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3       **Strain patterns in glacitectonically thrust sediments and**  
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23 Strain patterns in glacitectonically thrust sediments and conditions during  
24 thrusting

25 **Abstract**

26 Glacitectonically thrust blocks of unlithified sediment are commonly inferred to have been  
27 frozen during thrusting, with implications for paleoclimate and glacier dynamics. We inferred  
28 strain patterns within thrust blocks of glaciolacustrine mud in the Rubjerg Knude and Møns  
29 Klint glacitectonic complexes of coastal Denmark to try to assess whether the mud was frozen  
30 during thrusting. Fabrics based on the anisotropy of magnetic susceptibility (AMS) of the muds  
31 are interpreted with results of ring-shear experiments and models of AMS fabric development  
32 during layer-parallel shortening (LPS). In intact distal stratigraphy, fabrics indicate moderate  
33 LPS. Fabrics where thrusts have disrupted more proximal stratigraphy indicate rotation of mud  
34 sheets during thrusting with insufficient penetrative strain to reset the LPS fabric. The exception  
35 is within decimeters of faults at Rubjerg Knude where shear overprinted the LPS fabric.  
36 Although these data indicate that mud sheets were mostly rigid during thrusting, this is not  
37 necessarily evidence of permafrost. Critical-taper theory indicates that even a gentle slope of the  
38 proglacial surface away from the glacier margin would have allowed slip without internal  
39 deformation of thrust sheets, requiring only minimal pore-water pressures.

40 **1. Introduction**

41 Glacitectonic thrust complexes with along-flow lengths of kilometers and depths of tens to a  
42 few hundreds of meters (e.g., Pedersen, 2014; Phillips, 2018) are among the most spectacular of  
43 glacial geologic structures. Interest in them derives from their geomorphic expression,  
44 commonly as composite ridges that form end moraines or as the hills of hill-hole pairs (e.g.,  
45 Aber and Ber, 2007). They are also of interest as analogs for orogenic belts (Croot, 1987;

46 Hudleston, 1992; Bennett, 2001; Van der Wateren, 2002; Phillips, 2018) and because of the short  
47 periods over which they can form (Benediktsson et al., 2010). Environmental effects of thrust  
48 complexes include their influence on subsurface water flow (e.g., Klint et al., 2013), on rates of  
49 mass wasting and erosion of coastal cliffs (Pedersen and Møller, 2004; Kołodziejczyk et al.,  
50 2018), and on site selection for future nuclear waste repositories (Talbot, 1999; Iverson and  
51 Person, 2012).

52 Importantly, glacitectonic thrust complexes may also provide information about whether  
53 climates at the margins of former glaciers were sufficiently cold to sustain permafrost. Thrust  
54 complexes form beneath glacier margins and can extend in front of them more than 5 km in  
55 exceptional cases (Aber and Ber, 2007). Although complexes sometimes contain thrust blocks  
56 consisting of sedimentary rocks, some or all of thrust material is usually weaker, unlithified,  
57 glacial sediment. As emphasized in reviews by Bennett (2001) and Van der Wateren (2002),  
58 such sediments are commonly inferred to have been frozen during thrusting (e.g., Mathews and  
59 Mackay, 1960; Moran et al., 1980; Thomas, 1984; Menzies, 1990; Mooers, 1990; Boulton et al.,  
60 1999; Benn and Clapperton, 2000; Clayton et al., 2001; Burke et al., 2009).

61 Although proglacial thrusting can definitively occur in the absence of permafrost (e.g.,  
62 Ingólfsson, 1988; Van der Wateren, 2002; Kuriger et al., 2006; Benediktsson et al., 2009), we  
63 explore whether the distribution of strain in individual thrust blocks of complexes can be used to  
64 test whether sediments were frozen during thrusting. Specifically, frozen sediments are expected  
65 to be stronger (e.g., Moore, 2014) and less subject to ductile strain than unfrozen sediments (e.g.,  
66 Feeser, 1988), particularly at temperatures well below the freezing point, at which weakening by  
67 pre-melted water is minimal (Moore, 2014; Wang and Nishimura, 2017).

68        Herein we investigate strain patterns within the fine-grained sediments of selected thrust  
69 sheets of two glacitectonic complexes of coastal Denmark: Rubjerg Knude and Møns Klint (e.g.,  
70 Johnstrup, 1874, 1882; Jessen, 1899; Pedersen, 2014). Strain patterns are determined by  
71 measuring the anisotropy of magnetic susceptibility (AMS) of the sediments. Determination of  
72 the magnetic mineralogy, results of ring-shear experiments in which sediments were sheared, and  
73 models of AMS fabric development in orogenic fold and thrust belts are used to interpret the  
74 AMS data. We find that thrust blocks behaved too rigidly to reset fabrics during thrusting, except  
75 within decimeters of bounding thrust surfaces. Considering shear stresses on thrust faults  
76 indicates, however, that a combination of positive pore-water pressure and a proglacial surface  
77 sloping down-flow above thrusts can cause thrusting of rigid slabs without added shearing  
78 resistance provided by pore ice.

## 79 **2. Field settings**

80        The Rubjerg Knude and Møns Klint glacitectonic complexes of Denmark consist of  
81 décollement surfaces that dip gently up-glacier, as inferred from reconstructions based on  
82 exposed stratigraphy and structures and isostatic depression by ice (Pederson, 2005; Pedersen  
83 and Gravesen, 2009). The décollements are overlain by thrust faults consisting of ramps and  
84 flats and associated anticlines and synclines. Both complexes formed in front of the advancing  
85 margin of the Scandinavian Ice Sheet (e.g., Houmark-Nielsen & Kjær, 2003; Pedersen, 2014)  
86 and are structurally similar to thrust and folded orogenic belts. These complexes lie in the  
87 region that Sollid and Sorbel (1988) thought was a sub-freezing marginal zone of the ice sheet,  
88 based on relict ice-cored moraines and ice-wedge polygons.

89

90

91 *2.1. Rubjerg Knude*

92 The Rubjerg Knude complex, first recognized by Johnstrup (1874, 1882) and studied in  
93 detail by Pedersen (2005), is located in northwestern Denmark along the northwest coast of  
94 Jutland (Fig. 1). The complex is well exposed for 6 km along a coastal cliff that is 60 m above  
95 sea level at its highest point. The complex consists entirely of Weichselian or younger deposits,  
96 including marine mud, glaciolacustrine mud, glaciofluvial sand and gravel, and till.

97 Of interest here, with decreasing age, are the Stortorn Formation (SF), Lønstrup Klint  
98 Formation (LKF), and Rubjerg Knude Formation (RKF). The SF consists of predominantly clay  
99 of the Older Yoldia Sea of the Middle Weichselian (Jensen, 1993). The sea existed until about 32  
100 ka BP (Seidenkrantz and Knudsen, 1993) when the outlet to the North Sea was blocked by the  
101 Norwegian Channel Ice Stream. This created an ice-dammed lake that persisted from ~32 to 29  
102 ka BP (Sadolin et al., 1997; Houmark-Nielsen, 1999) and deposited the glaciolacustrine mud that  
103 dominates the LKF. Close to 29 ka BP, the lake drained catastrophically, resulting in an  
104 unconformity between the LKF and overlying glaciofluvial sand and gravel of the RKF (Sadolin  
105 et al., 1997). At ~29 ka BP, during deposition of the RKF, the Kattegat Ice Stream (Houmark-  
106 Nielsen, 2008), advanced south-southeast across the northern tip of Jutland (Fig. 1), initiating  
107 deformation at Rubjerg Knude along a décollement ~40 m below sea level in the marine clay of  
108 the SF (Pedersen, 2005). Faulting and folding extended 12 km in front of the glacier margin and  
109 resulted in average shortening of 50%; thrust faults generally dip more steeply in the northern  
110 and central areas where the décollement is deepest (Fig. 2A) (Pedersen, 2005).

111 In this study we focus on a distal section of the complex, called Ulstrup (Pedersen, 2005),  
112 and a central section called Grønne Rende, with steeply dipping thrust sheets (Fig 2). The  
113 Ulstrup section consists of predominantly horizontal layers of the LKF overlying the RKF. The

114 section was considered to be undeformed until Pedersen (2005) found evidence for a horizontal  
115 décollement at the southern end of the section along which the flat-lying sediment layers have  
116 been displaced ~500 m. Otherwise the stratigraphy in this distal part of the complex is mostly  
117 intact. In contrast, the Grønne Rende section consists of 13 steeply-dipping, and in some cases  
118 near-vertical, thrust sheets. The LKF forms the most conspicuous sheets (Fig. 3), owing to the  
119 ability of its mud to support vertical exposures. The sand and gravel of the RKF is interpreted to  
120 have been syntectonically deposited in between and on top of thrust sheets during progressive  
121 faulting and sheet rotation during longitudinal shortening (Pedersen, 2005). The average  
122 displacement along these faults is 70 m (Pedersen, 2005).

123 Small-scale structures may provide insight into the formation of the complex. Ball-and-  
124 pillow structures within the LKF may indicate where rapid loading caused pore-water pressure to  
125 increase, leading to local diapir-like deformation of bedding surfaces (Lowe, 1975). Frost  
126 wedges observed by Pedersen (2005) in the RKF near the paleo-ground surface indicate that  
127 some frozen sediments were present during deformation. Also present in the RKF and perhaps  
128 indicative of frozen sediments are kilelags (Pedersen, 2005), fissures that have opened during  
129 initial brittle deformation and are filled with water-transported, syntectonically-deposited sand  
130 (Sjørring, 1977).

## 131 2.2. *Møns Klint*

132 Møns Klint, in southeastern Denmark at Høje Møn (Fig. 1), has been a foundational location  
133 for study of glacitectonics (e.g., Puggaard, 1851; Aber, 1980, 1982; Aber and Ber, 2007). The  
134 exposure, in coastal cliffs that reach heights of 130 m and span 4 km, consists of Upper  
135 Cretaceous chalk thrust over Weichselian sediments (Fig. 4). The sedimentary succession  
136 includes the Ristinge Klint Till deposited ~60 ka BP by the Baltic ice advance from the

137 southeast, glaciolacustrine mud deposited after the recession of the Baltic ice, and till deposited  
138 25-18 ka BP by ice advances from the northeast and glaciofluvial sand (Houmark-Nielsen, 1987;  
139 Pedersen and Gravesen, 2009).

140 The initial deformation at Møns Klint commenced during the advance of the Young Baltic  
141 Ice Stream from the south-southeast at ~18 ka BP (Houmark-Nielson and Kjær, 2003).  
142 Deformation occurred along a décollement 80-100 m below sea level (Pedersen and Gravesen,  
143 2009) and extended approximately 9 km in front of the advancing glacier. A later ice advance  
144 from the northeast out of Sweden (16-17 ka) (Houmark-Nielsen, 2007) superimposed  
145 deformation onto the eastern edge of the northern part of the complex from Slotsgavlene to  
146 Maglevandsfald (Fig. 4) ( Pedersen and Gravesen, 2009). The southernmost expression of the  
147 superimposed deformation is near Maglevandsfald where a till wedge within chalk is folded  
148 along an axis trending NW-SE (Pedersen and Gravesen, 2009). Farther south in the proximal part  
149 of the complex (Pedersen, 2000), there is no evidence of the advance from the northeast, with  
150 thrust faults striking approximately perpendicular to the Baltic Ice Stream advance from the  
151 south-southeast (Fig. 4).

### 152 **3. Methods**

153 We use AMS, as a proxy for particle alignment, to interpret strain patterns in thrust blocks.  
154 This method has been applied to tills deformed subglacially, using ring-shear experiments to  
155 calibrate AMS to strain magnitude and direction (Thomason and Iverson, 2009; Shumway and  
156 Iverson, 2009, Vreeland et al., 2015, McCracken et al., 2016; Ives and Iverson, 2019), and  
157 applied to glacier ice with debris (Fleming et al., 2013a) and to sediments with glaciotectionic  
158 structures (Fleming et al., 2013b). Using AMS in glacial sediments requires collecting multiple,  
159 closely-spaced, intact sediment specimens, so a fabric representative of the sampled region can



160 be determined. Tests to determine magnetic mineralogy of the sediments (Appendix) and a ring-  
161 shear experiment on mud from Rubjerg Knude also contribute to our interpretations.

162

### 163 *3.1. AMS Sampling*

164 To collect samples a planar face is created by scrapping an exposure sufficiently to expose  
165 undisturbed sediment. Aluminum, 18 mm, cubic boxes, open on two ends, are inserted in the  
166 face in as tight a grid as was possible without disturbing adjacent boxes (Fig. 5), with 18-25  
167 samples used to determine a fabric. Plastic boxes usually used for such sampling (e.g.,  
168 McCracken et al., 2016) are too weak to be pressed into the hard, consolidated muds of  
169 glacitectonic complexes. After measuring the orientation and position of each box, it is  
170 excavated, with excess mud trimmed from the open ends of the box with a wire saw. With a  
171 plunger the mud is extruded into a plastic box of the same size and the box capped, labelled, and  
172 sealed in plastic to inhibit moisture loss. In a few cases sandier layers can be sampled by pushing  
173 plastic boxes into the sediment directly.

174 At Rubjerg Knude, sampling was focused on thrust sheets in the Grønne Rende section (Fig.  
175 2B), but additional samples were collected within the mostly intact stratigraphy of the distal  
176 Ulstrup section (Fig. 2C). The distal end of the complex was chosen for sampling to determine  
177 strain patterns in the absence of pervasive thrusting, so the effects of thrusting on strain in the  
178 Grønne Rende section could be isolated. Samples at both sections were mainly from the  
179 glaciolacustrine mud of the LKF because its cohesion allowed the collection of minimally  
180 disturbed samples, unlike the friable sand of the RKF. At Ulstrup, flat-lying mud (striking 273°,  
181 dipping 3° south) of the LKF (Fig. 2B) was sampled along two vertical transects (three fabrics  
182 per transect), beneath the unconformity with the RKF.

