



Svartisen Subglacial Laboratory

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14
2000

D O C U M E N T

A large, vertical photograph occupies the center-left portion of the page. It depicts a massive, crystalline rock formation, likely ice, with intricate internal structures and a light-colored, glowing interior. The surrounding environment appears dark and rugged.

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BIBLIOTEK

Foreword

Svartisen Subglacial Laboratory was initiated in 1992 and since then has been used by researchers from several different countries. The laboratory takes advantage of subglacial intakes beneath Engabreen and associated tunnel system for hydropower purposes to give researchers direct access to the bed of a glacier. This is the only such laboratory in the world.

This report gives an overview of the laboratory as well as copies of the abstracts from all papers that have been published so far based on work done in the laboratory. It is intended that this report is the first in a regular series of reports that will be published biennially.

Miriam Jackson is the researcher responsible for the laboratory and wrote this report. Jim Bogen contributed the section on sediment sampling. Hallgeir Elvehøy reviewed the report and made comments.

Oslo, May 2000



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Forsidefoto: Ice tunnel beneath Engabreen. *Photo Bo Landin, Scandinature.*

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Abstract: Svartisen Subglacial Laboratory is situated under 200 m of ice in northern Norway. The laboratory provides a unique opportunity for direct access to the bed of a temperate glacier for the purposes of measuring sub-glacial parameters and performing experiments on the ice. The laboratory was initiated in 1992. Since then, scientists from several different universities and institutions have taken advantage of the laboratory to perform glaciological research. This is the first report from the laboratory and is intended to give a description of the facilities that the laboratory has to offer and other information for researchers wishing to work there, as well as to give a thorough account of work already performed in the laboratory.

Sammendrag:

Emneord: Glaciology/glaciologi, Ice deformation

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Abstract

This report is a description of the research that has been performed so far in the Svartisen Subglacial Laboratory, which is situated under 200 m of ice in northern Norway. The laboratory provides a unique opportunity for direct access to the bed of a temperate glacier for the purposes of measuring sub-glacial parameters and performing experiments on the ice. As well as summarising previous work, we have also included some logistical details for researchers who wish to become involved in work in the laboratory.

A sub-glacial intake was constructed beneath Engabreen, one of the valley glaciers draining western Svartisen, for hydro-electrical purposes. Permanent tunnels were made through the rock underneath the glacier and lead to access points that open directly at the ice-bed interface. One of these access points has been used to provide a laboratory for the purposes of studying sub-glacial processes.

A variety of projects have already been completed in the laboratory by researchers from a number of different institutions in several different countries. Several load cells have been installed beneath the ice and the anti-correlation between basal pressure and discharge has been examined, as well as the relation between load cell pressure and other parameters. An instrumented obstacle was installed at the bed surface and sliding speed, temperatures and stresses on the obstacle were measured. Using these data in a 3-d finite element model, it was possible to determine the viscosity parameter in the flow law, which was smaller than published values for clean ice. Chemical and isotopic ($\delta^{18}\text{O}$ and δD) analysis of a two metre long basal ice core was performed to investigate the mechanisms by which different ice facies have been formed.

NVE welcomes the participation of different research groups in performing co-operative research in the laboratory. This report is intended to describe the work already completed in order to give researchers an idea of the range of projects that can be performed there. It also lists the facilities available and gives some information on the procedures for initiating research in the laboratory and the costs involved.

Svartisen Subglacial Laboratory

Introduction

Location

Svartisen Subglacial Laboratory is located in northern Norway. It is on the western edge of the Svartisen icefield just north of the Arctic Circle at approximately 66° 40' N. The laboratory is situated underneath Engabreen, one of the main outlet glaciers draining western Svartisen.

The laboratory is accessible by a tunnel that has an entrance at 550 m above sea level. The tunnel system was built as part of the system of water intakes that carry water from the glacier to Storglomvatn reservoir. This part of the tunnel system extends underneath Engabreen with an offshoot leading from the tunnels to the research shafts where it is possible to gain access to the base of the ice at a location where it is 200 m thick.

Access

It is possible to access the tunnel system either on foot or by helicopter. The nearest airports to the laboratory are at Bodø, which has several daily flights direct to and from Oslo, and Mo i Rana, which has one direct flight a day to and from Oslo. Flying time by helicopter to the tunnel entrance is 30 minutes from Bodø and 20 minutes from Mo i Rana, although can be somewhat more in bad weather.

It is also possible to drive or take a bus from Bodø to Holandsfjord, from which it is a ten-minute boat trip to Svartisen Gård. A road goes approximately 2 km from Svartisen Gård to the glacier front. From the glacier front there is a marked route up to the tunnel entrance. It takes between 1 and 2 hours to hike up to the lab, depending on weather conditions and how much equipment is being carried. The hike is fairly strenuous and those intending to work in the lab should ensure that they are fit enough to be able to undertake it without endangering themselves or others.

History

Engabreen is the third place in the world where a subglacial intake has been constructed and the second in Norway. The first was constructed under the Glacier D'Argentière in France, beneath 100 m of ice. A hydroelectric company performed engineering work to divert and use the subglacial water. During this work a subglacial cavity was found and this was isolated from the rock by watertight bulkheads so it could be used for glaciological research; several other natural subglacial cavities were also found. Several scientists took advantage of this opportunity. Vivian and Bouquet (1973) examined subglacial cavitation phenomena, as well as looking at the nature of the basal ice and the variation in sliding speed.

