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► **To cite this version:**

M. Montagnat, D. Buiron, L. Arnaud, A. Broquet, P. Schlitz, et al.. Measurements and numerical simulation of fabric evolution along the Talos Dome ice core, Antarctica. *Earth and Planetary Science Letters*, 2012, 357-358, pp.168-178. 10.1016/j.epsl.2012.09.025 . hal-03815176

HAL Id: hal-03815176

<https://hal.science/hal-03815176>

Submitted on 14 Oct 2022

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Measurements and numerical simulation of fabric evolution along the Talos Dome ice core, Antarctica

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Abstract

We present measurements of fabrics and microstructures made along the Talos Dome ice core, a core drilled in East Antarctica in the framework of the TALDICE project. Fabric and average grain size data are analyzed regarding changes in climatic conditions. In particular, the fabric strength increases sharply going downward from Holocene to Wisconsin ice. Following (Durand et al., 2007), this change is associated with a positive feedback between variations in ice viscosity, due to variations in dust content, and the impact of a shear stress component, increasing with depth. A ViscoPlastic Self Consistent modeling approach is used to simulate the fabric evolution for a "perfect dome" configuration. The discrepancies between the measured and the simulated fabrics highlight the depth ranges where shear strongly affects the fabric strengthening. Finally, the grain size and fabric analyses show the occurrence of dynamic recrystallization mechanisms (continuous

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and discontinuous) along the core.

This version is the personal copy of the article published in EPSL:

<http://dx.doi.org/10.1016/j.epsl.2012.09.025>

Keywords: ice core, fabric, grain size, VPSC model, chronology

1 **1. Introduction**

2 A 1620 m deep ice core was drilled at Talos Dome in East Antarc-
3 tica in the framework of the TALDICE (TAlos Dome Ice CorE) project
4 (www.taldice.org) during the field seasons 2004-2008. Talos Dome is a pe-
5 ripheral dome, located in the Ross Sea sector (Urbini et al., 2006). The
6 TALDICE coring site (159° 11'E 72° 49'S; 2315 m a.s.l.; annual mean tem-
7 perature -41°C) is located 5 to 6 km SE from the dome summit, along the
8 main ridge (Urbini et al., 2006). The current accumulation rate is of 85 mm
9 ice equivalent per year and is quite uniform 5 to 10 km from the summit
10 (Stenni et al., 2002; Frezzotti et al., 2007; Urbini et al., 2008). The temper-
11 ature along the coring hole was not measured. An estimation was given in
12 the field of a bottom temperature close to -20°C. This estimate comes from
13 the measured temperature of the bottommost core when removed from the
14 borehole.

15 The entire TALDICE ice core provides a paleoclimatic record covering at
16 least 250 kyr BP back to Marine Isotope Stage 7.5 (MIS 7.5), with the start
17 of the last deglaciation at around 820 m depth (Buiron et al., 2011). Owing
18 to the relatively high accumulation rate, the record benefits from a decadal
19 scale resolution.

20 The coring site was chosen close but not at the geographical dome, in a

21 location on top of a relatively flat bedrock, in order to reduce the effect of
22 flow perturbations on the climatic signal (Bianchi et al., 2003; Urbini et al.,
23 2006). Very inclined tephra layers are observed below 1460 m depth. They
24 indicate a non negligible contribution of a shear stress component on the ice
25 flow which is coherent with the fact that the coring site is located down the
26 ridge from the dome summit. This contribution could also be intensified by
27 the topology of the bedrock close to the Talos Dome coring site. Indeed, the
28 last 200 m of the core are located close to a deep valley, with abrupt elevation
29 changes, as shown in the radargram in Fig. 1.

30 Ice flow is known to be strongly influenced by the induced anisotropy
31 that develops during deformation in ice sheet conditions, in the form of pre-
32 ferred ice crystal orientations (see Castelnau et al. (1998); Gillet-Chaulet
33 et al. (2006); Pettit et al. (2007) for instance). Under deformation conditions
34 typical around ice cores, the c-axes of the ice crystals rotate towards a com-
35 pression axis, perpendicular to a shear direction, and away from a tension
36 axis (Gow and Williamson, 1976; Alley, 1988; Paterson, 1994). The c-axis
37 distribution (referred to as fabric in the following) along a core is then a good
38 candidate to evaluate the nature of the flow and to extract some irregularities
39 in the deformation history.

40 In the specific case of a perfect dome, the ice deforms mainly by compres-
41 sion along the vertical direction (Alley, 1988). This is qualitatively confirmed
42 by the fabrics measured along cores such as the ones of GRIP (Thorsteins-
43 son et al., 1997), Dome Fuji (Azuma et al., 1999), or EPICA Dome C (Wang
44 et al., 2003; Durand et al., 2009) which are all located at geographical domes.
45 Nevertheless, deviations from the "perfect dome" tendency, and local vari-

46 ations of the fabric strengthening are observed along these cores. They are
47 mostly observed at depths corresponding to climatic changes (termination
48 1, Holocene - Wisconsin transition, at 1500 m depth along the GRIP ice
49 core (Thorsteinsson et al., 1997), termination 2 at 1750 m depth, along the
50 EPICA Dome C ice core (Durand et al., 2009)). Below 2800 m depth, very
51 similar abrupt variations in the fabric signal were measured along the GRIP
52 and EPICA Dome C ice cores. They were attributed to dynamic recrystal-
53 lization mechanisms (Thorsteinsson et al., 1997; Durand et al., 2009).

54 Dynamic recrystallization mechanisms (DRX) are known to accommodate
55 the deformation as observed along ice cores. The three main processes are
56 classically described as being, successively from the top of the cores, nor-
57 mal grain growth, continuous (or rotation) dynamic recrystallization and
58 discontinuous (or migration) dynamic recrystallization (de la Chapelle et al.
59 (1998) for instance). All of them are well documented in materials science
60 (Humphreys and Hatherly, 2004). Normal grain growth is mostly driven by
61 the decrease in the grain boundary energy. During continuous DRX, new
62 grains are formed by the progressive rotation of subgrains during straining,
63 with little accompanying boundary migration. The kinetics of the grain
64 size increase is similar to the one measured during normal grain growth
65 (de la Chapelle et al., 1998; Montagnat and Duval, 2000). These two mecha-
66 nisms should not strongly impact the fabric, but continuous DRX could slow
67 the c-axis strengthening under compressive strain (Castelnau et al., 1996b).

68 The occurrence of discontinuous recrystallization is characterized by abrupt
69 changes in grain size, shape and orientation. It is driven by a high stored
70 deformation energy, and favored by a high value of grain boundary migra-

71 tion rate. These conditions are mainly encountered in the bottom part of
72 the cores (Azuma et al., 1999; Wang et al., 2003; Durand et al., 2009).

73 Changes in fabrics, grain sizes and/or impurity contents can induce changes
74 in viscosity between layers, and could induce differences in fabric evolution
75 with depth for a similar state of stress. Along the EPICA Dome C ice core,
76 Durand et al. (2007) calculated the impact on flow of an abrupt strength-
77 ening of the fabric similar to the one they measured at 1750m depth during
78 termination 2. They used an anisotropic 2D ice flow model (Gillet-Chaulet
79 et al., 2006) to quantify the impact of this change on ice flow and concluded
80 that a positive feedback is initiated when a shear stress affects the flow. In-
81 deed, more clustered fabrics become easier to shear, which in turn enhances
82 the clustering (Paterson, 1991). Such observations are in favor, at least qual-
83 itatively, of a non negligible role of local changes in viscosity associated with
84 climatic conditions, on flow heterogeneities.

