

# 1 **Small-scale disturbances in the stratigraphy of the NEEM** 2 **ice core: observations and numerical model simulations**

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## 13 **Abstract**

14 Disturbances on the centimetre scale in the stratigraphy of the NEEM ice core (North  
15 Greenland) can be mapped by an optical line scanner as long as the ice does have a visual  
16 layering, such as, for example, cloudy bands. Different focal depths allow, to a certain extent,  
17 a three dimensional view of the structures. In this study we present a detailed analysis of the  
18 visible folds, discuss their characteristics and frequency and present examples of typical fold  
19 structures. We also analyse the structures with regard to the deformation boundary conditions  
20 under which they formed. The structures evolve from gentle waves at about 1500 m to  
21 overturned z-folds with increasing depth. Occasionally, the folding causes significant  
22 thickening of layers. Their similar-fold shape indicates that they are passive features and are  
23 probably not initiated by rheology differences between alternating layers. Layering is heavily  
24 disturbed and tracing of single layers is no longer possible below a depth of 2160 m. C-axes  
25 orientation distributions for the corresponding core sections were analysed where available in  
26 addition to visual stratigraphy. The data show axial-plane parallel strings of grains with c-axis  
27 orientations that deviate from that of the matrix, which shows a single-maximum fabric at the  
28 depth where the folding occurs.

29 Numerical modelling of crystal viscoplasticity deformation and dynamic recrystallisation was  
30 used to improve the understanding of the formation of the observed structures during  
31 deformation. The modelling reproduces the development of bands of grains with a tilted  
32 orientation relative to the single maximum fabric of the matrix, and also the associated local  
33 deformation. We conclude from these results that the observed folding can be explained by  
34 formation of kink bands

35

## 36 **1 Introduction**

37 The NEEM (North Greenland Eemian Ice drilling) ice core, located at 77° 27' N 51° 3.6' W in  
38 the northwest of Greenland, has been drilled between June 2008 and July 2012. It is located  
39 on a topographic ridge, which dips towards the northwest so that the surface velocities on the  
40 ice divide have a non-negligible component of along ridge flow of about 6 m a<sup>-1</sup> ([NEEM  
41 community members, 2013](#)). In July 2010 the bedrock was reached at 2537.36 m depth. The  
42 site has been chosen in order to recover an undisturbed Eem warm-period ice layer. However,  
43 it was found later that the ice below 2200 m was heavily disturbed and probably folded on a  
44 large scale ([NEEM community members, 2013](#)).

45 Visual stratigraphy of the NEEM ice core revealed folding also on a small scale, with fold  
46 amplitudes varying from less than 1 cm to a few decimetres ([Samyn et al., 2011](#)). These types  
47 of folds occur well above the large scale disturbances reported by the [NEEM community  
48 members \(2013\)](#). Similar structures have been found in the lower parts of other deep ice cores  
49 ([Alley et al., 1997](#); [Thorsteinsson, 1996](#); [Svensson et al., 2005](#); [Faria et al., 2010](#); [Fitzpatrick  
50 et al., 2014](#)). Stratigraphy bands are visualized by an indirect light source scattering on  
51 surfaces inside the ice, mainly particles and air bubbles / hydrates ([Svensson et al., 2005](#)).  
52 High impurity content is found in ice that originates from snow accumulated during glacial  
53 periods. Changing impurity contents between ice from glacial and interglacial periods have  
54 been linked to rheological differences (e.g. [Paterson, 1991](#)) and may lead to shear localization  
55 in distinct horizontal layers.

56 Due to their potential influence on the integrity of the climatic record, folds have been subject  
57 to modelling studies (e.g. [Waddington et al., 2001](#)). [Thorsteinsson and Waddington \(2002\)](#)  
58 explored the amplification of small disturbances in the layering of ice cores for isotropic and  
59 anisotropic conditions, investigating the potential for the existence of overturned folds near  
60 ice sheet centres. [Azuma and Goto-Azuma \(1996\)](#) concluded from their proposed anisotropic

61 flow law formulation that an inclined single maximum fabric could lead to vertical strain even  
62 in simple shear and thus influence the stratigraphy. They also suggested that horizontal  
63 variations in the inclinations could then cause alternating thickening and thinning of layers,  
64 leading to folding or boudinage in the stratigraphy. However, the initial formation of the  
65 disturbances is not fully understood.

66 Here we present a characterisation of the small-scale folding observed in the NEEM ice core.  
67 Another feature occasionally observed along with folding in deep ice cores are “fabric  
68 stripes” (Alley et al., 1997). They describe bands of deviating grain orientations with respect  
69 to the surrounding matrix, which is essentially a single maximum fabric in regions where  
70 folding occurs. We discuss possible folding mechanisms and the link to the so called “Alley-  
71 stripes” in the crystal fabric of grains. Microstructural modelling with ELLE reproduces  
72 similar fabrics and fold structures to the ones we observe in the NEEM ice core.

73

## 74 **2 Methods**

75 The data used in this study were obtained by different observational methods, which will be  
76 introduced only briefly in the following section. For technical details we recommend to check  
77 the original literature cited in the subsections.

### 78 **2.1 Linescan visual stratigraphy**

79 The visual stratigraphy of the NEEM ice core was recorded by means of an automated  
80 linescan instrument (see Svensson et al. (2005) for a detailed description of the instrument  
81 and data from the North GRIP ice core). Clear ice appears dark when illuminated by an  
82 indirect light source. Dust particles or bubbles cause scatter of light and make the ice appear  
83 bright in the linescan image. A clear correlation between backscatter and dust content has  
84 been found in the North Grip ice core (Svensson et al., 2005). The method can be applied  
85 directly in the field and in the case of the NEEM ice core was applied continuously for the  
86 entire core, with a gap between 860 m and 1150 m, which corresponds to the brittle zone  
87 where the core quality did not allow preparation for the linescanner. For the NEEM ice core  
88 the linescan images were recorded with a standardised exposure time and three focal planes  
89 within the ice core section with a vertical distance of 1 cm (Kipfstuhl, 2010). This allows to a  
90 certain degree a three-dimensional mapping of the visible layering in the ice core. The data  
91 are stored in high-resolution (118 pixel per centimetre) bmp images. One drawback of this

92 method is, of course, that it only shows disturbances in the ice if scattering surfaces are  
93 included. However, it is possible to even reveal structures at low dust content by means of  
94 image processing and filtering.

## 95 **2.2 Automated Fabric Analyzer**

96 The crystal fabric orientation of discrete samples was measured using a G50 Automatic  
97 Fabric Analyzer (Australian *Russell-Head* type, see e.g. [Russell-Head and Wilson, 2001](#);  
98 [Peternell et al., 2010](#), data set: [Weikusat and Kipfstuhl, 2010](#)). Samples cut from the physical  
99 properties part of the NEEM core were cut to 250  $\mu\text{m}$  thin sections to measure c-axis crystal  
100 lattice orientations by polarized light microscopy, where the thin section is placed between  
101 systematically varying crossed polarizers (e.g. [Wilson and Russell-Head, 2003](#)). The data  
102 coverage is much better than in previous ice cores with continuous sampling of selected core  
103 sections (bags) to investigate meter-scale variations in fabric throughout the core. However,  
104 due to the time-consuming preparation of the samples it was not possible to produce a  
105 continuous record.

