# IMPLICATIONS FOR AND FINDINGS FROM DEEP ICE CORE DRILLINGS — AN EXAMPLE: THE ULTIMATE TENSILE STRENGTH OF ICE AT HIGH STRAIN RATES

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## 1 INTRODUCTION

At present, several deep ice core drilling operations have just been finished and new ventures are in the planning phase. In this paper we discuss ice properties related data attained when drilling the Dronning Maud Land (DML) deep ice core[1] in the framework of the European Project for Ice Coring in Antarctica (EPICA). The drill site is located[2] in East Antarctica at 75° S, close to the Greenwich meridian. The pull force rating of the winch to break the core at the end of a drill run is one of the key design parameter for ice coring winches. Amongst drilling personnel it is common knowledge that core breaks are getting harder in warm ice. However this has never been quantified, but is consistent with the experience based on safety tests for ice-screws. The engineers of the German Alpine Club's security-council quote the warm ice (just below the melting point) to be tougher and attribute this to its "more plastic behaviour"[3]. When designing heating for railway switches, engineers want to estimate under which conditions the frozen blade can be ripped from the track. The literature on tensile strength of ice suggests a decrease with increasing temperature for low strain rates[4,5] (in the order of $10^{-6}$ … $10^{-5}$ $s^{-1}$), however the latest review of all compiled data suggests that for low strain rates the tensile strength of ice is independent from temperature[6], but for high strain rates this might be completely different as crack healing acts or cracks become blunt[7]. The core breaks presented here represent much higher strain rates and should be well in a crack-nucleation regime[8]. On the other hand we frequently observed refrozen water on the drill head, when drilling at temperatures above –10 °C. Liquid water at the cutters could either act as lubricant or even heal micro-cracks that were initiated by the cutting process. Both processes would lead to a reduction of the number of initial micro-cracks and thus strengthen the ice core. The remarkably smooth ice core surfaces we observed towards the bedrock at higher temperatures also suggest the presence of liquid water during the cutting process.

2 ICE CORE DRILLING PROCEDURE

## 2.1 Experimental setup

Deep ice cores are drilled by cutting a ring into the glacier. The inner remaining cylinder moves into a tube, the so called core barrel. After a certain depth increment, depending on the used drill system between about 0.8 m to more than 4 m, the cylindrical ice core is broken off from the bore-hole's bottom and hoisted to the surface. The drill system's layout is described elsewhere[9,10]. Figure 1 gives an overview about the drill system. During the breaking and hoisting process the core is held by the three core catchers (Figure 1a) and the force is applied by pulling with a winch (Figure 1b). Even though the core catchers are designed to introduce fracture into the core, they quite often abrade the core's surface and the abrasion wedges the core into the core barrel. Thus, the pulling force is in most core breaks applied to the core's entire cross section. The applied pulling force is measured with a strain gauge, calibrated in kilogramme (force), which is situated in the drill towers top pulley. When breaking the core, one spools in the cable with a speed of a few cm/s. The maximum tension is recorded automatically and is noted as "core break", as well as the final plumbing depth, for each respective drill run.

