Marine ice deformation experiments: an empirical validation of creep parameters

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[1] Marine ice is increasingly recognized as an important component of ice shelves in Antarctica. Because it mainly accretes in "weak" locations, it plays a crucial role in ice shelf stability. Little is known however on the rheology of this particular material (low salinity, no bubbles, specific fabrics). We present marine ice deformation experiments in unconfined uniaxial compression at $-10\,^{\circ}$C, $-6\,^{\circ}$C, and $-3\,^{\circ}$C. Generally, marine ice samples confirm the value of $n=3$ for Glen's power law. It also appears to behave systematically "harder" than artificial or meteoric isotropic ice samples used in the past, in the studied stress condition. Bulk salinity does not seem to have a significant impact on the viscosity. All deformation curves compare well with a generalized empirical temperature/viscosity relationship. They represent the first experimental validation of the lower boundary of this rheological relationship recommended for use in modeling ice dynamics. **Citation:** Dierckx, M., and J.-L. Tison (2013), Marine ice deformation experiments: an empirical validation of creep parameters, *Geophys. Res. Lett., 40*, 134–138, doi:10.1029/2012GL054197.

1. Introduction

[2] Ice shelves play a major role in the global stability of Antarctica in that they regulate the ice flux from the continent to the ocean. Marine ice is increasingly recognized as an important contributor to the ice shelf mass around Antarctica. It results from the consolidation of loose frazil ice forming under supercooling in the outflowing Ice Shelf Water branch of the Deep Thermohaline Circulation, a feature of ocean circulation in sub-ice shelf cavities [*Jacobs et al.*, 1992]. It accretes, generally rapidly and in large amounts [*Morgan*, 1972; *Oerter et al.*, 1992; *Eicken et al.*, 1994; *Khazendar and Jenkins*, 2003; *Jansen et al.*, 2012], in all the "weak" points of the ice shelf such as bottom crevasses at the grounding line, suture zone between individual ice streams feeding into the ice shelf, frontal rifts, and sides of pinning points. It then slowly consolidates under the conductive heat flux towards the colder atmosphere (the ice shelf surface). By nature, and regardless of its rheology, marine ice is therefore a good candidate for stabilizing the ice shelf flow. Several studies have described marine ice properties and compared it to the meteoric ice formed through snow metamorphism on the continent [*Moore et al.*, 1994; *Oerter et al.*, 1994; *Souchez et al.*, 1995; *Tison et al.*, 1998; *Khazendar et al.*, 2001; *Treverrow et al.*, 2010, and references therein]. The sample properties differ significantly: marine ice is 2 orders of magnitude more saline than meteoric ice (but also 2 orders of magnitude less saline than sea ice), shows a positive $\delta^{18}O$ signature because it is formed from the freezing of sea water, is devoid of bubbles, and can contain solid inclusions of marine or detritic origin. As can be expected, marine ice presents a whole range of ice fabrics (optic axes orientation) from random to highly oriented. This suggests that besides its "welding" role, marine ice could also impact ice shelf rheology because of its specific properties.

[3] Using inverse modeling, *Khazendar et al.* [2009] has concluded that potential locations of marine ice accretion show lower inferred viscosities, suggesting marine ice deforms faster than meteoric ice. In recent work where they study grain size, texture, and ice fabrics of marine ice in the Amery Ice Shelf, *Treverrow et al.* [2010] suggested that compression experiments be performed on marine ice to characterize its rheological properties. Preliminary tests have already been initiated by *Samyn et al.* [2007] and *Dierckx et al.* [2010] in that respect, but a detailed experimental study is still lacking.