## 106 **2.3 Microstructural modelling with ELLE and full field crystal plasticity**

107 We use 2-D numerical modelling to investigate the development of strain localization in a  
108 polycrystalline aggregate. At the moment it is not possible to combine simple shear and pure  
109 shear boundary conditions. We chose simple shear boundary conditions as an approximation  
110 for the in-situ conditions in the lower part of the ice shelf where the fabric stripes are  
111 observed, and where horizontal shear is dominant. The simulation approach couples a full  
112 field method based on the fast Fourier transform (FFT) that simulates viscoplastic  
113 deformation, with a front-tracking codes that simulate dynamic recrystallisation processes  
114 (DRX), included within the open-source numerical modelling platform ELLE  
115 (<http://www.elle.ws>; [Bons et al., 2008](#)). ELLE has been successfully used to simulate  
116 evolution of microstructures during deformation, such as recrystallization ([Piazolo et al.,](#)  
117 [2008](#); [Roessiger et al., 2011](#); [2014](#)) or strain localisation ([Jessell et al., 2005](#); [Griera et al.,](#)  
118 [2011, 2013](#)). The full-field crystal plasticity (FFT) code ([Lebensohn, 2001](#); [Lebensohn et al.,](#)  
119 [2008](#); [Montagnat et al., 2014a](#)) simulates deformation by pure viscoplastic dislocation glide.  
120 An experimental run consists of iterative applications of small increments ( $\Delta\gamma=0.04$ ) of simple  
121 shear deformation, each followed by a sub-loop of processes simulating dynamic  
122 recrystallisation (grain boundary migration and recovery). While grain boundary migration

123 covers the motion of high-angle grain boundaries, recovery achieves a decrease in  
124 intracrystalline heterogeneities by means of local rotation without motion of high-angle  
125 boundaries. The recrystallisation sub-loop may be called more than once to simulate the  
126 different balance between deformation and recrystallisation as a function of strain rate, since  
127 all simulations are performed with the same intrinsic mobility value ( $M_0$ ) and boundary-  
128 diffusion activation energy ( $Q$ ) (Roessiger et al., 2014; Llorens et al., in review). Exchange of  
129 data between ELLE and FFT is possible, as both use periodic boundary conditions and the  
130 physical space is discretised into a shared regular node mesh.

131

132 The ELLE data structure consists of three layers: (1) a network of nodes (boundary nodes or  
133 *bnodes*) that are connected by straight boundary segments that define the high-angle grain  
134 boundaries that enclose individual ice grains, (2) a set of unconnected nodes (*unodes*) to map  
135 lattice orientations and dislocation densities, used for the FFT calculation, and (3) a passive  
136 marker grid utilised to track finite strain. Distances between nodes are kept between  $5.5 \times 10^{-3}$   
137 and  $2.5 \times 10^{-3}$  times the unit distance (in a 1x1 bounding box), by removing *bnodes* when their  
138 neighbours are too close or adding *bnodes* when two nodes are too far apart. The space is  
139 discretised in a mesh of 256x256 Fourier points, resulting in a unit cell defined by 65,536  
140 discrete nodes. Each *unode* represents a small area or crystallite with a certain lattice  
141 orientation, defined by Euler angles, and a dislocation density value. The ELLE data structure  
142 has fully wrapping boundaries. The 10x10 cm<sup>2</sup> initial microstructure has 1632 grains, each  
143 with a homogeneous lattice orientation, showing a c-axis preferred orientation almost  
144 perpendicular to the shear plane, in order to simulate an intrinsic anisotropic material. The  
145 misorientation between grains was set at  $<5^\circ$  (i.e. initial noise). Dislocation glide of ice-single  
146 crystal was defined by slip on the basal {0001}{11-20}, prismatic {1-100}{11-20} and  
147 pyramidal systems {11-22}{11-23}. In these simulations, the ratio  $A$  of critical resolved shear  
148 stress (CRSS) for non-basal versus basal slip systems was set to  $A = 20$ . The same stress  
149 exponent ( $n = 3$ ) is set for all slip systems. The physical values used for recrystallisation are:  
150 intrinsic mobility  $M_0$  ( $0.023 \text{ m}^2\text{kg}^{-1}\text{s}$ ; Nasello et al., 2005), boundary-diffusion activation  
151 energy  $Q$  ( $40 \text{ KJ mol}^{-1}$ ; Thorsteinsson, 2002), isotropic surface energy  $\gamma_e$  ( $0.065 \text{ Jm}^{-2}$ ;  
152 Ketcham and Hobbs, 1969) and temperature was set to  $T = -30^\circ\text{C}$ . To simulate recovery  
153 numerically, a modification of the approach proposed by Borthwick et al. (2013) was used.  
154 As the time step for the simulation of recrystallisation is smaller than necessary for the

155 computationally expensive FFT-calculation, we modelled ten DRX steps of  $\Delta t=6.3 \times 10^8$  s for  
156 each shear strain increment of  $\Delta \gamma=0.04$ , giving a shear strain rate of  $6.35 \times 10^{-12}$  s<sup>-1</sup>.  
157 Simulations with other shear strain rates were performed for comparison, but not presented  
158 here. See [Llorens et al. \(in review\)](#) for a complete description of the methods.

159

## 160 **3 Results**

### 161 **3.1 Stratigraphy and fold classification**

162 The stratigraphic data were visually inspected for all parts of the ice core containing cloudy  
163 bands, in order to categorise disturbances of the visible layers. It has to be noted that this  
164 method is only appropriate where sufficient layers are visible, since clear ice may have been  
165 deformed as well. [Figure 1](#) shows an overview of the layering structures we find in the NEEM  
166 ice core. All images shown are confined to the core sections above the major disturbances in  
167 the Eemian ice beginning at a depth of approximately 2200 m. Around this depth the ice is  
168 heavily sheared and the layering becomes more and more diffuse. Below that it is no longer  
169 possible to see fold structures in the visual stratigraphy data as the ice of the Eemian is mostly  
170 clear. The panels display the scans of entire core sections of about 1.10 m, which were cut  
171 into segments of 0.55 m after scanning. The top always represents the upper part of the core  
172 segment. Some segments differ in length, as the recovered core pieces are not always exactly  
173 1.10 m long. Some of the pieces also fractured during the recovery process or during  
174 preparation, which is highlighted with red lines in [figure 1](#). The images have been partly  
175 processed by applying a Gauss filter to enhance the visibility of the layering, and therefore the  
176 grey values are no absolute measure for impurity content or of other parameters that could  
177 influence the backscatter within the ice.

178 The upper part of the NEEM ice core shows little or no disturbances. [Figure 1a](#) shows an  
179 example from 1430 m depth with perfectly horizontal layers. The layer thickness and opacity  
180 does vary in the core segment, and single layers have a constant thickness throughout the 10  
181 cm wide core section. A close up of one of the layers shows no particular structure within it  
182 ([fig. 2a](#)). According to the NEEM chronology published in [Rasmussen et al. \(2013\)](#), the  
183 annual layer thickness changes from about 2 cm at 1500 m to less than 1 cm at 2000 m depth.  
184 Below a depth of about 1700 m the structure of the layering begins to change, as examples  
185 from depths of approximately 1760 m and 1867 m show ([fig. 1b,c](#)). Wave-like features with

186 cm-scale amplitudes and wavelengths in the order of the core diameter can be observed. In  
187 some parts of the core segments these disturbances can be clearly followed through several  
188 layers. **Figure 2b** shows an enlarged section of **figure 1b**, showing a well-developed  
189 asymmetric z-fold. Its shape indicates sinistral shear and the fold is beginning to overturn.  
190 The fold hinge is a sharp feature, which can be followed over several layers. The  
191 enlargements in **figure 2b** also show that the cloudy layers themselves appear to be laminated.

192 For the core sections shown in **figure 1b,c** the layers vary in thickness within the core, as can  
193 be clearly seen in **figure 2b**, where the central greyish layer (indicated with green dashed  
194 lines) nearly doubles its thickness in the centre of the image due to the folding. This shape is  
195 typical for so-called similar folds in geology ([Ramsey et al., 1987](#)). **Figure 1d,e** show  
196 examples from 1977 m and 2098 m depth, where the layering is significantly more disturbed.  
197 The vertical scale of the disturbances has risen to the scale of ten centimetres (**fig. 2d,e**). In  
198 between the larger-scale folds the layering appears to be more regular again, however the  
199 limited width of the core sections limits our interpretation here, as the layers could be  
200 overturned folds of which the limbs became near-horizontal due to a combination of the on-  
201 going shear and vertical thinning. **Figure 2c** shows a stack of flattened folds, where the  
202 doubling of layers may not be immediately obvious to the observer when focusing on the left  
203 part of the image. Tracing one boundary between a clear and a cloudy band highlights that the  
204 thin layers are probably limbs of an overturned fold (indicated with a blue dashed line). There  
205 are also new generations of folds standing out through their well-defined and steeper axial  
206 planes and which are not yet overturned (**fig. 2c**, on the left, fold axis indicated with a green  
207 dashed line).

