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Geophysical and Geodetic Studies of Bedrock, Permafrost and Continental Ice in Queen Maud Land, Antarctica

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Abstract

During the austral summers 1993–1994 and 1997–1998 the Finnish geophysical subgroup in expedition teams 'Finnarp 93/94 and 97/98' carried out geophysical and geodetic investigations in Western Queen Maud Land, Antarctica. The area studied belongs to the Vestfjella mountains near the Finnish base station Aboa (73º03'S, 13º25'W). The aim of the geophysical and geodetic measurements was to study the characteristics of ice, permafrost and bedrock geology between the nunataks. In this study is given results of the geophysical and glaciological investigations on a ca. 38 km long profile between nunataks Basen and Fossilryggen.

Using gravity and magnetic methods connected with petrophysical data we interpreted litholocigal variations in bedrock on nunataks and under continental ice. Using electromagnetic sounding methods we obtained information of conductivity variations in the ice and underlying bedrock. When permafrost is present in bedrock, its geometry can be determined by defining the depth variations of the conductive layer of saline waters enriched below permafrost. These measurements can further be used for estimating temperature variations in bedrock and ice.

The velocity vectors of the ice were determined using high precision differential GPS. The measurements were executed with ca. 1 km intervals in the beginning and in the end of the expedition, time interval being 33–39 days between the measurements. The depth of the ice was determined by gravity interpretation and by radio echo sounding. The GPS measurements reveal that the velocity of the ice in the profile varies from ca. 0 to 27 m/a. When considering the velocities versus ice thickness it can be seen that there is an approximately linear positive correlation with the parameters between thicknesses of ca. 400–900 metres. That means that the increase of velocity versus increase of depth (dv/dz) is approximately constant below depths of ca. 400 meters. Moreover, variations of stake lengths and upper surface of ice during the field season give estimations of ice consolidation and evaporation.

Key words: Antarctica, Queen Maud Land, geophysics, geology, permafrost, ice dynamics, GPS

1. Introduction: Study area and used methods

During the austral summers 1993–1994 and 1997–1998 Finnish geophysical subgroup in expedition teams 'Finnarp 93/94 and 97/98' carried out geophysical and geodetic investigations in Western Queen Maud Land, Antarctica. The area studied belongs to the Vestfjella mountains near the Finnish base station Aboa (73º03'S, 13º25'W; Fig. 1a), located on a nunatak named Basen. In this paper is given a summary of results of the geophysical and glaciological investigations on a ca. 38 km long profile between nunataks Basen and Fossilryggen (Fig. 1b). The region is covered by ice up to ca. 1000 m thick; only nunataks rise above the ice surface. Radio echo profiles have been measured parallel to Basen-Plogen and Basen-Fossilryggen profiles by a Swedish expedition team (*Holmlund*, 1994). They also reported that the maximum velocity of the ice in the Basen-Plogen profile close to Plogen is about 90 metres/year. No velocity values have been reported for the Basen-Fossilryggen profile. The geology in the area has been described by *Grind et al*. (1991); the main rock types exposed on the nunataks are basalts intruded by mafic sills. On Fossilryggen sedimentary rocks with some graphite bearing layers are also present.

The Basen-Fossilryggen profile was measured at ca. 1 km intervals using gravity, magnetic and electromagnetic sounding methods and high precision GPS (x,y,z). Moreover, bedrock samples were collected for petrophysical studies to support the geophysical interpretation. This paper gives an updated and complemented summary of our previously published reports (*Ruotoistenmäki and Lehtimäki*, 1995; 1997 and 1999; *Lehtimäki and Ruotoistenmäki*, 1997).

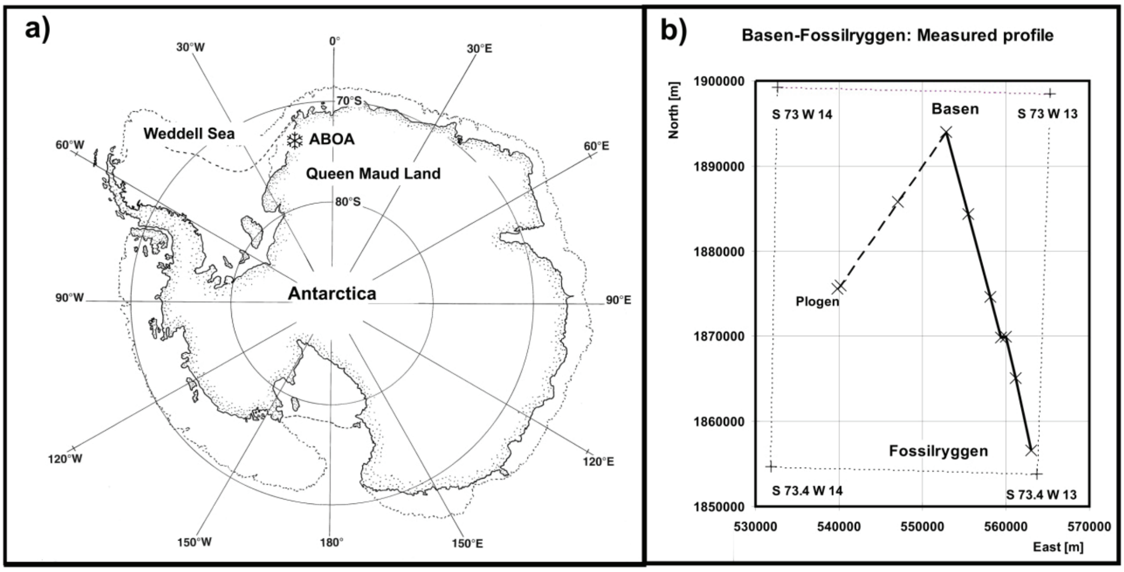

Fig. 1. (a): Location of the study area close to Finnish base station Aboa. (b): The measured profile between nunataks Basen (Aboa) and Fossilryggen.