85 At a larger scale, recent modeling efforts using finite element computa-
86 tion, have demonstrated the effects of anisotropy on ice flow (Gillet-Chaulet
87 et al., 2006; Pettit et al., 2007; Seddik et al., 2008). Martín et al. (2009)
88 showed the strong impact of the anisotropy and the non-linearity of ice rhe-
89 ology on the age-depth relation along a divide and Pettit et al. (2011) showed
90 the strong influence of fabrics on the pattern of flow near the divide at Siple
91 Dome (Antarctica).

92

93 We present here the fabric measurements performed along the Talos Dome
94 ice core, using an Automatic Ice Texture Analyser (AITA) (Russell-Head and
95 Wilson (2001), <http://www.russellheadinstruments.com>) which provides c-

96 axis values at a resolution of $43 \mu\text{m}^2$ and about 5° (section 2). We use a
 97 ViscoPlastic Self Consistent (VPSC7) (Lebensohn et al., 2005) scheme under
 98 the crude assumption of compression at a constant strain rate, in order to
 99 model the fabric strengthening along the core in a perfect dome configuration
 100 (section 3). This VPSC model integrates both anisotropy and non-linearity
 101 of the ice rheology but does not reproduce dynamic recrystallization mech-
 102 anisms. Section 4 provides the analyses of the measurement and modeling
 103 results, and demonstrates the benefits from combining both approaches to
 104 extract information about the flow conditions along the core.

105 **2. Fabric and grain size measurements along the Talos Dome core**

106 *2.1. Measurements*

107 Fabrics (c-axis orientations) were measured along the full Talos Dome
 108 core, every 10 to 20 m, from 18 m depth down to 1611 m depth. The AITA
 109 provides c-axis orientations from thin sections of dimensions up to 12×12
 110 cm^2 , every pixel of $43 \mu\text{m}^2$ size. The orientation data are further represented
 111 in Schmidt pole figures. Orientation measurements are provided together
 112 with a quality factor which makes possible the elimination of pixels with too
 113 low a resolution, such as grain boundary pixels (Peternell et al., 2011).

114 The c-axis orientation \mathbf{c}^k is defined by two angles: the co-latitude $\theta_k \in [0, \pi/2]$
 115 (or tilt angle) and the longitude $\varphi_k \in [0, 2\pi]$ given in the local reference frame,
 116 \mathbf{R} , with the third axis perpendicular to the thin section. The expression of
 117 \mathbf{c}^k in this reference frame is;

$$\mathbf{c}^k = (\cos\varphi_k \sin\theta_k, \sin\varphi_k \sin\theta_k, \cos\theta_k) \quad (1)$$

118 Following Durand et al. (2006a) the second-order orientation tensor $\mathbf{a}^{(2)}$
 119 was used to characterize the c-axis orientation distribution. $\mathbf{a}^{(2)}$ is defined
 120 as:

$$\mathbf{a}^{(2)} = (1/N_p) \sum_{k=1}^{N_p} \mathbf{c}^k \otimes \mathbf{c}^k \quad (2)$$

121 where \mathbf{c}^k is given by Eq. (1), and N_p is the total number of pixels over which
 122 the \mathbf{c}^k values are obtained for a given sample (thin section). Since the \mathbf{c}^k
 123 values are obtained at a pixel size, the definition of $\mathbf{a}^{(2)}$ given by Eq. (2)
 124 implicitly takes into account the volume fraction of grains.

125 By construction, $\mathbf{a}^{(2)}$ is symmetric and there exists a symmetry reference
 126 frame, \mathbf{R}^{sym} (or principal reference frame), in which $\mathbf{a}^{(2)}$ is diagonal. Let $a_i^{(2)}$
 127 ($i=1,2,3$) denote the three corresponding eigenvalues and \mathbf{e}_i ($i=1,2,3$) the
 128 associated eigenvectors (the three base vectors of \mathbf{R}^{sym}). The eigenvalues of
 129 $\mathbf{a}^{(2)}$ can be seen as the lengths of the axes of the ellipsoid that best fits the
 130 density distribution of grain orientations. The eigenvectors give the directions
 131 of the axes of the ellipsoid.

132 The three eigenvalues $a_1^{(2)}$, $a_2^{(2)}$ and $a_3^{(2)}$ follow the relations :

$$a_1^{(2)} + a_2^{(2)} + a_3^{(2)} = 1 \quad (3)$$

133

$$0 \leq a_3^{(2)} \leq a_2^{(2)} \leq a_1^{(2)} \leq 1 \quad (4)$$

134 For an isotropic fabric, $a_1^{(2)} = a_2^{(2)} = a_3^{(2)} = 1/3$, and when the fabric is
 135 transversely isotropic, two of the eigenvalues are equal:

$$\begin{aligned} a_2^{(2)} &\approx a_3^{(2)} < 1/3 && \text{for a single-maximum fabric,} \\ a_1^{(2)} &\approx a_2^{(2)} > 1/3 && \text{for a girdle fabric} \end{aligned} \quad (5)$$

136 Errors in the data can have several origins. In the following, we present
137 several approaches used to estimate the various components of this error.

138 The first approach consisted in changing, manually, the correction crite-
139 rion which makes possible the elimination of data with too low a reliability
140 (mainly based on the quality factor data provided by the analyzer). Stan-
141 dard deviations smaller than 0.01 were obtained over extreme manual ad-
142 justments. The second source of error was associated with the angle range
143 of accuracy of the analyzer measurements. A normal distribution, with a
144 standard deviation equal to this error range was added to the measured az-
145 imuth and colatitude data. Calculations of the orientation tensor eigenvalues
146 were then performed on a sufficient number of samplings extracted from this
147 reconstructed data set. The obtained standard deviation, for different error
148 angles was lower than 0.001. Finally, a bootstrap approach (Efron and Tib-
149 shirani, 1993; Palm, 2002) was used to theoretically estimate the standard
150 deviation of the measured eigenvalues based on a re-sampling of angle data
151 at each depth, standard deviations lower than 0.0003 were obtained. Con-
152 sidering the very low values of the standard deviations obtained with these
153 three techniques, they were not taken into account in the standard deviation
154 value. Another source of error is the one induced by a sampling on a limited
155 number of grains. We estimated this error following Durand et al. (2006a).
156 This method used a 3D-Pott model to evaluate the influence of the under-
157 sampling of a sample of 10 000 grains on the evaluation of the orientation
158 tensor eigenvalues. They obtained a relation between the standard deviation,
159 the number of grains in the thin section, N_g , and the eigenvalue, Eq. (6).