[4] Because of its crucial importance in ice dynamics modeling, much attention has been given to the value of the creep parameter A in Glen's flow law for ice deformation (equation (1)) [*Glen*, 1958].

$$\dot{\varepsilon} = A\sigma^n \tag{1}$$

[5] In their recent synthesis of prior research [for example, *Budd and Jacka*, 1989], *Cuffey and Paterson* [2010] concluded that for practical applications, the parameter A should be dissociated into an effect of the temperature field (Arrhenius law) and effects of intrinsic material properties such as grain size, *c* axis orientation fabric, impurities, and water content. Their relationship is shown in equation (2),

$$\dot{\varepsilon}_{jk} = AE_*\tau_E^{n-1}\sigma'_{jk}$$

$$\begin{aligned} A &= A_* exp\left(-\tfrac{Q_c}{R}\left[\tfrac{1}{T_h} - \tfrac{1}{T_*}\right]\right) \\ with \quad \tau_E^2 &= \tfrac{1}{2}\Sigma_{j,k}\left(\sigma'_{jk}\right)^2 \\ and \quad \sigma'_{jj} &= \sigma_{jj} - \frac{1}{3}\left(\sigma_{ii} + \sigma_{jj} + \sigma_{kk}\right) \end{aligned} \tag{2}$$

where $\dot{\varepsilon}$ is the deformation rate, A the creep parameter, E_* the enhancement factor that takes into account the combined effect of all intrinsic factors, τ_E the effective shear stress, σ' the deviatoric stress (the crossed terms are zero on uniaxial compression), σ the normal stress component, A_* the constant prefactor (the value of A at the reference temperature $T_* = -10°$C), $Q_c[Jmol^{-1}]$ the activation energy for creep, R the universal gas constant, and T_h the pressure dependent

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temperature in Kelvin [*Hooke*, 1998; *Schulson and Duval*, 2009; *Cuffey and Paterson*, 2010]. The octahedral shear stress that will be used in this paper, is defined by $2\tau_E^2 = 3\tau_{oct}^2$. Considering ice shelf meteoric ice as the best equivalent of typical isotropic meteoric ice ($E_* = 1$), these authors use its observed/modeled mean A value at $-10\,°C$ ($A = 3.510^{-25}$ s^{-1} Pa^{-3}) as the reference value for A_* (with n = 3). While field and experimental measurements agree on a value of $Q_c = 60$ kJ mol^{-1} for the activation energy if $T_h < T_*$, they select $Q_c = 115$ kJ mol^{-1} for the temperature range [$-10\,°C$ to $0\,°C$] [*Weertman*, 1983], in order to match the results of inverse modeling of the flow of temperate glaciers. The authors [*Cuffey and Paterson*, 2010] then recommend different values for the enhancement factor, ranging from 1 to 5, depending of the grain size, impurity content, fabric, etc. Equation (2) presents the advantage of separating the temperature and material dependent parameters A and E_*, respectively.

[6] In this paper, we investigate the rheological properties of marine ice samples originating from the Nansen Ice Shelf (Ross Sea, Antarctica) [*Khazendar et al.*, 2001; *Tison and Khazendar*, 2001], across the [$-10\,°C$ to $-3\,°C$] temperature range under vertical compression in unconfined conditions and compare them with both results from artificial and natural isotropic ice (referred here as clean ice) deformation in a similar stress setting [*Jacka*, 1984; *Budd and Jacka*, 1989; *Jacka and Li*, 1994] and predictions from the above described empirical relationship (equation (2)) of *Paterson* [1994] and *Cuffey and Paterson* [2010].

2. Site Description

[7] The Nansen Ice Shelf (NIS) is located in Terra Nova Bay, Victoria Land, East Antarctica [*Khazendar*, 2000; *Khazendar et al.*, 2001; *Tison and Khazendar*, 2001]. Here marine ice forms in rifts opening throughout the entire ice shelf thickness (few hundred meters) at the grounding line and downstream, outcrops at the ice shelf surface, due to net ablation from severe katabatic wind regimes. Two 45 m ice cores have been collected during the 1995–1996 austral summer in the framework of a Belgo-Italian drilling program. The two ice cores were located along a central flow line of the ice shelf at, respectively, 7.5 km (NIS1 – 74°51′S 162°50′E) and 24.5 km (NIS2 – 75°00′S 163°06′E) downstream from the grounding line. All cores had a diameter of 8 cm and were collected with an electro-mechanical (SIPRE-type) ice corer.