2. *Petrophysics*

The petrophysical parameters of the rocks in the survey area must be determined before quantitative geophysical interpretation can be made satisfactorily. The samples were analyzed in the petrophysical laboratory of Geological Survey of Finland (methods described in *Puranen*, 1991 and *Korhonen et al*., 1993). The parameters defined were density, susceptibility, remanence and resistivity. In Figure 2 is a density – susceptibility diagram for samples from the Nunataks surrounding survey area. From the diagram it can be seen that sediments (sandstones and graphite schists) are all non-magnetic and have the lowest densities. The basalts, sills and gabbros plot in para- and ferrimagnetic fields. Of these, the basalts have the lowest densities, while the sills overlap with low-density paramagnetic basalts and ferrimagnetic gabbros. The gabbros have the highest class of ferrimagnetic samples, although their densities are lower than those of the high-density, paramagnetic gabbro group.

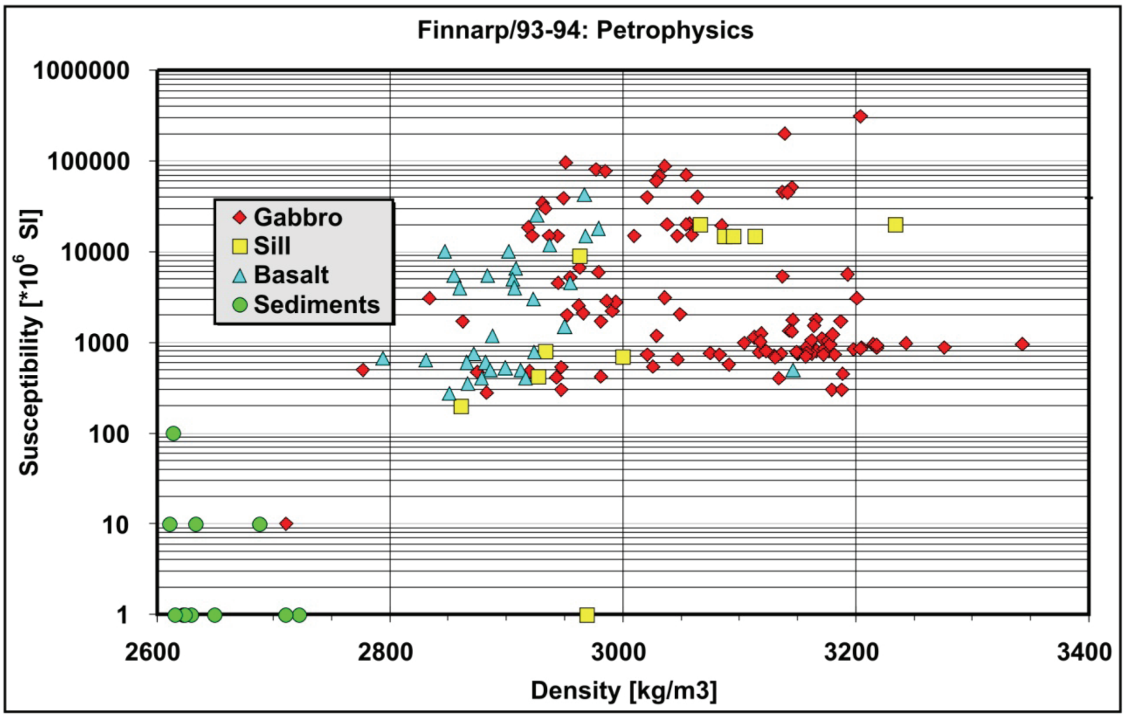

Fig. 2. Density-susceptibility -diagram of the samples from the survey area.

The Q-values (remanent magnetization / induced magnetization) of ferrimagnetic samples vary between 0–2 and those of paramagnetic samples between 0–10. The paramagnetic high-density gabbros are interpreted to represent the lowermost parts of magma chambers (mainly olivine, plagioclase and clinopyroxene). The highly ferrimagnetic gabbros (susceptibility ca. 40 000 or higher) are considered to represent more enriched upper parts of the chambers, reflected in greater abundances of magnetite (Mika Räisänen, Finnarp 1993–94, personal communication). The resistivities of the samples are generally high (ca. 7000–27000 Ohm-m), with the exception of some graphite bearing schists (from ca. 300 to 1000 Ohm-m).

3. *Gravity and magnetic modeling: ice thickness, lithology below ice*

The magnetic and gravity models interpreted along the Basen-Fossilryggen profile are shown in Figure 3. The interpreted models are shown with the vertical scale strongly exaggerated and with vertical and horizontal scales being the same. The magnetic measurements were done with proton magnetometers. The time variations in the earth's magnetic field were recorded by an automatic base station and removed from measured data.

