

3D microstructural architecture of deformed glacial sediments associated with large-scale glacitectonism, Jasmund Peninsula (NE Rügen), Germany

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Abstract

The Wissower Bach Syncline on the Jasmund Peninsula (NE Germany) has been examined to understand the complicated glacitectonic environment in the southern Baltic Sea region, comprising folds and thrust faults from the Weichselian Pleniglacial. Soft-sediment thin sections from a SW-dipping thrust fault at the southwestern limb of the syncline between Cretaceous chalk (hangingwall) and Pleistocene deposits (footwall) were analysed using micromorphology and microstructural mapping. Within the diamicton bounding the fault, three different clast microfabrics were distinguished: an older, but dominant S1 fabric; a second S2 foliation orientated perpendicular to S1; and a younger subvertical S3 fabric. These fabrics developed during large-scale folding and thrusting, subsequent fabric rotation adjacent to the thrust fault accompanied by dewatering of the diamicton and extension; the latter implying late-stage reactivation and gravitational relaxation at the southwestern limb of the syncline as the ice retreated. The combination of a 3D microstructural model and the macroscale information has led to the development of a detailed model for the evolution of the Wissower Bach Syncline during glacitectonism and the localised reactivation of the associated thrusts in response to ice retreat. Moreover, this methodology provides a robust dataset on which to interpret the structural evolution of glacitectonic complexes.

Keywords: Isle of Rügen, 3D microstructural architecture, microfabrics, glacitectonics, Weichselian Pleniglacial

Introduction

Large-scale glacitectonic deformation, resulting in locally significant disruption and shortening of both bedrock and sedimentary sequences, has been reported from a number of previously glaciated areas, including North America (e.g. Moran *et al.*, 1980; Bluemle and Clayton, 1984), the United Kingdom (e.g. Harris *et al.*, 1995, 1997; Thomas and Chiverrell, 2007; Phillips *et al.*, 2008; Burke *et al.*, 2009) and northern Europe (e.g. van der Wateren, 1986; van der Wateren *et al.*, 2000; Huuse and Lykke-Andersen, 2000; Pedersen, 2005, 2014). The detailed analysis and interpretation of the structural features developed within these glacitectonic complexes, employing the techniques routinely used by structural geologists, has not only led to a more systematic approach to investigation of complicated polydeformed glacial sequences, but also provides important information on the character of these deformation events and their relationship to glacier/ice sheet dynamics (e.g. Benn and Evans, 1996; Pedersen, 2005, 2014; van der Wateren *et al.*, 2000; Phillips *et al.*, 2002; Lee and Phillips, 2008; Benediktsson *et al.*, 2008; Phillips *et al.*, 2008). Microstructural analysis, in combination with field macroscale studies, is also increasingly being used as a principal tool for investigating the progressive development of folds, faults and foliations resulting from subglacial and proglacial deformation (e.g. van der Meer *et al.*, 2003; Menzies, 2000; Phillips and Auton, 2000; van der Wateren *et al.*, 2000; Menzies *et al.*, 2006; Phillips *et al.*, 2007; Lee and Phillips 2008; Denis *et al.*, 2010; Vaughan-Hirsch *et al.*, 2013; Narloch *et al.*, 2012, 2013), as well as investigating the role played by pressurised melt water during glacier induced deformation (Hiemstra and van der Meer, 1997; Baroni and Fasano, 2006; Phillips and Merritt, 2008; van der Meer *et al.*, 2009; Denis *et al.*, 2010; Phillips *et al.*, 2012; Narloch *et al.*, 2012, 2013).

Germany's largest island, the Isle of Rügen, located in the SW-Baltic Sea (Fig. 1a) is well-known for large-scale glacitectonic folding and thrusting (Groth, 2003; Müller and Obst, 2006; Ludwig, 2011), which is well-exposed in the steep sea cliffs along its eastern and southeastern coast (Fig. 1). This glacier-induced deformation affected not only the Pleistocene glacial sediments, but also the chalk bedrock and is widely considered to have occurred during the Weichselian (Devensian) glaciation of the region (Groth, 2003; Müller and Obst, 2006; Ludwig, 2011). The deformation structures on the Jasmund Peninsula in the NE of the Isle of Rügen (Fig. 1) have been intensively investigated for more than a century (Credner, 1892; Gripp, 1947; Bülow, 1955; Groth, 2003; Müller and Obst, 2006; Ludwig, 2011). Recent work by Groth (2003), Müller and Obst (2006), and Ludwig (2011) have provided a contradictory structural interpretation of the glacitectonic evolution of the peninsula.