3. Experiments and Results

[8] A selection of 10 marine ice samples has been chosen from the NIS1 and NIS2 marine ice cores. Samples were shaped as cylinder of $\simeq 3.5$ cm diameter and $\simeq 7$ cm tall. Physical properties along the length of the cores were examined with thin sections following the conventional procedure of *Langway* [1958] and analyzed for texture and fabric using a G50 LED-White Automated Fabric Analyzer [*Russell-Head and Wilson*, 2001; *Wilson et al.*, 2003]. The salinity of each sample was deduced from Cl^- anion determination, using HPLC (Dionex 100) measurements (precision ≤ 4%). Assuming that the Cl^-/salinity ratio does not change during formation or melting, bulk ice salinity is deduced from the mean Cl^-/salinity ratio in sea water (19.35/35) [Sarmiento and Gruber, 2006]. Although this is clearly an approximation with limited accuracy (0.03 ± 0.0012 to 0.3 ± 0.012), we consider it as sufficient for the purpose of this paper.

[9] We aimed to select samples with ice fabrics as close as possible to a random crystal orientation distribution. The salinity range usually encountered in marine ice (0.03 to 0.3) [e.g., *Tison et al.*, 1993; *Tison and Khazendar*, 2001] allows us to test the contribution of the salinity to the enhancement factor E_*. Finding marine ice with an isotropic fabric was a significant challenge, given the specific setting of the NIS marine ice outcrops, prone to develop sustained folding [see *Khazendar et al.*, 2001]. Figure 1 shows two examples of textures and fabrics from the NIS1 core. Most of the selected samples showed crystallographic properties similar to sample NIS1-59c, i.e., a fabric reasonably close to random. A few samples had however to be selected in more oriented ice (eigenvector S1 close to 0.77, Figure 1), such as sample NIS1-82b, with sub-vertical folds and crystal elongation.

[10] Samples of low (min 0.027) and high (max 0.234) bulk salinities were chosen for each of the selected temperatures, as shown in Table 1. The experimental temperatures were designed to adequately cover the usual range of observed temperatures within ice shelves [e.g., *Zotikov*, 1986]. The grain size was homogeneous between samples, with a mean value of 1.65 mm^2.

[11] The samples were deformed in unconfined uniaxial compression using the pneumatic device developed at the Laboratoire de Glaciologie of the Université Libre de Bruxelles and described in details by *Samyn et al.* [2011]. As in previous studies, the aim of the deformation experiment is to reach the secondary creep at which the strain rate is minimal. Minimum creep is a unique point within the ice creep curve that allows for comparison between the effects of the properties of one ice type as compared to another. Each sample is submitted stepwise to an increasing stress, beginning with a stress close to 0.1 MPa and incrementing up to a maximum of 0.8 MPa. This procedure allows to keep the same sample for different applied stresses and therefore keep the same parameter "A" to analyze only the parameter "n". At each step, the secondary creep stage is achieved, with its recorded associated minimum strain rate. It should be noted again that using secondary instead of tertiary creep means that pre-oriented fabric can play a role on the viscosity, resulting in dispersion in the data set. Combining these stepwise records in a log-log plot then allows easy representation of Glen's flow law and deducing values for the "n" and "A" parameters. We also compared the stepwise load approach with a continuous case to check for the validity of the former. For this, sample NIS1-91b has been directly loaded to 0.67 MPa. The obtained data point perfectly fits with the determined trend.

[12] Figure 2 summarizes the results of our compression deformation tests at the three selected temperatures (red triangles). Each symbol is an experimental data point which represents the minimal strain rate at secondary creep for a given applied stress (octahedral shear stresses and strain rates are used here to ease the comparison with the other data sets) [*Schulson and Duval*, 2009]. The tabulated values can be found in the auxiliary material.[1] The red lines are linear fits through each of these experimental data sets. Also shown in Figure 2 are (a) previous experimental results obtained in uniaxial compression on clean ice (blue symbols) [*Jacka*, 1984; *Budd and Jacka*, 1989; *Jacka and Li*,

[1]Auxiliary materials are available in the HTML. doi:10.1029/2012GL054197.