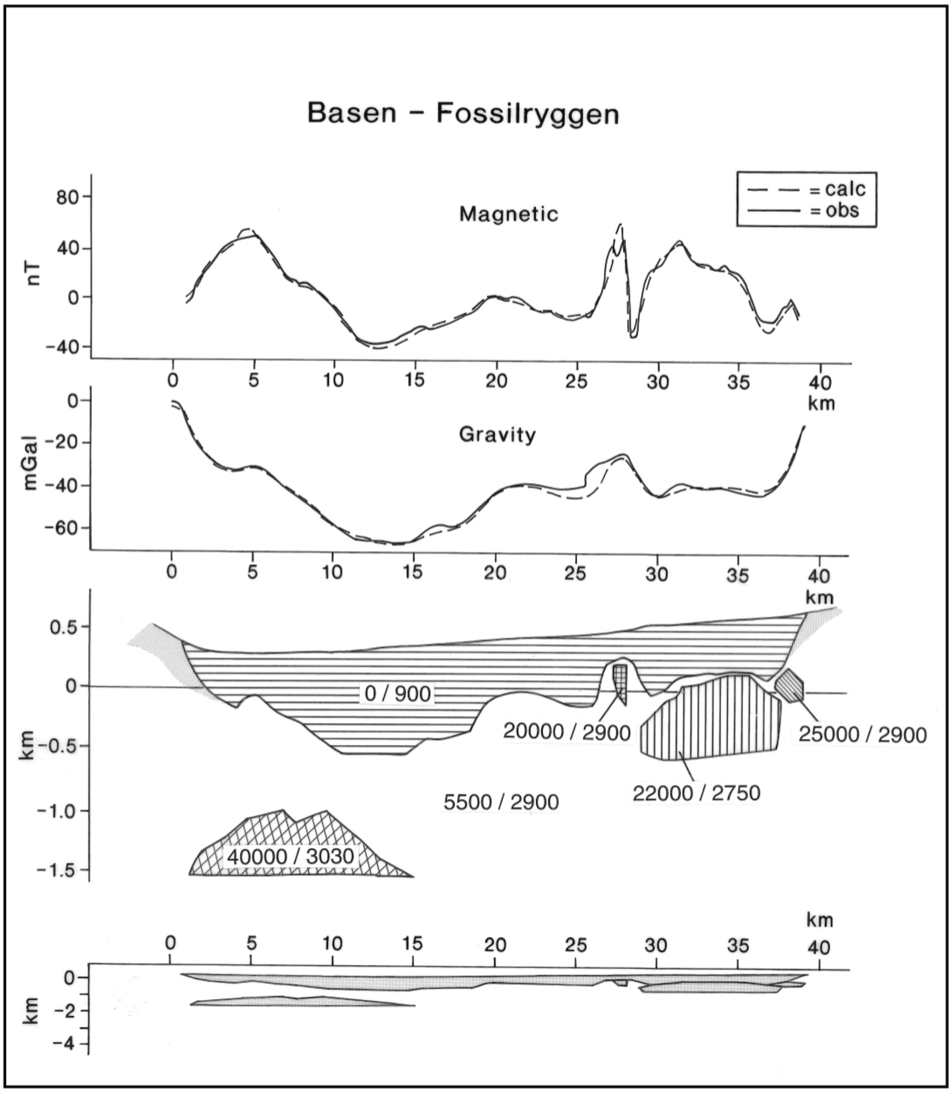

Fig. 3. Magnetic and gravity modelling along the Basen-Fossilryggen profile. Numbers on models refer to susceptibility [SI*10^6] and density [kg/m^3] values. Horizontal hatching refers to ice. In the lowermost model the vertical and horizontal scales are same while in the upper model the vertical scale has been strongly exaggerated.

Most features in the profiles can be explained by variations in ice thickness. The most significant magnetic feature is a 10 km long roundish anomaly, ca. 50–100nT in amplitude, near Basen (at ca. 0–15 km). According to the modelling the source can be a large unexposed lensoid body (oblique cross hatching in the figures). The magnetization and density of the interpreted source correspond to those of the highly magnetic gabbros in the diagram in Figure 2. Thus, it can be interpreted as a gabbroid intrusion, possibly representing the upper parts of a former magma chamber. This magnetic anomaly source can be detected also in the corresponding Basen-Plogen anomaly profile (*Lehtimäki and Ruotoistenmäki*, 1997). The interpreted sources in the bedrock beneath the ice near Fossilryggen are apparently 'mixtures' of sediments, sills and basalts, as is evident from outcrops on nunataks *Grind et al*. (1991).

The gravity observations were made with a Worden gravimeter and altitudes were measured using three barometer altimeters. On the profile the ice thicknesses determined by gravity measurements agree well with radar depths by *Holmlund* (1994). This means that there are no regionally extensive density variations in the bedrock beneath the ice. Based on field observations and petrophysics, the underlying rocks can be interpreted as dominantly basalts in composition. Small density variations cannot be detected because the high density contrast between ice and rock dominates the gravity measurements.

4. Electromagnetic measurements: Geometry of permafrost and temperature gradients in ice and bedrock

Using electromagnetic deep sounding methods one can get information of electrical conductivity variations in the ice and underlying bedrock. If permafrost is present in bedrock, its geometry can be determined by defining the depth variations of the conductive layer of salty waters enriched below permafrost (*Ruotoistenmäki and Lehtimäki*, 1997). The principle of this method is based on the hypothesis that the saline content of wet ground is reduced by freezing and the resulting enriched saline waters are 'squeezed' below the permafrost (e.g. *Daniels et al.*, 1976, *Pisarskii*, 1983 and *Nurmi*, 1985). The electromagnetic sounding work was carried out with a three-component multifrequency (2–20000 Hz) SAMPO electromagnetic sounding system (*Soininen and Jokinen*, 1991).

The results of the electromagnetic measurements along the Basen-Fossilryggen profile are given in Figure 4. The measurements indicate very good conductors (resistivity less than 200 Ohm-m) in the bedrock below ice shown as red dots in the figure. The interpreted conductors between ca. x = 8–17 km (shown by blue dots in the figure) were rejected because they were below the detection limit of the method and thus unrealistic. Values from ca. x = 30 to 40 were rejected because there are probable lithological conductors in the bedrock (graphite schists observed in outcrops in Fossilryggen) thus affecting the results. Moreover, we made some separate measures in the survey area, mainly on the slopes of the Basen nunatak on shallow ice areas. The location of those points is not given in the figure, while they are outside of the profile close to point x = 0.0 km.

When plotting the depth of the conductors in the bedrock as a function of ice thickness (Fig. 5), it can be seen that there is a strong linear correlation between these parameters. Such a correlation could be caused by glacial erosion in bedrock above conductors which are situated at constant depth. However, from Figure 4 it can be seen that the depth variation between the conductors is more than 300 meters. Moreover, such a correlation due to tectonic processes is improbable. Thus, we can conclude that the conductors are not sedimentary layers but predominantly represent saline groundwaters enriched beneath the permafrost layer.