160 The same relation applies for the three eigenvalues.

$$\sigma(a_i) = \left[-1.64 \times (a_1^{(2)})^2 + 1.86 \times a_1^{(2)} - 0.14 \right] \times N_g^{-1/2}. \quad (6)$$

161 Data and error bars corresponding to a $\pm 1\sigma$ confidence interval are reported
162 in Fig. 2.

163 Grain sizes were measured along the core by extracting grain size con-
164 tours out of the orientation-colored images provided by the AITA. Manual
165 corrections were applied systematically. The size of a grain corresponds to
166 the square root of the surface occupied by the grain on the binary image
167 obtained. Standard deviation due to the sectioning effect (to obtain a grain
168 size radius out of a 2-D section) and to the limited number of grains were
169 evaluated following (Durand et al., 2006a) estimates. As for the standard de-
170 viation on the fabric measurements, they used the 3-D Potts model with a 3-D
171 microstructure of a large number of grains further under-sampled (Gagliar-
172 dini et al., 2004). The Potts model is known to properly reproduce the
173 topological, grain-size distribution and morphological features of natural ice
174 microstructures (Anderson et al., 1989). The obtained standard deviation is
175 given by Eq. (7).

$$\sigma(\langle R \rangle) \approx (0.02 + 0.44 \times N_g^{-1/2}) \times \langle R \rangle, \quad (7)$$

176 with $\langle R \rangle$ the average grain size, and N_g the number of grains in the thin
177 section.

178 Fig. 5 represents the grain size evolution with error bars corresponding
179 to a $\pm 1\sigma$ confidence interval. The number of grains extracted from each thin
180 section is also shown.

181 *2.2. Fabric evolution*

182 As shown in Fig. 2, the fabric evolution is characterized by a strength-
183 ening with increasing depth from a near-isotropic distribution of **c**-axes at
184 18 m, to a very strongly concentrated vertical single maximum. Fig. 2 also
185 represents the evolution with depth of the isotopic signal (Stenni and co au-
186 thors, 2011). A change in the rate of strengthening of the fabrics appears
187 between 750 m and 900 m, which corresponds to the Antarctic Cold Reversal
188 and the climatic transition to the last glacial period. Another change occurs
189 close to 950 m depth with a stagnation of the fabric strengthening, down
190 to about 1200 m where a sharp strengthening of the fabric takes place, to-
191 ward a saturation close to the limit that can be reached for a polycrystalline
192 ice (very close to a uniform orientation in only one direction). This abrupt
193 change is in phase with the AIM 12 (Antarctic Isotope Maximum) cooling
194 measured in the isotopic data (Stenni and co authors, 2011).

195 The discontinuity at 1171 m depth (arrow in Fig. 2) in the orientation tensor
196 eigenvalues can be attributed to a few big grains with orientations at about
197 40 to 50° away from the single maximum (see Fig. 3). A similar observation
198 is done at 1411 m depth (arrow in Fig. 2) (see Fig. 4). Then, below about
199 1450 m the fabric strength decreases, in phase with the transition that leads
200 to the last interglacial and to older cycles, too much compressed to be clearly
201 identified.

202 Fig. 4 represents the evolution of the microstructures and the fabrics in the
203 range 1361 - 1581 m (grey area in Fig. 2). Fabrics and microstructures
204 from 1200 to 1361 m are very similar to those from 1361 to 1381 m. From
205 1411 m down to 1500 m depth, however, an increasing number of grains with

206 orientations departing from the single maximum appear. These orientations
207 explain the progressive decrease of the fabric strength, although the fabric
208 remains dominated by a strong single maximum. The bottom part of the
209 core is characterized by a transition to very large grain size ice (up to 40-50
210 cm) occurring between 1481 m and 1500 m. From this depth, owing to the
211 low number of grains in each thin section, the measurements have no more
212 statistical meaning and are not represented in the figures.

213 *2.3. Grain size evolution*

214 Grain size evolution down to 1481 m depth is shown in Fig. 5 together
215 with the dust content evolution extracted from (Delmonte et al., 2010).
216 Fig. 6 presents the grain size evolution with the ice age, extracted from
217 the TALDICE-1 chronology (Buiron et al., 2011). The focus on the first 30
218 000 years (first 950 m) shows a trend similar to the one measured along the
219 first 1500 m of the GRIP ice core (Thorsteinsson et al., 1997) or the first
220 1000 m of the Byrd ice core (Alley et al., 1995) with a grain size increase
221 followed by an average stabilization. The stabilization is around a value of
222 2.1 mm between 350 and 950 m depth. The theoretical normal grain growth
223 law which predicts a grain size increase following the Eq. (8) (Gow, 1969)
224 was applied to the data down to 5600 years.

$$D^2 = D_0^2 + K \times t \quad (8)$$

225 with D the mean grain size, D_0 the initial mean grain size, K the grain
226 boundary migration rate.

227 A good match is found with a grain boundary migration rate $K = 6.9 \times 10^{-10}$
228 m^2yr^{-1} (R^2 coefficient of 0.9). This value is about five times lower than

229 the rate measured at GRIP ($K = 3.8 \times 10^{-9} \text{ m}^2\text{yr}^{-1}$) where the surface
230 temperature is -32°C (against -41°C at Talos Dome) and the average grain
231 size 4 mm.

232 Around this mean value of 2.1 mm, the grain size variability is quite
233 high. This is coherent with the dust content variability in this range (see
234 Fig. 5). The LGM/Holocene dust concentration ratio is about 12 at Talos
235 Dome (Delmonte et al., 2010), compared with more than 50 at EPICA Dome
236 C (Lambert et al., 2008) where the correlation between grain size and dust
237 concentration is stronger (Durand et al., 2006b).

238 **3. Modeling the fabric evolution using a ViscoPlastic Self-Consistent** 239 **scheme**

240 Following pioneer work of Castelnau et al. (1996b, 1998) on the GRIP ice
241 core, we applied a ViscoPlastic Self Consistent model to represent the fabric
242 evolution along the Talos Dome ice core.

243 *3.1. The VPSC scheme adapted to ice*

244 The VPSC formulation, also known as a “mean-field” approach, is based
245 on a statistical description of the microstructure of polycrystalline aggre-
246 gates. Grains exhibiting the same crystallographic orientation are treated
247 as a single “mechanical phase”. Each phase is embedded in an infinite ho-
248 mogeneous medium with the same mechanical behavior as the polycrystal.
249 The self-consistent (SC) approximation used to estimate the mechanical re-
250 sponse of polycrystals was originally developed for linear elastic materials
251 (Hershey, 1954). The key benefit of this method is the estimation of the
252 stress and strain localization within each phase (a phase represents all grains

253 with the same orientation), in relation with the microstructure (orientation
254 distribution) and the boundary conditions.

255 In the ViscoPlastic SC approaches, the problem is solved by finding an
256 equilibrated stress field related to a compatible strain field, which is adapted
257 to the local constitutive relation that describes the non-linear viscoplastic
258 deformation at the grain scale (Molinari et al., 1987).

259 Ice deformation occurs in such a non-linear viscoplastic regime, characterized
260 by a Glen flow law (9) (Glen, 1955) that associates the effective strain rate
261 ($\dot{\epsilon}$) to the effective stress (σ) with a stress exponent n varying between 2 and
262 3.

$$\dot{\epsilon} = B \times \sigma^n, \quad (9)$$

263 with B a parameter following an Arrhenius dependence on the temperature.
264 For nonlinear aggregates like ice, the SC scheme is applied by providing a
265 local linearization of the mechanical behavior, in order to reduce the prob-
266 lem to the case of the well-constrained thermo-elasticity (Molinari et al.,
267 1987). The obtained mechanical behavior is therefore an approximation that
268 strongly depends on the linearization approach (Ponte-Castañeda and Su-
269 quet, 1998).