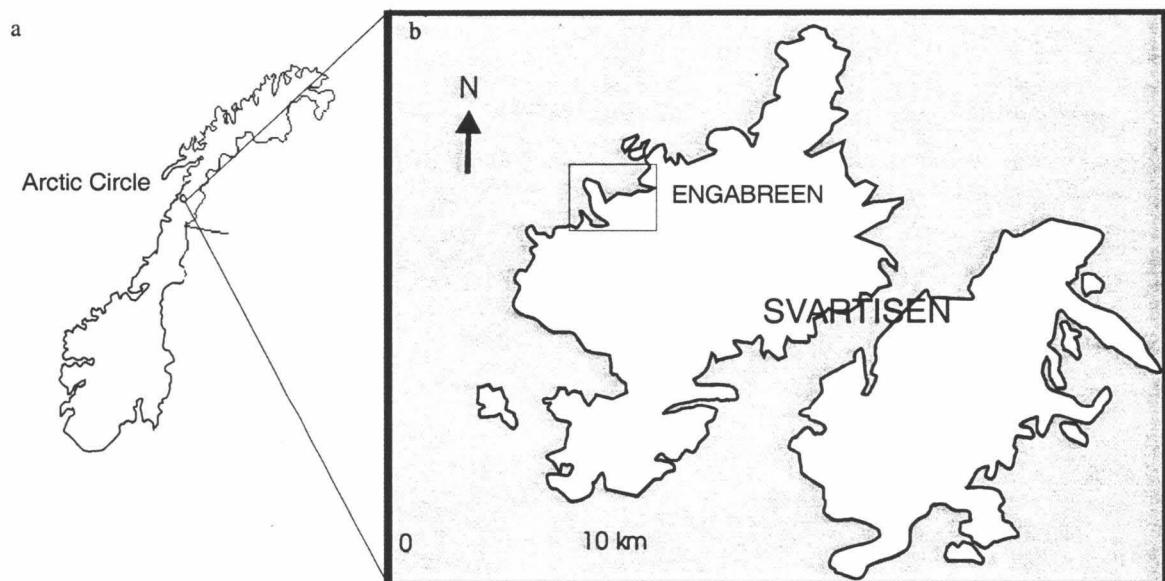


Figure 1. Location maps of Svartisen and Engabreen

Souchez *et al* (1973) studied the chemical composition of the ice in order to learn more about the refreezing of interstitial water. Boulton *et al* (1979) performed direct measurements of shear stress and pressure changes at the base of D'Argentière.

The first subglacial intake in Norway was constructed under Bondhusbrea, an outlet glacier of Folgefonna, work beginning on this project in 1974. The ice here is 160 m thick. Access to the base of the glacier for glaciological research was attained by first going in the tunnel system that had been dug out in the rock by the power company and then melting out ice tunnels, rather than using natural cavities as was done under Glaciere D'Argentière. Hagen *et al* (1983) and Hooke *et al* (1985) studied such aspects as the subglacial hydrology, sediment transport, pressure and temperature. From their work they learnt that conditions at the base of the glacier, such as direction of ice movement, can change significantly from year to year and that the subglacial hydrology evolves over a melt season.

The decision to build a proper glaciological research laboratory under Engabreen was first formulated in 1982, after the successful glaciological research that was carried out under Bondhusbrea had come to an end. The difficult logistical conditions involved in working here meant that it was not desirable to start a new research project at the same site. Both NVE and Statkraft (which at that time was a part of NVE) thought it desirable to increase knowledge about subglacial processes, in particular subglacial hydrology. It was therefore decided to build a more permanent research station in connection with the Svartisen hydropower project. The construction of a subglacial water intake under Engabreen was one feature of the Svartisen project, so this was an obvious place to site the subglacial laboratory.

Work on constructing the subglacial intake began in 1989, and the decision to create a subglacial laboratory was approved and work started in spring 1991. The glacier and snow section at NVE carried out an intensive research programme in the ice tunnels in winter 1992/3, which included drilling boreholes in the rock for instrument access and installing load cells. Work on the laboratory building itself started in 1994. Since then, one or more research projects have taken place in the subglacial tunnels and laboratory each year.

Statkraft

Statkraft is a state-owned company that produces 30% of the total electrical power in Norway. They operate 48 power plants throughout Norway, including the Svartisen power plant which started producing power in 1993 and powers a 350 MW generator, enough to supply 80 000 households with electricity annually. Several dozen intakes, including the subglacial ones, provide water to the power plant. Statkraft constructed the tunnel system that accesses the subglacial meltwater as part of the 100-km total extent of tunnels that were excavated for the Svartisen project. They own and operate the tunnel system underneath the glacier, apart from the research tunnels and laboratory area that are the responsibility of NVE.

Further information

Web pages

There are web pages giving information about the laboratory at <http://www.nve.no/glacier>. Follow the link to Svartisen Glaciological Observatory.

Documentary films

Swedish film team, Scandinature (<http://www.scandinature.se>), led by Bo Landin, filmed in the laboratory in October 1999. The footage they shot was incorporated into a film called 'Dangers of the Ice Age' that was shown on the Discovery channel in March 2000.

A film called Kraft fra Breen (Energy from the Glacier) was made by Wind (<http://home.c2i.net/wind>), led by Inge Bergset. This film shows the construction of the tunnel system under Engabreen, followed the building of the Svartisen power plant between 1987 and 1993, and was made for the power company, Statkraft.