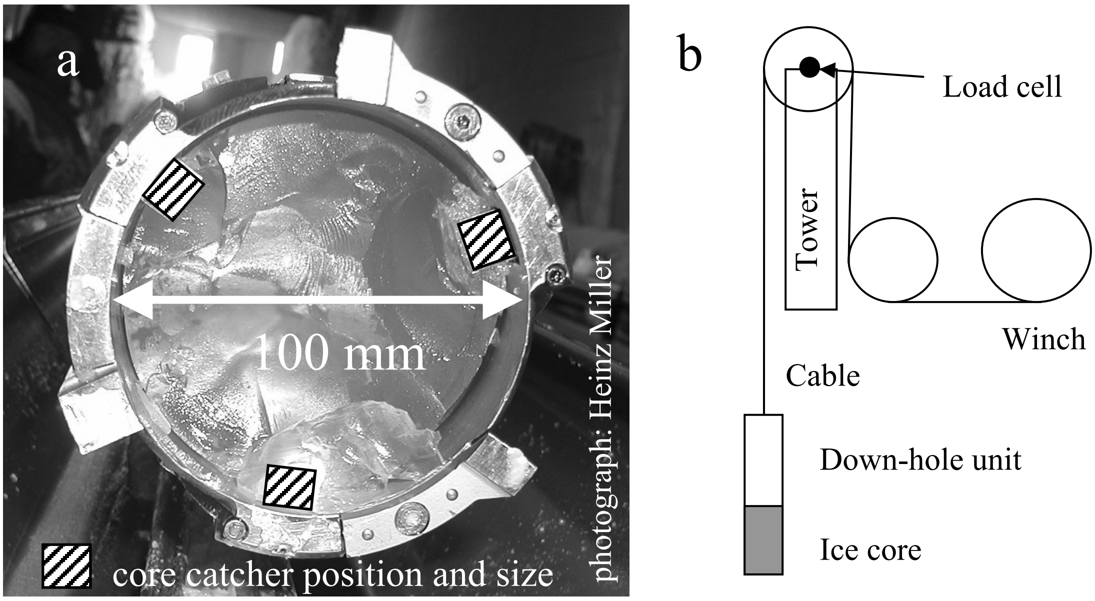


**Figure 1** *The experimental setup; a: Drill head with cutters and hatched core catcher area; b: The core catchers hold the core when pulling with the winch and recording the break force with the load cell.*

## 2.2 Core-break data treatment

From the recorded force data the cable and the drill's weight in the drilling liquid are subtracted and the data are converted into true force readings. The confinement pressure does not contribute to the net force, as the drill is permeable to fluid and thus the fluid can be easily displaced around the ice core. For each core break the cable depth plumbing is also recorded, so that one has a core break versus depth data set. In total there are about 1500 core breaks, so that on average there are about 40 core breaks in a depth interval of 50 m, which is used to average the data for further investigation. The core break errors are the quadratic sum of 6 % systematic error from load cell calibration and the standard error of the mean of each depth interval.

### 2.3 Temperature and pressure logging of the hole

The bore-hole was logged several times with a logging tool, thus measuring temperature, pressure and the geometry of the bore-hole. The tool is described elsewhere[11], relevant for the discussion here is the temperature measurement with an absolute precision of better than 50 mK. The pressure in the hole deviates by less than 500 kPa from the ice pressure over the whole range and can be calculated roughly from the given drilling depth by multiplying with the average drill liquid/ice density of 0.92 $Mgm^{-3}$ and the acceleration of gravity of 9.8 $ms^{-2}$. It thus increases linear from about 0.1 MPa (atmospheric pressure) at the top of the hole to about 25 MPa at the bottom of the hole in 2774 m depth.

## 3 THE TEMPERATURE DEPENDENCE OF ICE'S ULTIMATE TENSILE STRESS

### 3.1 Ultimate tensile stress calculated from break strength

Figure 2 presents the dependence of break strength versus temperature for raw (grey dots) and averaged (error bars) data. As the ultimate tensile stress, or also called fracture stress, is the average force per area to break the sample, the fracture stress is strictly proportional to the break strength with the factor of inverse cores cross section $1/(\pi\ (0.049\ m)^2)$. The right axis of the Figure is thus the fracture stress to break off the core. The top axis of the Figure presents the coincident depth and pressure for the respective ordinate temperature.

### 3.2 Comparison with published data and consistency check

As we present an increase of tensile fracture strength at high strain rates for the first time, we can not compare them directly to previously published data. But we can compare certain aspects of our data with the literature and thus check for consistency.

*3.2.1 Tensile fracture stress reading at a certain temperature.* For polycrystalline ice with a grain size of 10 mm one finds a fracture stress of about 800 kPa at –10 °C reported in the literature[8] for high strain rates. This finding is consistent with the observed fracture stress in this study of about 700 kPa at 263 K.

*3.2.2 Variation with crystal size.* The dependence of fracture stress on crystal size is well established in the literature[8], thus one could argue that the observed temperature dependence is truly a change in crystal size? This kind of artefact can be excluded, as the fracture stress decreases with increasing grain size[8]. In deep ice cores in general and, also observed in the core from DML here, the grain size increases with depth and as temperature also increases with depth, one should expect a decrease of fracture stress with increasing temperature. The contrary is the case and the increase in fracture stress with temperature might even be stronger than observed here.

*3.2.3 Variation with crystal orientation fabrics.* One could also argue that the observed increase is an artefact due to a change in the fabric's crystal orientation of the ice core. For the DML core discussed here the fabric changes from a random orientation steadily to a girdle type fabric at a depth of about 1000 m and then quite suddenly within an interval of about 20 m around 2040 m to a single maximum type fabric, where it remains further down. Thus, in the interval of dramatic change, the fabric does not change and has changed before without a significant change in fracture strength. Thus the textural and fabric changes that occur in an ice core can be excluded to be the source of our observed increase of fracture stress with depth.