270 Castelnau et al. (1996b) applied the tangent version of the linearization
271 scheme developed by Lebensohn and Tomé (1993) to simulate the fabric
272 development along the GRIP ice core. Since then, it was shown that the
273 tangent prediction strongly overestimates the fabric development (Wenk and
274 Tomé, 1999). It suffers from significant inconsistencies (Gilormini, 1995;
275 Masson et al., 2000) that lead to a significant underestimation of the effective
276 viscosity for materials with a large viscoplastic anisotropy such as ice (with

277 only one easy slip system for dislocations, the basal system).

278 The second-order linearization scheme (SO) proposed by Liu and Castañeda
279 (2004), was shown to provide the better mechanical response, in comparison
280 with full-field approaches that integrate real microstructures. For polycrys-
281 tals with a strong viscoplastic anisotropy, strong deformation gradients are
282 likely to develop inside grains owing to the contrast of properties between
283 neighboring grains. The second-order approach takes into account a statis-
284 tical representation of these intragranular fluctuations by incorporating the
285 field fluctuations at the grain scale in the linearization procedure (Liu and
286 Castañeda, 2004). Such an improvement appears essential to provide a good
287 representation of the mechanical behavior of materials with a high viscoplas-
288 tic anisotropy such as ice.

289

290 This VPSC-SO model was selected to simulate the fabric development
291 along the Talos Dome ice core. A polycrystal with 500 grains (or mechanical
292 phases) of the same size (the absolute value has no impact as there is no
293 length scale in the code), deforms by dislocation glide on basal, prismatic
294 and pyramidal slip systems as in Castelnau et al. (1996b). Dynamic recryst-
295 tallization mechanisms are not taken into account in this formulation.

296 The rheological behavior at the grain scale is given by a standard power
297 law

$$\dot{\gamma}_{(k)} = \dot{\gamma}_0 \left| \frac{\tau_{(k)}}{\tau_{0(k)}} \right|^{n-1} \frac{\tau_{(k)}}{\tau_{0(k)}}, \quad (10)$$

298 with $\dot{\gamma}_{(k)}$ the rate of slip on slip system (k) , $\tau_{(k)}$ the shear stress, and $\tau_{0(k)}$
299 the critical shear stress necessary to activate slip on the system k . The
300 classical $n = 3$ value was adopted for the stress sensitivity (Castelnau et al.,

1996b,a, 1997). The basal, prismatic and pyramidal systems were assigned the respective critical stresses τ_0 , $50 \times \tau_0$ and $50 \times \tau_0$ (τ_0 is an arbitrary reference stress). This critical stress is the minimum resolved stress on the slip system necessary to induce slip on this system. The basal slip is therefore 50 times easier to activate than the prismatic and pyramidal slips. These parameters were adjusted to accurately reproduce the anisotropic viscoplastic response of the ice polycrystal following Castelnau et al. (1996b,a, 1997).

3.2. Modeling of the fabric evolution

The run was performed assuming a vertical compression under a uniform strain rate of 10^{-12} s^{-1} , based on an accumulation rate estimation of 8 cm ice/yr.

In order to compare measured and simulated fabric data, their evolutions are represented as a function of the cumulated compressive strain. In the specific case of a perfect dome, the ice is supposed to deform mainly by compression along the vertical direction. The cumulated compressive strain is then directly linked to the thinning of a layer by:

$$\bar{\varepsilon}_c = \frac{a}{a_0} - 1, \quad (11)$$

with a the thickness of a layer of initial thickness a_0 . The cumulated compressive strain evolution, as a function of depth, was deduced from the thinning function provided by the TALDICE-1 chronology (Buiron et al., 2011). For this chronology, the thinning function is provided for a given scenario of the evolution of the accumulation rate. The first scenario for the accumulation rate is obtained from isotopic data, and the thinning function is first estimated from a 1-D flow model following Parrenin et al. (2007). Both are later

324 adjusted using the inverse method of Lemieux-Dudon et al. (2010) which gen-
325 erates an optimal compromise between the a priori scenario provided by the
326 flow model and the chronological information from different time markers.

327 Fig. 8 represents the modeled and measured fabric evolutions as a func-
328 tion of the cumulated compressive strain, and the evolution of this strain with
329 depth. To estimate the impact of an initial anisotropic fabric in firm on the
330 global fabric evolution, initial eigenvalue inputs were allowed to vary around
331 the value measured at 18 m depth (see section 2.3). Dashed lines in Fig.
332 8 represent the range between an isotropic initial fabric and an anisotropy
333 slightly higher than the one measured in the firm.

334 Although shear could affect the deformation along the core, it was not in-
335 cluded in the simulation for several reasons. First of all, the mechanical
336 scheme of the VPSC approach requires the activation of at least four inde-
337 pendent slip systems (see Eq. (10)), with a slight amount of non-basal slip.
338 For the specific conditions of simple shear, this non-basal slip has a strong
339 impact on the macroscopic behavior. Because of this necessary non-basal
340 activity, the model is unable to predict the fabrics measured in conditions
341 of shear, that are characterized by a strong single maximum perpendicular
342 to the shear plane (Hudleston, 1977; Bouchez and Duval, 1982; Wenk and
343 Tomé, 1999). Similar conclusions were reached for olivine, which mechani-
344 cal behavior is highly anisotropic, similarly to ice (Zhang and Karato, 1995;
345 Tommasi et al., 2000). Secondly, the purpose of this modeling exercise is not
346 to strictly reproduce the measured fabric evolution, as a 3D configuration
347 would be required to integrate the exact flow conditions (with exact bound-
348 ary constraints) (Gillet-Chaulet et al., 2006; Martín et al., 2009) but rather

349 to highlight the inaccuracies arising from the assumption of a perfect dome.

350 4. Result analyses

351 4.1. Fabric and grain size evolution

352 The global trend of the c-axis strengthening along the Talos Dome core
353 compares qualitatively well with the one measured along the EPICA Dome
354 C, the GRIP or the Dome Fuji cores (Thorsteinsson et al., 1997; Azuma et al.,
355 1999; Wang et al., 2003; Durand et al., 2009). This type of fabric evolution is
356 coherent with a first order influence of a dominating compressive strain along
357 the core. Nevertheless, clear departures from this trend are visible, which we
358 will try to analyze in the following part.

359 We have measured fabrics that are not isotropic in firn samples, as high as
360 technically possible with non-impregnated samples, i.e. up to 18 m depth.
361 Similar observations were done along the Siple Dome ice core (Diprinzio et al.,
362 2005) and the EPICA Dome C ice core (Durand et al., 2009). At 18 m depth,
363 in the Talos Dome coring site, a compressive strain of less than 1% is expected
364 from the TALDICE-1 thinning function. With isotropic initial conditions,
365 the $a_1^{(2)}$ eigenvalue of the orientation tensor predicted by the VPSC-SO model
366 after 1% of deformation is about 0.35. The $a_1^{(2)}$ eigenvalue measured at 18 m
367 is 0.39 (0.40 at 28 m and 0.44 at 48 m), clearly higher than the 0.35 value
368 predicted, and 7% of compressive strain is required to reach 0.39 with the
369 VPSC-SO model (see Fig. 8).