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3 Unravelling the complex deformation history recorded by the rocks and sediments of the
4 Jasmund Peninsula, however, is critical to our understanding of ice sheet dynamics in this part
5 of the Baltic Sea during the Weichselian (Devensian).
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8 This paper presents the results of a detailed structural study of the polydeformed
9 glacigenic sediments present within the core of the Wissower Bach Syncline on the Jasmund
10 Peninsula (Figs. 1b and c). The combination of macro (field) and microstructural
11 (micromorphology) techniques is used to investigate the processes active during large-scale
12 folding of the Pleistocene sediments and chalk bedrock affected by the Wissower Bach
13 Syncline. Orientated, large format thin sections of the diamicton exposed immediately
14 adjacent to the contact with the folded chalk bedrock are used to investigate ductile shearing
15 along this major lithological/rheological contact and to construct detailed models of the 3D
16 fabric geometries developed within these sediments. This information is used to develop a
17 progressive deformation model for large-scale fold development in this part of the Jasmund
18 Peninsula and relating it to ice sheet dynamics. The combination of a 3D microstructural
19 analysis and the macroscale information gives rise to a detailed model of the evolution of this
20 glacitectonic complex and provides new information, which is not recognisable at macroscale.
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30 **Location of the study area and its geological setting**

31 The Wissower Bach Syncline (see Steinich, 1972), the focus of this study, is situated on the
32 southeastern coast of the Jasmund Peninsula, 1.5 km northeast of Sassnitz on the Isle of
33 Rügen (Fig. 1). It is exposed in a c. 200 m wide and 40 m high section of sea cliffs (Fig. 2).
34 This syncline (axial surface dips to the SW, 200-250/45-50) is one of a number of large-scale
35 folds and associated thrusts which form an imbricate thrust stack, or duplex, deforming both
36 the Upper Cretaceous (Maastrichtian) chalk bedrock and overlying unconsolidated
37 Pleistocene glacigenic deposits (Credner, 1892; Gripp, 1947; von Bülow, 1955; Groth, 2003;
38 Ludwig, 2011). The large-scale and structural characteristics of the Jasmund thrust-fold
39 complex are comparable to many of the large glacitectonic complexes described in areas of
40 former glaciated terrain, such as Møns Klint in SE Denmark (Pedersen, 2000; Pedersen and
41 Gravesen, 2009; Pedersen, 2014).
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50 The glacial deposits exposed at the Jasmund study area have been subdivided into at
51 least three tills (M1 to M3) with intercalated units (I1 and I2) comprising gravel, sand and
52 clay. The regional stratigraphic correlation of the individual tills and their relationships to the
53 interbedded sediments is still under debate (see Kenzler *et al.*, 2015 and references therein).
54 The older M1 till is widely thought to have been deposited during the Saalian (Wolstonian)
55 glaciation (Marine Isotope Stage (MIS 6) (Panzig, 1995; Müller and Obst, 2006) and is
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3 interpreted as a subglacial traction till (Evans *et al.*, 2006). No unequivocal Eemian aged
4 sediments (MIS 5e) have been identified in the Jasmund cliff sections (Steinich, 1992;
5 Ludwig, 2006). The majority of the Pleistocene sedimentary record (I1, M2, I2 and M3; Fig.
6 2) of the Jasmund Peninsula is considered to have been laid down during the Weichselian
7 glaciation when the Scandinavian Ice Sheet extended southwards across the Baltic Sea and
8 into northern Europe. In this part of the Baltic Sea the Weichselian glaciation has been
9 divided into three ice advances; the Brandenburg/Frankfurt phase (W1, oldest), the
10 Pomeranian phase (W2) and finally the Mecklenburg phase (W3, youngest) (Katzung and
11 Müller, 2004; Müller, 2004; Litt *et al.*, 2007; Janke and Niedermeyer, 2011). These three
12 phases resulted in the deposition of regionally extensive till sheets intercalated by interstadial
13 sediments (Groth, 1969; Ludwig, 2005; Müller and Obst, 2006; Panzig, 1995; Janke and
14 Niedermeyer, 2011). While the M2 till at Jasmund has been assigned to the
15 Brandenburg/Frankfurt W1 phase, the age of the M3 till is poorly constrained and has
16 previously been correlated with either the Pomeranian W2 ice advance, or locally the
17 Mecklenburg W3 phase. If the regional correlations are correct, it would suggest that the
18 formation of the glacitectonic complex of Jasmund post-dated the deposition of the M2
19 diamicton and the I2 sands and gravels, and therefore the Brandenburg/Frankfurt W1 advance
20 phase. Consequently, glacitectonism of the Jasmund Peninsula probably occurred after the
21 Last Glacial Maximum (MIS 2), with large-scale folding and thrusting occurring in response
22 to a re-advance of the Scandinavian Ice Sheet during the Pomeranian W2 phase (around 18.5
23 – 16.0 ka) (Groth, 2003; Müller and Obst, 2006).