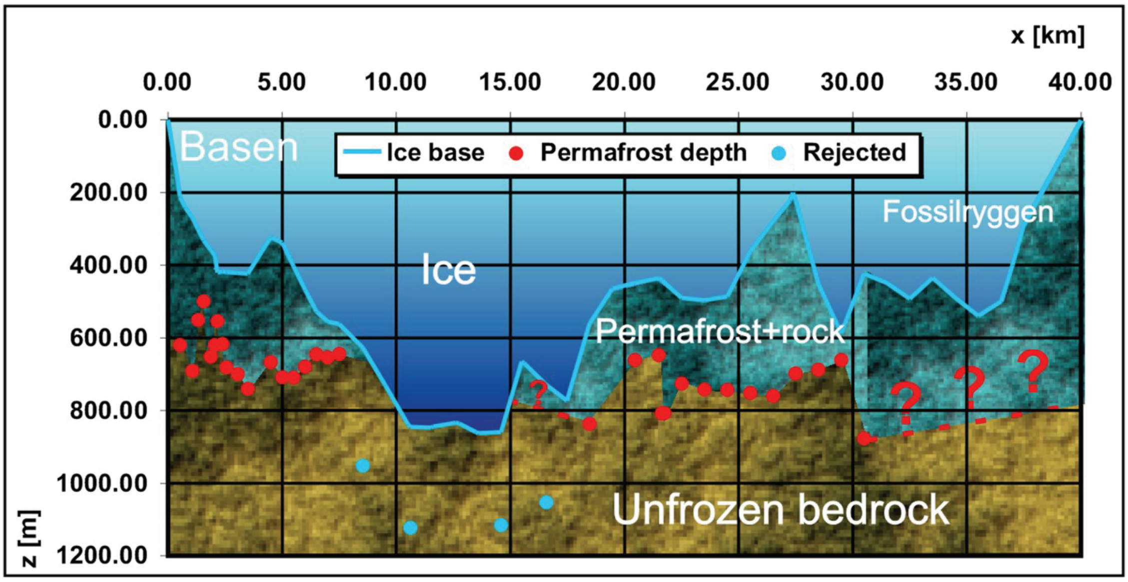

Fig. 4. The results of the electromagnetic measurements along the Basen-Fossilryggen profile. The red dots refer to very good electric conductors interpreted to be saline waters enriched below the permafrost in the bedrock. Blue dots are rejected because of unrealistic depths.

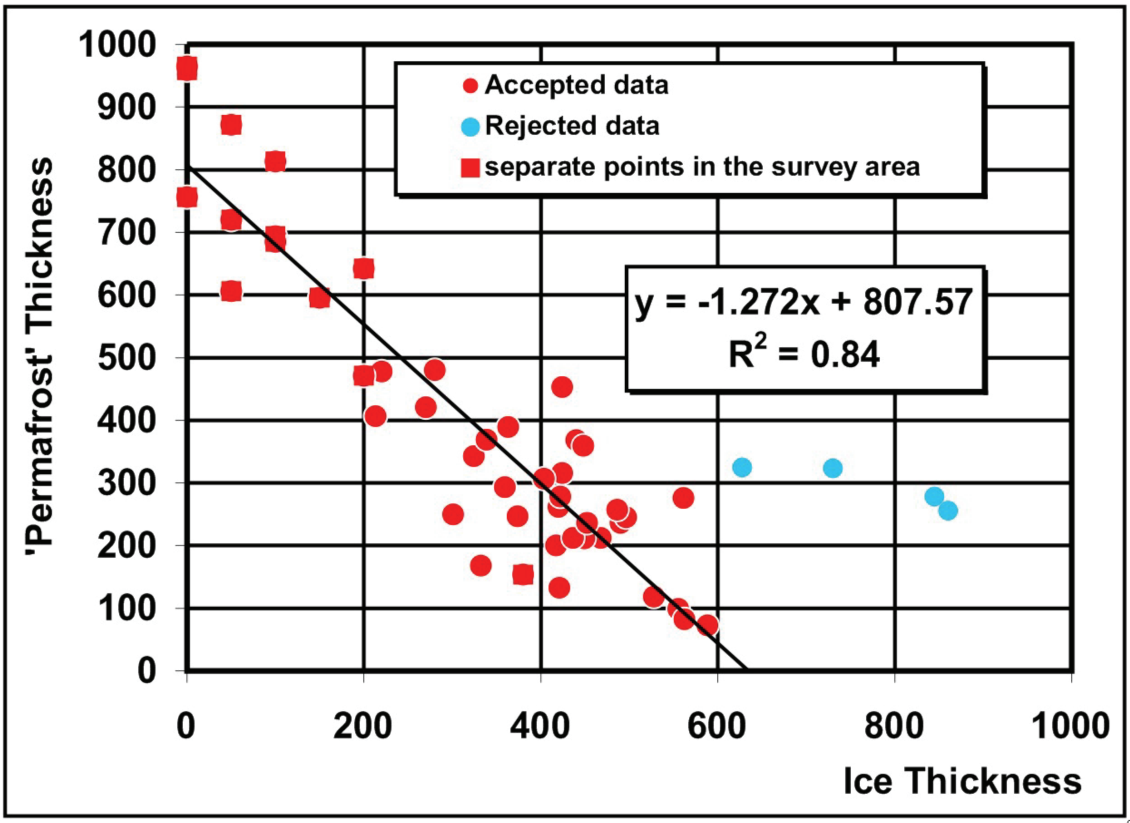

Fig. 5. Relation between the depth of the conductor in bedrock (i.e. base of permafrost) and ice thickness along the Base-Fossilryggen profile.