Figure 2. Engabreen glacier. Photo: Hallgeir Elvehøy, 1998.

Facilities

The Svartisen Glaciological Laboratory includes the following facilities:

- ➔ Fully-equipped living quarters with beds for up to 8 researchers in four bedrooms, kitchen with cooking facilities, dining/living area, bathroom including shower etc.
- ➔ Three laboratory rooms, a freezer room and a workshop;

- ➔ Hot-water system (1600 kW) for melting subglacial tunnels;
- ➔ Computer, electronics supplies, miscellaneous tools and heavy equipment for instrument installation;
- ➔ Telephone system with telephones at the main entrance, in the living area, in each laboratory room and at the entrance to the research tunnels.

Previous Work

Overview

Several different projects have been carried out in the subglacial laboratory, some of which are still in progress.

The subglacial hydrology beneath Engabreen has been studied by recording subglacial pressure variations, as measured by load cells installed at the bed. The relation between the pressure measured at different load cells and natural and artificial pressure variations is studied. Natural variations in subglacial pressure are



Figure 3. In the tunnel. *Photo: Bo Landin.*

due to such factors as increased meltwater input in warm weather or periods of rainfall, or large clasts being dragged across a load cell by the overriding ice. Artificial variations in water pressure were induced by connecting a high-pressure pump to the subglacial water system. Most of this work was conducted by Jack Kohler, previously of NVE, and Gaute Lappgard and Jon Ove Hagen at the University of Oslo.

The rheology of the basal ice and basal sliding has been fairly extensively studied. An instrumented panel, containing load cells, pressure transducers, video cameras and thermistors, was installed at the bed surface. From direct measurements it was possible to measure such parameters as the sliding speed, ice-flow direction, friction between sediment particles in the ice and the plate, as well as the variation from one year to the next of such parameters. By using measurements of the sliding speed, bed-parallel force and normal stress in conjunction with a three-dimensional finite-element model it was possible to estimate rheological parameters for the sediment-laden ice layer. Ice fabric and texture have also been measured, the near-isotropic fabrics indicating that there is not a preferred fabric orientation in the basal ice. Most of this work was led by Denis Cohen while he was at the University of Minnesota.

The chemistry of the ice and meltwater has been well studied as an aid to understanding more thoroughly the subglacial hydrological system. The process of solute acquisition in glacial meltwaters has been investigated by studying major ions and trace elements, from melted ice samples and meltwater from different parts of the hydrological system. $\delta^{18}\text{O}$ and δD investigations have also been performed. This work was carried out mainly by Laura Ruffles and Giles Brown of the University of Aberystwyth.

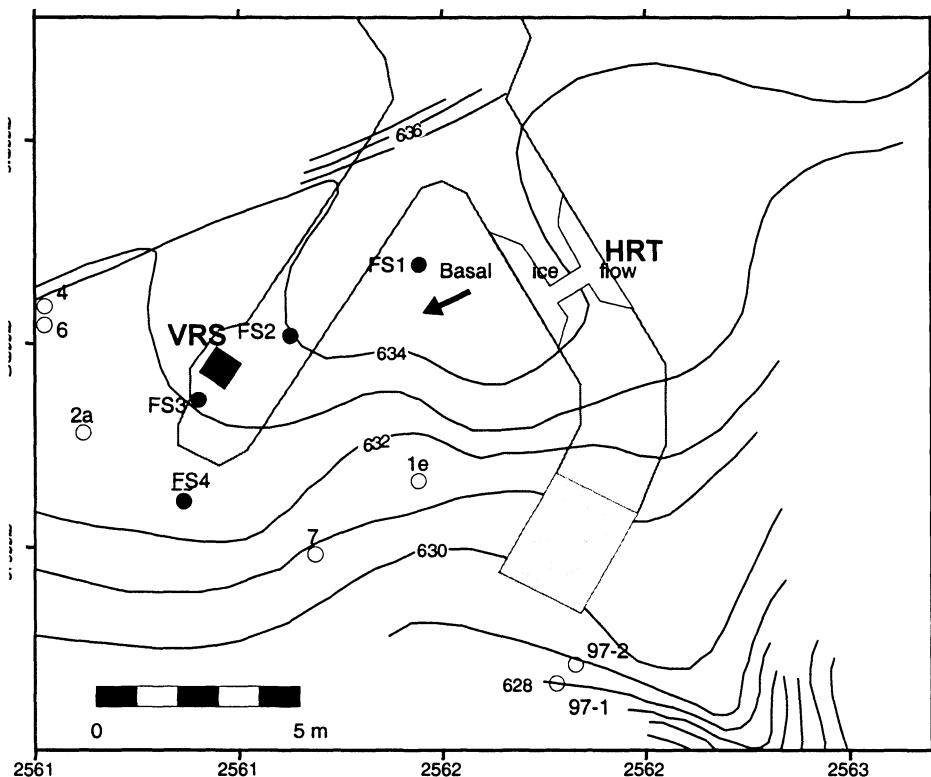


Figure 4: Map view of bed and tunnels beneath Engabreen giving access to glacier bed via two different "windows" into the ice. HRT and VRS are the Horizontal Research Tunnel and Vertical Research Shaft respectively. HRT breaks out under the glacier with the opening (grey rect.) facing down-flow. VRS is blocked by a 60 x 60 cm removable panel lying flush with the glacier bed. Open circles are load cells that measure ice or water pressure or both. Filled circles are locations of tunnel boreholes at the glacier bed.