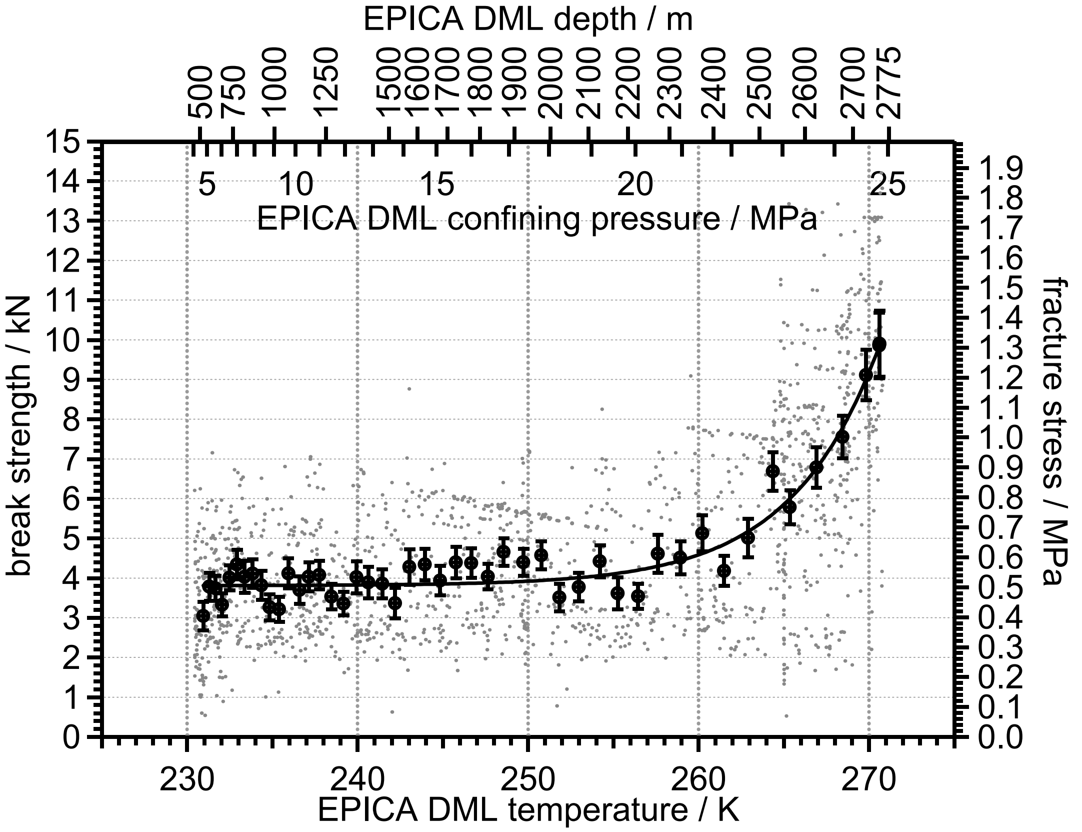


**Figure 2** *The fracture stress of polar ice under high strain rates; from the raw breaking strength (dots), averaged values with error bars (6% systematic error and standard error of the mean) have been calculated in 50 m intervals. By division with the cross section one yields the fracture stress of ice. The solid line is a least squares curve fit to the data.*

### 3.3 An empirical fit in the temperature range above 230 Kelvin

A more succinct description is given by an empirical curve to the averaged data. Fitting an exponential function by minimizing the $\chi^2$, yields a best fit for: (fracture stress)/kPa = 505 + 1.4E–20*exp((absolute temperature)/5.17 K).

## 4 CONCLUSION

We report an effect quantitatively that seems to be well known in practical engineering, but is to our knowledge not yet described in the scientific literature. Astonishing is that the ordinate found in section 3.3 is the same as the ordinate in the theory to describe (fracture stress)/kPa = 510 + 30 (m/grain size)$^{1/2}$ in terms for crack nucleation[8]. This is consistent with the observation in the cited work, as at high strain rates the fracture stress is crack nucleation controlled. In the cited work Schulson explains the discrepancies to the theoretical value for the grain size dependent factor with a thermally activated mechanism that relaxes the stress concentrated at the grain boundaries. A quasi liquid layer at the grain boundaries could help to relax piled dislocations. Liquid water in the bore hole could reduce the number of introduced cracks at the ice core surface or even heal cracks. At present, there seems to be no theory available to describe the fracture stress adequately. Thus our empirical fit will provide needed information to engineering branches, as e.g. railway engineers who required data on ultimate tensile stress of ice from us to estimate under which conditions frozen railway switches would simply break the ice freezing the blade to the track. These data will serve until systematic tests under laboratory conditions are available. If liquid water plays a significant role in the bore hole, the machining procedure of samples for stress tests should be addressed carefully. Machining at high temperatures to minimise the number of induced cracks at the sample surface should be considered.

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