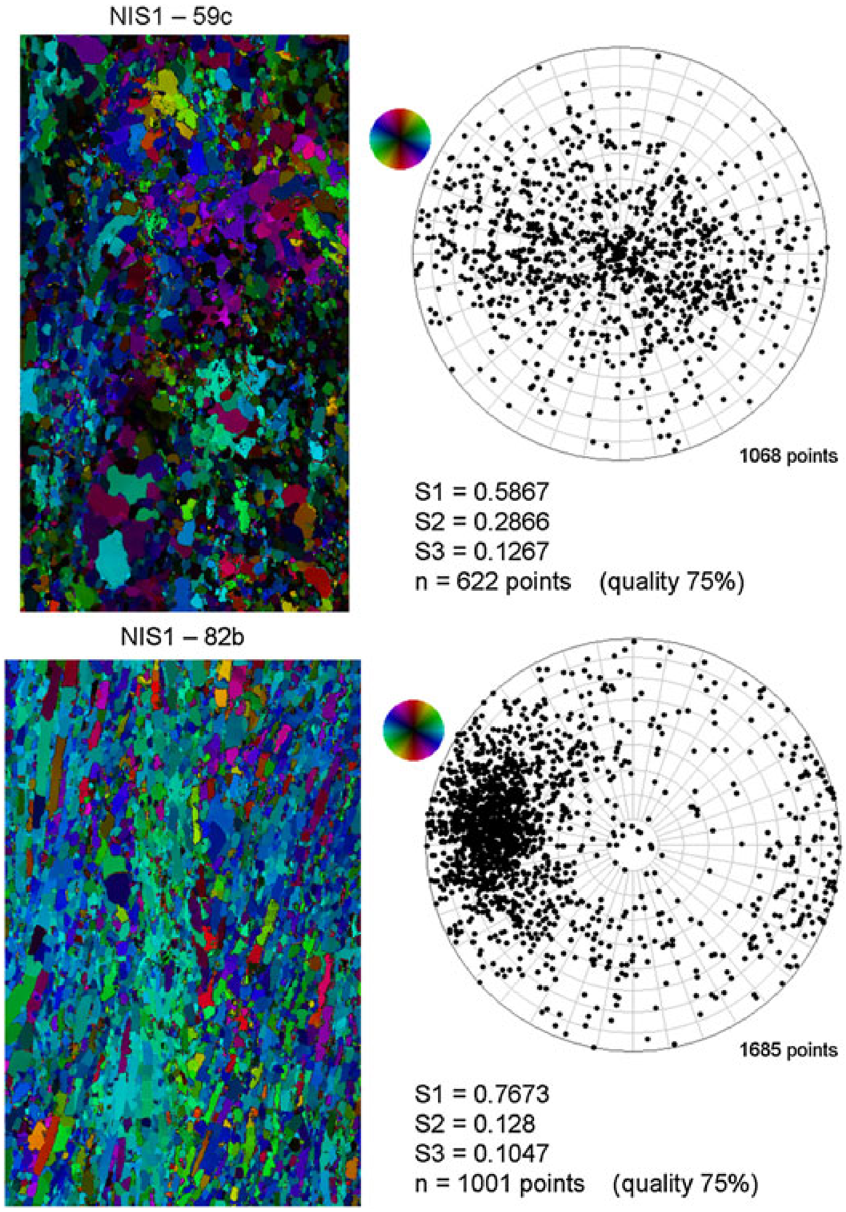

Figure 1. Typical sample fabrics before compression experiment, using an automated fabric analyzer system (G50). Thin sections are in artificial color. Sample NIS1—59c is representative of most of the marine ice samples used. A few samples show a more oriented fabric, as represented by NIS1—82b.

Table 1. Temperature and Salinity of the Marine Ice Samples

Sample ID	Experimental Temperature [°C]	Salinity [—]	Mean Grain Size [mm^2]
NIS2 53c	−3	0.234	2
NIS1 82b	−3	0.047	1.45
NIS2 96a	−3	0.055	1.9
NIS1 97d	−6	0.035	1.45
NIS1 74e	−6	0.051	1.4
NIS1 59c	−6	0.089	1.85
NIS1 91b	−6	0.057	1.5
NIS1 49b	−10	0.131	—
NIS2 53b	−10	0.224	2
NIS2 4a	−10	0.027	1.35

1994] and (b) empirical laws from *Paterson* [1994] (black dashed line) and *Cuffey and Paterson* [2010] for $E_* = 1$ (black solid line).