From the regression line we can estimate that the ice base will be close to melting point of saline waters (approximately ca. -2 ºC, permafrost thickness = 0.) for ice thicknesses greater than ca. 650 m, and that the base of the permafrost in outcropping bedrock in nunataks is at ca. 800 m (when ice thickness = 0). These results also explain why no (realistic) conductors were found between x = 8–17 km of the profile: Because of the greater thickness of the ice sheet the ice base is 'warm' and no saline waters enriched by permafrost are present. Using the average annual surface temperature in the area of ca. -15 ºC (e.g. *Kärkäs*, 2004) and taking the freezing point of saline waters as -2 ºC we can estimate the mean linear temperature gradients in the ice to be about (13 ºC/650 m) = ca. 20 ºC/km and in the bedrock (13 ºC/800 m) = ca. 16 ºC/km. Moreover, in Figure 8 showing the relation between the horizontal velocity and thickness of ice along the Base-Fossilryggen profile it is demonstrated that the base of ice is plastic enough (though, apparently not 'wet') to allow movement when the ice thickness exceeds ca. 400–500 metres.

In Figure 6 is given a simplified model of permafrost effects on nuclear waste repository. When predicting the effects of future ice ages on the nuclear waste disposal depositories it is important to study sites where present day permafrost characteristics in bedrock below continental ice are well known. The method described here gives a rapid method for measuring the geometry and conductivity of permafrost giving thus background material for modelling permafrost behaviour. If, e.g. in Fennoscandia the average annual temperature during future ice age will be close to -15 ºC, as predicted, it can be assumed that permafrost and underlying pulse of saline waters will reach depths of ca. 800. However, the intensity of saline water pulse in e.g. Finland will apparently be different due to different composition and structure of bedrock (basaltic in Basen-Fosilryggen and mainly crystalline in Finland).

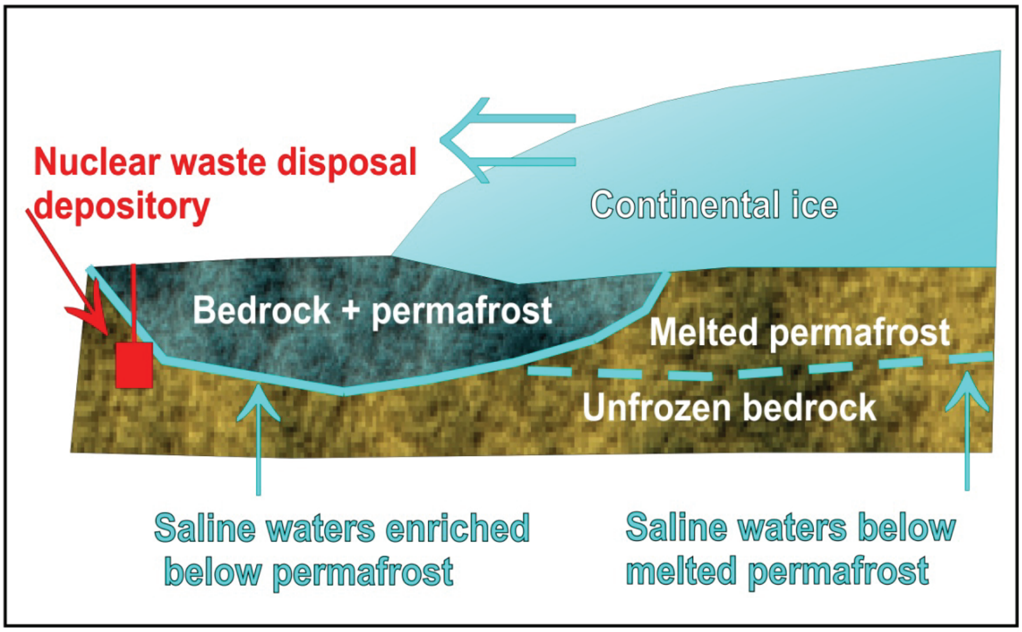

Fig. 6. Model of permafrost effects on nuclear waste repository.

Moreover, even in areas where continental ice and permafrost have already melted, the deep layers of saline waters can still give indications of the geometry of the ancient permafrost, as depicted in Figure 6.

5. High-precision GPS: Ice displacements

The velocity vectors of the ice were determined using high precision differential GPS. The measurements were executed with ca. 1 km intervals in the beginning and the end of the expedition, time interval being 33–39 days between the measurements. The accuracy of the GPS measurement in the Basen-Fossilryggen profile can be estimated to be better than 1 cm. The thickness of the ice was determined by gravity interpretation and by radio echo sounding (*Holmlund*, 1994; Fig. 3).

In Figure 7 the red arrows depict the measured ice movement. For clarity, the vectors have been 'scaled' to 150 000 days while in reality they are too short to be represented in the map scale. During the measurement time interval of max 39 days the