370 To our knowledge, there exist no detailed analyses of the link between
371 densification processes and fabric evolution, but only isolated data of fab-
372 ric measurements along firn cores (Spaulding et al., 2011). From Arnaud

373 et al. (1998, 2000), between about 5 to 20 m depth and for conditions similar
374 to the Talos Dome site, densification is expected to be isothermal, and the
375 main process is believed to be re-arrangement by grain boundary sliding. No
376 preferred orientation is expected to occur during such process. Closer to the
377 surface, temperature gradient metamorphism dominates the grain size evolu-
378 tion, and the impact on fabric development has only been seldom investigated
379 (Carns et al., 2010). From observation of individual snow crystals, Adams
380 and Miller (2003) made the hypothesis that, during temperature gradient
381 metamorphism, there could exist favored orientation growth which depends
382 on the conditions of the metamorphism (temperature range, level of super-
383 saturation, ice-grain/pore space). High resolution fabric measurements in
384 firn are therefore necessary to better explain this measured anisotropy, but
385 it has to be taken into account, especially when modeling the fabric evolution.

386

387 In the first 350 m of the core, the grain size evolution well matches a
388 normal grain growth law as measured along the GRIP and Byrd ice cores.
389 Then, the average grain size stabilizes around 2.1 mm down to about 950
390 m. The continuous DRX model suggested by de la Chapelle et al. (1998);
391 Montagnat and Duval (2000) therefore applies in the central part of this core.
392 Continuous DRX mechanism is supposed to slow the fabric strengthening.
393 Indeed, the associated nucleation mechanism (by progressive misorientation
394 of sub-boundaries) is supposed to slightly open the fabrics (Wenk et al.,
395 1997; Castelnau et al., 1996b), and the associated grain boundary migration
396 reduces the deformation stored energy.

397 Local discontinuous DRX events were observed at 1171 m depth (Fig. 3),

398 with isolated grains of size bigger than the average, and orientation deviating
399 from the main orientation direction, and at several other depths below 1400
400 m. The big grain sizes are explained by a rapid grain boundary migration,
401 and the obvious departure from the average grain orientation results from
402 new grain nucleations (de la Chapelle et al., 1998). The 10 m sampling of
403 the fabric measurements probably prevents the observation of further local-
404 ized discontinuous DRX events. These events are the signature of a highly
405 heterogeneous state of stress at the origin of a local level of strain high enough
406 to induce nucleation and fast grain boundary migration. Nevertheless, down
407 to 1500 m depth, the localized events of discontinuous DRX do not drasti-
408 cally change the fabric toward isotropy or multiple maxima as observed along
409 the Siple Dome ice core (Diprinzio et al., 2005), and in the bottom of the
410 GRIP ice core (Thorsteinsson et al., 1997) for instance.

411

412 The fabric evolution tendency shows a break, with a higher strengthening
413 rate below 750 m and continuing down to 900 m depth. This depth range
414 corresponds to the Holocene - Wisconsin transition. Following Durand et al.
415 (2007), this faster fabric strengthening could be explained by the associated
416 impact of a change in ice viscosity due to the glacial-interglacial transition
417 and of the progressive influence of a shear stress component.

418 Along ice cores, thinning is only controlled by the compressive strain
419 (Paterson, 1991). As extrusion flow can not occur, two layers with different
420 viscosity will experience the same amount of thinning. On the other hand,
421 shearing by itself will not produce any thinning but will strongly enhance
422 fabric strengthening. As currently observed along ice cores, smaller grain

423 sizes and strengthened fabrics are measured in glacial ice with respect to
424 interglacial ice (see for instance de la Chapelle et al. (1998); Diprinzio et al.
425 (2005); Durand et al. (2006b, 2009)). The higher fabric strengthening rate
426 measured in the glacial ice layer of the Talos Dome ice core confirms the
427 occurrence of a positive feedback with glacial ice layer experiencing more
428 shear, so that its fabric gets more clustered and then softer for shear (Pater-
429 son, 1991).

430

431 Between 950 m and 1150 m depth, the fabric is constant, with similar
432 fabrics in adjacent layers. Here we provide two possible analyses. The first
433 one considers that these adjacent layers could have experienced the same
434 deformation history (same flow) but with different initial viscosities. They
435 would therefore be differently influenced by the shear stress, and end up with
436 very similar fabrics at adjacent depths. The dust level measured in this range
437 of depth is highly variable (see Fig. 5), and about twice to five times higher
438 than during the Holocene (Delmonte et al., 2010). The high variability of
439 dust content during this period could induce variability in the viscosity be-
440 tween adjacent layers from the very top of the core. The second explanation
441 could be related to some changes in the dome configuration during the cor-
442 responding period of time. In this case, the layers would have experienced
443 different, but close, deformation histories. Urbini et al. (2008) showed that
444 variations in the accumulation rate during the last few centuries could have
445 resulted in some dome summit migration. Although highly speculative, such
446 an explanation could also hold for this anomaly in the fabric evolution.

447

448 *4.2. Comparison with the fabric evolution along the EPICA Dome C ice core*

449 The EPICA Dome C ice core was drilled at Dome C, in Antarctica (75°
450 $06'S$, $123^{\circ} 21'E$) down to 3259.72 m depth. Owing to the low accumulation
451 observed in this inland site of Antarctica, the upper 3139 m of the core
452 provide about 800 000 years of climatic records (Jouzel et al., 2007).

453 Because of the difference in depth (and age) between the two ice cores, a
454 direct comparison between them on a depth scale cannot be done; however,
455 they can be compared on a scale of cumulated compressive strain. For EPICA
456 Dome C, we used the EDC3 chronology from Parrenin et al. (2007) to obtain
457 the cumulated compressive strain as a function of depth, following Eq. 11.
458 The fabric data along the EPICA Dome C core are given by (Durand et al.,
459 2009).

460 Talos Dome and EPICA Dome C fabrics show very similar evolutions,
461 when compared as a function of cumulated compressive strain, see Fig. 7.
462 Since the overall location and conditions at the two coring sites are much
463 different, such a comparison tends to demonstrate that the cumulated com-
464 pressive strain is the main parameter controlling the fabric strengthening.
465 In particular, one can note that the fabric evolution changes measured at
466 1750 m along the EPICA Dome C core (Durand et al., 2007) and at 750 m
467 along the Talos Dome core occur for the same cumulated compressive strain
468 of about 0.6. Both depths correspond to climatic changes from glacial to
469 interglacial conditions but at different times. The feedback between changes
470 in layer viscosity (probably related with variation in dust content) and shear
471 stress would then mainly affect the fabric evolution after a given level of fab-
472 ric anisotropy is reached, and therefore after a given amount of cumulated

473 compressive strain.

474 *4.3. Comparison between the measured and the simulated fabric evolution.*

475 The modeling of fabric evolution under the assumption of uniaxial com-
476 pression at constant strain rate represents well the configuration of a perfect
477 dome. The comparison between simulation and measurements thus allows to
478 identify the departures from this ideal state of strain.

479 Fig. 8 shows that the model provides a good overall estimate of the fabric
480 evolution trend, especially when a non isotropic initial fabric is considered
481 according to the measurements.

482 Since continuous dynamic recrystallization processes, as expected along
483 the core (section 2.3), are not represented in the VPSC-SO scheme adopted
484 here, the slight overestimation of the fabric strengthening in the range 350
485 to 950 m depth (strain from ≈ 0.25 to 0.7) was expected (Castelnau et al.,
486 1996b; de la Chapelle et al., 1998; Thorsteinsson, 2002).

