the source area, the transport and deposition process. The source areas vary about the time. The primary dust source for Greenland was the Asian desert in the Last

Glacial Maximum [e.g. Svensson et al., 2000] and during present day [Bory et al. 2002]

Ruth et al. [2002] describe that the calcium concentration is used as a proxy parameter for the total mineral dust in ice cores, because it is the major part of the readily dissolved fraction of the dust aerosols. During different climate periods the soluble proportion of dust is not constant [Ruth et al., 2000]. Cold climate conditions are characterised by a high dust concentration and milder periods by lower concentrations [Svensson et al., 2000].

Additionally, the calcium concentration shows seasonal variation with a maximum in spring, when the variability in atmospheric circulation is largest in the North Atlantic region [Hutterlie et al., 2007].

Density variability

Due to the layering of polar firn the density varies with depth. With the standard deviation the density variability can be quantified.

Freitag et al. [2004] and Gerland et al. [1999] found that the density variability change in frequency and amplitude depending on density and depth. At the surface the density variability is very high. With increasing depth the variability decreases at 10-20 m to a minimum. The density in this depth is 0.6 g/cm³. Subsequently the variability increases to a second relative maximum at the firn-ice-transition at density above 0.83 g/cm³ until the variability finally decrease to zero.

Hörhold et al. [2011] studied the influence of impurities on the densification of polar firn. The density was correlated to the calcium concentration for different depths. At the surface no correlation between density and calcium concentration was found, but with deeper depth the correlation increased. At the firn-ice transition, where the density variability is highest, a correlation between the density and the calcium concentration is significant.

Because of the seasonal variation of the calcium concentration it seems that the density variability also reflects seasonal variations at the firn-ice transition [Hörhold et al., 2011].

Methods

To measure pore microstructure and density the new high-resolution method of X-ray computertomography (Micro-CT) was applied, which is located inside a cold room at -15 °C. The ice cores were put in an integrated microfocus X-ray tube, which was placed between source and detector. The scanning produces a grey-level image of the firn cores, which indicated the microstructure of the firn, due to the large differences in X-ray absorption between ice and air [Freitag et al., 2004]. The density was calculated with a mathematical algorithm.

For each bag the mean density and the gravimetric density, which is the quotient of mass and volume, as well as the standard deviation were calculated.

With the established method of Continuous Flow Analysis (CFA) the concentrations of calcium, dust particle, ammonium, natrium, nitrate, hydrogen peroxide and the conductivity was measured in depth resolution of 5 cm, which was then correlated to the Micro-CT microstructure. For this measurement a part of the ice core was cut off and placed on a melter head, which has an inner and outer section. Only the melted ice sample from the inner section was analyzed [Kaufmann et al., 2008]. Due to this there is a very efficient decontamination of the sample. The calcium measurement based on the fluorescence method [Röthlisberger et al., 2000]. The melted ice is mixed with a reagent protected from light. A spectrometer with a wavelength of 495 nm measures the fluorescence intensity with which the Ca^{2+}-concentration can be determined [Ruth et al. 2008].

Results and Discussion

First results of my study are shown in Figures 2 - 3

Figure 2 shows the density measured using the Micro-CT, the mean and gravimetric density and the density variability for all three ice cores.

For all three ice cores the density increases with the depth. The mean and gravimetric densities of the B22 and B30 are in good agreement contrary to the B19. For the upper part of the B19, the mean and gravimetric density show good agreement, but shows differences with increasing depth. The reason for this is not clear at his point.

The development of the density variability, which was described by Freitag et al. [2004] and Gerland et al. [1999], is displayed in Figure 2. At the surface the variability is high and decreases to a minimum at 20 m and increases again to the second relative maximum at 50 m.

The density variability between the three ice cores develops differently. The reasons for this different behavior are ice layers, which were presented by the single peaks of higher density. The density variability was measured with the standard deviation. Single higher densities produce higher standard deviations. Because of that, there is higher distinct development of the ice core B30 contrary to the B19 and B22. Firstly to get a more meaningful statement about the development of density variability a running average of the density should be calculated with fixed number of data points and then the standard deviation can be calculated.

Figure 3 shows the density and Ca^{2+}-concentration for different depths of B22. Due to the high-resolution of the density and the disperse curves of the Ca^{2+}-concentration the comparison is difficult. This indicates that the density should be mean about a fixed running window.