Several other projects have been performed in the laboratory, either independently of or as a minor part of some other project. These include studying tunnel closure rates, in order to learn more about the ice rheology, studying the stratigraphy of the basal ice, collecting sediment samples for grain size analyses and investigating the water bubbles present in the basal ice.

The following is a chronological list of papers that have previously been published based on work done in the laboratory, as well as the abstract or a summary for each paper. Some articles are presently in press and these will be included in a later edition of this report.

List of publications

Subglacial experiments at Engabreen, northern Norway. (a)

Kohler, J. and N. Iverson. 1993. *Eos.* v. 74 (43), p. 263.

Abstract.

As part of a large hydropower scheme, a tunnel has been constructed beneath Engabreen, one of several outlet glaciers draining the ice cap Svartisen. The project includes the establishment of a permanent subglacial research facility, with several 'windows' that enable direct access to the glacier bed. There are currently two such windows, and several experiments are in progress.

Tunnels melted along the bed indicate that sediment in the basal ice is sparse, occurring in thin, distinct bands. Locally, the ice is separated from the bed by a layer of sediment several centimetres thick. The ice is mostly bubble free and commonly contains water pockets that are elongated in the direction of flow. Rates of tunnel closure are quite high, on the order of 0.5/day. This summer *ca.* 5-10 m³ s⁻¹ of water flowed through each of the windows, effectively postponing access to the bed until this winter. Subglacial water pressure is measured through rock boreholes, and both water and ice pressure are monitored by load cells mounted in the bed. An instrumented sinusoidal bump with a truncated lee face has also been installed with the goal of measuring sliding speed, temperatures and normal stresses.

Engabreen subglacial observatory: fieldwork report, March 1993.

Kohler, J. NVE HB-Notat 11/93.

Summary.

Includes description of tunnel melting and stratigraphy observed, calculations of tunnel closure rates and description of water pockets. Also some initial results from pressure transducer and load cell records.

Subglacial experiments at Engabreen, northern Norway. (b)

Kohler, J., V. Pohjola and P. Jansson. 1994. *Eos.*, v. 75 (44), p. 227.

Abstract.

Subglacial intakes constructed as part of a hydropower project in northern Norway permit access to the bottom of a 200 m active glacier. Tunnels were melted from one of the intakes into the basal ice and crude stratigraphic sections were mapped along the tunnel walls. Bed topography is fairly steep and rugged in this area, with bump wavelengths of roughly 1-10 m and heights of 10-100 cm. The basal ice consists of subhorizontal, occasionally folded, bands of dirty ice with variable debris content. The total thickness of this basal debris layer is roughly 1 m measured perpendicularly from the glacier bed. Throughout the basal ice are numerous water-filled cavities.

They are elongated in the direction of flow, and become progressively larger and more elongate away from the bed. A pervasive 'chaotic' debris layer is found close to the boundary between the debris layers and the overlying clean ice, and is characterized by 1) convoluted banding, 2) an increase in sediment content and debris size, 3) deformed water pockets, and 4) clear-ice 'augen' features around larger sediment particles. Several 1-2 m ice cores were collected and are being analyzed for 1) ice-crystal size and orientation, 2) sediment content and grain-size distribution, and 3) isotope content. Preliminary results of the isotope analysis show enrichment toward the rock-ice interface and depletion toward the contact with the overlying clean ice, which has an intermediate isotopic value. Co-isotopic ratios are relatively constant, except in the vicinity of the chaotic zone.

Measurements on and under Engabreen (Målinger på og under Engabreen).

Kohler, J. and J. Bogen. 1994. NVE HB-Notat 1/94.

Summary.

Short description of load cell measurements from load cells installed under the ice, and water pressure records. Also includes description of basic meteorological measurements and discharge as well as concentration of suspended sediment in water samples from the intake.

Characteristics of Basal Ice at Engabreen, Northern Norway.

Jansson, P., J. Kohler and V.A. Pohjola. 1996. *Annals of Glaciology*. No. 22, pp. 114-120. [NVE Meddelelse nr. 93]

Abstract.

Subglacial intakes in a tunnel system underneath Engabreen, northern Norway, provide access to the underside of a 200 m thick glacier. Detailed observations and

measurements were made in several tunnels melted out along the glacier bed. A 20–200 cm thick basal sediment layer is overlain by clean glacier ice. Stratigraphy is complex, with alternating sediment-rich and sediment-free layers, and pervasive shearing. Throughout the basal ice are numerous spheroidal water pockets, which increase both in size and degree of elongation with distance from the bed. Ice cores were retrieved from ice-tunnel walls for sediment, cation and isotope analysis. Our observations and measurements provide evidence for both accretion in and water movement through the basal ice. This supports the modification to classical regelation theory proposed recently by Lliboutry in which water flow in the vein network is required to achieve net accretion of regelation layers.

A study of the flow of ice past an instrumented obstacle at the bed of Engabreen, Norway.

Cohen, D, N.R. Iverson, R.LeB. Hooke, J. Kohler and H. Elvehøy. 1996. *Eos.. v. 77* (46), p. 193.

Abstract.

Despite widespread interest in glacier sliding, studies at glacier beds have generally not yielded information that is sufficiently comprehensive to evaluate the principal tenets of sliding theories.