208 At even greater depth the layering becomes less distinct (**fig. 1f,g,h**). In some parts of these  
209 sections the layers appear to be undisturbed but inclined, which may indicate that they are part  
210 of a larger deformation structure. The now very thin layers still show new generations of  
211 folds.

### 212 **3.2 Crystal fabric orientation anomalies connected to folds**

213 In comparison to previous deep ice cores, the amount of data gathered to analyse ice fabric is  
214 relatively high. To investigate small-scale variations entire bags of 55 cm from certain depths  
215 were processed. The general evolution of ice fabric with depth in the NEEM ice core was  
216 described in [Montagnat et al. \(2014b\)](#). The c-axis orientation distribution develops more or

217 less linearly from an isotropic fabric to a single maximum at a depth of about 1400 m, which  
218 represents the transition from the Holocene to the last glacial (Rasmussen et al., 2013). Within  
219 the well-developed single maximum fabric we found inclined bands of grains with a deviating  
220 c-axis orientation. We assume that the bands are planar features, but as the thin sections are  
221 vertical cuts through the cylindrical core section the inclination of the bands is not necessarily  
222 equal to the inclination of the planes. Similar bands were described in the GRIP ice core  
223 (Thorsteinsson, 1996) and the GISP2 ice core (Alley et al., 1997). In case of the NEEM ice  
224 core, however, significantly more fabric data are available, which enables us to follow these  
225 structures through entire core sections.

226 One of the first examples of such a band, shown in figure 3a, appears at a depth of 1800 m.  
227 The c-axis orientation of grains within the bands is tilted anti-clockwise relative to the single  
228 maximum, which is indicated by the blue-greenish colours in the colour wheel used to  
229 illustrate c-axis orientation (inset in figure 3a). The grain size does not differ from the average  
230 grain size of the sample. The subgrain boundary density in these grains does not differ  
231 significantly from the surrounding ones, which indicates that they are most likely not newly  
232 nucleated grains (fig. 4). However, while the subgrain boundaries in grains with vertical c-  
233 axes are mostly parallel to the basal planes, they are mainly perpendicular to the basal plane in  
234 grains within the band, indicating the onset of rotation recrystallisation.

235 The direct comparison of the fabric data with the line scan images (figure 3) reveals that these  
236 bands are connected with disturbances in the layering. The inclination is in agreement with  
237 the sense of shear that is derived from the asymmetry of the folded layers. However, layer  
238 disturbances are not always visible where fabric anomalies are found.

239 In figure 5a,b,c the three linescan images available from the different focal depths are plotted  
240 next to each other to illustrate the three-dimensional nature of the observed folding in the  
241 layering. The shape change of the highlighted layer indicates that the fold axis shifts to the  
242 left towards the centre of the core (fig. 5e). The thin sections for the fabric analysis are  
243 prepared from the physical properties sample in the upper part. The linescan measurement is  
244 performed on the remaining part of the core with 1 cm between the different focal planes (fig.  
245 5d).

246 Figure 6 shows an example from approx. 1978 m depth where we see finely laminated layers  
247 and asymmetric folds that indicate dextral shear. The fold hinges indicated by the arrows are  
248 not very distinct, which is probably due to light diffusion caused by the distorted fine layers.



249 The two distinct bands in the right half of [figure 6a](#) are relatively steep and exhibit a small tilt  
250 in the c-axes, while the feature indicated by the central arrow is more flattened and also shows  
251 a higher tilt in the c-axes. Another example can be found in the supplementary material  
252 ([figure S1](#)). Where several bands occur in one core section, their inclination and orientation  
253 appears to be consistent throughout ([fig. 7](#)).

### 254 **3.3 Model results**

255 To understand the development of the observed fabric anomalies and the related disturbances  
256 in the layering, we simulated the fabric evolution under simple shear with an initially well-  
257 developed single maximum orientation distribution. A random noise of  $<5^\circ$  was added to  
258 grain orientations. The setup of the simulation does not fully represent the probable kinematic  
259 boundary conditions in the region of the ice core where we observe the structures, which  
260 would be a combination of vertical compression and simple shear ([Montagnat et al., 2013](#)).  
261 We, however, model these structures in simple shear for simplicity. This approach is  
262 reasonable, since there is a significant flow along the ridge of about  $6 \text{ m a}^{-1}$  ([NEEM](#)  
263 [Community Members, 2013](#)), which gives the core location the character of a flank with  
264 relatively high shear strain rates, rather than a divide. Moreover, the choice of simple-shear  
265 boundary conditions is also justified by the fact that the bands start to appear in the lower  
266 third of the ice sheet where shear stress becomes the dominant driver for deformation  
267 ([Montagnat et al., 2013](#)). However, there might be aspects of the evolution of the folds that  
268 cannot be reproduced due to the simple shear approximation.

269 In the model simulation vertical bands similar to the ones observed in the ice core begin to  
270 stand out after a shear strain of  $\gamma = 0.6$ , but start to appear already after small strains  
271 (supplementary material [figure S3](#)). In the initial conditions the small deviations of the c-axes  
272 from the vertical are randomly distributed and do not show alignment ([figure S3 a](#)). During  
273 the first deformation steps narrow vertical bands develop with deviations from the single  
274 maximum towards the shear direction as well as broader bands with an opposite rotation of  
275 the c-axes. The rotation of c-axes in the narrow bands intensifies during the next steps and the  
276 bands begin to tilt due to the continuing shear deformation (supplementary material [figure](#)  
277 [S2](#)). The rotation of the c-axes is twice the inclination of the band, which is typical for  
278 flexural-slip kink bands (supplementary material [figure S4](#); [Dewey, 1965](#); [Tanner, 1989](#)).  
279 [Figure 8a,b,c](#) shows the c-axis orientations for the sample after shear strains of  $\gamma=1$ ,  $\gamma=2$  and  
280  $\gamma=3$ . The bands seem to develop in different generations, which can be distinguished by their

281 inclination as the new bands are steeper. There are areas between the bands where orientations  
282 of c-axes rotate anti-clockwise (magenta coloured), but on a larger scale and with less well-  
283 defined boundaries. In later stages of the simulation the oldest bands begin to disintegrate  
284 with the grains recrystallizing back to a vertical c-axis fabric.

285 **Figure 8d,e,f** shows the development of a passive marker grid during the simulations. The  
286 blue lines were perfectly horizontal at the beginning of the simulation and can be regarded as  
287 an analogue to the stratigraphic layering observed in the ice core. It is apparent that the bands  
288 with abnormal grain orientation are connected with folding in the layering. At first these  
289 disturbances appear as small steps, but they develop into overturned folds with a short and  
290 steep limb with progressive deformation. They correspond to the well-developed bands in the  
291 fabric, and to a long, less inclined limb, representing the area in between the bands. The  
292 disturbances in the layering are permanent, and therefore the bands are visible in the passive  
293 grid even when they no longer exist in the orientation plot. The rotation rate of the kink bands  
294 in the model run is controlled by the applied overall perfect simple shear deformation. If there  
295 is an additional component of vertical shortening, as in a natural ice sheet, the rotation rate is  
296 expected to increase.

297 **Figure 8g,h,i** shows the equivalent von Mises strain-rate for the deformation steps  $\gamma=1$ ,  $\gamma=2$   
298 and  $\gamma=3$ . The strain-rate appears to be localized around the margins of the bands where  
299 bending strain is the highest, which is most apparent for newer bands with steep inclinations.  
300 One also sees that strain rate localises in horizontal zones as well, which is not visible in  
301 passively deformed horizontal lines (**fig. 8d-f**).