487 Below 950 m depth (strain ≈ 0.75), the measured fabric is much stronger
488 than the modeled fabric, and the rate of fabric strengthening from strain of
489 ≈ 0.6 (about 750 m depth) can not be reproduced by the model under the
490 hypothesis of uniaxial compression. This comparison therefore reinforces the
491 assumption made in section 4.1 of the influence of a shear stress component on
492 the fabric strengthening. In particular, the shear stress would be responsible
493 for the fabric strengthening below 750 m (strain ≈ 0.6), and for the strong
494 c-axis clustering below 950 m depth.

495 5. Concluding remarks

496 The fabric evolution measured along the Talos Dome ice core is charac-
497 terized by a strengthening toward the vertical direction, very similar to the
498 one measured along several other Greenland and Antarctic cores, where the
499 main deformation component is vertical compression. Nevertheless, varia-
500 tions in the c -axis clustering rate are observed at locations corresponding to
501 the climatic transitions.

502 In particular, an increase in the rate of fabric strengthening is observed in
503 the depth range covering the Last Glacial Maximum - Holocene transition.
504 The influence of a shear component of stress associated with viscosity changes
505 between successive layers is therefore suggested, following (Durand et al.,
506 2007). This hypothesis is strengthened by the comparison performed between
507 the measured fabric evolution and the one simulated under the assumption
508 of a "perfect dome", using the VPSC-SO mean-field approach. Under the
509 perfect dome assumption, i.e. under uniaxial compression at a constant rate,
510 the model can not represent the strength of the fabrics measured below 950
511 m depth, that could be explained by a non negligible shear stress.

512 Above 750 m depth, the simulation provides a qualitative good match
513 with the measured fabrics, providing that (i) we enter a non-isotropic fabric
514 in the top layer, similar to the one measured in the firn, and (ii) we explain
515 the slight overestimation between 350 m and 750 m depth by continuous
516 DRX not being taken into account in the model. Although continuous DRX
517 was probably active in the lower part of the core, we loose track of it because
518 of the shear-induced fabric strengthening.

519 Indeed, the analysis of the grain size evolution measurements, associated

520 with the fabric data, highlights the occurrence of dynamic recrystallization
521 processes. The first part of the core, above 950 m depth, is dominated by
522 normal grain growth and continuous DRX, while discontinuous DRX is only
523 observed locally at various depths below 1170 m. Discontinuous DRX does
524 not seem to influence the fabric evolution down to 1400 m.

525 **6. Acknowledgements**

526 TALos Dome ICE core project (TALDICE), a joint European program led
527 by Italy, is funded by national contributions from Italy, France, Germany,
528 Switzerland and the United Kingdom. The main logistical support was pro-
529 vided by PNRA at Talos Dome. We thank the logistic and drilling TALDICE
530 team for their efficiency over each drilling season. Funding support for the
531 laboratory measurements and dating work was provided by the Institut INSU
532 of CNRS through its program LEFE. Many thanks to Hugh Corr who pro-
533 vided the radar images (BAS/PNRA collaboration in 2005/06). We thank
534 Ricardo Lebensohn and Carlos Tomé from LANL (USA) for the access to
535 the VPSC7 code, and Paul Duval, Gaël Durand, Fabien Gillet-Chaulet and
536 Olivier Gagliardini from LGGE for fruitful discussions. This is TALDICE
537 publication no 26.

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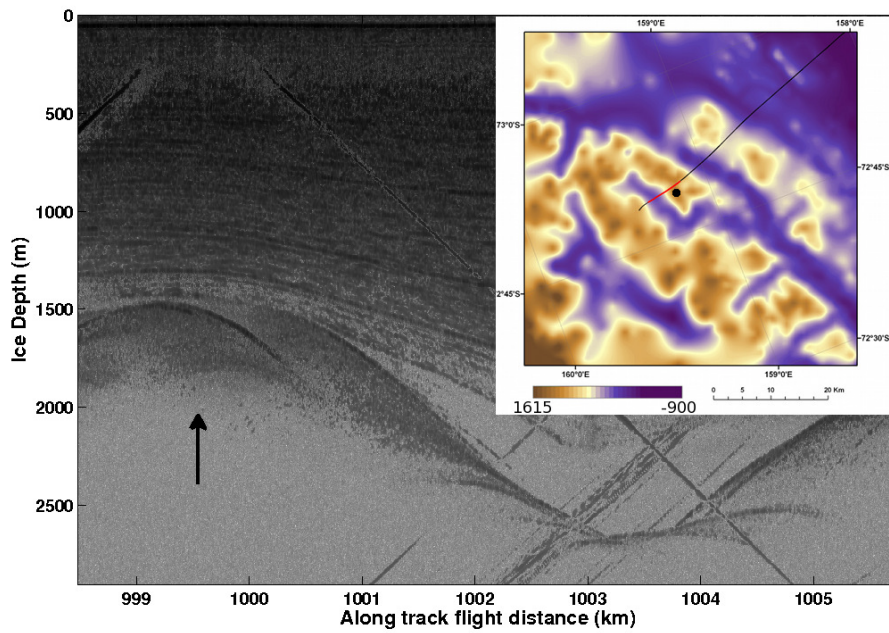


Figure 1: Radargram of the area around the Talos Dome coring site. The flight passed within 50 m from the borehole, at the position indicated by the black arrow. The inner figure represents the bedrock elevation map with the position of the coring site (black dot), the flight track followed the line (from top right), the red part being the one presented on the radargram.