Nevertheless the following results are detected. In the first interval from10 m to 12 m (Fig. 3a) a distinct density variability and no correlation between density and Ca^{2+}-concentration is found. In depth from 33 m to 35 m (Fig. 3b) the variability is smaller and the correlation rises.

The two curves in Figure 3c for the depth from 46 m to 48 m show a similar development. There is also a good agreement with a comparable rise and fall of the calcium concentration curve and the density curve during the interval of 58 m to 59 m and 66 m to 67 m. On the contrary this was not found between 57 m to 58 m. The Ca^{2+}- concentration varies during 1 m significantly more than the density. The reason for this is not clear at this point.

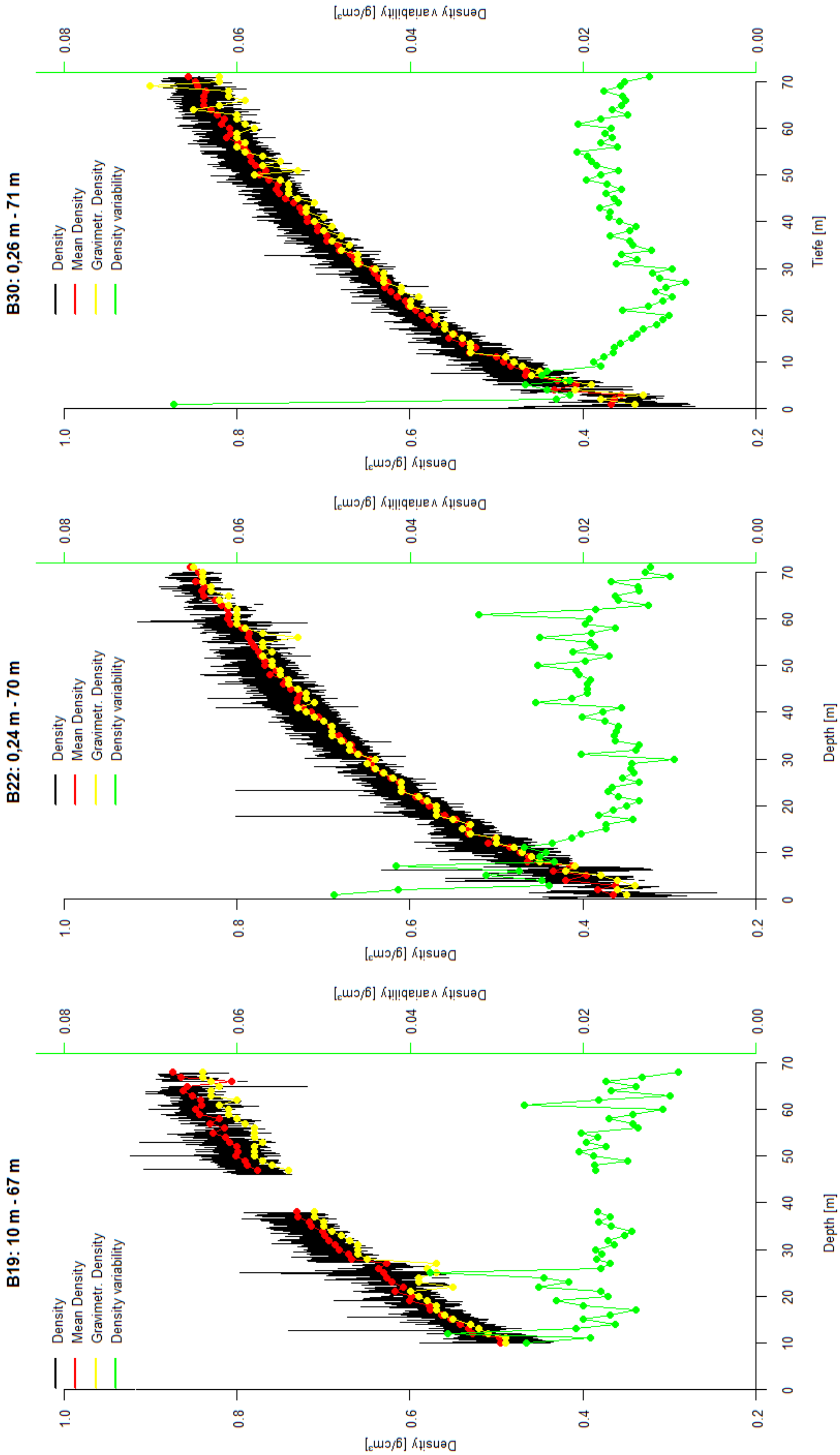
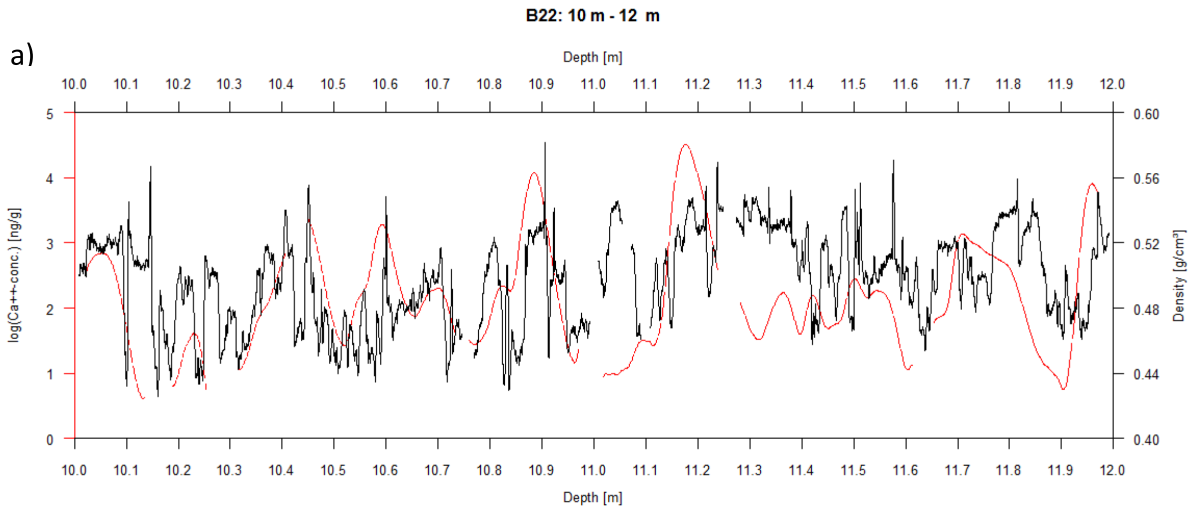
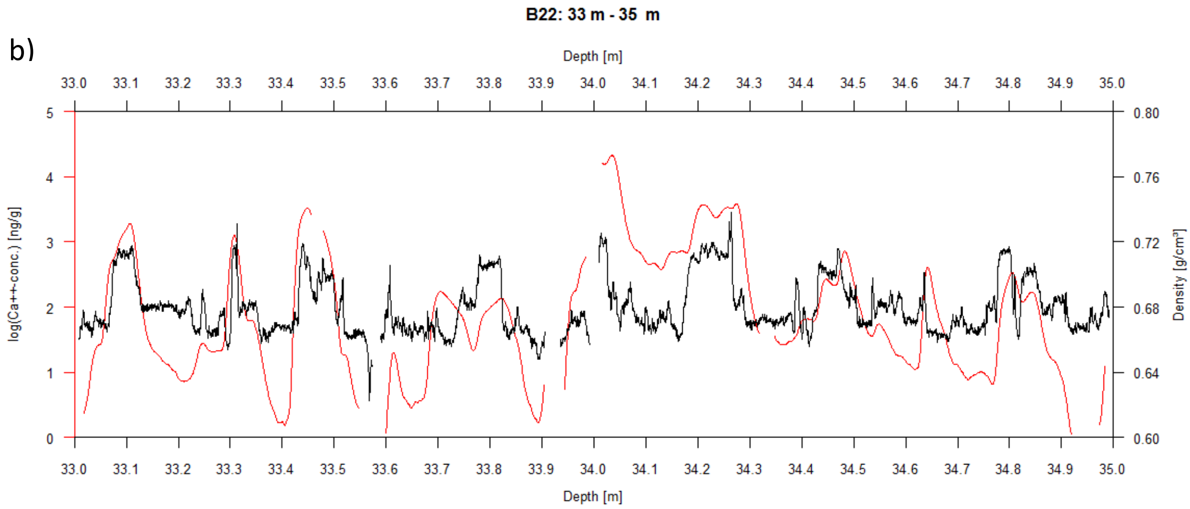


Figure 2. The measured density (black line) of the ice cores B19, B22 and B30 together with the mean density of each bag (red points) and the gravimetric density (yellow points) of each bag. Also is displayed the density variability for each bag (green line). The data gap between 39 and 45 m is due to lost ice.