302

## 303 **4 Discussion**

### 304 **4.1 General discussion of folds**

305 The shape of the observed folds in the NEEM ice core is typical for similar folds, as the layers  
306 are thickened in the hinge region and thinned in the fold limbs. Similar folds are passive  
307 features, where all layers of the package are deformed in a similar way (**fig. 9a**). They form by  
308 passive shearing of the layering and can evolve to become overturned z-folds or even sheath  
309 folds (Quinquis et al., 1978; Bons and Urai, 1996; Alsop and Carreras, 2007). Competence or  
310 viscosity contrast between the different layers plays no or only a minor role. In contrast,  
311 buckle folds (**fig. 9b**) develop when layers have different viscosities. A competence contrast

312 with a ratio of at least about 25 between strong and weak layers is required to develop distinct  
313 folds (Llorens et al., 2013a,b). When a stack of strong and weak layers is shortened, the  
314 strong layers form folds by bending, which suppresses thickening or thinning of these layers.  
315 The weak layers accommodate this bending by ductile flow into the hinge regions, a process  
316 known as flexural flow (Donath and Parker, 1964). Strong and weak layers are thus different  
317 in shape (fig. 9b). The folding shapes observed in the NEEM core, however, appears to be  
318 consistent in a stack of several layers (figs.1 and 2), which indicates that viscosity contrast are  
319 very low and the folds formed by passive shearing, although there may be differences in the  
320 flow strength of the ice between the layers due to different impurity content (Paterson, 1991).

321 Figure 10 gives an overview of the onset of folding (black line) and the evolution of an  
322 anisotropic fabric (red line) for several ice cores. Comparison with data from EDML (Faria et  
323 al., 2010) and WAIS (Fitzpatrick et al., 2014) in Antarctica and with GRIP (Thorsteinsson,  
324 1996), GISP2 (Alley et al., 1997; Gow et al., 1997) and North GRIP (Svensson et al., 2005;  
325 Wang et al., 2006) from Greenland reveal that the onset of visible folding is dependent on the  
326 relation between vertical strain rates (shortening) and shear strain rates (figure 10). Due to the  
327 high vertical strain rates, fold structures are flattened out before they overturn, and are thus no  
328 longer visible. This has been theoretically described by Waddington (2001). Thus, the  
329 dynamical setting of the borehole location is, in addition to the anisotropy, an essential  
330 parameter for the onset of visible folding. An ice core at flanks or on divides with non-  
331 negligible flow along the ridge, samples ice which experiences more shear strain than an ice  
332 core at dome positions. While the GISP 2 and North GRIP ice cores are very similar in ice  
333 thickness and accumulation rate to GRIP, the onset of folding for the latter is 300 m deeper,  
334 which may be due to its dome position and the lower surface velocity (for a comparison of ice  
335 core parameters see Faria et al. (2014)). In the region of the NEEM ice core there is an even  
336 higher along-ridge flow. A comparison of shear strain rates profiles with depth at the NEEM,  
337 GRIP and North GRIP locations can be found in Montagnat et al. (2014b). The depths of the  
338 crossing points of the curves for shear and vertical strain rates that is displayed in Montagnat  
339 et al. (2014b) corresponds approximately to the onset of folding in the cores.

340 The EDML ice core stands out in the comparison shown in figure 10, as the folding begins  
341 significantly higher than the establishment of a single maximum fabric. However, Faria et al.  
342 (2010) report that a strong girdle fabric has formed in the region of the onset of folding, thus  
343 the fabric does show some anisotropy there as well.

344 The scale of the disturbances found in the layering of the NEEM ice core is very similar to the  
345 ones observed at EDML (Faria et al., 2010) and North GRIP (Svensson et al., 2005), for both  
346 of which a linescan dataset of comparable quality as for the NEEM ice core is available.

347 The very deep onset of folding in the WAIS ice core might be due to strong basal melting at  
348 this site (Fitzpatrick et al., 2014; WAIS Divide Project Members, 2013).

#### 349 **4.2 Kink bands as a source for folding**

350 Ice is a mechanically highly anisotropic mineral, as is polycrystalline ice with a strong single-  
351 maximum c-axes distribution. Kinking has been observed in single ice crystals as well as in  
352 polycrystalline aggregates under compression (Wilson et al., 1986). Kink bands are also  
353 common in well-foliated rocks, which therefore exhibit a strong mechanical anisotropy  
354 (REFS). There are basically two mechanisms for the formation of kink bands (Dewey, 1965),  
355 which may act in concert. The first is shear localisation, which occurs approximately parallel  
356 to the planes that experience the highest net shear stress. The result is a conjugate set of kink  
357 bands, originally at a high angle to each other. The second mechanism is a combination of  
358 localised bending and flexural slip. There is no thickening or thinning perpendicular to the  
359 foliation if the material can only deform by slip parallel to that foliation. A geometric  
360 necessity of this type of folding is that the axial plane must be the bisector of the interlimb  
361 angle (fig. 9c) (Frank and Stroh, 1952; Dewey, 1965; Cobbold et al., 1971). With the  
362 interlimb angle at the beginning of folding being  $180^\circ$ , the kink bands initiate at  $90^\circ$  to the  
363 foliation.

364 Simple shear parallel to a foliation is a special case where the orientations of kink bands  
365 formed by both mechanisms is identical:  $45^\circ$  to the maximum compression, which coincides  
366 with parallel and perpendicular to the foliation. Foliation-normal kink bands have indeed been  
367 observed in simple shear experiments (Misra and Burgh, 2012; Williams and Price, 1990),  
368 and developed in our numerical model. Kink bands parallel to the foliation are difficult to  
369 observe in natural samples, as these would not fold the foliation. However, the numerical  
370 model shows shear-plane parallel localisation of strain rate as well (Fig. g-i).

371 Kink bands rotate passively, if there is a layer-parallel shear component, which does not  
372 necessarily have to be the dominant deformation component. As the kink band rotates by an  
373 angle  $\alpha$  to the long limb, the short limb has to rotate by  $2\alpha$ , as is observed in the NEEM core  
374 and numerical simulations (fig. 8d,e,f). Alley et al. (1997) suggested that the rotation of the c

375 axes of grains in the stripes lag behind the rotation of the bands themselves, while our model  
376 results are following the relation typical for kink bands, with c-axes rotating twice as fast as  
377 the axial plane or stripe (supplementary [figure S4](#)). [Alley et al. 1997](#) explained the growth in  
378 length by the sense of shear at the perimeter of the stripe, which would cause a “spinning” to  
379 adjacent grains, causing their c-axes to rotate towards the inclination of the band and thus  
380 elongate it. In our numerical model we observe that kink bands are seeded by individual  
381 grains and develop by linking these ([fig S3](#)). However, their intensification under rotation  
382 appears to propagate along their length ([fig. S4](#)).

383 With progressive rotation of the kink bands they become more distinct. Rotation of the short  
384 limb occurs by sliding parallel to the basal plane with a sense opposite to the overall shearing  
385 direction ([fig. 9c](#)). Kink bands finally "lock up" when the interlimb angle reduces to 90°, i.e.  
386 when the kink bands are approximately 45° to the layering. In the numerical simulations we  
387 see that kink bands begin to disintegrate at this stage, with recrystallization and recovery  
388 consuming the grains with deviating orientations and flow homogenizing again ([see fig. 8](#)).  
389 However, marker lines, such as the layers in the NEEM core, will still record the kink bands,  
390 which now continue shearing and develop into passive folds.

391 In summary, the model results indicate that the evolution of kink bands is a consequence of a  
392 fabric with a strong anisotropy with superimposed small random disturbances. In this way  
393 grains orientated unfavourably for basal glide are rotated by rigid body rotation and internally  
394 reversed shear into a more favourable position in relation to the bulk shear strain. Thus,  
395 kinking appears to be an essential process in ice deformation under shear.

396 [Azuma and Goto-Azuma \(1996\)](#) suggested that horizontal variation in the single maximum  
397 direction could explain heterogeneous layer thinning or thickening of initially horizontal  
398 layers, eventually leading to folding. The development of kink bands is a process providing  
399 such variations in the fabric.

400 A difficulty in comparing the results of the simulation with the observational data is that with  
401 fabric measurements we can only capture a 2-dimensional section of a 3-dimensional feature.  
402 Assuming that the kink bands are planar features, the angle at which the cylinder of the ice  
403 core is cut relative to the inclination of the plane determines its appearance in the 2-  
404 dimensional section. Thus, the inclination of the observed bands in the plane is not sufficient  
405 to describe the full orientation of the kink-band plane, but instead gives a minimum

406 inclination of the plane. This also has to be taken into account when interpreting the fold  
407 structures on the linescan images.