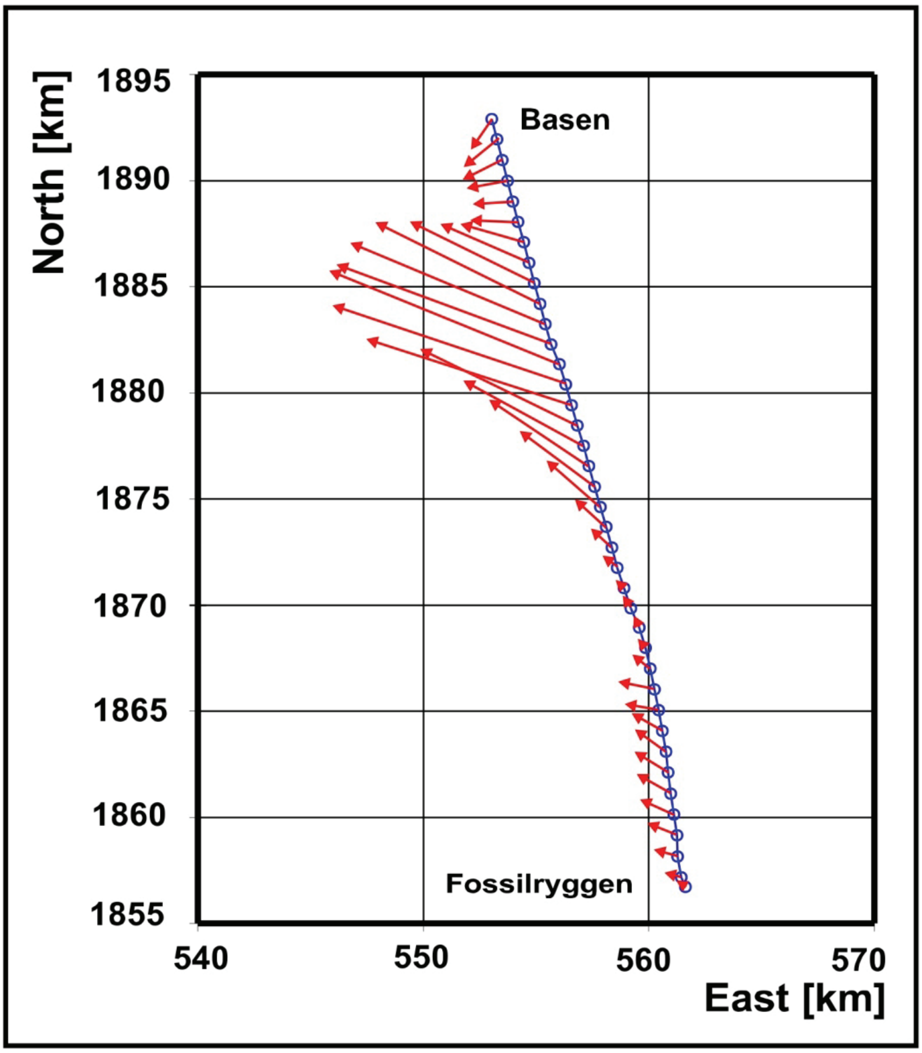

Fig. 7. Velocity vectors of ice along the Basen-Fossilryggen profile. The vector length is 'stretched' to 150 000 days. Thus the true length of the vector is ca 1/4000 of that shown in the figure.

horizontal shift of stakes varied from ca. 10 cm to ca. 2.9 metres (ca 1–25 m/a). From the figure it can be seen that the velocity vectors behave very systematically even at velocities less than 5 m/a thus emphasizing the high accuracy of the method. When considering the high-velocity vectors between ca. N1875 – N1890 it can be seen that the ice flow is 'squeezed' in the thick ice area at ca. 10–15 km shown in Figure 4. Moreover, it appears that the flow is turning northwest.

When comparing the velocity vectors with the ice thickness variations shown in Figure 4 it can be seen that there is a strong correlation between these parameters as is verified in Figure 8. From the figure it can be seen that for ice thickness values below ca. 450 m the velocity of ice is less than 5 m/year. However, for greater ice thicknesses corresponding the topographic depression between ca. x = 5–20 km in Figure 4 the velocities begin to rise linearly as a function of ice thickness.

From the regression line it can be concluded that the rheological parameters of the ice change when its thickness exceeds ca. 450 metres mainly due to increasing temperature in the ice at greater depths resulting to plastic flow of the ice even before it becomes wet-based (at ca. 650 metres, as concluded above).

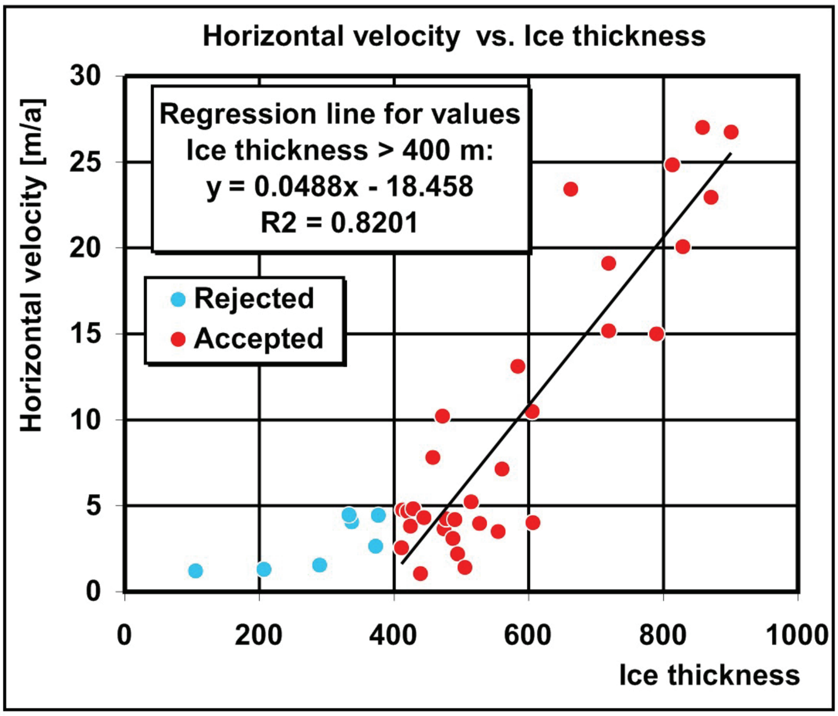

Fig. 8. Relation between the horizontal velocity and thickness of ice along the Basen-Fossilryggen profile.

6. High-precision GPS: Evaporation and consolidation of ice and snow cover

The high-precision GPS has also been used for studying the vertical variations of the ice surface. During the field season 1997–98 we measured the vertical coordinates of the tops of the stakes and their lengths above snow cover. The time interval between measurements was 33 or 39 days. The purpose of the measurements was to get estimates of the evaporation and consolidation of the snow cover and total consolidation of the underlying continental ice (see Figure 9).