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38 One striking feature of the Jasmund Peninsula seen on the digital elevation model
39 (DEM) of the area is the sequence of SW-NE-trending ridges in the southern part of the
40 region (southern structural complex), and approximately NW-SE-trending landforms in the
41 north (northern structural complex) (Fig. 1c). Given that deposits relating to the Mecklenburg
42 W3 phase are only locally preserved/developed, if at all, it can be argued that these landforms
43 are also related to the Pomeranian W2 phase ice advance. Previous workers (Credner, 1892;
44 Gripp, 1947; von Bülow, 1955; Groth, 2003; Ludwig, 2011) have divided the Jasmund
45 glacitectonic complex into northern and southern zones, with these structural “domains”
46 broadly corresponding to landform assemblage zones observed on the DEM (see Fig. 1c).
47 Ludwig (2011) has suggested that the Jasmund glacitectonic complex, which includes the
48 Wissower Bach Syncline, developed at the confluence of two major ice streams which were
49 active during the Pomeranian W2 phase. In this model, the Jasmund Peninsula would have
50 formed a topographic high or nunatak which at least initially separated the Baltic ice into two
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3 ice streams. Pressure formed between the two competing flows resulted in folding and
4 thrusting of the chalk bedrock and its Pleistocene cover, as well as the formation of the
5 associated landforms (composite ridges) as the peninsula was progressively inundated by ice
6 from both the northeast and southeast (see Fig. 1c).
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10 **Methods**