408 Within one 55cm section of the ice core (bag) the cutting plane through the core is consistent  
409 and so are the samples used to prepare the thin sections for the fabric measurements. **Figure 7**  
410 shows that within one bag the inclinations of the kink bands are consistent as well,  
411 strengthening the assumption that they are connected to the local stress environment and to  
412 the sense of shear, projected onto the plane of the thin section or linescan image. A  
413 consistency between the direction of shear and the shape of z-folds in the stratigraphy has  
414 been also reported for the GRIP and GISP2 ice cores (Alley et al., 1995). In both examples  
415 displayed in **figure 7** different generations of kink bands can be detected, differing in  
416 inclination of the bands as the older bands have been subjected to more shear strain since their  
417 formation, and the corresponding shift in c-axes orientation, as it is seen in the model results  
418 as well.

419 The mechanism of kinking as a trigger for stratigraphic disturbances has already been  
420 suggested by Samyn et al. (2011). Together with the microstructural model results the  
421 observations can be interpreted with an improved understanding of the kinking process. Alley  
422 et al. (1997), who described similar bands in the GISP2 ice core, state that the observed bands  
423 are most likely not kink bands, as they would require a compressional regime in the horizontal  
424 direction. However, the model results clearly show that kink bands can form in simple shear  
425 conditions. At the moment it is not clear why the bands sometimes appear dark in the linescan  
426 images, but from deeper parts of the core where the crystals are larger in size the linescan  
427 images give indication the backscattering can be subject to the crystal orientation.

428

## 429 **5 Summary and conclusions**

430 The onset of small-scale folding can be observed at the start of the lower third of the NEEM  
431 ice core, which is similar to the fold evolution observed in EDML. Below a depth of about  
432 2160 m it is no longer possible to track stratigraphic layers. The shape of the observed  
433 structures indicates that they are not buckle folds, which means that they are not originated by  
434 a competence contrast between alternating layers. The amounts of folding as well as the state  
435 of disturbance increase with depth.

436 Folding causes thickening of cloudy bands and can potentially influence the resolution of  
437 climate data extracted from the NEEM ice core. Folding causing doubling of layers was  
438 observed below a depth of about 2100 m. In some core sections the layering appears to be  
439 intact in between larger folds in the linescan data. However, within a core section, only folds  
440 and doubling of layers up to the scale of 10 cm can be delineated with certainty. It is therefore  
441 difficult to ascertain that the climate signal is not disturbed in regions with parallel layering,  
442 as these could potentially be part of larger-scale folds.

443 Microstructural numerical modelling results indicate that the observed folding is initiated by  
444 kinking. The onset of kinking requires a highly anisotropic material and thus a well developed  
445 single maximum fabric. Local deviations from the single maximum in the direction of shear  
446 provide the seeds for kink band development and thus folding. Here we have shown that this  
447 process is active on the microstructural scale. Their possible link to larger scale folds still has  
448 to be investigated, but could be in line with suggestions by [Azuma and Goto-Azuma \(1996\)](#).  
449 Grains with inclined basal plane orientations within the kink bands are eventually eroded  
450 through recrystallisation and recovery. However, the kink bands formed folds in material  
451 planes that further evolve by passive folding, which is visible in the layering, but not in the  
452 c-axes patterns.

453

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469

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- 613

614 **Figure Captions**

615 **Figure 1:** Visual stratigraphy overview. Linescan images of different depths. A Gauss filter  
616 was applied to images shown in panel a, d, e, f, g, and h to enhance the visibility of the layers.  
617 Red lines indicate fractures. Blue squares and associated figure codes indicate location of  
618 enlargements shown in figure 2. The 1.10 m line at the right indicates the scaling of the  
619 images and is also the typical length of a recovered core section.

620 **Figure 2:** Close-ups from the overview figure 1. (a) Undisturbed layering. (b) Angular z fold  
621 consistent throughout layering. Green dashed line indicates a layer discussed in section 3.1 (c)  
622 Different generation of folds. The dashed lines indicate features discussed in section 3.1 (d)  
623 Strongly disturbed layer significantly thickened. (e) Strongly disturbed layering with different  
624 generations of folds.

625 **Figure 3:** Comparison of fabric data and visual stratigraphy in detail, Bag 3276, approximate  
626 depth 1803 m. (a) fabric data in a vertical section, (b) linescan image in a vertical section, (c)  
627 stereoplot of c-axes orientations (horizontal plane).

628 **Figure 4:** (a) Close-up of kink band grains at approximately 1803 m depth (bag 3276). Inset  
629 shows the colour code for c-axes orientation (b) subgrain structures (blue) visible on LASM  
630 (Large Area Scanning Microscope) data. Black lines indicate grain boundaries; the red  
631 outlines highlight the kink band grains.

632 **Figure 5:** Linescan images from the same sample as shown in fig. 3 from three focal depths  
633 with one highlighted layer (a) close to the surface, (b) in the centre of the core section, (c)  
634 close to the lower surface. (d) Sketch of the core sections, the upper part represents the  
635 physical properties sample, from which the thin sections are prepared. (e) Change of shape of  
636 the highlighted layer for the different foci.

637 **Figure 6:** Comparison of fabric data and visual stratigraphy in detail, Bag 3596, approximate  
638 depth 1977.8 m. (a) fabric data in a vertical section, (b) linescan image, in a vertical section  
639 (c) stereoplot of c-axes orientations (horizontal plane).

640 **Figure 7:** Comparison of entire 55 cm core sections (full bags) of linescan (a, d) and fabric  
641 data (b,c).

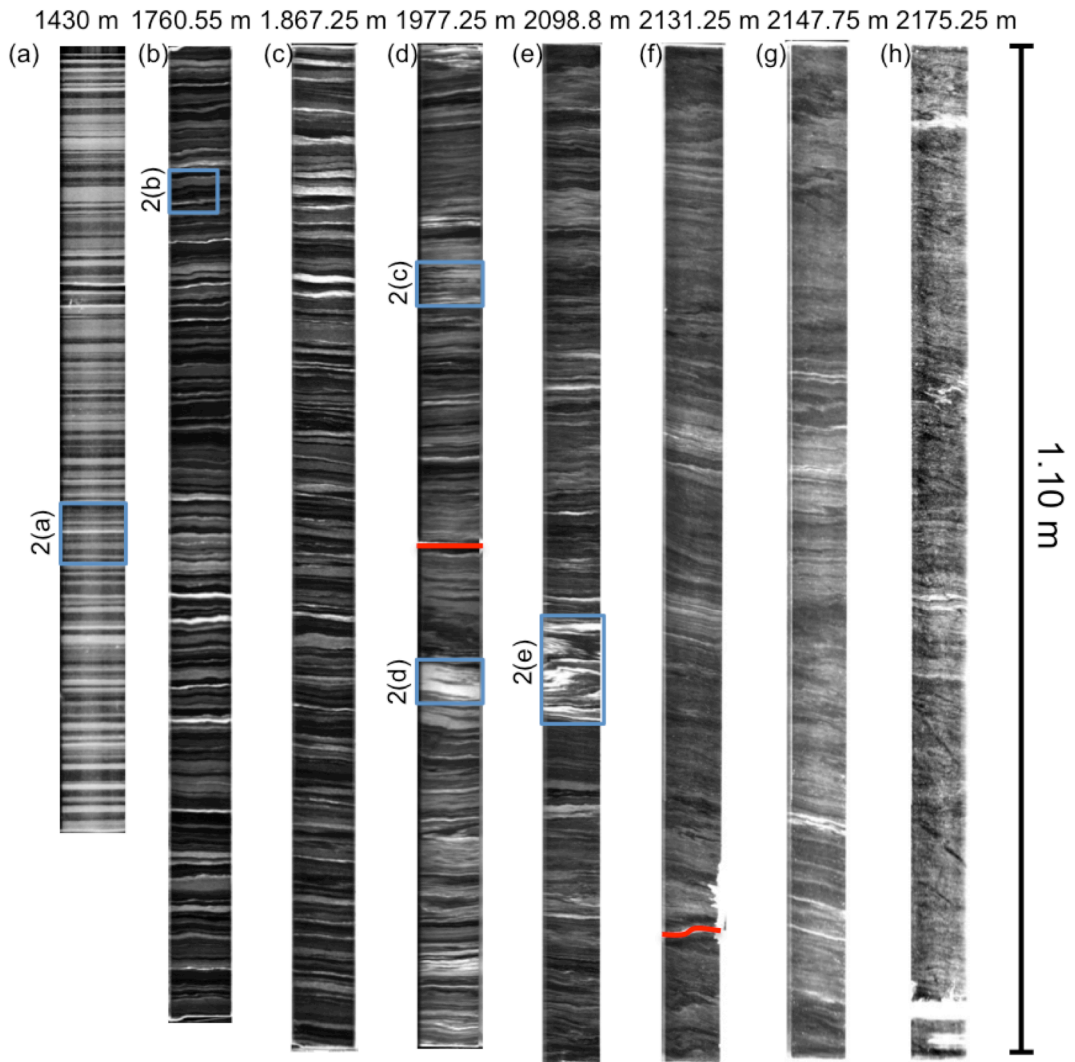
642 **Figure 8:** ELLE model results for the simple shear experiment. Panels (a), (b) and (c) show c-  
643 axes orientations for shear strains of  $\gamma=1$ ,  $\gamma=2$  and  $\gamma=3$ . Panels (d), (e) and (f) show the