With the goal of obtaining such data, an instrumented conical bump was installed flush with the bedrock surface beneath Engabreen, an outlet glacier of the Svartisen ice cap in Norway, where tunnels in the rock beneath the glacier allow access to the bed. The bump, 0.15 m high and 0.23 m in diameter, is part of a removable panel that fits into the mouth of a vertical shaft that extends to the glacier sole. The panel contains two CCD video cameras that record ice motion through quartz-glass windows. Pressure sensors record forces normal to the surface of the bump. A load cell, mounted on the side of the panel, presses against the wall of the surrounding shaft and records the bed-parallel force on the bump. Sixteen thermistors record temperatures in the bump and panel.

The instrument was installed in April 1996, and yielded five consecutive days of data before it was removed. Video recording yielded a relatively steady sliding speed along the flank of the bump of about 0.1 m/d. Entrained debris precluded seeing more than a few millimetres into the ice. Basal shear stress measured with the side load cell was about 0.19 MPa, close to the value obtained by integrating the measured normal stresses across the bump, 0.17 MPa. Temperatures at the surface of the bump were about 0.1 °C below the pressure-melting temperature. Temperature and pressure gradients across the bump were in general agreement.

We anticipate that these measurements, together with the future application of a 3-D finite-element ice-flow model, will help evaluate aspects of the sliding problem, including the rheology of basal ice.

Basal ice rheology of flow past an obstacle at the bed of Engabreen, Norway.

Cohen, D., N.R. Iverson, R. LeB. Hooke, J. Kohler and H. Elvehøy. 1997. *Eos.*, v. 78 (46), p. 229.

Abstract.

The mechanical properties of glacier ice are often described using Glen's flow law. The viscosity and power-law exponent in this constitutive model have been estimated by comparing experimental data gathered in the laboratory or in glaciers to simple flow models. However, there are few measurements that pertain to basal ice. An experiment at the bed of Engabreen, an outlet glacier of the Svartisen ice cap in Norway, combined with a three-dimensional finite element model, has allowed us to estimate the flow law parameters.

The model solves the Navier-Stokes equations. Simple dimensional analysis shows that in the case of Newtonian flow, only the sliding speed and the normal stress difference across the obstacle are needed to determine the basal ice viscosity. For non-Newtonian flow, additional information on the velocity field away from the bed or measurements of sliding speed and normal stresses on two obstacles of different shape are needed to fully determine the viscosity and the power-law exponent.

To obtain such data, an instrumented conical obstacle, 0.15 m high and 0.23 m in diameter, was installed flush with the bedrock surface beneath Engabreen. A CCD video camera recorded ice motion through a quartz-glass window. Pressure sensors recorded forces normal to the stoss and lee surfaces of the obstacle. During observations made in April 1996, video recording yielded a sliding speed of 7 cm/day. Normal stresses of 20 MPa and 0.3 MPa were measured on the stoss and lee side of the obstacle respectively, with no evidence of a cavity on the lee side.

These measurements, together with an assumed value of 3 for the power law exponent in the numerical model, yields a viscosity of $0.8 \text{ bar} a^{1/3}$. This is lower than other measurements of glacier or laboratory ice. Higher than usual water and debris content, or strong anisotropic fabric may account for the low viscosity.

Subglacial pressure variations beneath Engabreen, northern Norway.

Lappgard G., J. Kohler and J.O. Hagen. 1998. *Eos.*, v. 79 (45), p. 310.

Abstract.

Subglacial intakes beneath Engabreen, northern Norway, permit access to the ice/bedrock interface beneath a 200 m thick glacier. In 1992, six vibrating-wire load cells were installed in the bedrock sole along a 20 m transect. Since then, with some

interruptions, the load cells have been logging pressure variations at 15-minute intervals. Load cell signals may reflect the pressure contribution of any combination of, variously: basal ice, water, or sediment particles. In general, most pressure events occur as sharp, short-lived peaks, with complicated phase relations between the various load cells that depend on the placement of the sensor and on the time of year. Some diurnal variation sequences are recorded. During one such episode, surface velocity measurements were being made every 5 min at 10 stakes located 1 km downglacier of the load cell site. During this time there was a positive correlation between surface velocities and the time rate of change of proglacial water discharge, and a negative correlation between surface velocities and the load cell pressures. Apparently, the load cells were sensing water pressures in isolated cavities, that is, cavities not connected to the subglacial drainage system. At other times, however, timing and amplitudes of pressure peaks, not to mention steady, significant discharge from a nearby tunnel borehole, indicate more direct contact with the subglacial drainage system. We were able to insert a packer into the connected tunnel borehole and conduct slug-tests by closing a shut-off valve and logging the reaction with a pressure sensor. This gave useful information on the characteristics of the channel to which the borehole was connected but had minimal effect on the load cells. A more interesting reaction was obtained when a high-pressure (100 bar) pump was used to inject water into the packed tunnel borehole. All of the load cells sensed these high-pressure bursts, to various degrees and with different delays, in ways that are reminiscent of natural pressure events in the load cell record.

Rheology of Basal Ice at Engabreen, Norway.

D. Cohen. 1998. Ph.D. thesis. University of Minnesota, U.S.A.

Abstract.

The ability to predict the dynamic response of glaciers to a changing climate depends on accurate knowledge of the rheological properties of basal ice, which are different from ice higher in the glacier owing to, among other things, high sediment concentrations. The rheology of basal ice is studied by means of field experiments at the bed of Engabreen, a temperate glacier in Norway, coupled with numerical modelling. Measurements of the deformation of ice past a three-dimensional obstacle are used to obtain information on the ice rheology. The water content of the basal ice and of the clean ice above was also measured, and ice samples were collected to study fabric and texture.