11 The structural architecture of the Wissower Bach Syncline and the deformation history
12 recorded by glacial sediments and pre-glacial chalk bedrock exposed on the limbs of this
13 major glacitectonic structure, have been investigated using a range of macroscale techniques.
14 The section was described on the basis of its macroscale features with particular emphasis
15 being placed on recording the type of bedding, sediment-type, bed geometry and structure
16 (both sedimentary and glacitectonic). The orientation of the bedding planes on both limbs of
17 the fold, the main fault, and flint bands within the hangingwall were recorded from a number
18 of points along the length of the section (dip direction/dip). These data were plotted on lower
19 hemisphere stereographic projections (Fig. 3) using the open source software OpenStereo
20 (Grohmann and Campanha, 2010). These data were integrated with previously published
21 information from the area (Steinich, 1972). Overlapping photographs were taken of the cliff
22 (at a distance of 500 m from the cliff face) enabling the analysis of the larger-scale syncline
23 (Fig. 2). Additionally, the digital elevation model (DEM) of Jasmund (Fig. 1c), which is
24 based on LiDAR data provided by the LAiV M-V, has been consulted to place the results
25 from the microstructural mapping and the local macroscopic structural investigations at the
26 Wissower Bach Syncline within the broader context of regional ice sheet dynamics.
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38 The chalk at the glacitected boundary and the underlying diamicton were sampled
39 for detailed microstructural analysis. Prior to sampling the sections at both sites were logged,
40 photographed and described in detail (Fig. 4) with particular emphasis being placed on
41 recording the macroscale variation in lithology and structure of the diamictons. In order to
42 examine the range of microstructures developed associated with the partitioning of
43 deformation along this glacitected boundary two orientated blocks (JA03, JA04) were
44 collected; (i) sample JA03 includes the boundary between the chalk and diamicton enabling
45 deformation within the bedrock to be directly compared with the adjacent diamicton; and (ii)
46 sample JA04 is of the apparently massive diamicton approximately 10 cm below this contact
47 (Fig. 2 inset b). The samples were taken using 10 cm cubed Kubierna tins which were cut
48 (using a knife) into the face in order to limit sample disturbance (see van der Meer, 1993;
49 Menzies, 2000). The position of the sample within the glacial sequence, its orientation
50 relative to magnetic north, depth and way-up were marked on the outside of the tin during
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3 collection. Each sample was then removed from the face and stored in a drying furnace (c. 25
4 °C) for at least two weeks to get rid of pore water residues in a gentle way prior to sample
5 preparation.
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8 Samples were impregnated involves the impregnation with polyester resin and stored
9 in a vacuum drying oven (c. 25 °C, 700-800 mbar) for c. two weeks, then six weeks outside
10 the oven, hence allowing the resin to cure. Large format orientated thin sections were taken
11 from the centre of each of the prepared samples, thus avoiding artefacts associated with
12 sample collection. Three mutually perpendicular thin sections were cut from each sample to
13 allow the detailed examination of the microstructures in 3 dimensions (see Phillips *et al.*,
14 2011). The thin sections were examined using a petrological microscope with the terminology
15 used to describe the various microtextures following that proposed by van der Meer (1987,
16 1993) and Menzies (2000). Detailed microstructural maps and quantitative data for the clast
17 microfabrics developed within the diamicton layers were obtained using the methodology of
18 Phillips *et al.* (2011) (also see Vaughan-Hirsch *et al.*, 2013; Phillips *et al.*, 2013). This
19 microstructural mapping approach was used alongside existing methods of analysis resulting
20 in the detailed microstructural and sedimentological analysis of the glacial sediments.
21 Plotting of the orientation data obtained for the long axes of fine sand to pebble sized clasts
22 (skeleton grains) within the diamictons on rose diagrams was carried out using the open
23 source software OpenStereo (Grohmann and Campanha, 2010). Successive generations of
24 fabrics (S1, S2, ...Sn) are distinguished by the nomenclature normally used in structural
25 geological studies (S1 earliest fabric to Sn latest). However, this nomenclature does not
26 necessarily imply that these structures were developed in response to separate deformation
27 events (D1, D2, ...Dn).
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42 **Sedimentary sequence and macroscale deformation structures**