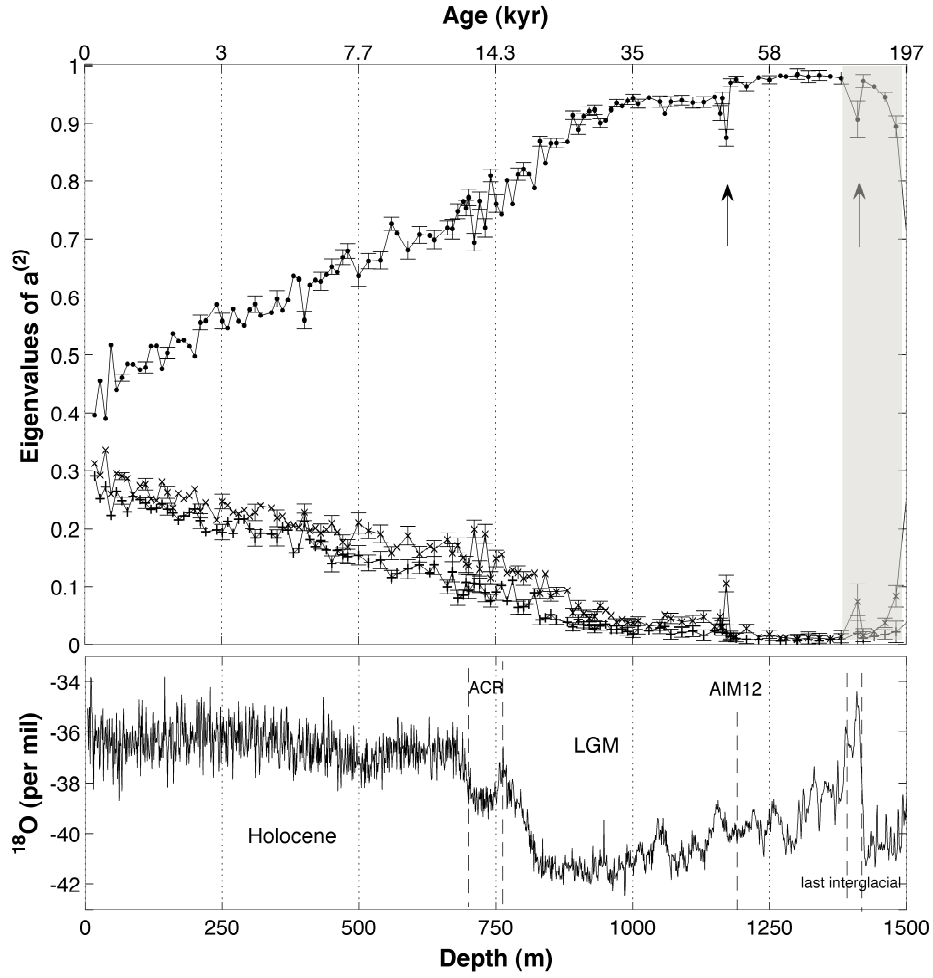


Figure 2: Orientation tensor eigenvalues along the Talos Dome core, as a function of depth (dots: $a_1^{(2)}$, crosses: $a_2^{(2)}$, plus: $a_3^{(2)}$) and ^{18}O isotope evolution as a proxy of climate changes. Error bars in the $a_i^{(2)}$ plots correspond to $\pm 1\sigma$ confidence level. The arrows show two depths with remarkable recrystallized grains, 1171 m and 1411 m. The grey area corresponds to the depth range presented in Fig. 4.

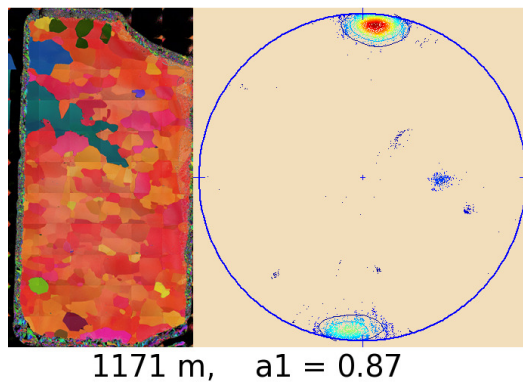


Figure 3: Microstructure in orientation color-scale and Schmidt plot obtained from the 1171 m depth thin section. In the pole figure, the blue spots out of the single maximum correspond to the orientation of the green and blue grains of the microstructure. The core vertical axis coincides with the vertical direction in the figure.

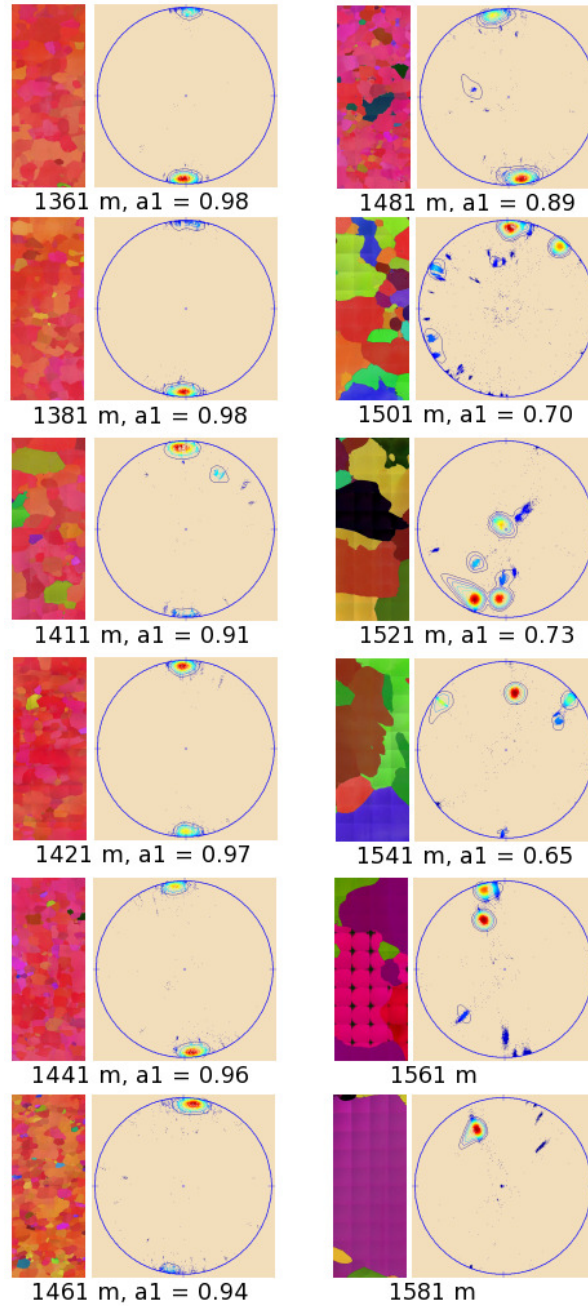


Figure 4: Microstructures in orientation color-scale and Schmidt plots obtained from 1361 m to 1581 m depth. $a_1^{(2)}$ eigenvalue is not provided after 1541 m due to the too low number of grains. The core vertical axis coincides with the vertical direction in the figure.

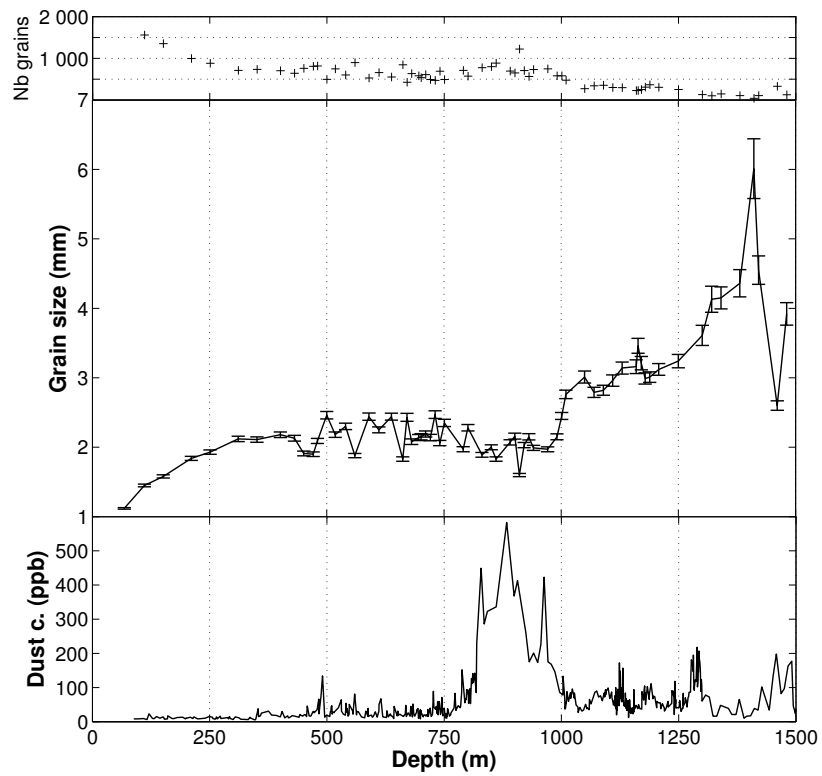


Figure 5: Average grain size (error bars correspond to $\pm 1\sigma$ confidence interval), dust content, and number of grains analyzed (in each thin section), as a function of depth along the Talos Dome ice core.