183 At Grønne Rende the primary objective was to sample thrust blocks along transects normal to  
184 fault surfaces. Three thrust sheets (GR10, GR07, and GR05, Fig. 2a) with conspicuous, near-  
185 vertical exposures of the LKF were chosen for study based largely on their accessibility and  
186 safety concerns. These sheets have strikes of 266-285° in agreement with thrusting driven by the  
187 Kattegat Ice Stream advancing from the north and dips of 56° N to near vertical. Also accessible  
188 at GR10 and GR07 were dip-slopes of the LKF eroded into the cliff-face by mass wasting  
189 processes along bedding planes, so these surfaces were also sampled, taking care in all cases to  
190 measure the orientation of samples.

191 Our principal concern is how strain varied with distance from the surfaces of thrust faults, so  
192 through-going fault surfaces needed to be identified. At Rubjerg Knude we used slickensides that  
193 result from P shears and Riedel shears that grow and intersect during slip, forming asymmetric  
194 steps on fault surfaces (Petit, 1987; Doblas, 1998) near the base of the LKF (Fig. 6). In thrust  
195 sheets GR10 and GR05, slickensides could at some locations be identified and were used to  
196 reference fault-normal transects of AMS samples (Fig. 7A, B). No slickensides were found at  
197 thrust sheet GR07. Although some samples for AMS fabrics were gathered in thrust sheets in the  
198 absence of adjacent slickensides (Warbritton, 2019), we report data from fault-normal transects  
199 only where slickensides provided an indicator of thrust position (13 fabrics). We also consider  
200 AMS fabrics collected from two eroded dip-slopes (6 fabrics) distant from thrust faults.

201 At Møns Klint, glaciolacustrine mud of the Middle Weichselian in the proximal part of the  
202 complex (Fig. 4), overlain along a sharp, gently dipping contact by Maastrichtian chalk (Fig. 5),  
203 was sampled along a 4 m long section (Fig. 8). The fault between the chalk and mud strikes 79°  
204 ( $\pm 7^\circ$ ) and dips 18° ( $\pm 4^\circ$ ), consistent with thrusting driven by the Young Baltic ice stream  
205 advance from south-southeast (Pederson and Gravesen, 2009). Samples were gathered in four

206 adjacent vertical transects, 0.9-2.0 m high, referenced to the contact and sufficient for 17 AMS  
207 fabrics.

### 208 3.2. AMS analysis

209 AMS was measured with a KLY-3S Kappabridge at the University of Wisconsin-Madison.  
210 This device subjects a sample to a magnetic field of constant strength,  $H$ , in 15 different  
211 orientations. The intensity of magnetization,  $M$ , is defined as  $kH$ , where  $k$  is the susceptibility  
212 (Jelínek, 1978; Tarling and Hrouda, 1993). In three dimensions, the susceptibility is described  
213 with a second-rank tensor, and the principal susceptibilities of this tensor,  $k_1$ ,  $k_2$ , and  $k_3$ , are  
214 represented as the long, intermediate, and short axes, respectively, of an ellipsoid. In materials  
215 that are anisotropic, the susceptibility varies with sample orientation. For non-equant magnetic  
216 grains that are multi-domain or pseudo-single-domain and have shape anisotropy, such as  
217 magnetite, the susceptibility is strongest parallel to the long axes of grains (Tarling and Hrouda,  
218 1993). Deformation of sediment preferentially aligns grains and creates AMS. As described in  
219 the Appendix, mineral magnetic analyses were conducted at the *Institut de Physique du Globe de*  
220 *Paris* to determine the mineralogy and magnetic grain size of the dominant AMS carrier of the  
221 muds from the two complexes.

222 If the orientations of principal susceptibilities are measured for each of multiple till samples,  
223 they together define a fabric that helps indicate the magnitude and orientation of strain (Hooyer  
224 et al., 2008). The orientations of maximum clustering of  $k_1$ ,  $k_2$ , and  $k_3$  are each characterized with  
225 a  $V_1$  eigenvector, and the strength of the preferred orientation about  $V_1$  is characterized with an  $S_1$   
226 eigenvalue (Mark, 1973). We thus analyze orientations of principal susceptibilities separately,  
227 rather than using tensor statistics. For poorly clustered data, our technique can lead to  $V_1$   
228 eigenvectors for  $k_1$ ,  $k_2$ , and  $k_3$  orientations that are not orthogonal. However, principal

229 susceptibility orientations from our field samples are well-clustered, so we elect to follow the  
230 tradition in glacial geology of using eigenvectors and eigenvalues to characterize fabrics.  $S_1 = 1.0$   
231 indicates perfect alignment and  $S_1 = 0.33$  indicates an isotropic distribution (i.e., no alignment).  
232 Orientation data are plotted in lower hemisphere, equal-area stereonet. Importantly, in  
233 stereonet displaying fabrics from dipping thrust sheets, the plane of the primitive circle is taken  
234 to be the attitude of the thrust sheet, as indicated by the orientations of thrust faults adjacent to  
235 sampling locations or as indicated by bedding attitude in the case of samples from dip-slopes.  
236 This allows easier comparison with experimental and field data in which shear or bedding is  
237 horizontal. At sections studied where both fault and bedding attitudes could be measured, they  
238 tended to be nearly the same ( $< 3^\circ$  differences in strike and dip), although elsewhere at Rubjerg  
239 Knude that is not necessarily true (Pederson, 2005). In the massive mud sampled at Møns Klint,  
240 no bedding could be identified.

### 241 *3.3. Ring-shear experiment*

242 To help establish the relationship between shear strain orientation and the AMS signature, an  
243 experiment with a ring-shear device was conducted with mud of the LKF. The device (Iverson et  
244 al., 1997) has been used extensively to shear subglacial till with the same objective (Hooyer et  
245 al., 2008; Shumway and Iverson, 2009; Vreeland et al., 2015; McCracken et al., 2016; Ives and  
246 Iverson, 2019). Sediment with its pore water drained to atmospheric pressure is sheared within a  
247 ring-shaped chamber (O.D.= 0.6 m, width = 0.115 m) between horizontal platens. The upper  
248 platen, which can move up or down as sediment porosity changes, applies a steady stress normal  
249 to the shear plane. During shear, the lower platen and lateral walls of the lower half of the sample  
250 chamber rotate at a constant speed. Shearing occurs in a zone,  $< 35$  mm thick, centered on the  
251 break between the rotating lower walls and static upper walls.

252 The LKF mud was first vigorously mixed with distilled water so aggregates would break  
253 down and grain orientations would be randomized. The mixture was then added to the sample  
254 chamber as a slurry to a thickness of 0.06 m. A normal stress (65 kPa) was applied for a period  
255 of 11 days to consolidate the mud. The amount of consolidation (14.5%) was determined by  
256 using two dial gauges to measure the downward movement of the upper platen, which resulted  
257 from the decrease in specimen thickness. The test was then run at a constant shear rate of  $1.27 \times$   
258  $10^{-5}$  m/s to a displacement of 0.6 m along the sample centerline. After the test was completed, 53  
259 samples were collected for AMS analysis. A smooth, flat surface was exposed just below the  
260 uppermost extent of the shear zone, as inferred from past experiments on tills (Hooyer et al.,  
261 2008), and samples were collected by pressing into the mud plastic boxes like those used for the  
262 field measurements.

## 263 4. Results

### 264 4.1. Experiments

265 Tests aimed at assessing magnetic mineralogy indicate that the dominant carrier of magnetic  
266 susceptibility of the glaciolacustrine muds from the two thrust complexes is multi-domain or  
267 pseudo-single domain magnetite (Appendix). Such magnetite has normal shape anisotropy  
268 (Tarling and Hrouda, 1993), so the orientations of principal susceptibilities should reflect grain  
269 orientation.

270 This expectation is confirmed at Rubjerg Knude by the ring-shear experiment conducted on  
271 the mud sampled there (Fig. 9A). The  $V_1$  orientation based on 53  $k_1$  orientations indeed parallels  
272 the shearing direction and plunges “up-glacier”  $11^\circ$ , consistent with past ring-shear experiments  
273 on AMS of tills with magnetite as the dominant carrier mineral, including tills derived from  
274 remobilized lake sediments (Fig. 9B) (Hooyer et al., 2008; Thomason & Iverson, 2009; Vreeland

275 et al., 2015; Ives and Iverson, 2019). Also consistent with past experiments are the orientations  
276 of  $V_1$  for  $k_2$  and  $k_3$ :  $k_2$  orientations are horizontal and perpendicular to shear, and  $k_3$  orientations  
277 plunge steeply ( $\sim 80^\circ$ ) “down-glacier.” However, unlike past results of experiments on tills,  
278 including on those consisting of remobilized lake sediments (Fig. 9B), clustering of  $k_1$  and  $k_2$   
279 orientations is weak, with  $S_1 = 0.59$  in each case as opposed to  $S_1 > 0.9$  for fine-grained till  
280 (Hooyer et al., 2008). Rather than clustering strongly, these principal susceptibilities form  
281 asymmetric girdles that dip gently “up-glacier” (Fig. 9A).

282 Unlike many studies of the magnetism of deformed rocks, we do not use various indices of  
283 the magnitude of anisotropy of individual samples to infer strain; ring-shear experiments  
284 conducted to wide a range of strains on tills that contain magnetite as the source of AMS show  
285 no systematic dependence of these indices on strain magnitude (Hooyer and Iverson, 2008;  
286 Vreeland et al., 2015).

#### 287 4.2. *Rubjerg Knude*

288 Principal-susceptibility orientations for the six fabrics from the distal end of the Rubjerg  
289 Knude thrust complex (Ulstrup section) display a relatively uniform pattern (Fig. 10). Here, the  
290 mud and overlying sand units are horizontal and with little macroscopic evidence of deformation.  
291 A stereonet combining principal-susceptibility orientations from these fabrics (Fig. 11A)  
292 demonstrates strong clustering of the three principal susceptibilities ( $S_1 \geq 0.81$ ). Orientations of  
293  $k_1$  cluster near perpendicular to the glacier flow direction (south-southwest, Pedersen, 2005),  $k_2$   
294 orientations are close to horizontal and parallel to the flow direction, and  $k_3$  orientations plunge  
295 near vertically.

296 In thrust sheets of the Grønne Rende section, four fabric transects, one in GR10 and three in  
297 GR05, were measured normal to bounding thrust faults with well-exposed fault slickensides (Fig.

298 12, 13). In all cases, orientations of principal susceptibilities are clustered ( $S_1 \geq 0.77$ ). However,  
299 two distinct fabric patterns are evident depending upon distance from the fault. Within 0.1 m and  
300  $\sim 0.7$  m of the GR10 and GR05 fault surfaces, respectively, orientations of principal  
301 susceptibilities are similar to those of ring-shear experiments (Fig. 9), if data are plotted relative  
302 to the attitude of the fault surfaces. If all data from close to faults are combined in a single such  
303 stereonet, the similarity is clearest (Fig. 11B, compare with Fig. 9A, B): the  $V_1$  of  $k_1$  orientations  
304 is roughly parallel to the glacier flow direction (SSW) and plunges gently up-glacier relative to  
305 the plane of the fault. Orientations of  $k_2$  cluster perpendicular to the shear direction. Orientations  
306 of  $k_3$  are clustered the strongest ( $S_1 = 0.92$ ) and steeply plunge down-glacier relative to the plane  
307 of the fault. A difference between the field and ring-shear AMS data is that  $k_2$  and  $k_3$  clusters are  
308 rotated  $\sim 10^\circ$  around the axis of the  $k_1$  cluster

309 In contrast, farther away from faults, orientations of principal susceptibilities cluster similarly  
310 to fabrics from the distal part of the thrust complex at Ulstrup (Fig. 11C, compare with Fig.  
311 11A):  $k_1$  orientations cluster in the fault plane and sub-perpendicular to the flow direction;  $k_2$   
312 orientations also cluster in the fault plane but sub-parallel to the flow direction. Orientations of  $k_3$   
313 cluster normal to the fault surface. Unlike fabrics from Ulstrup,  $k_1$  and  $k_2$  clusters are rotated  
314 counterclockwise  $27^\circ$  from being perpendicular and parallel to the regional glacier flow  
315 direction, respectively. Possibly significant, however, is that five of the seven fabrics used to  
316 compile Figure 11C are from thrust sheet GR05, which strikes in a direction consistent with a  
317 local thrusting direction that is similarly rotated (Fig. 13).

318 All fabrics from samples collected from eroded dip-slope surfaces away from faults and  
319 plotted on stereonets relative to the dip of the bedding also have AMS fabrics similar to those at  
320 the distal end of the thrust complex. Combining the susceptibility orientations from these fabrics

321 on one stereonet shows this clearly (Fig. 11D, compare with Fig. 11A). Orientations of  $k_1$  cluster  
322 near perpendicular to the glacier flow direction;  $k_2$  orientations cluster in the plane of the bedding  
323 and parallel to the flow direction, and  $k_3$  orientations cluster parallel to the glacier flow direction  
324 and plunge near-normal to bedding. A slight difference is that  $k_2$  and  $k_3$  clusters from dip-slope  
325 fabrics indicate they dip up-glacier relative to bedding, approximately  $15^\circ$ .

#### 326 4.3. *Møns Klint*

327 Fabrics from the exposure at Møns Klint, if plotted on stereonets relative to the plane of the  
328 fault and grouped according to their distance from it (Fig. 14), are similar to some fabrics at  
329 Rubjerg Knude. Orientations of  $k_1$  cluster either roughly perpendicular to the glacier-flow  
330 direction (NNW, as inferred by Pedersen and Gravesen (2009) from the strikes of thrust faults in  
331 the complex) or at an angle less than  $\sim 45^\circ$  to the flow direction. Orientations of  $k_3$  tend to cluster  
332 with steep plunges up-glacier;  $k_2$  orientations are the most weakly clustered but tend either to  
333 plunge slightly down-glacier, where  $k_1$  clusters are perpendicular to flow (Fig. 14,  $< 0.36$  m,  
334 1.19-1.8 m), or to trend at an angle greater than  $\sim 50^\circ$  to the flow direction where  $k_1$  clusters are  
335 more closely aligned with the flow direction (Fig. 14, 0.51-0.98 m). The former fabrics are  
336 similar to those of the intact distal stratigraphy of the Rubjerg Knude complex (Fig. 11A), as  
337 well as parts of thrust sheets in that complex away from faults (Fig. 11C, D).