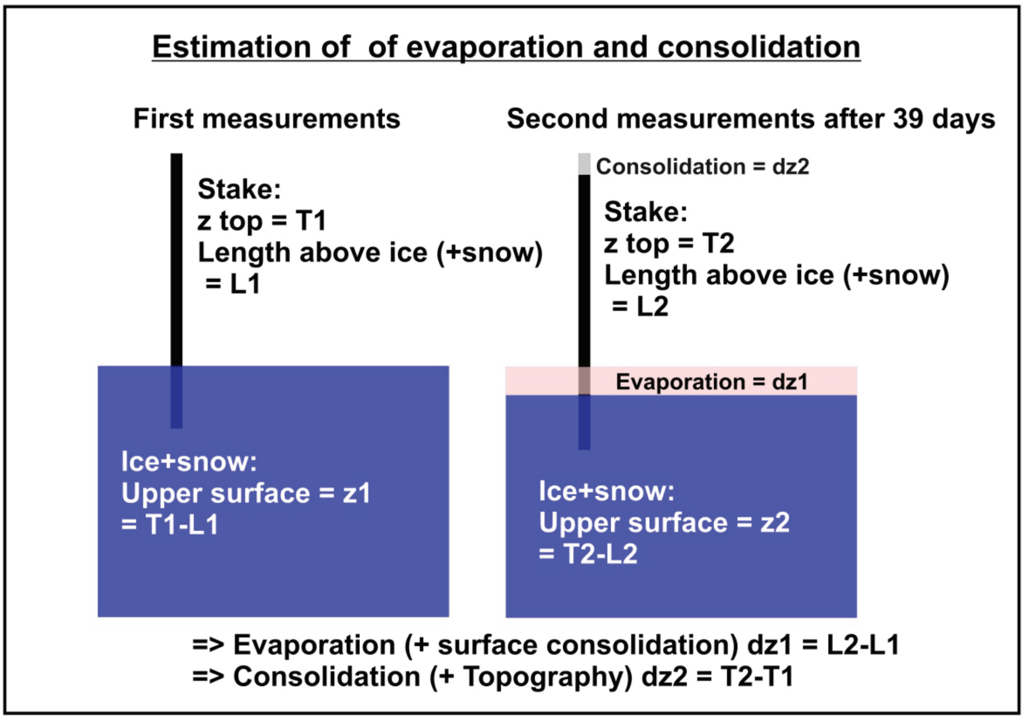

Fig. 9. Measured and calculated parameters for evaluation the vertical variations of ice and snow cover using the high precision GPS.

In the following it is assumed that the stakes have not been lowered (i.e. intruded) by melting in the ice while in the beginning of the season the stakes had been hammered relatively deep, ca. 30 cm in the very solid ice / consolidated snow surface. As shown in Figure 9, it is assumed that the variations in stake lengths are dominated by evaporation of snow cover (± smaller amounts of snow consolidation, windblown snow and fresh snow). The variations in vertical coordinates of stake tops are assumed to be dominated by consolidation of underlying ice cover. The effect of basement topography is assumed small while the maximum horizontal shift of ice during the season was below 2.9 metres.

In Figure 10 and Figure 11 are given the variations of the lengths and tops of the ice surface calculated for one day. From figures it can be seen that both, evaporation and consolidation along the profile can be estimated by sinusoidal curves both varying from ca. 3 to 1 mm/day. The total variation of the ice surface is estimated from the diagram in Figure 12 to be from ca. -5.3 to -2.7 mm/day systematically decreasing to south. The decrease of evaporation and consolidation to south is apparently mainly due to decreasing average temperature when moving towards the South Pole.

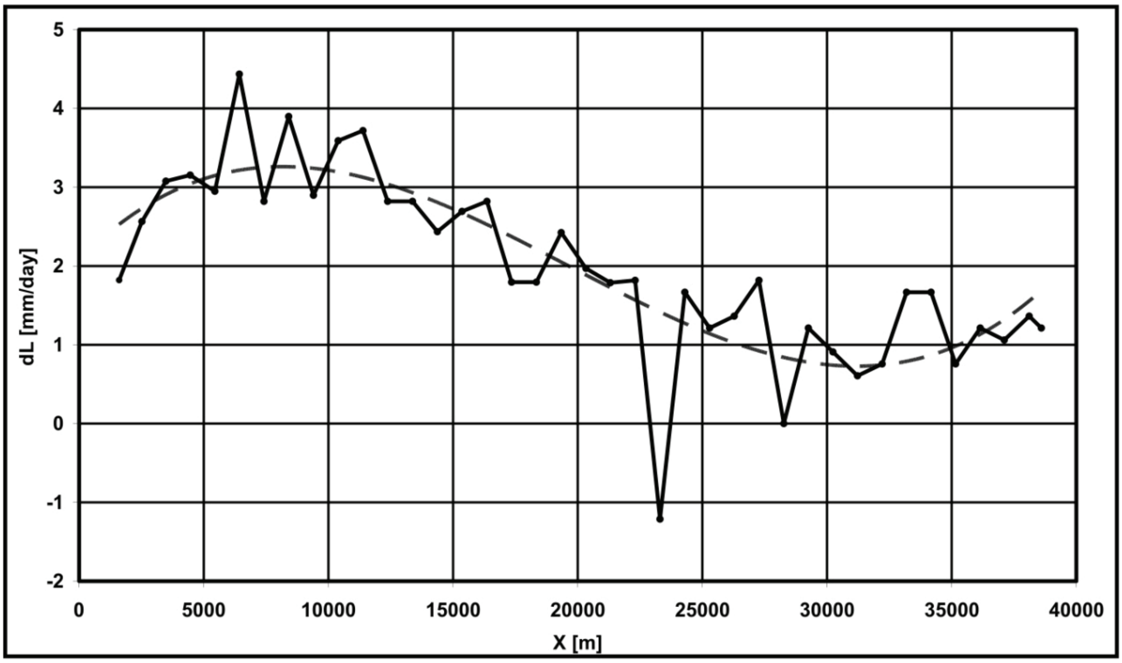

Fig 10. Variation of the stake lengths/day (=L2-L1 in Fig. 9). E.g. at point x=10000 m, the stake length has increased ca. 3.15 mm/day ≈ evaporation + upper snow cover consolidation.