4. Discussion

[13] The mean slope of the linear fits through our data sets is 2.93 ± 0.11, while the equivalent value for clean ice (all temperatures, through all data)[*Jacka*, 1984; *Budd and Jacka*, 1989; *Jacka and Li*, 1994] is 3.29 ± 0.2 but closer to $n = 3$ for each data set considered separately. This further supports the choice of $n = 3$ in Glen's flow law, for octahedral stresses ranging between 0.1 and 0.8 MPa.

[14] The variability around each marine ice trend can be explained by the crystal orientation fabric variability of the different samples. Indeed, it can be expected that some samples are harder or softer in compression compared to more isotropic samples. These effects will be discussed in detail in another paper (in preparation).

[15] Clear differences however exist between the various data sets in Figure 2 in terms of the relative position of each

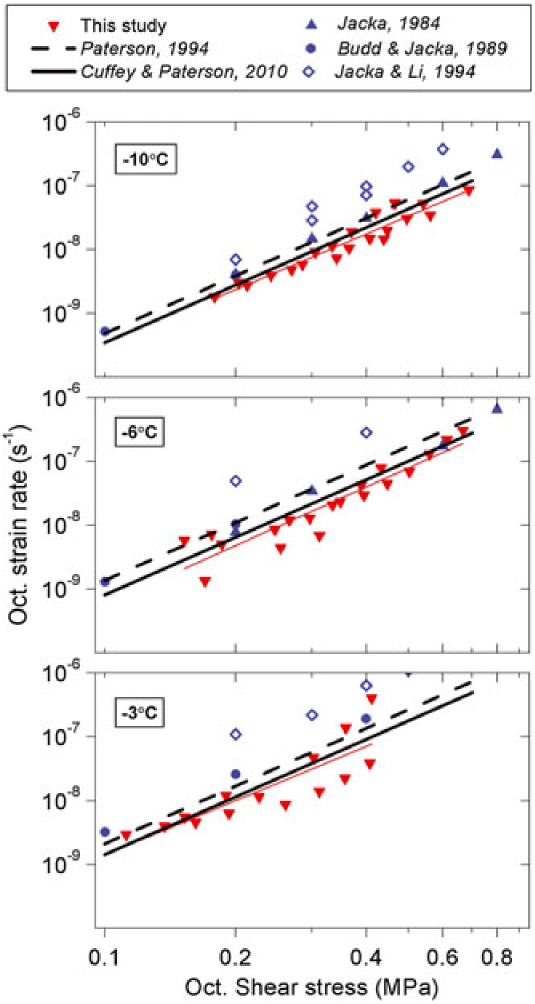

Figure 2. Comparison between this study (marine ice compression experiments, in red), clean ice compression experiments (artificial and natural isotropic ice), Jacka's data, in blue and literature (Paterson and Cuffey empirical laws, respectively, in dashed and solid black line). The mean slope of all our linear fits is around 2.93 ± 0.11. Marine ice data match the new calibration established by *Cuffey and Paterson* [2010].

trend. These differences represent the relative "softness" of the ice, as would be expressed in the enhancement factor E_* of the creep parameter A, following the approach of *Cuffey and Paterson* [2010]. As underlined in preliminary results from *Samyn et al*. [2007] and *Dierckx et al*. [2010], it appears that at all temperatures, marine ice samples are harder to deform than clean ice. This is therefore also the case, when compared to the relationship proposed by *Paterson* [1994], drawing considerably from the results of these experiments. However, the linear fits of our datasets are close to the trends of Cuffey and Paterson's empirical law, calculated for the lower boundary case of an enhancement factor $E_* = 1$, and this throughout the whole temperature range (i.e., using the appropriate values of the activation energy, depending on the temperature range). It therefore appears that marine ice recently consolidated into ice shelves provides an excellent natural example of isotropic ice with minimal viscosity. Our new data set also offers experimental validation of the lower boundary of *Cuffey and Paterson* [2010] relationship throughout the temperature range, for stresses greater than 0.1 MPa. It follows that isotropic marine ice does not deform specifically harder than other ice types but rather represents the lower boundary for natural ice deformation, with an enhancement factor equal to 1.