### 338 5. Discussion

#### 339 5.1. *AMS fabric interpretation*

340 In addition to our results indicating that the AMS of the thrust sheets is controlled by multi-  
341 domain or pseudo-single domain magnetite (Appendix), we have two means of interpreting AMS  
342 fabrics. Results from ring-shear experiments on the LKF mud and on tills provide a model for  
343 AMS development in till deformed predominately in simple shear. In addition, models of AMS



344 fabric development in larger-scale compressional tectonic environments, tested experimentally,  
345 provide guidance for interpreting fabric development during layer-parallel shortening.

346 Experimental shearing of the LKF mud yields  $V_1$  eigenvectors for the three principal  
347 susceptibilities that are similar to those obtained in identical experiments conducted on fine-  
348 grained tills in which magnetite was the dominant magnetic mineral (Fig. 9). Eigenvectors based  
349 on  $k_1$  orientations are close to the shearing direction (within  $11^\circ$ ) and plunge gently up-glacier;  
350 those based on  $k_2$  orientations are nearly perpendicular to the shearing direction (within  $7^\circ$ ) in the  
351 plane of the fault, and those based on  $k_3$  plunge steeply down-glacier.

352 Dissimilar, however, is that in the experiment on mud,  $k_1$  and  $k_2$  orientations did not cluster  
353 but formed asymmetric girdles (Fig. 9A), despite shearing displacements that were just as large  
354 as in the till experiments. The lack of clustering of  $k_1$  and  $k_2$  orientations likely reflects strain  
355 localization in the mud in thin shear bands, a characteristic behavior of clay-rich soils in  
356 geotechnical experiments in which strain commonly localizes in zones 0.3-10 mm thick  
357 (Morgenstern and Tchalenko, 1967; Hicher et al., 1994). AMS samples, in contrast, were  
358 collected after the experiment over a mud thickness of 16 mm (the sampling box dimension),  
359 which would have resulted in the collection of significant volumes of unsheared mud. This  
360 unsheared mud, owing to its consolidation prior to the experiment and associated rotation of  
361 particles toward the horizontal, would have had a  $k_1$ - $k_2$  girdle in the plane of shear and a vertical  
362 cluster of  $k_3$  orientations (e.g., Tarling and Hrouda, 1993; Parés, 2015). The asymmetric  $k_1$ - $k_2$   
363 girdle that is observed, therefore, likely reflects a significant volume of unsheared mud in the  
364 AMS samples. Thus, although eigenvectors from the mud experiment are fully consistent with  
365 those developed from simple shear of tills, clustering of  $k_1$  and  $k_2$  orientations from experiments  
366 with fine-grained till probably better reflects the AMS response of the mud to simple shear, as

367 long as thicknesses of shear zones sampled in the field exceeded the thickness of sample boxes.  
368 We conclude, therefore, that the clustered orientations of principal susceptibilities obtained in  
369 ring-shear experiments on tills, formed subglacially through remobilization of glaciolacustrine  
370 mud and with their AMS controlled by magnetite (Fig. 9b), is an appropriate model for the muds  
371 of this study, if they have been subjected to a sufficient strain.

372 On that basis, a solid conclusion is that the fabric pattern close to thrust faults ( $< \sim 0.7$  m) at  
373 Rubjerg Knude (Fig. 11b) reflects shear of the mud during thrusting. Shear must have been to a  
374 sufficiently high strain close to faults to fully overprint the AMS fabric that existed prior to  
375 thrusting. At Møns Klint, on the other hand, despite collection of AMS samples as close as 3 cm  
376 to the fault between the chalk and underlying mud, this fabric pattern indicative of simple shear  
377 is absent.

378 Additional insights into the fabric patterns at Rubjerg Knude and Møns Klint come from  
379 studies of AMS fabric development in deformed rocks (see Borradaile and Henry, 1997; Parés,  
380 2015, for reviews) and sediments (e.g., Collombat et al., 1995; Housen and Kanamatsu 2003;  
381 Caricchi et al, 2016) in crustal tectonic environments. A leading model developed from such  
382 field studies (notably by Averbuch et al., 1992; Borradaile and Henry, 1997; Bakhtari et al.,  
383 1998; Saint-Bezar et al., 2002) and more recently tested in analogue sandbox experiments  
384 (Almqvist and Koyi, 2018) allows interpretation of fabrics resulting from layer-parallel  
385 shortening (LPS) in fold and thrust belts and accretionary prisms. The model (Fig. 15) describes  
386 the change in AMS fabric pattern from a depositional fabric, found in forefield regions, to fabrics  
387 indicative of progressively higher-strain LPS towards the hinterland. The depositional fabric,  
388 with  $k_3$  orientations clustering vertically and  $k_1$  and  $k_2$  orientations in a horizontal girdle (fabric 1  
389 of Fig. 15), reflects the horizontal settling and subsequent consolidation during burial of oblate,

390 clay-sized particles (Tarling and Hrouda, 1993). Common in fold-thrust environments are  
391 intermediate fabrics in which this depositional fabric has been overprinted by a small amount of  
392 LPS. This fabric (fabric 2 of Fig. 15) reflects consolidation greater than LPS, such that  $k_3$   
393 orientations remain vertical. Orientations of  $k_1$ , however, rotate into the direction of maximum  
394 extension, which is horizontal and perpendicular to the shortening direction. With still more LPS,  
395 a vertical  $k_2$ - $k_3$  girdle forms parallel to shortening (fabric 3), which transitions at still greater  
396 strain to  $k_2$  and  $k_3$  clusters that are vertical and parallel to the shortening direction, respectively  
397 (fabric 4). This highest-strain AMS fabric has been measured in till interpreted to have been  
398 extruded upward into basal crevasses (Ankerstjerne et al., 2015).

399 AMS fabrics measured at Rubjerg Knude in the distal Ulstrup section and away from thrusts  
400 in the Grønne Rende section, as well as most fabrics measured at Møns Klint, are similar to  
401 fabric 2 of this model. Orientations of  $k_1$  cluster in the plane of the bedding or fault and  
402 perpendicular or sub-perpendicular to the thrusting direction;  $k_2$  orientations also cluster in the  
403 plane of the fault or bedding but are parallel or sub-parallel to thrusting, and  $k_3$  orientations either  
404 cluster vertically or are steeply dipping. Therefore, prior to thrusting of mud sheets at Rubjerg  
405 Knude and Møns Klint the mud was consolidated (fabric 1, Fig. 15) and underwent minor  
406 shortening parallel to bedding. More importantly, thrusting did not change this fabric at Grønne  
407 Rende, except within decimeters of fault surfaces where simple shear reset the LPS fabrics. At  
408 Møns Klint, there is no evidence of thrusting resetting this fabric, likely indicating that shear was  
409 focused in the ~3 cm of mud closest to the fault where the mud was not sampled (Figs. 5 and 14).  
410 AMS of sediments across basal décollements of accretionary prisms sometimes indicate a similar  
411 lack of detectable overprinting by shear deformation (Housen et al., 1996). In contrast, the  
412 superimposed deformation onto the eastern edge of the northern part of the complex from

413 Slotsgavlene to Maglevandsfald (Fig. 4), which occurred later, recumbently folded the glacial  
414 sediments (Pedersen and Gravesen, 2009), likely resetting LPS fabrics.

415 The clear implication is that during thrusting sheets were rotated, with little internal  
416 deformation except very near faults. As noted, a leading hypothesis for glacitectonic thrusting of  
417 rigid sheets of unlithified sediment is that permafrost made thrusting of coherent sheets possible  
418 through some combination of increasing their strengths and serving as a barrier for groundwater  
419 flow. In that case, the narrow zones of shear near thrust surfaces might be interpreted as the  
420 result of heat dissipation during slip and the associated warming or melting of pore ice there.  
421 Warbritton (2019) showed that heat dissipation from the average displacement on faults at  
422 Rubjerg Knude estimated by Pedersen (2005, ~70 m) was sufficient to warm permafrost  
423 substantially near slip surfaces. Potentially this softened the permafrost through production of  
424 pre-melted water, enabled strain localized in narrow zones, and reduced shear stresses  
425 sufficiently to allow the slip of mostly intact sheets.

## 426 *5.2. Thrusting of intact sheets without permafrost*

427 We now step back and consider more generally whether thrusting of largely intact sediment  
428 sheets can occur under fully thawed conditions, by appealing to the effects of pore-water  
429 pressure and thrust geometry rather than to permafrost. Consider a thrust sheet (Fig. 16) with the  
430 wedge geometry commonly considered in studies of crustal faulting (e.g., Turcotte and Schubert,  
431 2014). Wedge-shaped thrust sheets were also considered by Pedersen (2005) in his  
432 reconstructions of thrusting at Rubjerg Knude. The upper surface of the thrust wedge slopes at  
433 an angle,  $\alpha$ , toward the distal end of the wedge, as expected if layer-parallel shortening is largest  
434 near the glacier margin and is accompanied perhaps by proximal thrusting in the wedge. The  
435 thrust ramp dips in the opposite direction at an angle,  $\beta$ . The thickness of the wedge,  $H$ , is

436 defined normal to the thrust surface. The wedge is pushed from upstream along the  $x$  coordinate,  
 437 defined parallel to the thrust ramp, by a force that reflects the depth integral of the stress,  $\sigma_x$  (Fig.  
 438 16). In the opposite direction is a shear stress,  $\tau_b$ , acting along the base of the thrust ramp.

439 In their study of the mechanics of fold and thrust belts, Davis et al. (1983) balanced forces on  
 440 the wedge and considered the stresses required for its Coulomb failure to estimate  $\tau_b$  for the  
 441 special case of a wedge deforming internally at its Coulomb strength. In that case, shear failure  
 442 occurs under a traction,  $S = S_0 + \mu (\sigma_z - p_w)$ , where  $S_0$  is the sediment cohesion,  $\sigma_z$  is the total  
 443 stress,  $p_w$  is the pore-water pressure, and  $\mu$  is an internal friction coefficient commonly expressed  
 444 in terms of a friction angle  $\varphi$  such that  $\mu = \tan \varphi$ . For the small values of  $\alpha$  and  $\beta$  relevant to  
 445 this problem, for which  $\sin \alpha \approx \alpha$  and  $\sin \beta \approx \beta$ , and assuming the wedge is saturated with water  
 446 everywhere, Davis et al. (1983) derived the shear stress on the thrust fault required to deform the  
 447 wedge:

$$448 \quad \tau_b = (\rho - \rho_w)gH\alpha + (1 - \lambda)K\rho gH(\alpha + \beta), \quad (1)$$

449 where  $\rho$  is the density of the sediment grains of the wedge, and  $\rho_w$  is the density of pore water.

450 Two dimensionless quantities are particularly important in Eq. (1): the water pressure ratio,  
 451  $\lambda = p_w / \sigma_z$  and the parameter,  $K$ , which scales with the frictional strength of the wedge. The shear  
 452 stress at the base must balance the down-slope component of gravity acting on the sloping  
 453 surface of the wedge, as given by the first right-hand term, and must also balance the force on the  
 454 upstream end of the wedge as limited by the wedge's Coulomb strength and given by the second  
 455 right-hand term. In deriving Eq. (1), Davis et al. (1983) assumed zero cohesion in the wedge, so  
 456 for the fine-grained and likely cohesive muds of this study, Eq. (1) provides a minimum value of  
 457 the stress required to deform the wedge.

458 For the wedge to slip along its basal fault without deforming the wedge internally, the  
 459 frictional stress resisting slip,  $S_b$ , at the base of the wedge must be less than  $\tau_b$ . Defining  $\mu_b$  and  
 460  $\lambda_b$  as the friction coefficient and water pressure ratio, respectively, at the base of the wedge,

$$461 \quad S_b = \mu_b(1 - \lambda_b)\rho gH. \quad (2)$$

462 Thus, the condition for slip without internal deformation of the wedge is

$$463 \quad \mu_b(1 - \lambda_b)\rho gH < (\rho - \rho_w)gH\alpha + (1 - \lambda)K\rho gH(\alpha + \beta). \quad (3)$$

464 To maximize slip resistance on the fault and to thereby optimize the potential for deforming a  
 465 wedge of a given geometry and strength, we assume that  $\lambda_b = \lambda$ , despite the possibility that pore-  
 466 water pressure might be elevated along the fault relative to the wedge overall. Assuming  $\lambda_b = \lambda$ ,  
 467 and rearranging Eq. (3) yields the pore-pressure condition required for slip without internal  
 468 deformation of the wedge:

$$469 \quad \lambda > 1 - \frac{\alpha(1 - \frac{\rho_w}{\rho})}{\mu_b - K(\alpha + \beta)}. \quad (4)$$

470 Despite the possibility that sliding friction was less than internal friction, we set the friction  
 471 coefficient of the fault equal to the internal friction coefficient of the wedge,  $\mu_b = \mu = \tan \varphi$ , to  
 472 further optimize the potential for deforming it. In that case, as shown by Davis et al. (1983), a  
 473 good approximation for the Coulomb strength factor is

$$474 \quad K = \frac{\sin \varphi}{1 - \sin \varphi} + \frac{\sin^2 \varphi}{\cos^2 \varphi}. \quad (5)$$

475 Eqs. (4) and (5) illustrate that if the glacier forefield sloped down-glacier at even a small  
 476 angle  $\alpha$ , a wide a range of pore-pressure ratios could have resulted in thrusting without internal  
 477 deformation of the thrust sheet. Fields of  $\lambda$  and  $\alpha$  above and to the right of the plots of Figure 17  
 478 indicate thrusting without internal deformation. For the thrust-ramp inclination that characterized  
 479 initial thrusting in the Grønne Rende section at Rubjerg Knude (18°, Pedersen, 2005, p. 118),

480 even hydrostatic pore-water pressure (i.e., no upward groundwater flow) could have resulted in  
481 fault slip without internal deformation, as long as  $\alpha > 4.3^\circ$ . Still smaller surface slopes would  
482 have been required for later stages of faulting at Grønne Rende when thrust ramps became  
483 steeper than  $30^\circ$  (Pedersen, 2005). Also, given that upward groundwater flow is common in  
484 glacier forefields (e.g., Boulton and Caban, 1995), pore pressures could have easily exceeded  
485 hydrostatic. Assumptions made in the derivation of Eqs. (4) and (5) (i.e., no internal cohesion,  $\lambda_b$   
486  $=\lambda$ , and  $\mu_b = \mu = \tan \varphi$  also make the estimates of  $\lambda$  and  $\alpha$  in Figure 17 required for thrusting  
487 without internal deformation conservatively large.