For the depth of 65 m to 66 m the correlation of the density and the Ca^{2+}-concentration is not particularly good, but it seems that one curve has an offset.

However, in most cases the correlation between density and Ca^{2+}- concentration increases with depth. This was also found in the ice cores B19 and B30. Until now the reason for the increase of correlation with depth is unknown.





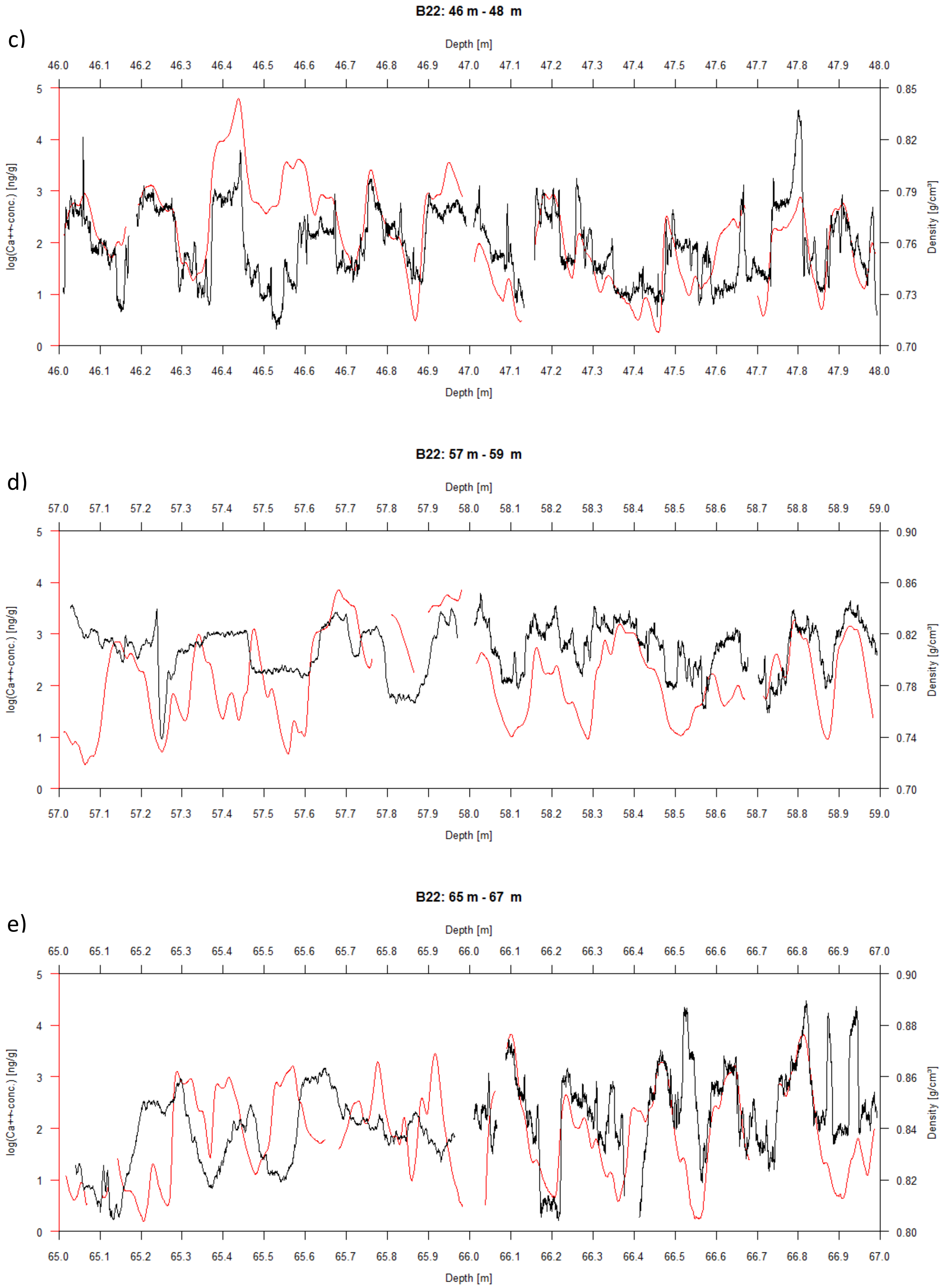


Figure 3. Density (black line) and calcium concentration (red line) for different depth of the B22

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Yours sincerely,

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