644 distortion of the passive grid marker. Panels (g), (h) and (i) show the equivalent von Mises  
645 strain-rate field.

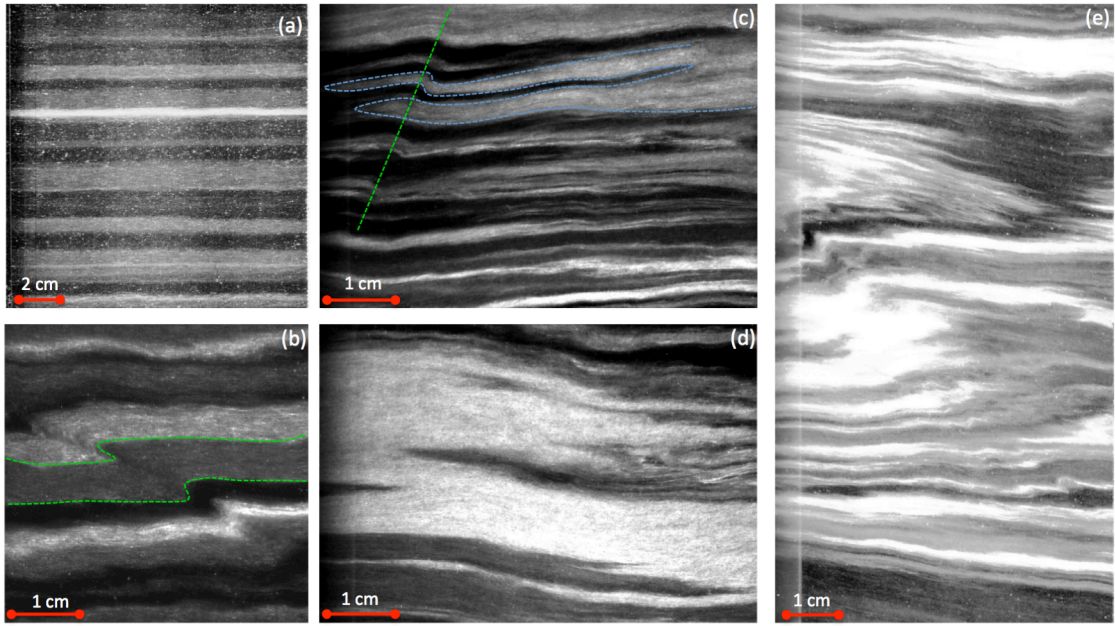
646 **Figure 9:** Basic folding mechanisms discussed in the text. (a) Passive folds form by shearing  
647 of disturbances in layering, without an active mechanical influence of that layering. Fold  
648 geometry is that of similar folds. (b) Buckle folds form by shortening of alternating strong and  
649 weak layers, in which the strong layers buckle and weak material flows into fold hinges. Fold  
650 geometry is that of parallel folds. (c) Kink bands form in case of strong intrinsic anisotropy,  
651 but do not require viscosity contrasts between layers.

652 **Figure 10:** Comparison of the onset of visible folding in ice cores with published visual  
653 stratigraphy. The red line indicates single maximum fabric, the black line indicates onset of  
654 folding, the dashed black line indicated the lower third of the ice core. Data from  
655 Thorsteinsson, 1996 (GRIP), Alley et al., 1997; Gow et al., 1997 (GISP2), Svensson et al.,  
656 2005; Wang et al., 2006 (North GRIP), Faria et al., 2010 (EDML), Fitzpatrick et al., 2014  
657 (WAIS).