488       Unfortunately values of  $\alpha$  are poorly known during thrusting at Grønne Rende. Pedersen's  
489 (2005, p. 159) reconstruction indicates  $\alpha > 5^\circ$  late during thrusting, but he argued that at the  
490 beginning of thrusting the hinterland of the complex sloped toward the glacier  $2^\circ$ , owing to  
491 isostatic depression by the glacier. Uncertainty in the value of  $\alpha$  and its evolution during  
492 thrusting clearly limit mechanical interpretations.

493       Nevertheless, at Rubjerg Knude and Møns Klint, during phases of thrusting when the  
494 proglacial surface sloped away from the glacier, positive pore-water pressure could have caused  
495 thrusting of intact sheets of mud in the absence of proglacial permafrost. This interpretation is  
496 consistent with the field observations of Pedersen (2005), who interpreted sand-filled cracks,  
497 local brecciation, and small-scale mud diapirism at Rubjerg Knude as reflecting high pore-water  
498 pressures. It is also consistent with real-time observations of proglacial thrusting of smaller  
499 sheets of unfrozen sediments by modern glaciers with little internal deformation of thrust sheets  
500 (e.g., Kuriger et al., 2006).

501       Our calculations do not rule out that parts of thrust sheets may have been frozen (Pedersen,  
502 2005) but support the viewpoint that permafrost is commonly not necessary for thrusting of

503 coherent sheets (e.g., Van der Wateren, 2002). The observation that shear at Rubjerg Knude  
504 occurred only near thrust faults may indicate that in mud immediately adjacent to them the  
505 condition  $\lambda_b > \lambda$  was met—a reasonable expectation if consolidated mud of the LKF served as a  
506 confining unit for groundwater flow.

## 507 **6. Conclusions**

508 Although AMS had been applied to sediments where macroscopic structures indicate  
509 glaciotectonic deformation (Fleming et al., 2013b), this study is the first attempt to apply AMS to  
510 the kinematics of glaciotectonic thrusting. Fabrics of intact stratigraphy near the distal end of the  
511 Rubjerg Knude thrust complex indicate that, before thrusting the LKF mud underwent  
512 consolidation with longitudinal horizontal shortening. This shortening was moderate, as  
513 indicated by clustering of  $k_1$  and  $k_2$  orientations perpendicular and parallel to the shortening  
514 direction and by the lack of rotation of vertical  $k_3$  orientations developed during mud deposition  
515 and consolidation (Fig. 15).

516 AMS fabrics of thrust sheets of LKF mud within the Grønne Rende section of Rubjerg  
517 Knude, indicate rotation of sheets mostly without internal deformation during thrusting. Within  
518 decimeters of fault surfaces, however, mud was sheared to strains sufficient to overprint the LPS  
519 fabric. The resultant fabric is observed consistently in ring-shear experiments conducted to large  
520 displacements ( $> 0.5$  m), with  $k_1$  orientations parallel to shear and plunging mildly relative to the  
521 shear plane. In thrust mud at Møns Klint, only rotation of LPS fabrics is observed, despite  
522 samples collected as close as 3 cm to the chalk-mud contact. Slip, therefore, was seemingly  
523 focused in a still narrower zone, with most of the thrust sheet behaving too rigidly to reset the  
524 fabric.



525 Permafrost was not required for thrusting of intact sheets. If topographic surfaces of thrust  
526 sheets sloped gently away from the glacier margin, a wide range of pore-water pressures could  
527 have enabled slip on thrusts without internal deformation of individual thrust sheets. Shear  
528 deformation observed close to faults at Rubjerg Knude may reflect elevated pore pressures in  
529 mud adjacent to faults during thrusting.

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747

#### 748 **Appendix: Magnetic mineralogy**

749

750 Interpreting anisotropy of magnetic susceptibility (AMS) data requires a priori knowledge of  
751 the mineral composition of the analyzed samples. Specifically, assessing whether paramagnetic  
752 minerals, ferrimagnetic minerals or a combination of both control the AMS is crucial. The AMS  
753 of paramagnetic minerals is dictated by the mineral's crystal symmetry and is said to have a

754 crystallographic preferred orientation. Ferrimagnetic mineral particles with high saturation  
755 magnetizations, such as magnetite and maghemite, have AMS controlled by the shape of the  
756 particle and are said to have a preferred shape orientation (Tarling and Hrouda, 1993). Rock  
757 magnetic analyses at room temperature and low-temperature were conducted at the *Institut de*  
758 *Physique du Globe de Paris* (France) in order to determine whether magnetite (or maghemite)  
759 were present and at what concentration.

760 Representative bulk samples from Rubjerg Knude (RK3) and Møns Klint (MUN01) were  
761 analyzed. Each bulk sample was homogenized using an agate mortar and pestle and dried at  
762 40°C overnight. The powdered bulk samples were then firmly packed in 0.21 ml gelatin capsules  
763 (14.3 mm in length and 5 mm in diameter). The RK3 and MUN01 subsamples contained 434.4  
764 mg and 476.6 mg, respectively, of bulk material.

765 Two room-temperature experiments were conducted on a Princeton Measurements Model  
766 3900 Vibrating Sample Magnetometer (VSM). First, hysteresis loops and initial magnetizations  
767 curves were measured in maximum magnetic fields of  $\pm 1.5$  T. Mass-specific low-field magnetic  
768 susceptibility was calculated from the initial slope of the first magnetization curves. Saturation  
769 magnetization, saturation remanent magnetization, coercivity and high field magnetic  
770 susceptibility were derived from the hysteresis loops after correction for the high field slopes.  
771 Second, an isothermal remanent magnetization (IRM) acquisition curve was measured on  
772 demagnetized subsamples by acquiring IRMs in progressively increasing magnetic fields from  
773 zero to 1.5 T with 200 logarithmically spaced steps.

774 Two low-temperature experiments were conducted on a Magnetic Properties Measurement  
775 System (MPMS) XL-5 Evercool. First a room-temperature (300 K) IRM was acquired in a 2.5 T  
776 magnetic field and measured as the subsample was cooled to 10 K and warmed back to 300 K at

777 a rate of 5 K/min. The second experiment measures a low-temperature (10 K) IRM acquired in a  
778 2.5 T magnetic field as the subsample is warmed from 10 K to 300 K at a rate of 5 K/min. The  
779 10 K IRM is acquired following one of two pre-treatments. The zero-field cooled (ZFC) pre-  
780 treatment cools the subsample from 300 K to 10 K in zero ( $< 500$  nT) magnetic field before  
781 acquiring the 10 K IRM and the field cooled (FC) pre-treatment cools the subsample from 300 K  
782 to 10 K in a 2.5 T magnetic field before acquiring the 10 K IRM.

783 The hysteresis loop and first magnetization derived parameters are listed in Table A1 and  
784 hysteresis loops before and after correction shown in Figure A1. Low-field magnetic  
785 susceptibility, inclusive of all minerals, of RK3 and MUN01 are quite similar  $20 \times 10^{-8}$  and  $17 \times$   
786  $10^{-8}$  m<sup>3</sup>/kg. However, the high-field magnetic susceptibility of RK3, which excludes  
787 ferromagnetic (sensus lato) that have saturated (primarily ferrimagnetic minerals), is more than 3  
788 times the value for MUN01. Saturation magnetization values confirm the higher concentration of  
789 ferrimagnetic minerals in MUN01 with values twice those of RK3. Squareness and coercivity  
790 ratios of RK3 and MUN01 are in agreement with a population of ferrimagnetic magnetic domain  
791 sizes larger than single domain. Therefore, inverse AMS fabrics are not expected.

792 The low temperature experiments shown in Figure A2 confirm that magnetite is the dominant  
793 ferrimagnetic mineral present in both RK3 and MUN01 subsamples. The Verwey transition,  
794 which is characteristic of stoichiometric magnetite, is observed by a sharp drop in remanence at  
795 120 K in the ZFC and FC 10 K IRM warming curves. The 300 K IRM cooling and warming  
796 cycles display more broadly but just as convincingly the Verwey transition. The remanence loss  
797 and gain in Figure A2A is identical in both samples, which attests to the very similar magnetic  
798 domain states of the magnetite population contributing to the AMS at Rubjerg Knude and Møns  
799 Klint.

800 Since magnetite is shown to be the dominant ferrimagnetic mineral, saturation magnetization  
801 values, which are independent of magnetic domain size (i.e. particle size) unlike remanent  
802 magnetization, can be used to calculate weight percent concentration of magnetite. The intrinsic  
803 saturation magnetization of stoichiometric magnetite is  $92 \text{ Am}^2/\text{kg}$  at room temperature (Dunlop  
804 and Özdemir, 1997). Assuming that stoichiometric magnetite is the sole contributor to the  
805 saturation magnetization RK3 contains 0.01 wt. % magnetite and MUN01, 0.03 wt. % magnetite.

806 In conclusion, magnetite is the dominant ferrimagnetic mineral in both RK3 and MUN01. The  
807 magnetite population grain-size distributions are similar at both sites and fall well into the  
808 pseudo single-domain to small multi-domain particle size range. Inverse AMS fabrics are  
809 therefore not expected. Magnetite concentrations are low, 0.01 wt% at Rubjerg Knude and 0.03  
810 wt% at Møns Klint but similar, for example, to the 0.03 wt.% magnetite calculated for the  
811 Batestown Till (Hooyer et al. 2008) in which magnetite controlled AMS fabrics.

812  
813 **Figure captions**

814  
815 **Figure 1.** Locations of the two glacitectonic complexes. Black line indicates the “Main  
816 Stationary Line,” i.e., the extent of the Scandinavian Ice Sheet during the last glacial  
817 maximum (~20 ka before present). The red line shows the maximum extent of the Norwegian  
818 Ice Advance at 28 ka before present (modified from Pedersen, 2005).

819 **Figure 2.** (A) Schematic cross-sections of the Rubjerg Knude complex, The three thrust sheets  
820 studied, as numbered by Pedersen (2005), are indicated. The complex’s (B) Grønne Rende  
821 section, and its (C) distal Ulstrup section, with ~1.2 vertical exaggeration. RKF and LKF refer  
822 to Rubjerg Knude and Lønstrup Klint Formations, respectively (see text) (modified from  
823 Pedersen (2005).

824 **Figure 3.** Thrusted mud sheets of the Lønstrup Klint Formation (grey) with intervening sand and  
825 gravel of the Rubjerg Knude Formation (brown), within the Grønne Rende section at Rubjerg  
826 Knude. The thrusted mud sheet at center-right is GR07 (see Fig. 2B). Note person for scale  
827 in the right-hand side of the photograph.

828 **Figure 4.** (A) Oblique photograph of the east coast of the island of Møn, Denmark (from  
829 GeoCenter Møns Klint), showing the chalk of Møns Klint and the location of the thrust fault  
830 studied. (B) Chalk (white) thrust over the glaciolacustrine mud (grey) sampled at Møns Klint.  
831 Dashed line indicates the contact, with colluvium at lower right.

832 **Figure 5.** Aluminum sample boxes pushed into the glaciolacustrine mud at Møns Klint,  
833 immediately underlying the Upper Cretaceous chalk that has been thrust over it from left to  
834 right. After excavation of the boxes, the mud was transferred to plastic boxes for storage,  
835 sealing, and subsequent AMS analysis.

836 **Figure 6.** View normal to the surface of a thrust fault at the base of sheet GR10 in the Grønne  
837 Rende section at Rubjerg Knude, showing slickensides at the base of the mud layer. The mud  
838 was thrust upward in the photograph, over sand that has been cleared to expose the fault  
839 surface. The treads on the stepped fault surface are P fractures. Mallet head for scale.

840 **Figure 7.** (A) Mud and sand of the Lønstrup Klint Formation thrust along a slickensided fault  
841 surface (dashed red line) and over sand of the Rubjerg Knude Formation, within the Grønne  
842 Rende section at Rubjerg Knude, thrust sheet GR10 (Fig. 2). The area of overthrust  
843 sediment outlined in yellow was sampled for AMS, at various distances from the fault  
844 surface. (B) The mud sheet of GR05 thrust along slickensided fault surfaces (red). AMS  
845 samples were collected at various distances from the fault over transects A, B and C.

846 **Figure 8.** Upper Cretaceous chalk overlying glaciolacustrine mud of the Middle Weichselian at  
847 Møns Klint, with intervening fault indicated by the red dashed line. AMS samples were  
848 gathered along transects A-D. Dark grey areas are where fresh mud has been exposed for  
849 sampling; light grey areas are the weathered and un-sampled mud surface. Colluvium is in the  
850 foreground.

851 **Figure 9.** (A) Orientations of the three principal magnetic susceptibilities of the mud from  
852 Rubjerg Knude after it had been sheared in a ring-shear device to a displacement of 0.6 m.  
853 Arrows at upper left indicate sense of shear. (B) Orientations of principal susceptibilities from  
854 a similar experiment conducted to a displacement of 0.5 m on a till deposited subglacially and  
855 derived from remobilized glaciolacustrine mud (Douglas till, Hooyer et al., 2008; Shumway  
856 and Iverson, 2009). Large orange symbols show  $V_1$  eigenvectors calculated from the  
857 principal-susceptibility distributions.

858 **Figure 10.** Principal-susceptibility orientations for the six fabrics from the distal end of the  
859 Rubjerg Knude thrust complex (Ulstrup section). Large orange symbols show  $V_1$  eigenvectors  
860 calculated from the principal-susceptibility distributions.