[16] As discussed above, none of the chosen samples has a truly isotropic *c* axes distribution, which might explain part of the spread of our data points around Cuffey and Paterson's relationship in Figure 2. These excursions are worth considering further in terms of potential other drivers. A wide range of solid and soluble impurity contents has been described in the marine or meteoric ice literature [e.g., *Jones and Glen*, 1969; *Oerter et al*., 1992; *Tison et al*., 1993; *Moore et al*., 1994; *Trickett et al*., 2000; *Khazendar et al*., 2001; *Treverrow et al*., 2010], and these can also potentially affect the E_* value. Even though our samples covered a relatively large salinity range, no significant *s*ystematic deviation could be isolated in the studied range of temperature and stresses. It therefore seems likely that the *s*oluble impurity content plays a negligible role in the enhancement factor for the whole documented range of marine ice samples. Differences in the concentration or granulometry of the solid impurity content could also be responsible for some deviations in our data set, but this factor could not be quantified in the present study. The ice grain size is shown to be homogeneous within our samples set and cannot therefore be held responsible for the dispersion of the data. Finally, the higher spread is observed at −3 °C, indicating a much higher sensitivity to sample and/or experimental conditions at warmer temperatures.

[17] It is also important to underline that our experimental data set covers the range of 0.1 to 0.8 MPa for applied stresses. This is probably a higher boundary for vertical deviatoric stresses in the central part of ice shelves (away from lateral friction, ice streams convergence, rifts, and crevasses suturing). This perspective is important in view of results from the deformation behavior of meteoric ice at low stresses [see, e.g., *Montagnat and Duval*, 2004; *Schulson and Duval*, 2009, and references therein], where the n parameter of Glen's flow law is different and closer to 2. Similarly, it is possible that the response of the E_* parameter to its driving factors might also differ at low stress. It should therefore be beneficial to run further marine ice deformation experiments at very low stress, to extend the validity of the present data set.

5. Conclusion

[18] We have presented here the first comprehensive set of unconfined uniaxial compression experiments on marine ice samples in a range of temperatures (−10 °C to −3 °C) that is coherent with those encountered in ice shelves. Our initial goal was to figure out how the specific intrinsic properties of marine ice might affect its rheological behavior and eventually corroborate findings from inverse modeling suggesting that marine ice is indeed softer than meteoric ice. Comparing our data set to the results from previous studies working with artificial and natural isotropic ice initially led us to the opposite conclusion, i.e., that marine ice is actually harder to deform than meteoric ice, in the studied stress condition. However, new developments on the calibration of the creep parameter in ice rheology also predict a harder than previously believed behavior for isotropic ice with an enhancement factor equal to unity [*Cuffey and Paterson*, 2010]. We show that our data set demonstrates the validity of this relationship and that newly formed marine ice can be considered as the lower boundary of the possible viscosities for natural isotropic ice across the

temperature range. This therefore suggests that the lower viscosities invoked for marine ice in inverse modeling exercises mainly results from changes in the temperature field (warmer marine ice embedded in colder meteoric ice) rather than in a specific enhancement factor resulting from the intrinsic properties of marine ice. Theoretical considerations and field observations [e.g., *Craven et al.*, 2009] indeed show that temperature profiles considerably depart from the expected linear gradient when marine ice bottom accumulation occurs below meteoric ice in significant amounts. Bulk salinity does not seem to play a major role in marine ice rheology, in the studied stress condition. However, no impurity specific study has been made. The impurity content may still influence the ice deformation and explain part of the enhancement factor. The role of the development of strong orientation fabrics resulting from folding structures, of the grain size and of solid inclusions often encountered in marine ice cores, still remains to be explored in further deformation tests.

[19] Marine ice is often mistaken for what is referred to as the "ice mélange" in rifts and open crevasses at the surface of the ice shelf. Marine ice is indeed only one potential component of the "ice mélange" which is a composite of various ice types such as fallen meteoric ice blocks, sea ice or snow, and firn, with an expected lower homogeneity and coherence. This difference in filling materials could be responsible for the contrasts in the rheological behavior of rifted areas in ice shelves, as discussed by *Rignot and Mac Ayeal* [1998] for the Lassiter Coast and the Hemmen ice Rise at the two geographical extremes of the Filchner-Ronne Ice Shelf front. Rifts mainly filled with marine ice bodies would show a coherent rheological behavior with the surrounding ice shelf, while this would lessen or not be the case for rifts filled with an "ice mélange".

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