658

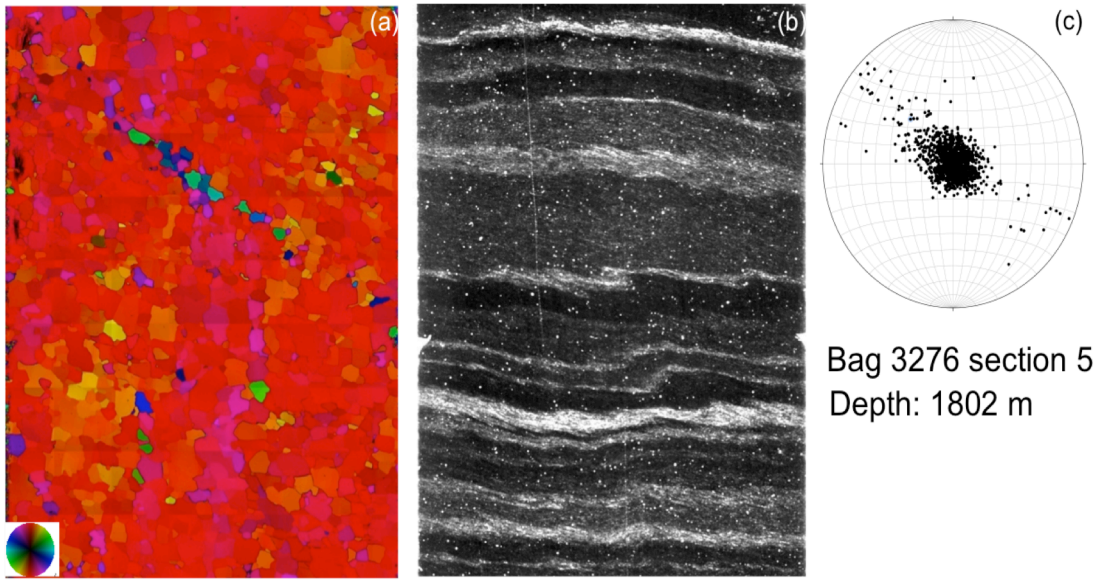


660  
661 Figure 1  
662

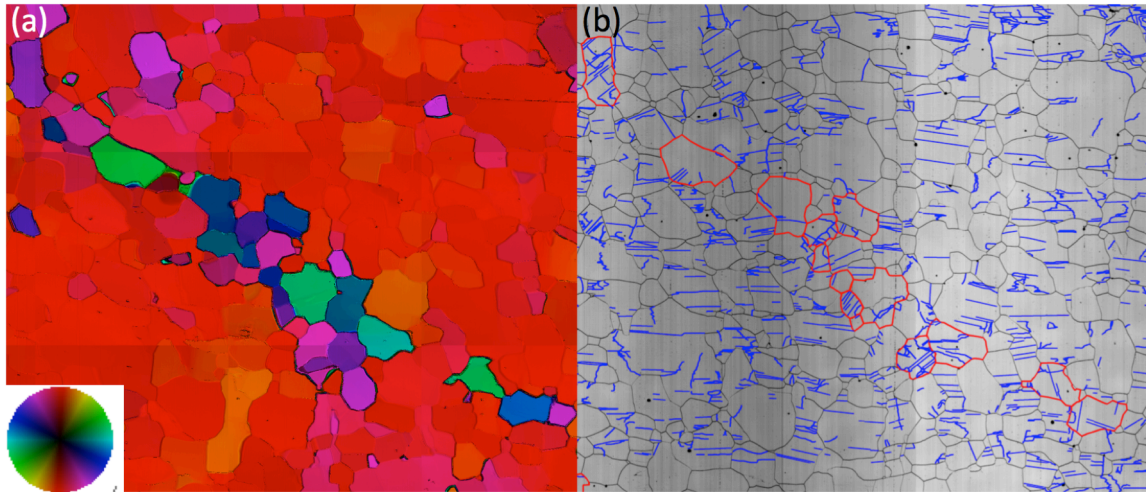


663  
664 Figure 2  
665



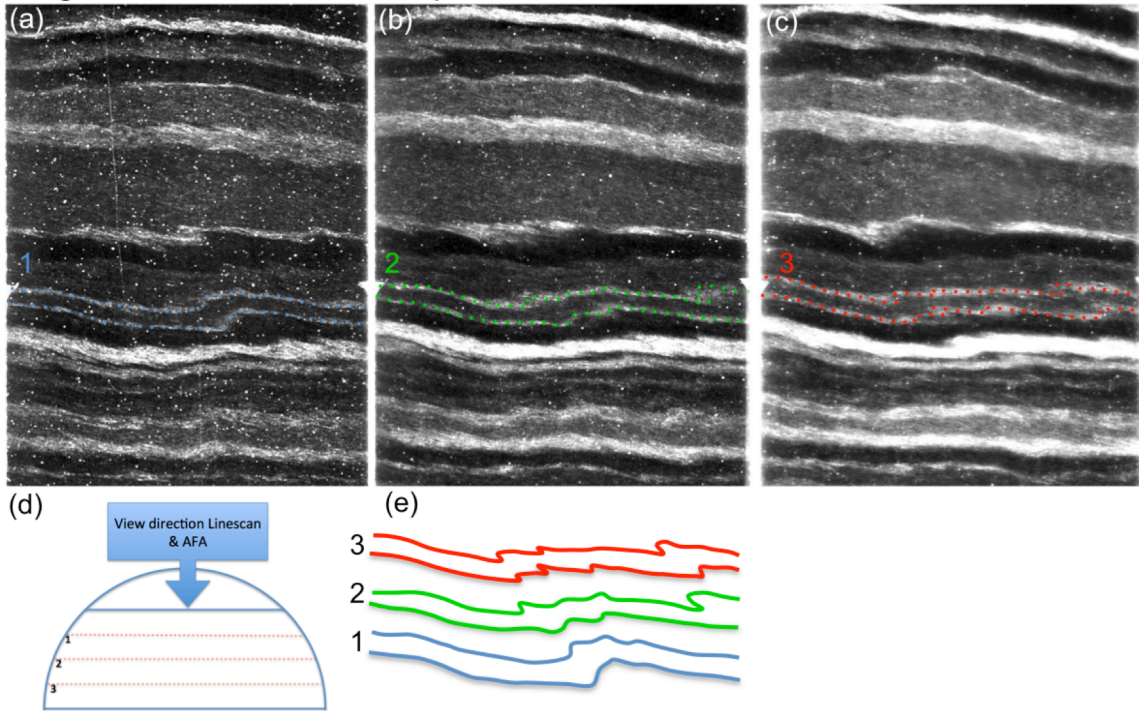


666  
667 Figure 3  
668

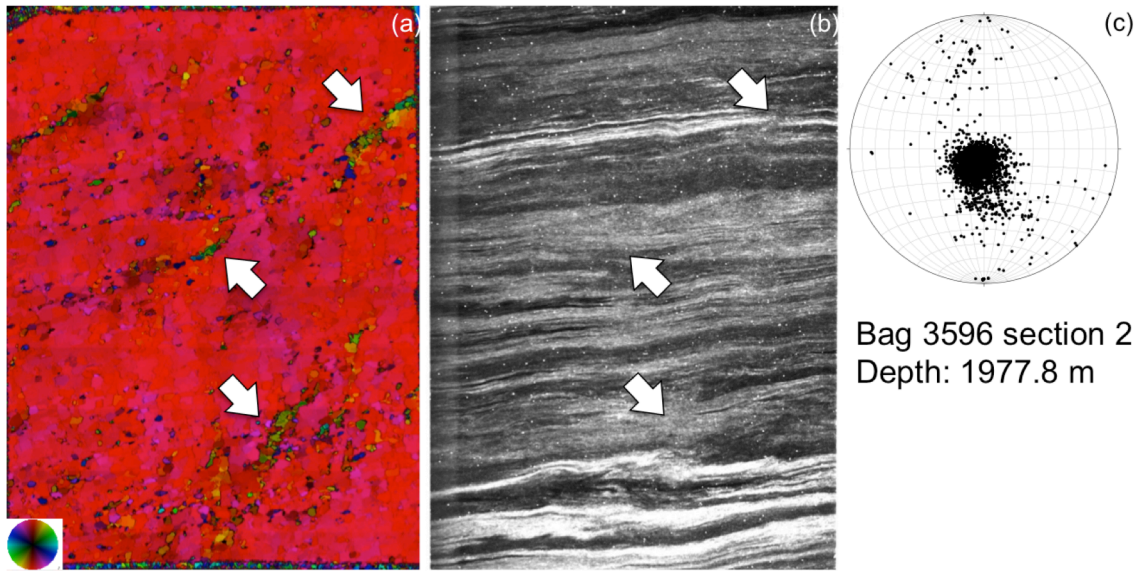


669  
670 Figure 4  
671

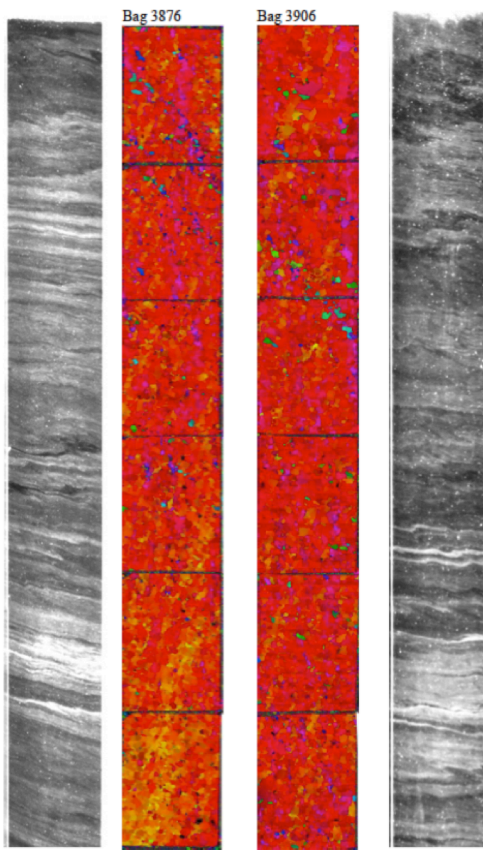
Bag 3276 section 5      Depth: 1802 m



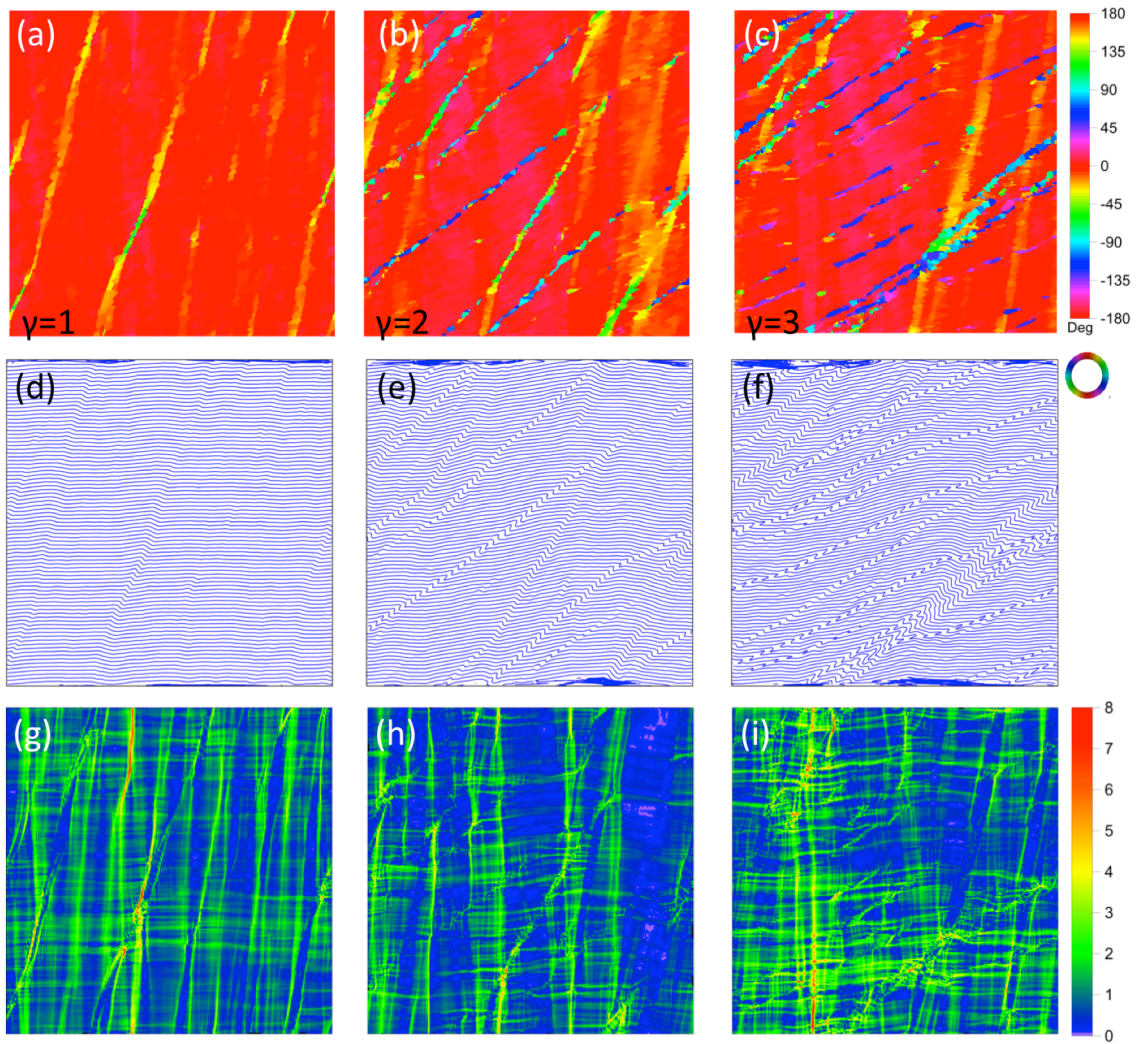