861 **Figure 11.** Aggregated principal susceptibility orientations at Rubjerg Knude. (A) Principal-  
862 susceptibility orientations aggregated for fabrics from the distal end of the thrust complex  
863 (Ulstrup section).  $S_1$  values for  $k_1$ ,  $k_2$  and  $k_3$  are 0.86, 0.81 and 0.89, respectively. (B)  
864 Principal-susceptibility orientations aggregated for fabrics within ~0.1 m and ~0.7 m of the  
865 GR10 and GR05 fault surfaces, respectively, within the Grønne Rende section.  $S_1$  values for  
866  $k_1$ ,  $k_2$  and  $k_3$  are 0.78, 0.77 and 0.92, respectively. (C) Principal-susceptibility orientations  
867 aggregated for fabrics more than 0.1 m and ~0.7 m away from the GR10 and GR05 fault  
868 surfaces, respectively.  $S_1$  values for  $k_1$ ,  $k_2$  and  $k_3$  are 0.81, 0.80 and 0.92, respectively. (D)

869 Principal-susceptibility orientations aggregated for fabrics from eroded dip-slope surfaces  
870 away from faults.  $S_1$  values for  $k_1$ ,  $k_2$  and  $k_3$  are 0.0.76, 0.73 and 0.85, respectively. Large  
871 orange symbols show  $V_1$  eigenvectors calculated from the principal-susceptibility  
872 distributions.

873 **Figure 12.** Four fabrics from thrust sheet GR10 from the Grønne Rende section of Rubjerg  
874 Knude. Distances listed are relative to the adjacent fault surface. The fault orientation is  
875 shown in a lower-hemisphere stereonet at upper-right, and the cyan arrow shows the ice-  
876 advance direction. Large orange symbols show  $V_1$  eigenvectors calculated from the principal-  
877 susceptibility distributions.

878 **Figure 13.** Nine fabrics from transects A, B, and C in the thrust sheet GR05 from the Grønne  
879 Rende section of Rubjerg Knude (see Fig. 7B for transects). Distances listed are relative to the  
880 nearest fault surface. The fault orientation is shown in a lower-hemisphere stereonet at upper-  
881 right, and the cyan arrow shows the ice-advance direction. Large orange symbols show  $V_1$   
882 eigenvectors calculated from the principal-susceptibility distributions.

883 **Figure 14.** Principal-susceptibility orientations for 17 AMS fabrics collected in the four  
884 transects at Møns Klint (see Figure 8), aggregated for five distance ranges from the fault at the  
885 chalk-mud boundary. The fault orientation is shown in a lower-hemisphere stereonet at upper-  
886 right, and the cyan arrow shows the ice-advance direction. Large orange symbols show  $V_1$   
887 eigenvectors calculated from the principal-susceptibility distributions.

888 **Figure 15.** Model for AMS fabric development during deposition/consolidation and layer-  
889 parallel shortening (modified from Almqvist and Koyi, 2018).

890 **Figure 16.** Schematic diagram of a thrust wedge subject to a push,  $\sigma_x$  (modified from Davis et  
891 al., 1983).



892 **Figure 17.** Threshold values of pore-pressure ratio,  $\lambda$ , and topographic slope of the thrust wedge,  
893  $\alpha$ , above which slip is expected on thrusts without internal deformation of thrust sheets, for  
894 different values of thrust dip,  $\beta$ . Zero internal cohesion,  $\lambda_b = \lambda$ , and  $\mu_b = \mu = \tan \varphi$  are  
895 assumed, making estimates of  $\lambda$  and  $\alpha$  required for slip without internal deformation  
896 conservatively large. Also assumed are  $\sin \alpha \approx \alpha$  and  $\sin \beta \approx \beta$ , good to within 5% for the  
897 largest angles considered ( $\beta = 30^\circ$ ). The hydrostatic value of  $\lambda = p_w / \sigma_z$  is based on a  
898 groundwater table at the ground surface, a sediment porosity of 50%, and rock particle density  
899 of  $2700 \text{ kg m}^{-3}$ .

900 **Figure A1.** (A) Hysteresis loops for samples from Rubjerg Knude (RK3) and Møns Klint  
901 (MUN01) before and after correction. (B) Detail of loops within inset shown in (A).

902 **Figure A2.** Results of low temperature experiments for samples from Rubjerg Knude (RK3) and  
903 Møns Klint (MUN01). (A) 300 K IRM cooling and warming cycles. (B) IRM warming  
904 curves.

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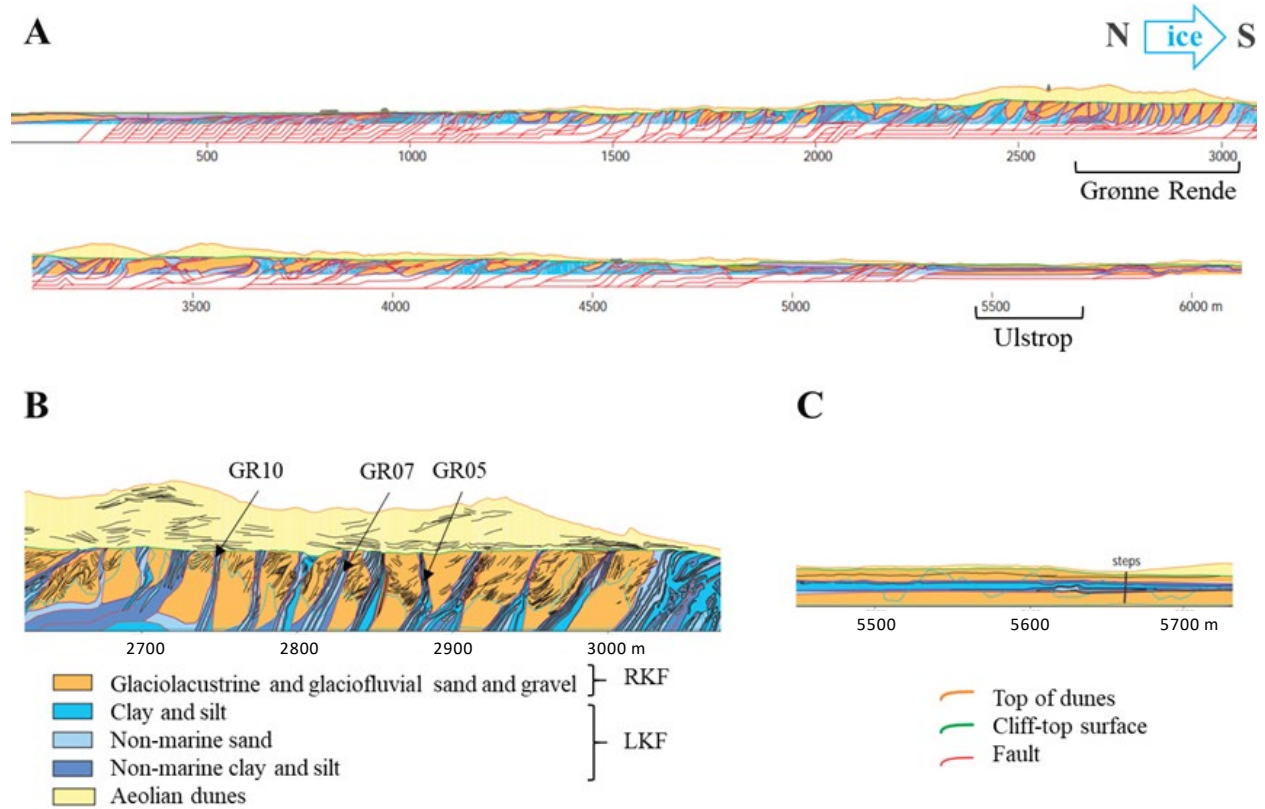
925 **Figures**  
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930 **Figure 1.** Locations of the two glacial complexes. Black line indicates the “Main  
931 Stationary Line,” i.e., the extent of the Scandinavian Ice Sheet during the last glacial  
932 maximum (~20 ka before present). The red line shows the maximum extent of the Norwegian  
933 Ice Advance at 28 ka before present (modified from Pedersen, 2005).

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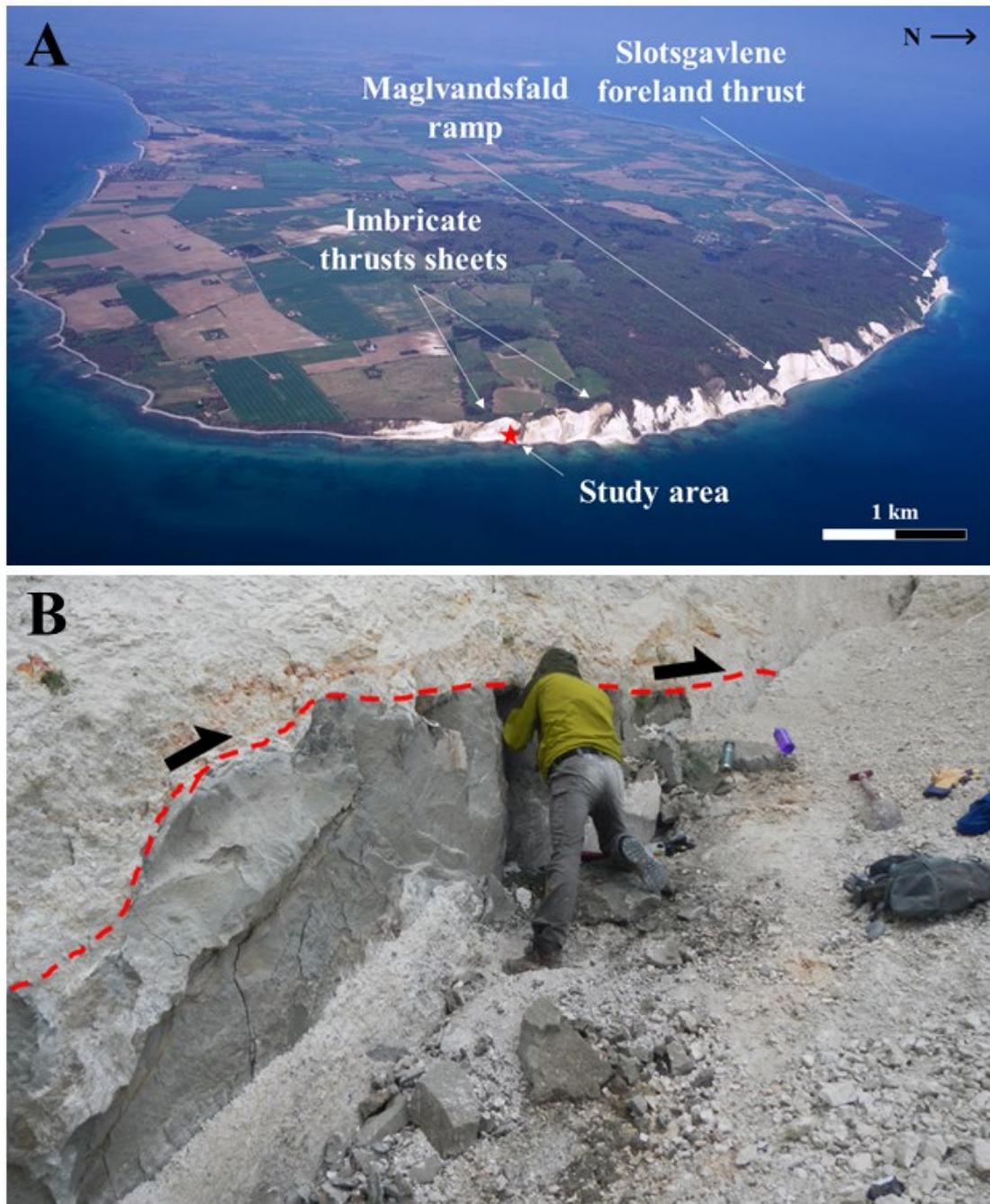
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**Figure 2.** (A) Schematic cross-sections of the Rubjerg Knude complex, The three thrust sheets studied, as numbered by Pedersen (2005), are indicated. The complex's (B) Grønne Rende section, and its (C) distal Ulstrup section, with ~1.2 vertical exaggeration. RKF and LKF refer to Rubjerg Knude and Lønstrup Klint Formations, respectively (see text) (modified from Pedersen (2005)).



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**Figure 3.** Thrusted mud sheets of the Lønstrup Klint Formation (grey) with intervening sand and gravel of the Rubjerg Knude Formation (brown), within the Grønne Rende section at Rubjerg Knude. The thrusted mud sheet at center-right is GR07 (see Fig. 2B). Note person for scale in the right-hand side of the photograph.



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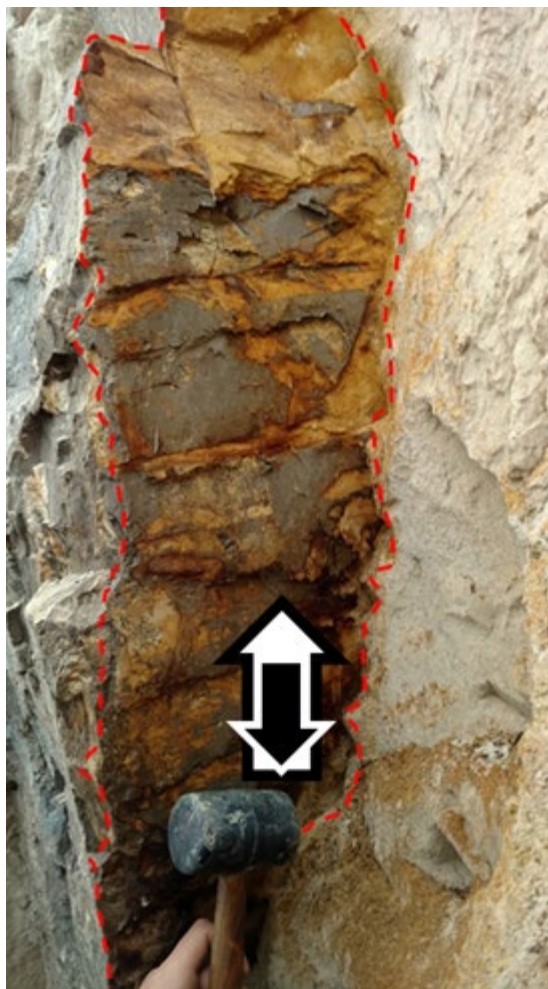
**Figure 4.** (A) Oblique photograph of the east coast of the island of Møn, Denmark (from GeoCenter Møns Klint), showing the chalk of Møns Klint and the location of the thrust fault studied. (B) Chalk (white) thrust over the glaciolacustrine mud (grey) sampled at Møns Klint. Dashed line indicates the contact, with colluvium at lower right.

