**Strain patterns in glacitectonically thrust sediments and
conditions during thrusting**

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Abstract

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

1. Introduction

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

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

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

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

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

2. Field settings

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

2.1. *Rubjerg Knude*

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

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

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

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

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

2.2. *Møns Klint*

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

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

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

3. Methods

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

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

3.1. AMS Sampling

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

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

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

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

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

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

3.2. AMS analysis

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

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

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

3.3. Ring-shear experiment

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

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

4. Results

4.1. Experiments

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

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

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

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

4.2. *Rubjerg Knude*

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

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

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

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

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

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

4.3. Møns Klint

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

5. Discussion

5.1. AMS fabric interpretation

In addition to our results indicating that the AMS of the thrust sheets is controlled by multi-domain or pseudo-single domain magnetite (Appendix), we have two means of interpreting AMS fabrics. Results from ring-shear experiments on the LKF mud and on tills provide a model for 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°) and plunge gently up-glacier;
350 those based on k_2 orientations are nearly perpendicular to the shearing direction (within 7°) 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

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

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

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

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

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

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

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

5.2. *Thrusting of intact sheets without permafrost*

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

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

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

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

where ρ is the density of the sediment grains of the wedge, and ρ_w is the density of pore water.

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

For the wedge to slip along its basal fault without deforming the wedge internally, the frictional stress resisting slip, S_b , at the base of the wedge must be less than τ_b . Defining μ_b and λ_b as the friction coefficient and water pressure ratio, respectively, at the base of the wedge,

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

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

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

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

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

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

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

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

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

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

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

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

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

6. Conclusions

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

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

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

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Appendix: Magnetic mineralogy

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

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

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

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

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

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

The hysteresis loop and first magnetization derived parameters are listed in Table A1 and hysteresis loops before and after correction shown in Figure A1. Low-field magnetic susceptibility, inclusive of all minerals, of RK3 and MUN01 are quite similar 20×10^{-8} and 17×10^{-8} m³/kg. However, the high-field magnetic susceptibility of RK3, which excludes ferromagnetic (sensus lato) that have saturated (primarily ferrimagnetic minerals), is more than 3 times the value for MUN01. Saturation magnetization values confirm the higher concentration of ferrimagnetic minerals in MUN01 with values twice those of RK3. Squareness and coercivity ratios of RK3 and MUN01 are in agreement with a population of ferrimagnetic magnetic domain sizes larger than single domain. Therefore, inverse AMS fabrics are not expected.

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

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

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

Figure captions

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

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)).

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.

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.

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.

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.

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.

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.

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.

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.

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 ~0.1 m and ~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 ~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 0.0.76, 0.73 and 0.85, respectively. Large orange symbols show V_1 eigenvectors calculated from the principal-susceptibility distributions.

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.

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.

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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Appendix Table and Figures

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	χ_{LF}	m ³ /kg	2.03 x 10 ⁻⁷	1.69 x 10 ⁻⁷
Saturation Magnetization	M _S	Am ² /kg	1.30 x 10 ⁻²	2.54 x 10 ⁻²
Saturation Remanent Magnetization	M _{RS}	Am ² /kg	1.29 x 10 ⁻³	1.37 x 10 ⁻³
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 _{RS} /M _S	--	0.083	0.054
Coercivity ratio	H _{CR} /H _C	--	4.04	7.43
Bulk high field magnetic susceptibility	χ_{HF}	m ³ /kg	7.15 x 10 ⁻⁸	1.93 x 10 ⁻⁸
Magnetite concentration (calculated)	weight percent	%	0.014	0.028

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