672 Figure 5  
673



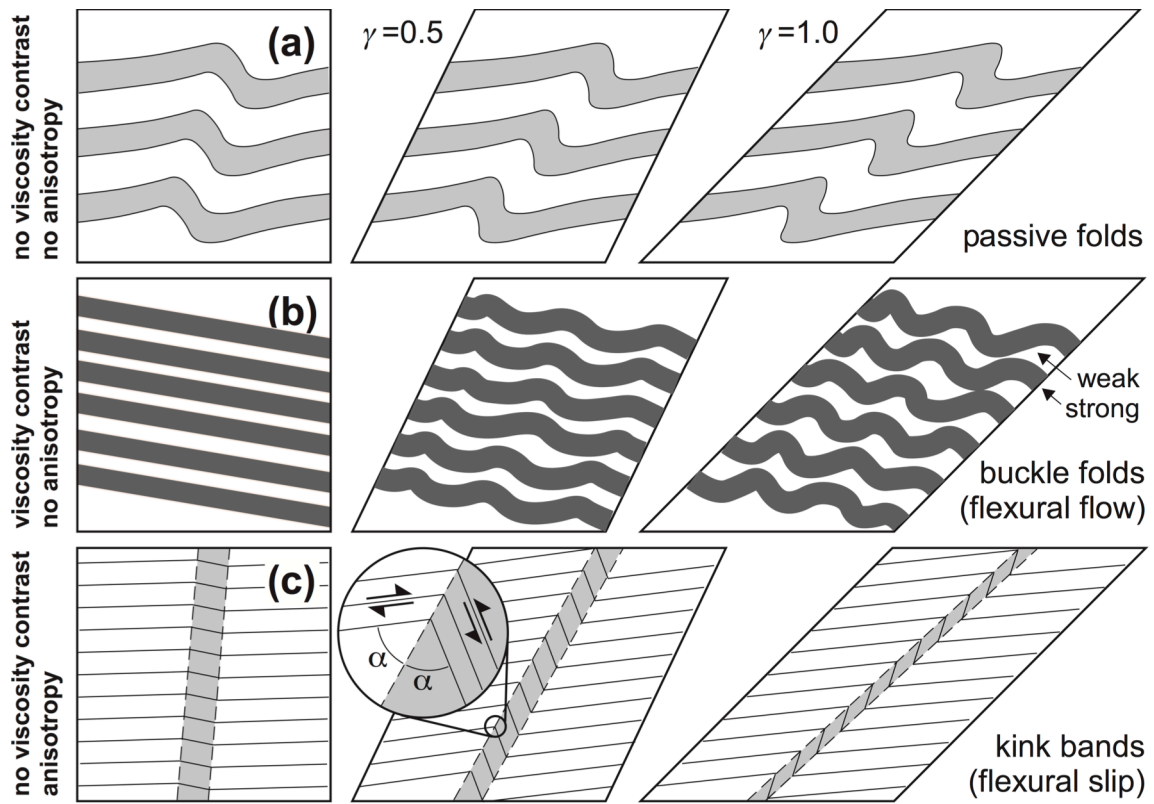
674 Figure 6  
675



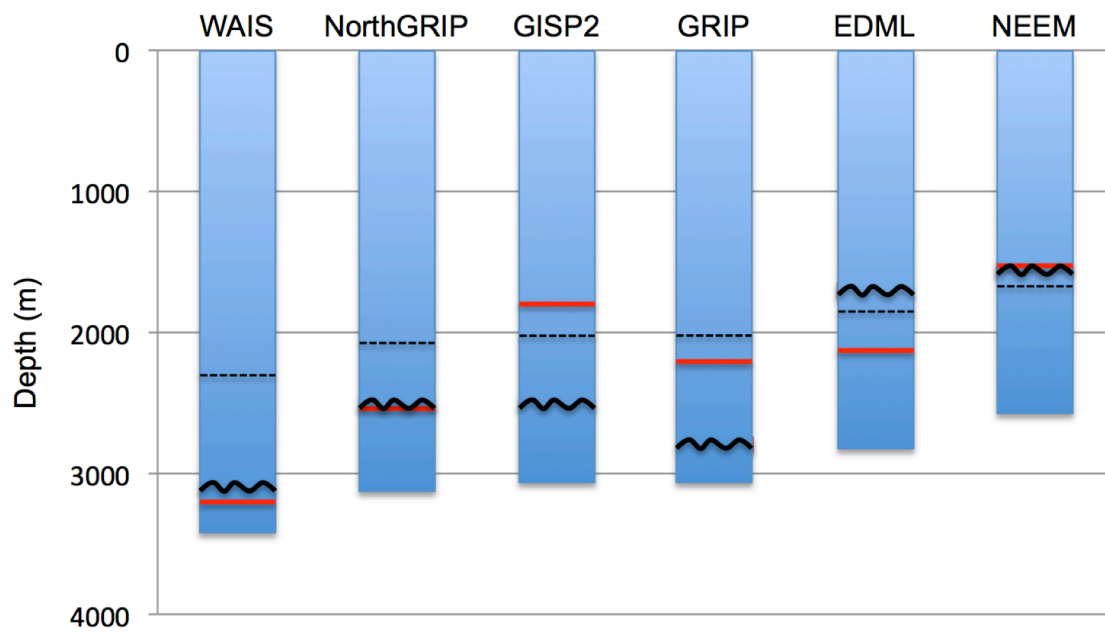
676 Figure 7  
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678 Figure 8  
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680 Figure 9  
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682 Figure 10  
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