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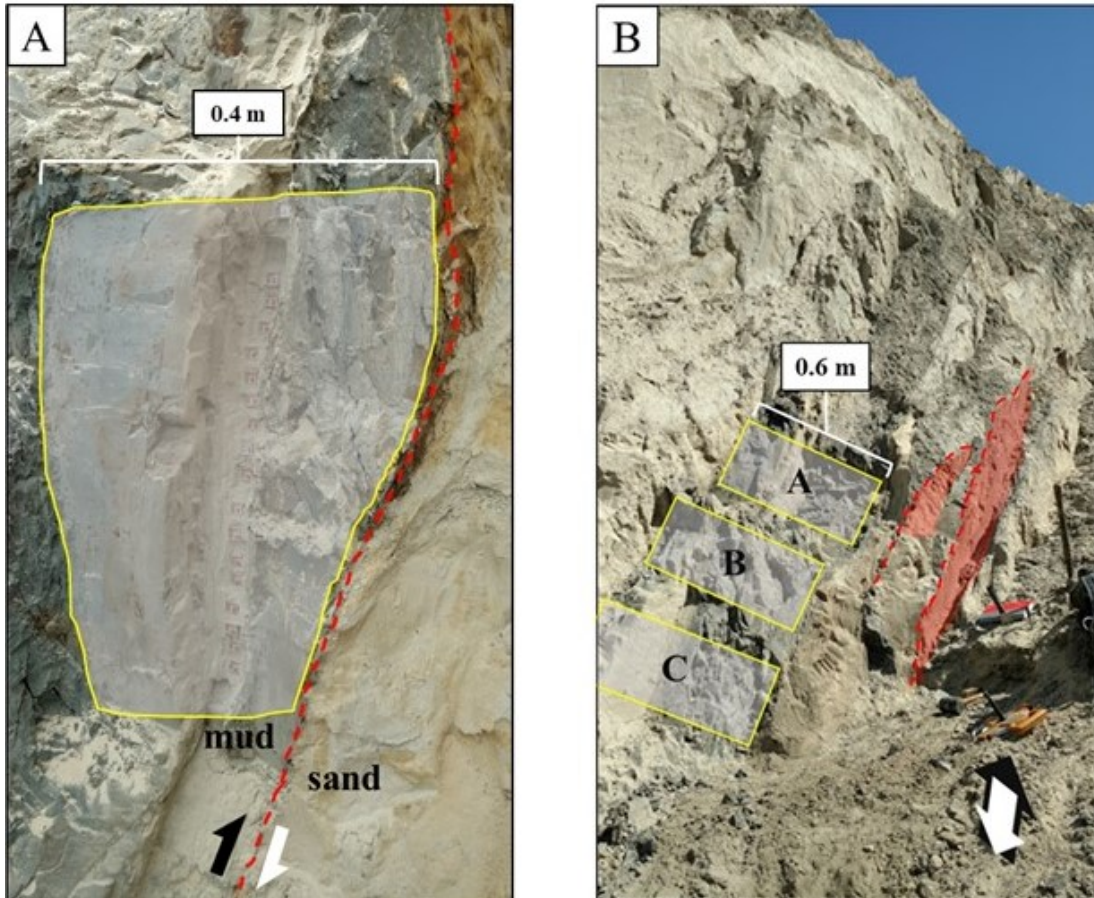
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**Figure 5.** Aluminum sample boxes pushed into the glaciolacustrine mud at Møns Klint, immediately underlying the Upper Cretaceous chalk that has been thrust over it from left to right. After excavation of the boxes, the mud was transferred to plastic boxes for storage, sealing, and subsequent AMS analysis.



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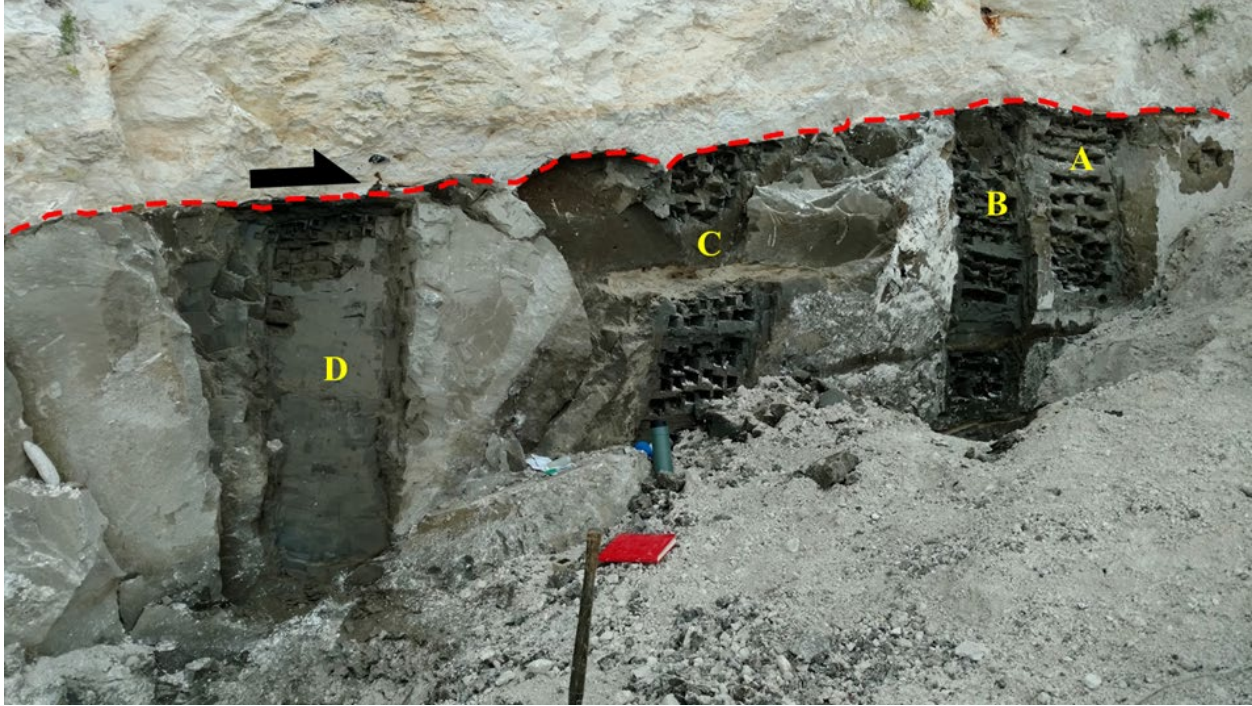
**Figure 6.** View normal to the surface of a thrust fault at the base of sheet GR10 in the Grønne Rende section at Rubjerg Knude, showing slickensides at the base of the mud layer. The mud was thrust upward in the photograph, over sand that has been cleared to expose the fault surface. The treads on the stepped fault surface are P fractures. Mallet head for scale.



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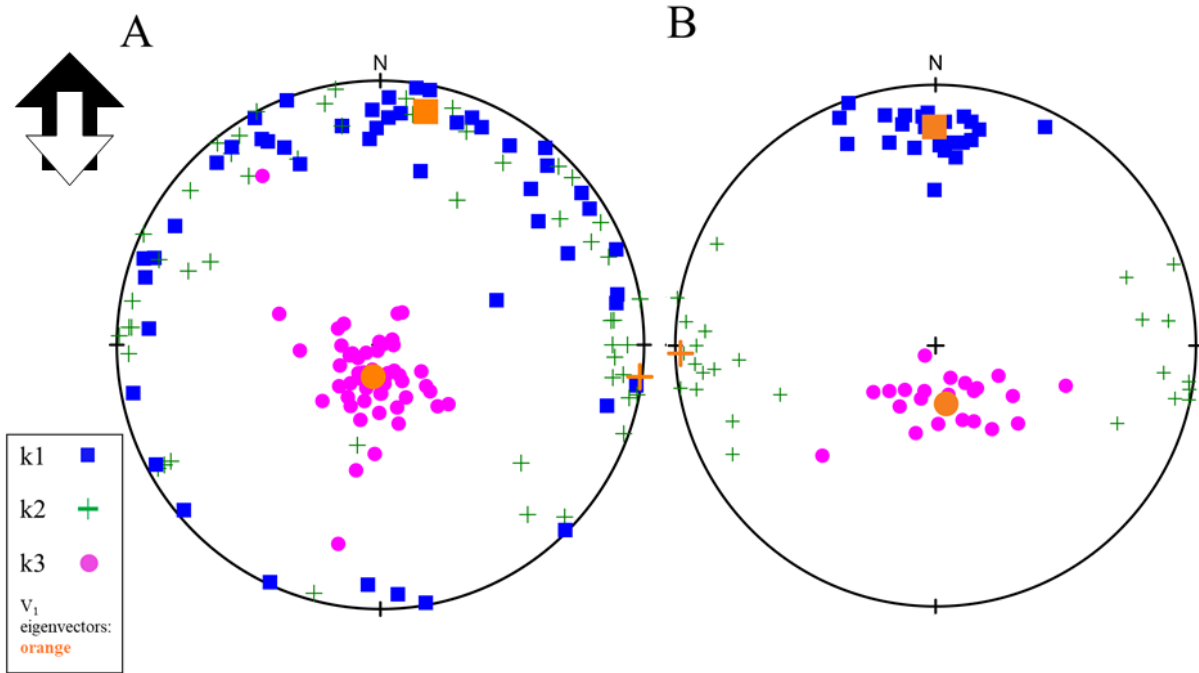
**Figure 7.** (A) Mud and sand of the Lønstrup Klint Formation thrust along a slickensided fault surface (dashed red line) and over sand of the Rubjerg Knude Formation, within the Grønne Rende section at Rubjerg Knude, thrust sheet GR10 (Fig. 2). The area of overthrust sediment outlined in yellow was sampled for AMS, at various distances from the fault surface. (B) The mud sheet of GR05 thrust along slickensided fault surfaces (red). AMS samples were collected at various distances from the fault over transects A, B and C.





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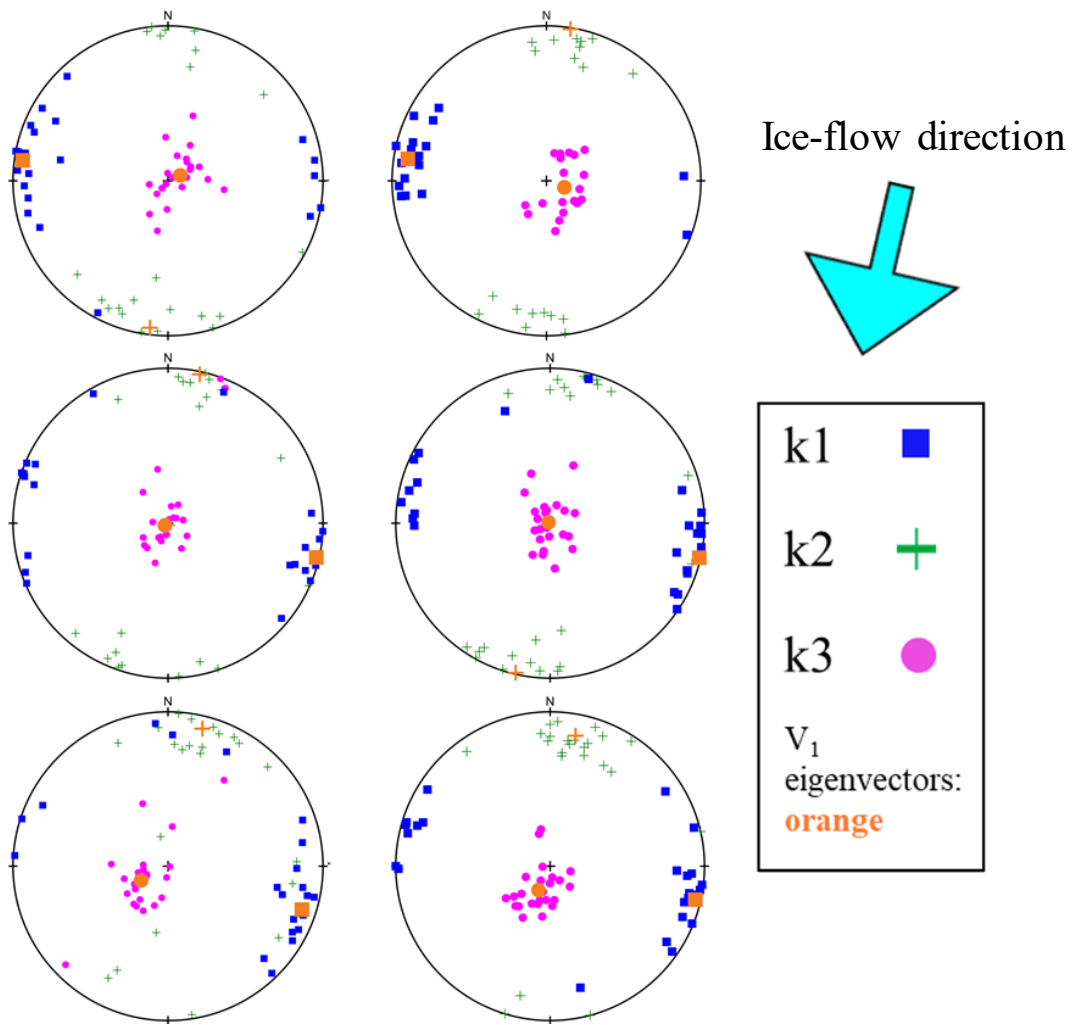
**Figure 8.** Upper Cretaceous chalk overlying glaciolacustrine mud of the Middle Weichselian at Møns Klint, with intervening fault indicated by the red dashed line. AMS samples were gathered along transects A-D. Dark grey areas are where fresh mud has been exposed for sampling; light grey areas are the weathered and un-sampled mud surface. Colluvium is in the foreground.