A wealth of experimental data on ice indicate that ice can be modelled as a power-law viscous fluid,

$$\dot{\varepsilon} = (\tau / 2\alpha_0)^{\frac{1}{m+1}},$$

where $\dot{\varepsilon}$ and τ are the effective strain rate and stress, respectively. With the goal of determining the two parameters α_0 and m , an instrumented panel containing a conical obstacle was installed beneath Engabreen. Measurements of the sliding speed and of

the force that the ice exerts on the obstacle were obtained for two different obstacle shapes during two field seasons in April 1996 and November 1997. These data, together with a three-dimensional finite element model of ice flow, yielded a consistent value of α_0 between 0.3 and 0.7 bar $a^{1/3}$ for $m = -2/3$. This is 25% to 100% lower than other measurements. It was not possible to determine the value of m independently.

Water content in basal ice was found to range between 2 and 4%. This is higher than the water content measured in the clean ice above (0.7 to 1.5%). Basal ice samples collected to study ice fabric indicated that fabric strength decreases near the bed where sediment concentration is highest. Furthermore, the sediment forms thin layers around small, equant ice crystals.

This unique data set indicates that the viscosity of basal ice is significantly lower than that of ice higher in the glacier. This is attributed to higher water content and to sediment particles in the basal ice which are surrounded by unbound water.



Figure 5. Jon Ove Hagen studies ice in the tunnel. Photo: Erik Roland, 1998.

Subglacial pressure variations beneath Engabreen.

G. Lappgard. 1999. Cand. Sci. Thesis. University of Oslo, Norway.

Summary.

Several load cells have been in place under the ice around the area of the research tunnels since late 1992, and have been recording almost half of the time since then, for several months at a time. Records from the load cells are analysed and compared with records of temperature, precipitation, water discharge etc.

Experiments were performed using artificially induced variations in water pressure, which triggered load cell events that appeared to correspond to natural water pulse events. Results from these records and experiments lend support to the presence of a thin water layer between the bedrock and the ice, usually known as the Weertman layer.

Measurement of water content at the base of Engabreen, Norway.

D. Cohen. 1999. *Eos.* v. 80 (46), p. 427.

Abstract.

The flow of ice near the bed of glaciers and ice sheets is greatly affected by the presence of water, whether in the ice or in the subglacial drift. In the basal ice, high water content reduces the ice viscosity, enhancing ice deformation and reducing the resistance to flow of bedrock obstacles. Laboratory experiments by Duval (1977) indicated that 1% water decreases the value of B in Glen's flow law

$$\dot{\varepsilon} = (\tau/B)^{\frac{1}{3}},$$

by 30%. At Engabreen, an outlet glacier of the Svartisen Ice Cap in Norway, basal ice viscosity was measured and found to be lower than in clean glacier and laboratory ice by up to 100%. Experiments were conducted to measure the in situ water content.

A cold source constructed of two concentric copper cylinders, where a refrigerant was allowed to flow, was inserted into the ice. As heat was removed from the ice, a cold "wave" propagated outward from the source. A thermistor positioned 10 cm from the source recorded the passage of the wave. The speed of propagation of this wave is directly related to the water content. This allows the inverse calculation of the water content.

In this calculation we assume that either: 1) the ice/water mixture is homogeneous and the cold wave separates two distinct phases, the temperate ice and the cold ice, or 2) the ice/water mixture is a single medium where temperature is controlled by vein size, impurities and pressure. The first model is equivalent to solving a Stefan problem. When compared with experimental data, this model indicates that water content in clean ice was about 1% while in dirty ice it was about 2%. The analysis of the data with the second model is underway and results will be presented.

These results suggest that the water content of basal ice is higher than elsewhere in the glacier. Despite the high sensitivity of ice viscosity to water content, such a high water content cannot explain the low viscosity measured at Engabreen. Explanations must be found elsewhere, possibly in the fine laminated texture of the ice where thin bands of debris and ice alternate over scales of a few millimetres.

Reference: Duval, P., 1977. The role of water of water content on the creep of polycrystalline ice. Isotopes and impurities in snow and ice. Proceedings of the Grenoble symposium, IASH 118, 29–33.



Figure 6. Miriam Jackson and Denis Cohen study the sediment-free ice. Photo: Bo Landin.

In-situ investigations of subglacial hydrology and basal ice at Svartisen Glaciological Observatory, Norway.

Ruffles, L.M. 1999. PhD. thesis. University of Wales, Aberystwyth.

Abstract.

This study utilises a unique opportunity to sample *in-situ* subglacial meltwaters and basal ice beneath Engabreen, Norway, using a unique glaciological laboratory which allows year-round access to the glacier bed via a bedrock tunnel system.

The work presented here details the processes by which glacial meltwaters draining a temperate glacier acquire solutes and how these may be related to, and provide scientific and applied information regarding subglacial hydrological regimes. This is achieved by detailed investigations of the chemical and isotopic characteristics of input water (snow and ice-melt), proglacial meltwaters, meltwaters draining into subglacial HEP intakes and subglacial meltwaters draining from the glacier bed into the bedrock tunnel system, during four field visits spanning a full hydrological year. Additionally, the hydrochemical and hydrological characteristics of *in-situ* basal ice have been assessed as these may relate closely to hydrological conditions during formation of the ice and its history since formation.