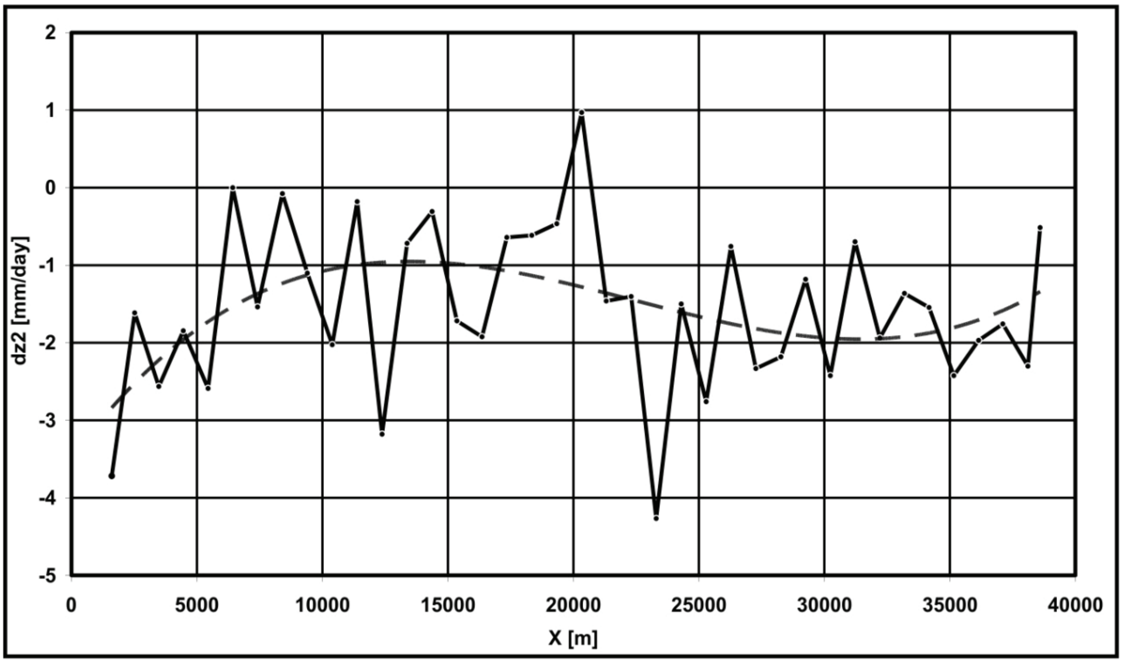

Fig. 11. Variation of the top of the stake/day (= dz2 in Fig. 9). E.g. at point x=10000 m, the stake top has lowered ca. 1.0 mm/day ≈ consolidation of the ice cover.

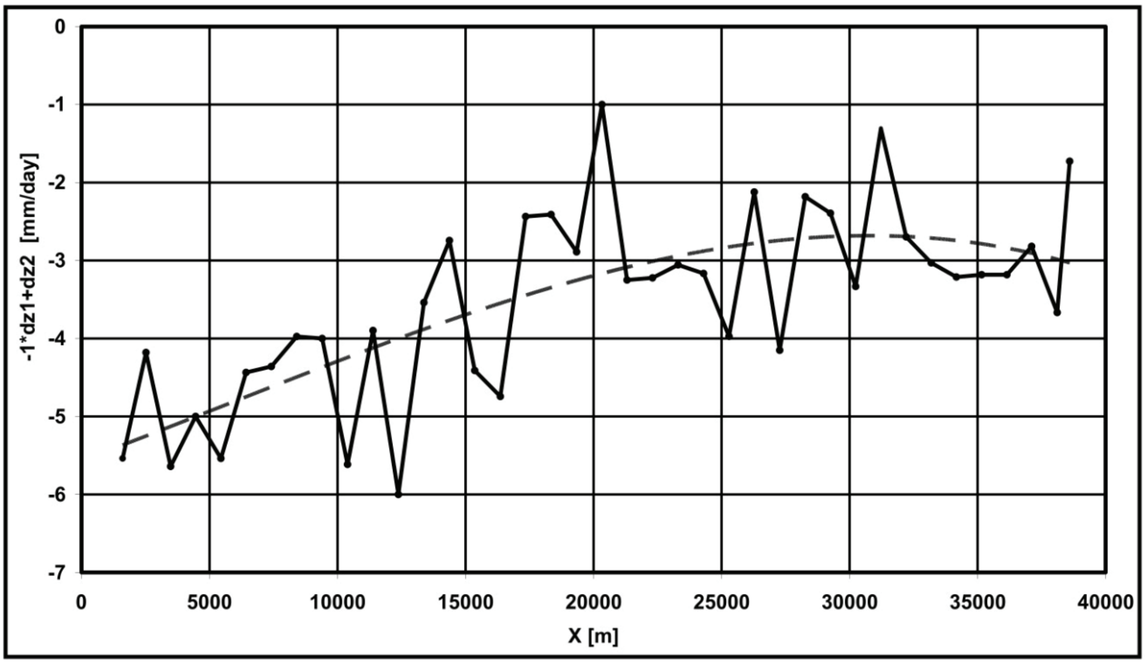

Fig. 12. Variation of the top of the ice surface /day (= -1*dz1+dz2 in Fig. 9). E.g. at point x=10000 m, the surface has lowered ca. 4.2 mm/day ≈ evaporation+consolidation.

7. Conclusions

A combination of proper geophysical and geodetic investigations in areas covered by continental ice can provide valuable information of litholocigal variations in bedrock on nunataks and under continental ice. Electromagnetic sounding methods reveal conductivity variations in the ice and underlying bedrock. When permafrost is present in bedrock, its geometry can be determined by defining the depth variations of the electrically conductive layer of saline waters enriched below permafrost. These measurements can further be used for estimating temperature variations in bedrock and ice.

The velocity vectors of the ice can be determined using high precision differential GPS. Moreover, variations of stake lengths, their tops and upper surface of ice during the field season give estimations of ice consolidation and evaporation. The data of GPS measurements are available from the authors. As such they form a good basis for future monitoring measurements of all x-, y-, and z-components thus giving valuable information of ice dynamics and mass balance in the area.

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