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**Figure 9.** (A) Orientations of the three principal magnetic susceptibilities of the mud from Rubjerg Knude after it had been sheared in a ring-shear device to a displacement of 0.6 m. Arrows at upper left indicate sense of shear. (B) Orientations of principal susceptibilities from a similar experiment conducted to a displacement of 0.5 m on a till deposited subglacially and derived from remobilized glaciolacustrine mud (Douglas till, Hooyer et al., 2008; Shumway and Iverson, 2009). Large orange symbols show  $V_1$  eigenvectors calculated from the principal-susceptibility distributions.

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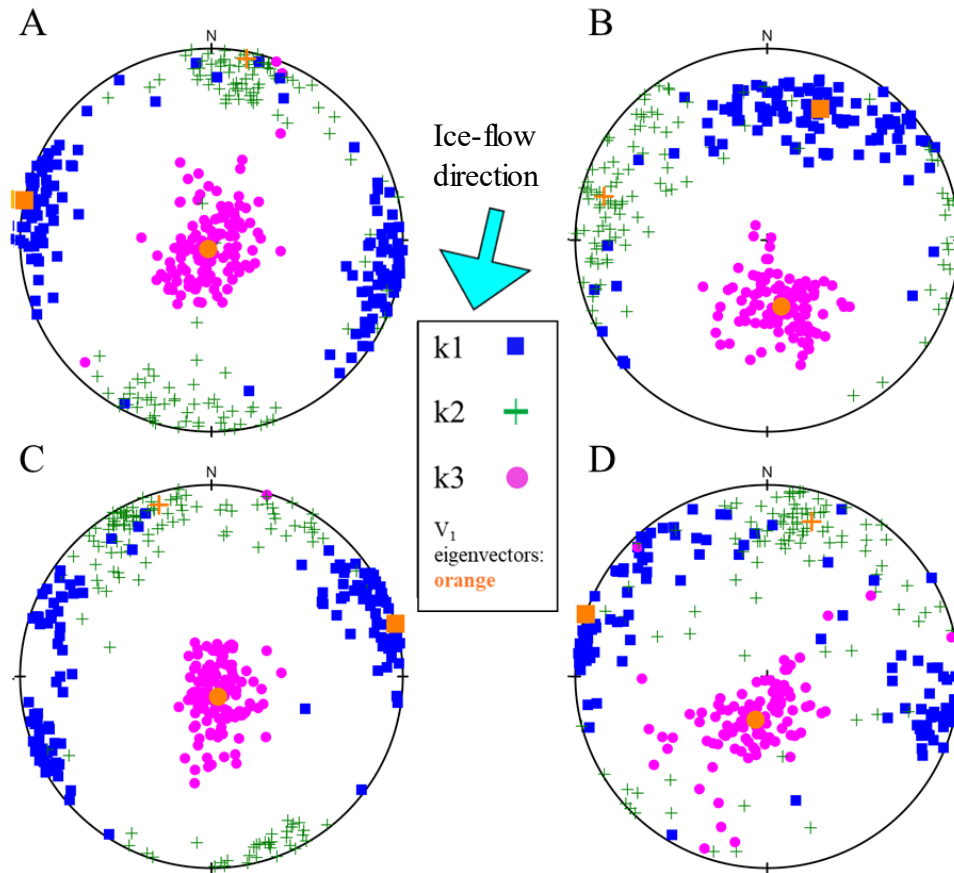
**Figure 10.** Principal-susceptibility orientations for the six fabrics from the distal end of the Rubjerg Knude thrust complex (Ulstrup section). Large orange symbols show  $V_1$  eigenvectors calculated from the principal-susceptibility distributions.

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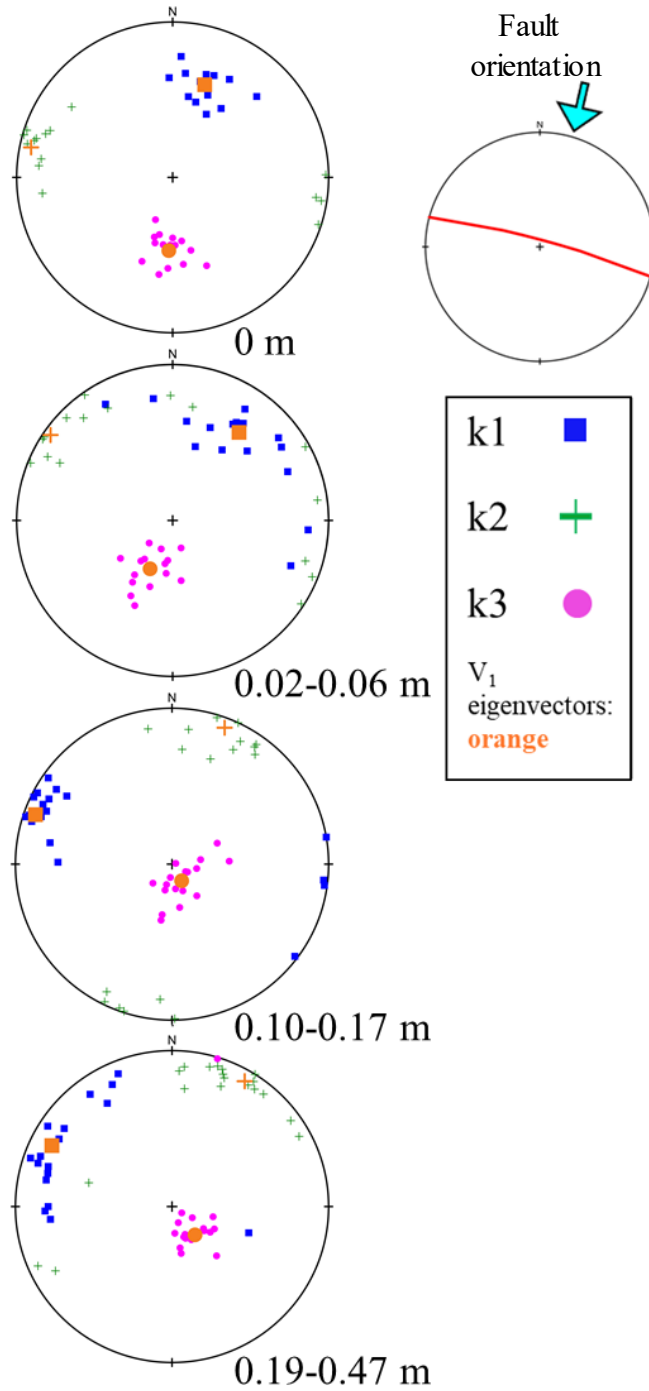
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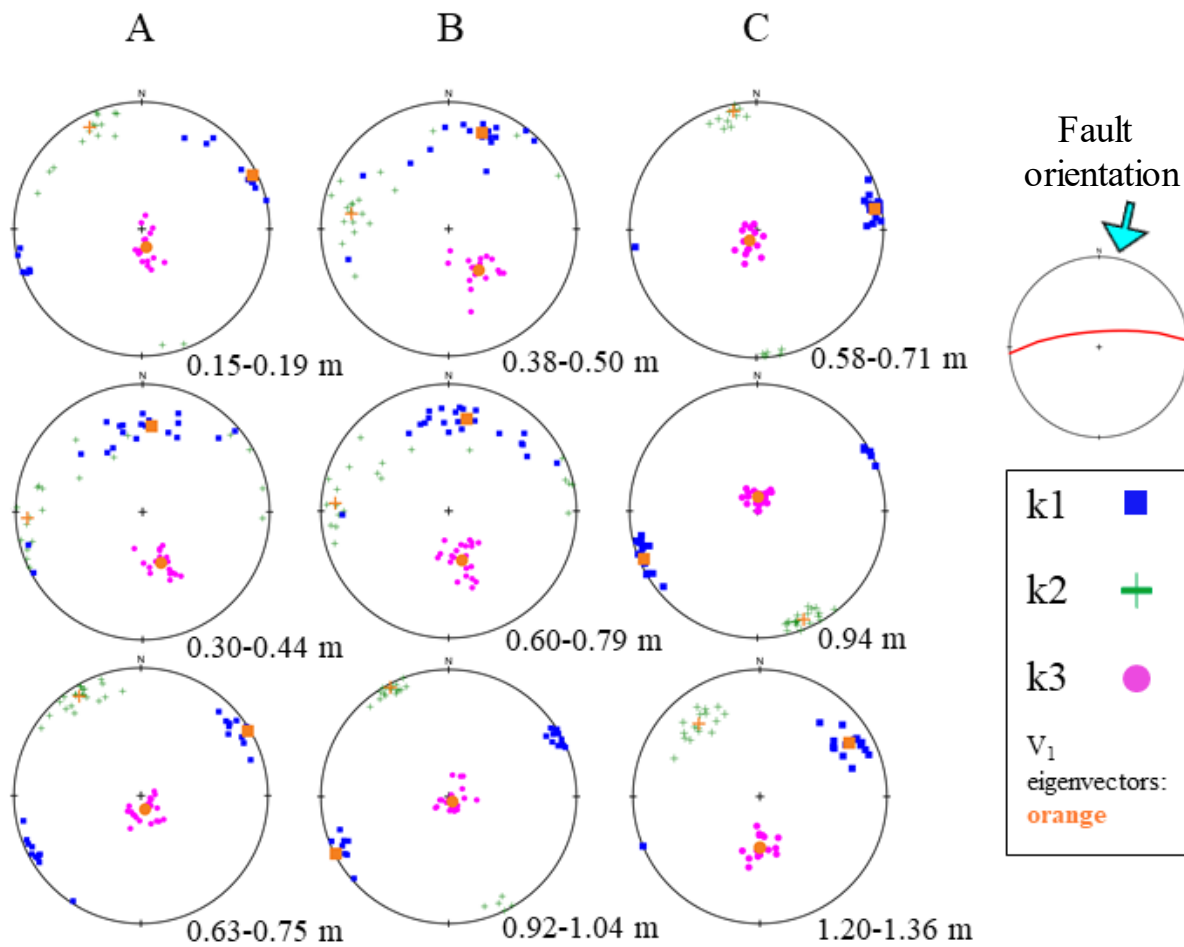
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**Figure 11.** Aggregated principal susceptibility orientations at Rubjerg Knude. (A) Principal-susceptibility orientations aggregated for fabrics from the distal end of the thrust complex (Ulstrup section).  $S_1$  values for  $k_1$ ,  $k_2$  and  $k_3$  are 0.86, 0.81 and 0.89, respectively. (B) Principal-susceptibility orientations aggregated for fabrics within  $\sim 0.1$  m and  $\sim 0.7$  m of the GR10 and GR05 fault surfaces, respectively, within the Grønne Rende section.  $S_1$  values for  $k_1$ ,  $k_2$  and  $k_3$  are 0.78, 0.77 and 0.92, respectively. (C) Principal-susceptibility orientations aggregated for fabrics more than 0.1 m and  $\sim 0.7$  m away from the GR10 and GR05 fault surfaces, respectively.  $S_1$  values for  $k_1$ ,  $k_2$  and  $k_3$  are 0.81, 0.80 and 0.92, respectively. (D) Principal-susceptibility orientations aggregated for fabrics from eroded dip-slope surfaces away from faults.  $S_1$  values for  $k_1$ ,  $k_2$  and  $k_3$  are 0.76, 0.73 and 0.85, respectively. Large orange symbols show  $V_1$  eigenvectors calculated from the principal-susceptibility distributions.



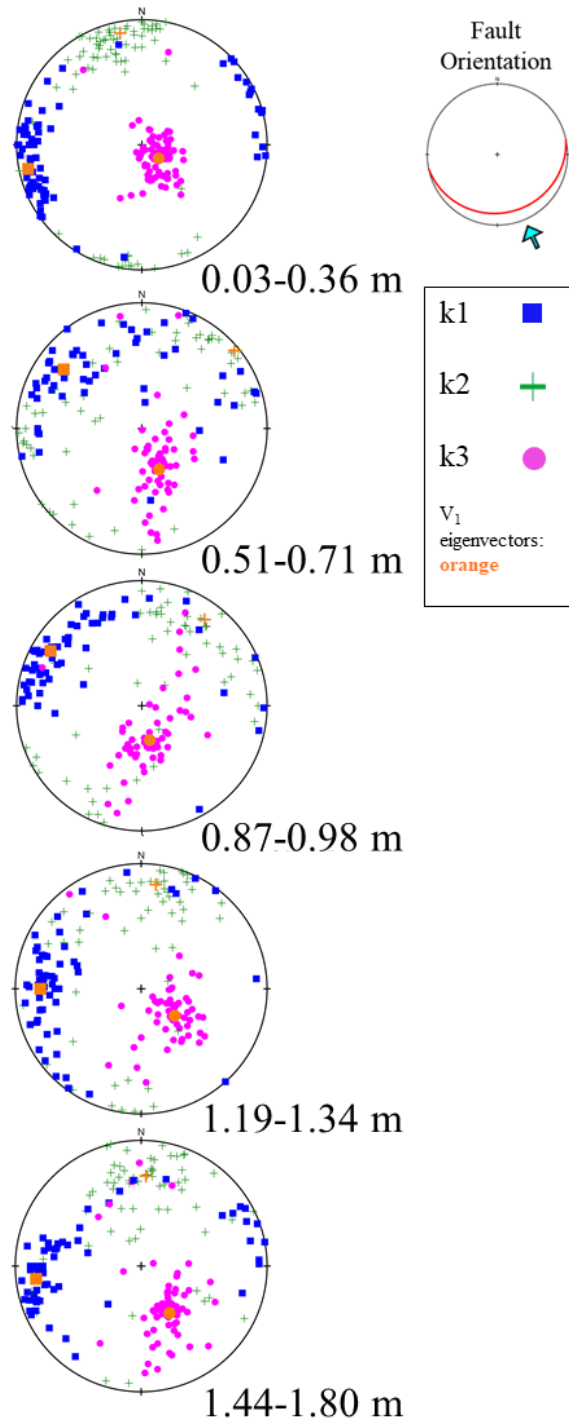
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**Figure 12.** Four fabrics from thrust sheet GR10 from the Grønne Rende section of Rubjerg Knude. Distances listed are relative to the adjacent fault surface. The fault orientation is shown in a lower-hemisphere stereonet at upper-right, and the cyan arrow shows the ice-advance direction. Large orange symbols show  $V_1$  eigenvectors calculated from the principal-susceptibility distributions.