A numerical model for interpretation of subglacial geochemical weathering mechanisms and environments is developed. This method focuses on the reactions that supply protons which drive subglacial geochemical weathering, as it is proton supply that is believed to most strongly reflect the configuration of subglacial pathways. Application of the model to meltwaters from Engabreen highlights inconsistencies with current models of solute acquisition in temperate glacial environments. It is suggested that these differences reflect the maritime location and large perennial snowcover at Engabreen.

Five ice types were identified at Engabreen on the basis of visual and isotopic characteristics. The formation mechanisms for these ice types suggest that basal ice may interact with the larger scale hydrological system. Supporting laboratory experiments highlight significant problems with existing methods used to sample basal ice for chemical analysis and suggest that trace elements may provide an alternative to major ions in basal ice investigations.

Related projects.

Several projects have been carried out that made only minimal use of the ability to access the base of the ice, or made use of the tunnel system only.

Tracing at Engabreen – August 1993.

J. Kohler. NVE HB-Notat 17/93.

Summary

This report summarises the results of nine dye-tracing tests conducted in August 1993 at Engabreen. The goal of these experiments was to determine the extent of the catchment areas upstream of the two subglacial intakes functioning beneath Engabreen at that time, and to characterise the connections between the tracer injection points and the intakes. Two of the three sampling locations were located within the tunnel system. Results from these experiments were used to delineate drainage boundaries on Engabreen and assisted in planning the location of new water intakes.

Tracing at Engabreen 1994.

J. Kohler. NVE HB-Notat 23/94.

Summary

This report summarises the results of nine dye-tracing tests conducted in July 1994 at Engabreen. As well as having a similar goal to the experiments performed in 1993, another goal of these experiments was to compare the results with the experiments performed in 1993. Three new subglacial intakes were blasted in May

1994 so water sampled in the tunnel came from a larger area than the previous year. Sampling locations were approximately similar to the ones used in the previous year, with two of them again being located inside the tunnel system. The results appeared to confirm that the new intakes are successful in capturing water from the southern side of Engabreen.

Grain size distribution in deforming subglacial tills: role of grain fracture.

Hooke, R.LeB. and N.R. Iverson. 1995. *Geology*. v. 23(1), pp. 57-60.

The main topic of this paper is deforming subglacial tills in general, but the particle size distribution of some of the discontinuous till layer that was sampled from beneath Engabreen is discussed.

Effect of a Controlled Discharge Pulse on the Subglacial Drainage System and Ice Flow at Engabreen, Northern Norway.

J. Kohler and 9 others. 1998. *Eos..* v. 79 (45), p. 274.

Abstract.

Intakes in bedrock tunnels beneath the glacier Engabreen are used to tap subglacial water for hydropower. Due to the high sediment load, the subglacial water must be diverted into a settling chamber before flowing further to the hydropower plant. Once a year, the accumulated sediment in the chamber is hydraulically flushed out of a tunnel draining above the side of the glacier. The power company first releases a small flow which drains into a pre-existing ice-tunnel under the glacier. The ice-tunnel enlarges until it is of sufficient size to handle the larger flow. The chamber is then opened, a torrent of sediment-laden water roars out of the drainage tunnel, into the glacier, and out again at the proglacial stream 1.5 km downglacier.

The power company agreed in 1997 to schedule a release to our specification. This is as close to a controlled jökulhlaup as it possible to get, and provides a unique opportunity to monitor the effect of discharge events on glacier dynamics. For several days prior to and one day after the emptying of the sediment chamber, we made the following measurements:

- 1) Dye traces every 3 hours using automatic injection and detection;
- 2) Continuous distances to 13 stakes on the glacier using a computer-controlled EDM, with complete surveys at regular intervals;
- 3) Continuous position using differential GPS at one stake;
- 4) Proglacial discharge and water quality.

The experiment was mostly successful, but the ice-tunnel into which the chamber drained was not large enough. Most of the water that should have flowed

under the glacier backed up instead and flowed along the side of the glacier to the front. Nevertheless, the effect of the discharge pulse was easily seen in the proglacial stream records (discharge, water chemistry, sediment concentration, conductivity), in the dye trace results, and, to a lesser extent, in the glacier velocity record.

The Effect of Subglacial Intakes on Ice Dynamics.

J. Kohler. NVE HB-Rapport 12/98.

Abstract.

As part of Statkraft's Svartisen hydropower project, an extensive tunnel system has been constructed in and under the Svartisen ice cap. One branch of the tunnel system lies beneath Engabreen, one of the main outlet glaciers draining western Svartisen. Specially built subglacial intakes were used to tap water from Engabreen's internal drainage system, and have been in operation since May 1993.

A variety of velocity measurements have been made at Engabreen between 1990 and 1995 to document dynamic changes that might result from the intakes. This report uses selected velocity and other data together with two different modelling methods, a glacier-flow model and a force balance model, to evaluate the dynamic changes that occurred as a result of intake construction.

The Röthlisberger (1972) model of subglacial drainage predicts an inverse relation between steady-state discharge and the pressure gradient required to drive that discharge. Cutting off the water supply to the main channel downglacier from the subglacial intakes at Engabreen should therefore have resulted in an increase in basal water pressures, which in turn should lead to an increase in sliding velocity.