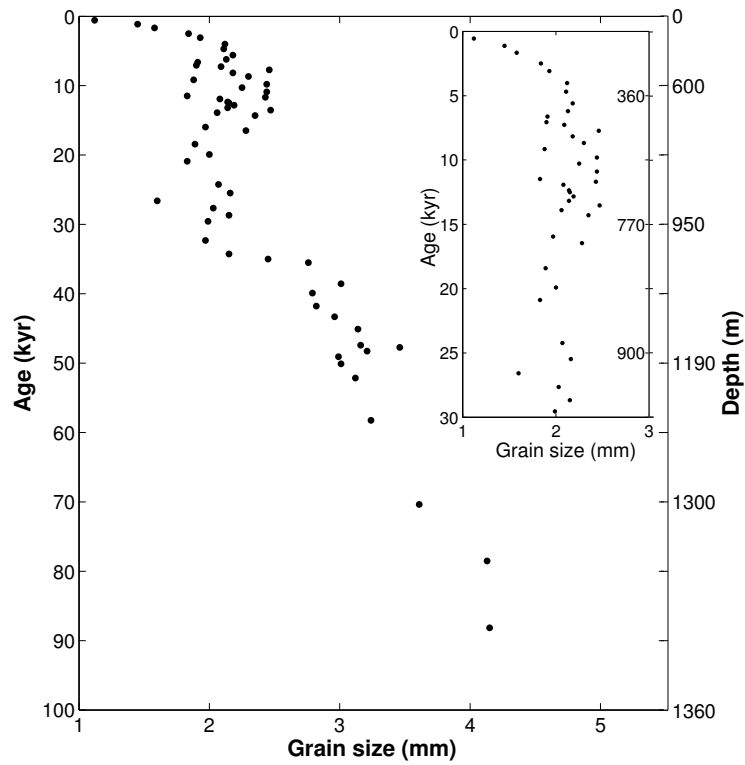


Figure 6: Average grain size as a function of ice age. The inner figure is a focus over the first 30 000 years.

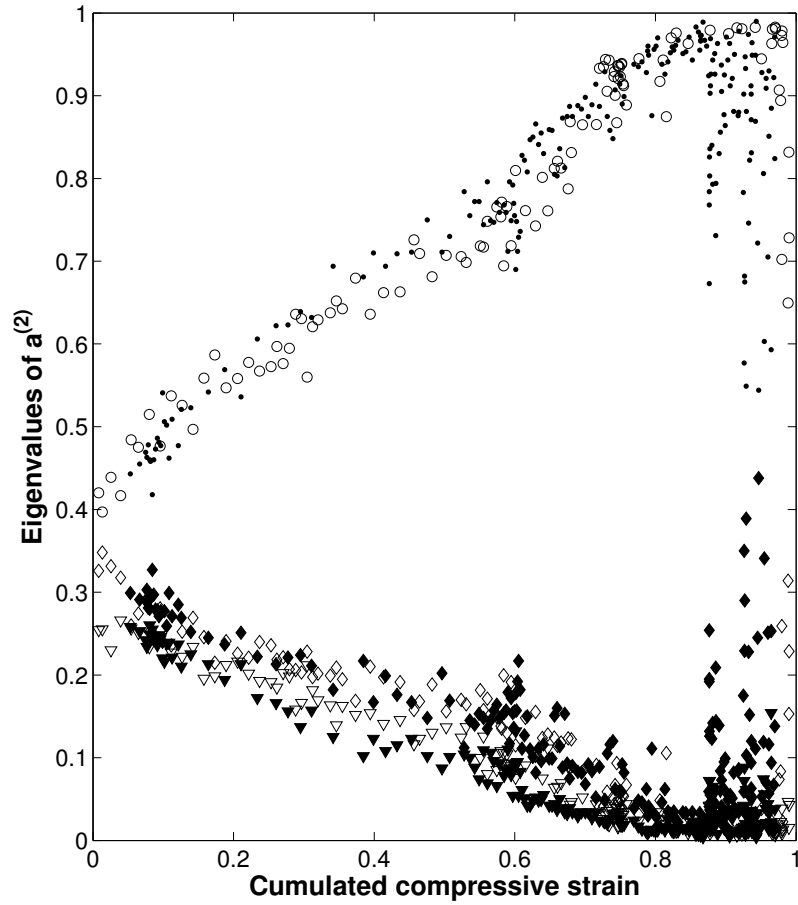


Figure 7: Eigenvalues of the orientation tensor $\mathbf{a}^{(2)}$ as a function of the cumulated compressive strain along the Talos Dome core (empty symbols) and EPICA Dome C core (full symbols). The cumulated compressive strain evolution with depth is deduced from the official chronologies of each core.

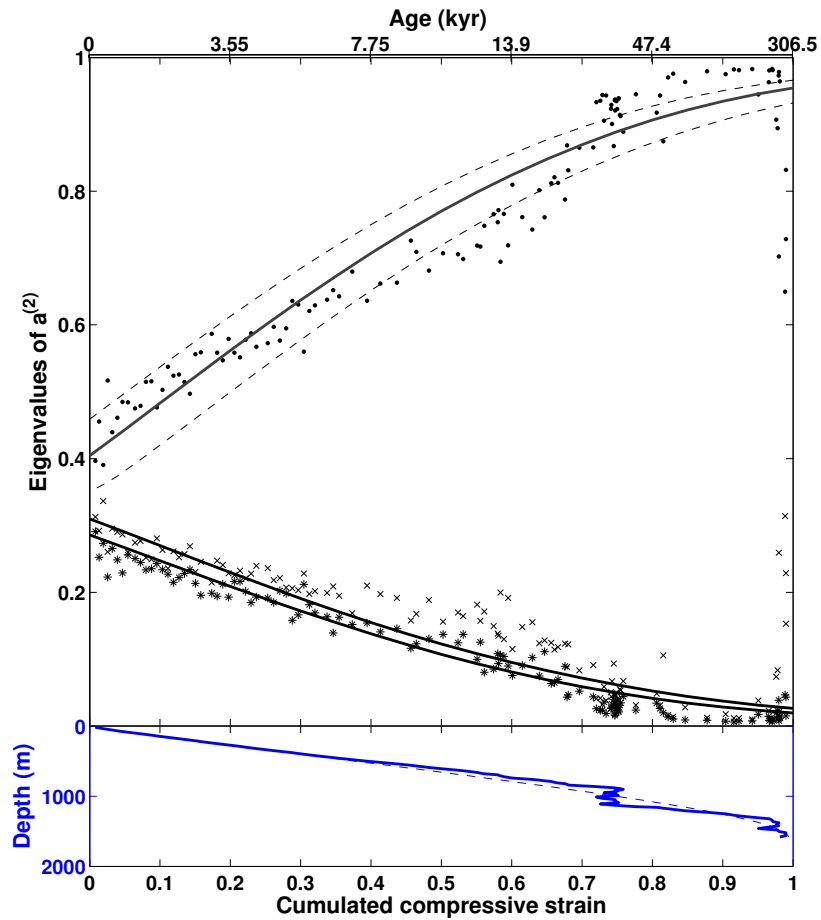


Figure 8: Upper part: evolution of $a^{(2)}$ eigenvalues as a function of cumulated compressive strain. Lines = model results. Dots, crosses and plus = measurements. Dashed line represents the range of fabric evolution simulated with variations in initial eigenvalues (see text). Bottom part: evolution of the cumulated compressive strain with depth, as estimated from the thinning function extracted from TALDICE-1 chronology. Inverse model (thick line) and direct model (dashed line). Age scale is reported on the top axis.