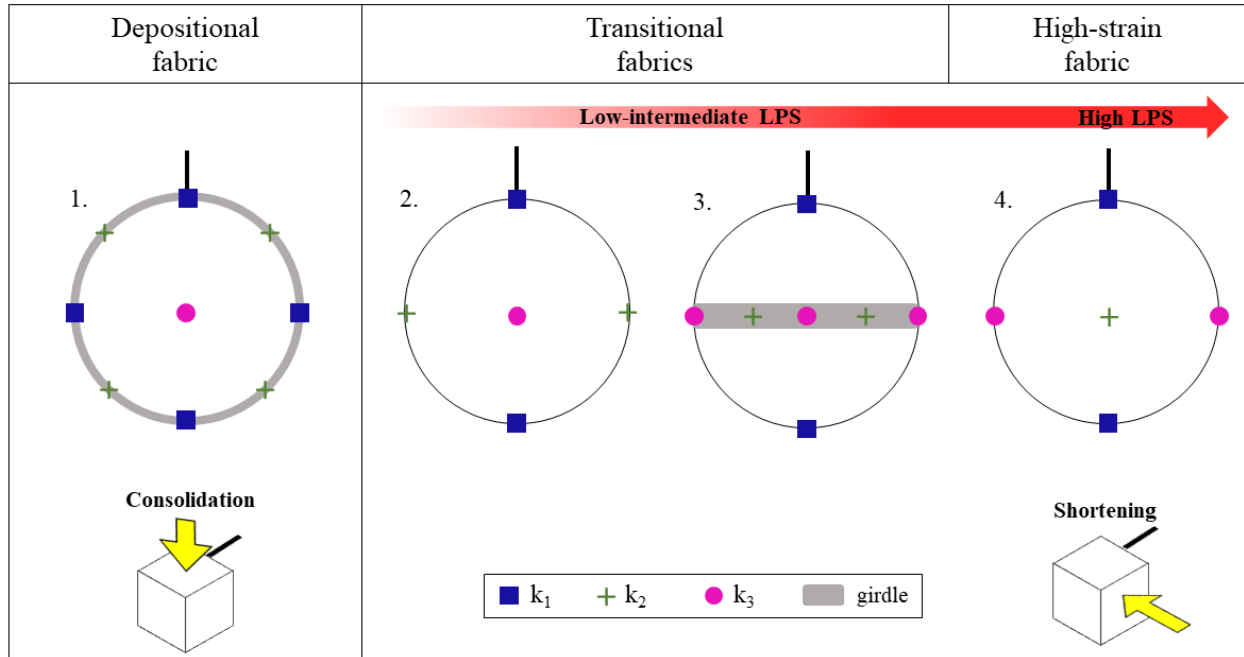
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**Figure 13.** Nine fabrics from transects A, B, and C in the thrust sheet GR05 from the Grønne Rende section of Rubjerg Knude (see Fig. 7B for transects). Distances listed are relative to the nearest fault surface. The fault orientation is shown in a lower-hemisphere stereonet at upper-right, and the cyan arrow shows the ice-advance direction. Large orange symbols show  $V_1$  eigenvectors calculated from the principal-susceptibility distributions.



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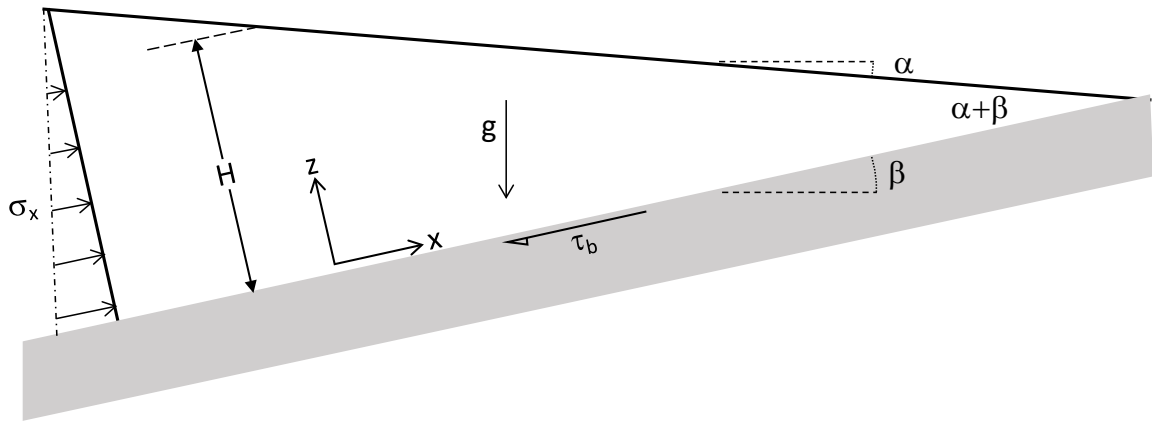
**Figure 14.** Principal-susceptibility orientations for 17 AMS fabrics collected in the four transects at Møns Klint (see Figure 8), aggregated for five distance ranges from the fault at the chalk-mud boundary. The fault orientation is shown in a lower-hemisphere stereonet at upper-right, and the cyan arrow shows the ice-advance direction. Large orange symbols show  $V_1$  eigenvectors calculated from the principal-susceptibility distributions.



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**Figure 15.** Model for AMS fabric development during deposition/consolidation and layer-parallel shortening (modified from Almqvist and Koyi, 2018).

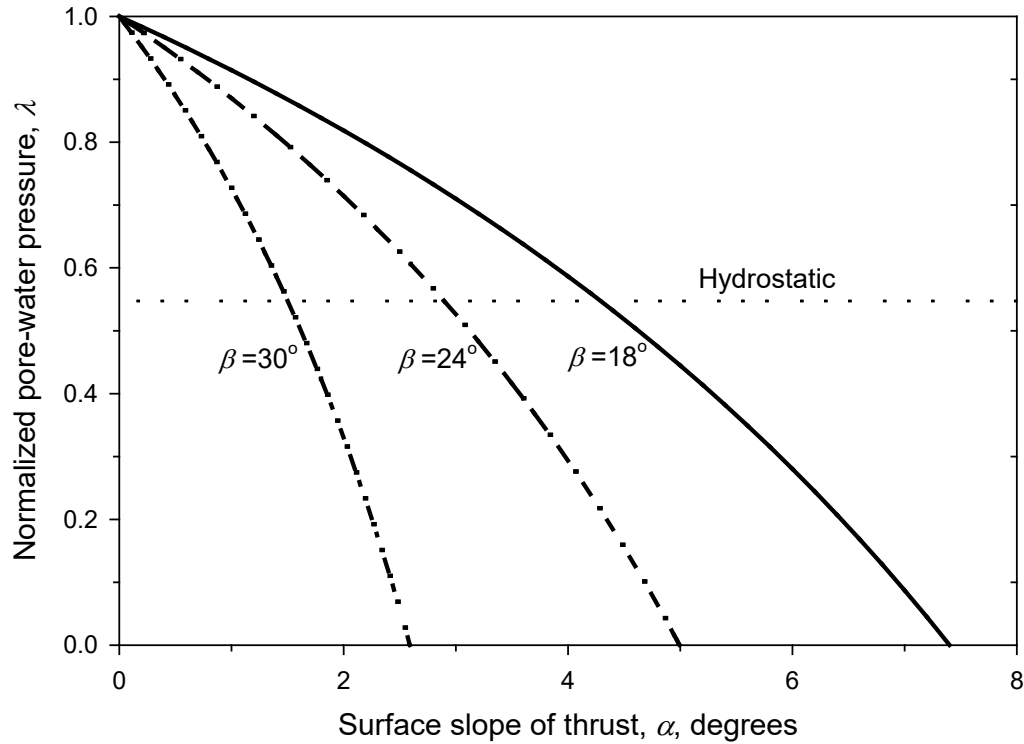




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**Figure 16.** Schematic diagram of a thrust wedge subject to a push,  $\sigma_x$  (modified from Davis et al., 1983).

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**Figure 17.** Threshold values of pore-pressure ratio,  $\lambda$ , and topographic slope of the thrust wedge,  $\alpha$ , above which slip is expected on thrusts without internal deformation of thrust sheets, for different values of thrust dip,  $\beta$ . Zero internal cohesion,  $\lambda_b = \lambda$ , and  $\mu_b = \mu = \tan \varphi$  are assumed, making estimates of  $\lambda$  and  $\alpha$  required for slip without internal deformation conservatively large. Also assumed are  $\sin \alpha \approx \alpha$  and  $\sin \beta \approx \beta$ , good to within 5% for the largest angles considered ( $\beta = 30^\circ$ ). The hydrostatic value of  $\lambda = p_w / \sigma_z$  is based on a groundwater table at the ground surface, a sediment porosity of 50%, and rock particle density of  $2700 \text{ kg m}^{-3}$ .

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1200 **Appendix Table and Figures**

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**Table A1.** - Parameters derived from hysteresis loop analyses of representative samples from Rubjerg Knude (RK3) and Møns Klint (MUN01)

Parameter	Symbol	Units	<i>Rubjerg Knude</i>	<i>Møns Klint</i>
			RK3	MUN01
Bulk low field magnetic susceptibility	$\chi_{LF}$	m <sup>3</sup> /kg	2.03 x 10 <sup>-7</sup>	1.69 x 10 <sup>-7</sup>
Saturation Magnetization	M <sub>S</sub>	Am <sup>2</sup> /kg	1.30 x 10 <sup>-2</sup>	2.54 x 10 <sup>-2</sup>
Saturation Remanent Magnetization	M <sub>RS</sub>	Am <sup>2</sup> /kg	1.29 x 10 <sup>-3</sup>	1.37 x 10 <sup>-3</sup>
Coercivity	$\mu_0 H_C$	mT	11.6	7.16
Coercivity of remanence	$\mu_0 H_{CR}$	mT	46.9	53.3
Squareness ratio	M <sub>RS</sub> /M <sub>S</sub>	--	0.083	0.054
Coercivity ratio	H <sub>CR</sub> /H <sub>C</sub>	--	4.04	7.43
Bulk high field magnetic susceptibility	$\chi_{HF}$	m <sup>3</sup> /kg	7.15 x 10 <sup>-8</sup>	1.93 x 10 <sup>-8</sup>
Magnetite concentration (calculated)	weight percent	%	0.014	0.028

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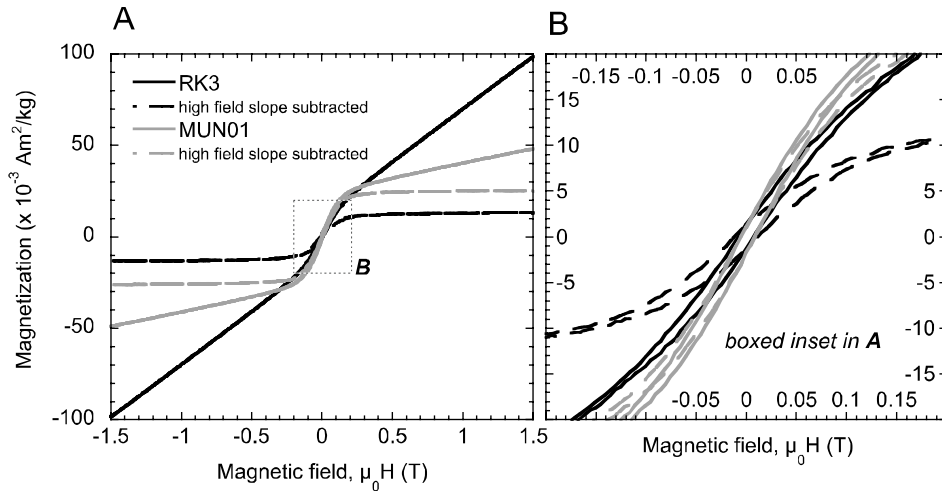
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1215 **Figure A1.** (A) Hysteresis loops for samples from Rubjerg Knude (RK3) and Møns Klint  
1216 (MUN01) before and after correction. (B) Detail of loops within inset shown in (A).

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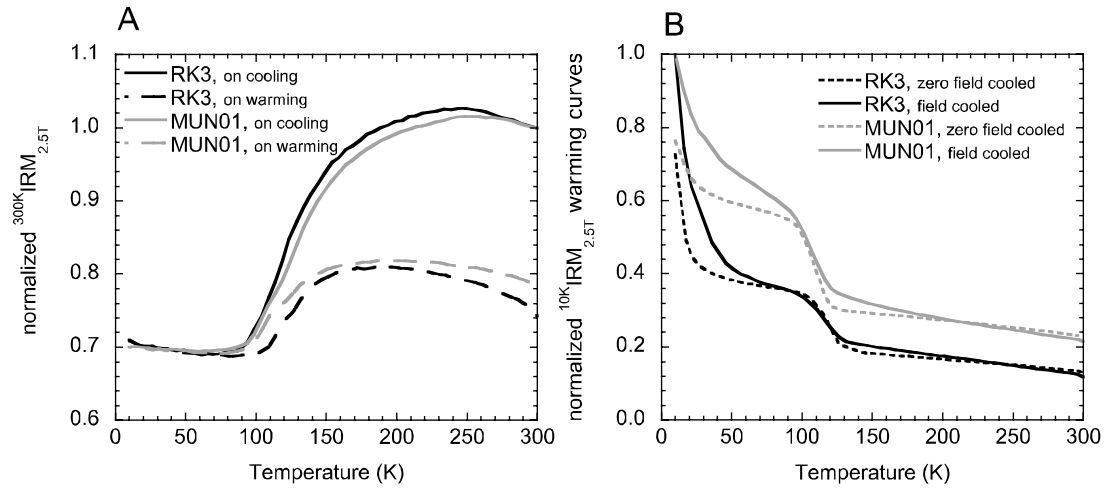
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1233 **Figure A2.** Results of low temperature experiments for samples from Rubjerg Knude (RK3) and  
1234 Møns Klint (MUN01). (A) 300 K IRM cooling and warming cycles. (B) IRM warming curves.

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