No direct observations of subglacial water pressure are available. However, the following indirect evidence points to an increase in sliding velocities in the years following construction of the subglacial intakes:

1. Velocities increased everywhere on the lower part of Engabreen;
2. Ice thickness decreased immediately downglacier from the intakes, but increased elsewhere;
3. The velocity increases cannot be explained by the thickness increases alone;
4. The decrease in ice thickness downglacier from the intakes is consistent with removal of ice there due to more rapid basal sliding;
5. The significant advance in front position during the period 1994-95 is consistent with the arrival of ice transported out from the intake area;
6. The glacier-flow model driven by observed and reconstructed mass balances was unable to model the front position advance of 1994-95, without introducing higher basal sliding speeds downglacier from the intakes in the years following 1993;
7. The force balance method using observed surface strain rates to estimate basal shear stress showed that basal shear stresses increased downglacier from the intakes after 1993, and decreased upglacier.

The large front position advance registered in 1994-95 was doubtlessly enhanced by the construction of the intakes; however, normal ‘background’ thickness and velocity changes driven by varying mass balance appear to be of the same order of magnitude as the changes due to the intakes. The advance would have occurred even if the intakes hadn’t been constructed in the first place. This is apparent both from the front advances observed at other glaciers draining Svartisen, and from the glacier modelling. The degree to which the 1994-95 advance might have been enhanced by the subglacial intakes is estimated by comparing two glacier-flow model scenarios, one with increased sliding downglacier from intakes after 1993, the other with unchanged sliding. With an increase in sliding, the glacier advances by nearly 290 m relative to the modelled 1993 front position over about 10 years, which with unchanged sliding, the glacier advances by only 110 m over about 25 years.

Sediment Sampling

Jim Bogen, NVE – HM

Sediment transport studies have been carried out at a monitoring station located at the subglacial intake. An ISCO automatic sampler collects samples 1 – 3 times a day and water discharge is measured at the outlet of the sedimentation chamber. Samples are taken also to analyse grain size distributions. The purpose of this study is to improve the understanding of the meltout processes of sediments from the glacier sole and to determine the sediment yield. Sediment yields from Engabreen before the intake was operative are published in Bogen (1996). Another important aim of this research is to evaluate the impact of the Svartisen power plant on the downstream sediment load (see Bogen and Bønsnes, 2000).

Complete results from the subglacial station have not yet been published due to problems with the operation of the monitoring station.

Bogen J. 1996. Erosion rates and sediment yield of glaciers. *Annals of Glaciology*, vol 22, p.48-52 .

Bogen, J. and Bønsnes, T.E. 2000 The impact of a hydroelectric power plant on the sediment load in downstream water bodies, Svartisen, Norway. 14 pp. Submitted to: *Science of the total environment, special issue*, May 2000 (Proceedings of the IASWS – symposium in Beijing, China, september 13 – 17, 1999).

How to start a project in the laboratory.

Preliminary

The first step in initiating a project in the subglacial laboratory is to contact the Glacier and Snow Section at NVE (hb@nve.no) This communication should include an outline of the project being considered as well as other relevant information such as experience of the researchers concerned, suggested timeframe for performing the

practical work etc. NVE encourages joint projects between NVE and one or more institutions.

Costs

Costs related to working in the subglacial laboratory can be split into the following categories:

travel; accommodation; personnel; electrical power.

It is mandatory that there is always someone present from NVE when work is being carried out in the laboratory. This means that the expenses also need to cover associated costs for this person.

The following costs are correct as of March 2000.

Travel: costs involved include airfare to and from Bodø (return airfare between Oslo and Bodø is approximately 5 000 NOK) and return travel between Bodø and the lab. Helicopter costs from Bodø to the lab are 9 000 NOK per hour (with a minimum of two hours if drop-off and pick-up are both by helicopter) or car rental costs 5000 NOK per week plus additional minor costs for boat travel across Holandsfjord.

Accommodation: this is usually charged at a rate of 200 NOK per person per night. See the 'Facilities' section for a brief description of the accommodation.

Personnel: Daily expenses for NVE personnel are approximately 1370 NOK per day or 9600 NOK per week. These expenses are imposed by the Norwegian government for employees working away from home and do not cover salary.

Electrical power: In order to access the horizontal research tunnel it is necessary to use hot water to melt-out tunnels in the ice. Electricity costs 300 NOK for one hour of hot-water melting and an approximate cost for one week's work in the ice tunnels is 20 000 NOK.

Funding

NVE has no funding available for external institutions towards research in the subglacial laboratory. A researcher interested in performing research in the subglacial laboratory should approach their own national research council. The last two grant-awarding bodies below award grants to researchers in the U.K. (and other countries, in the case of NATO CLGs) for performing collaborative international research.

Norway. Norges Forskningsråd. Awards grants to Norwegian researchers for those projects in which the principal investigator is at a Norwegian university. See: <http://www.forskningsradet.no/>

U.S. The Arctic Research Program at the Office of Polar Programs of the National Science Foundation awards grants to U.S. scientists to perform research in the Arctic. See: <http://www.nsf.gov/od/opp>.

U.K. and other countries. Collaborative Linkage Grants from NATO. The aim of these grants is to facilitate collaboration between research scientists or research teams in NATO or partner countries in order to stimulate scientific research through the pooling of capabilities and resources. Funding is available for reciprocal visits abroad of up to five members of each research team collaborating on a joint research project. See: <http://www.nato.int/science/cst.htm>. There are three closing dates each year for receipt of applications.

U.K. Joint Project grants from the Royal Society. This scheme provides funding for the support of joint projects between two individuals or two research groups over a period of two years. Funding covers international travel and subsistence, as well as a small amount for consumables. See: <http://www.royalsoc.ac.uk/>. There are two annual closing dates for receipt of applications.

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