43 The Wissower Bach Syncline (54°31. 923' N, 13°40.697' E) preserves a comprehensive
44 Pleistocene sedimentary record that is representative for the southern structural domain of
45 Jasmund. It is bounded at its base by an angular unconformity with a very low angle of
46 discordance, truncating the Maastrichtian chalk. The Pleistocene succession is most clearly
47 exposed and studied at the northeastern limb of the syncline, where it has been divided into
48 M1, I1, M2, I2 and M3 units (Figs. 2 and 4) (adapted from Jaekel, 1917).
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53 At the base of the sequence, the **M1** diamicton para-conformably overlies the chalk
54 (Figs. 2 and 4 (see inset c)). This dark grey to red-brown (at top of unit), sandy to gravelly
55 diamicton (c. 2.5 m thick; Fig. 4) is well jointed and possesses a clayey to silty matrix. The
56 gravels and coarse sands are predominantly composed of Palaeozoic limestone as well as
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3 granite and gneiss. Boulder-sized clasts comprising granite and gneiss are only a minor
4 component and appear to be concentrated at the base of the diamicton where it also contains
5 stringers or streaks of deformed chalk derived from the underlying bedrock. M1 also contains
6 a number of light grey, lenticular, channel-like units composed of clast-supported gravel
7 containing cobbles of limestone and crystalline rocks in a silt/clay matrix. The composition of
8 the gravel is comparable to the M1 diamicton, the key difference between the two sediments
9 being their depositional fabric.
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14 The M1 diamicton is conformably overlain by a composite sequence (**I1**) of sands and
15 gravels including a 2 m thick unit of clay. The sand unit representing the lower part is 2.5 to 3
16 m thick and preserves an overall fining-upwards sequence (Fig. 4). At its base, a clast-
17 supported cobble layer (clasts c. 10 to 15 cm diameter) occurs with a brown, silty to fine-
18 grained sand matrix. It is directly overlain by a bedded sequence of light brown to white,
19 parallel-laminated, fine-grained sand containing thin interbeds of medium-grained sand with
20 scattered clasts of coarse sand to fine gravel. Additionally, the sands contain out-sized
21 boulders (up to 30 cm in diameter) of crystalline rocks (gneiss, granite), which are
22 concentrated within a discrete layer or lens at a height of c. 4 m above the base of the cliff
23 (Fig. 4). The lower part of the sandy sequence is interrupted by a folded layer (c. 20 cm thick)
24 of brown-grey clay. Above this deformed layer, however, I1 is undisturbed and composed of
25 cross- to ripple-laminated, fine-grained sand (see Fig. 4), intercalated with several brown-grey
26 coloured silt/clay layers (c. 5 cm thick). The sands are locally oxidised resulting in a
27 yellowish to red-brown stain (see Fig. 4 inset b).
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38 The fining upward sand unit is overlain by a c. 2 m thick grey clay (Fig. 4). On the
39 northeastern limb of the syncline, the lower part of the clay unit is light grey in colour and
40 possesses a fine lamination. This passes upwards into a c. 90 cm thick layer of grey-brown
41 clay. However, on the southwestern limb this lamination is absent. Large out-sized clasts
42 locally occur, and range from coarse sand to gravel, as well as rare cobbles. The clays are
43 directly overlain by a second unit of light brown, fine-grained sands (Fig. 4). This upper I1
44 sand is much thinner than the lower sand and appears to be laterally discontinuous, possibly
45 being cut out by the base of the overlying M2 diamicton.
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51 The I1 deposits are in turn overlain by a 10 to 15 m thick massive, grey-brown
52 diamicton, **M2** (Fig. 4), which forms the core of the Wissower Bach Syncline (Fig. 2). This
53 diamicton has a silty matrix and contains relatively common coarse gravel to boulder sized
54 clasts, mainly comprising granite, gneiss and limestone. A number of gravel and sand lenses
55 are also present. In detail the M2 diamicton can be divided into two (see Ludwig, 1964;
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3 Panzig, 1995): (i) a lower, clast-poor M2 α (m2-2u) subunit which is grey-blue to grey-brown
4 in colour with a clayey matrix; and (ii) an upper, more clast-rich, sandy M2 β (m2-2o)
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6 diamicton.
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8 The **I2** sands and gravels form a narrow (1 to 2 m thick; Fig. 4) poorly exposed unit
9 within the core of the Wissower Bach Syncline (Fig. 2). These sediments occur near the upper
10 rim of the cliff section and were not accessible for detailed analysis.
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12 At the top of the cliff section the Wissower Bach Syncline is truncated by the erosive
13 base of the later **M3** sedimentary complex (Figs. 2 and 4). This light grey-brown, sandy
14 diamicton contains large boulders of crystalline rocks, as well as a very high proportion of
15 flint clasts and deformed stringers or streaks of chalk. It is characterised by internal folds and
16 interfingering of light brown and darker streaks. Additionally, the M3 diamicton contains
17 lenticular, channel-like features (mainly at its base) filled by stratified coarse cobble and
18 gravel (Fig. 4 inset a), comprising crystalline rocks and flint.
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20 The lithostratigraphic units **M1** and **M2**, which are both characterized by diamictic
21 lithologies, are interpreted as till units mainly formed by traction (lodgement and
22 deformation) and more rarely by melt-out in a subglacial environment. The M1 till includes
23 rafts of glacitectonised chalk and covers a boulder pavement, which is an erosional lag
24 deposit predating the deposition of the M1 till.
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26 The composite **I1** unit comprises glacialfluvial and glaciallacustrine deposits. The fining-
27 upward sequence within the lower part of the unit indicates an accumulation mainly
28 controlled by the melting and retreating M1 glacier. Clay beds are formed at quieter
29 conditions (standing water) and during low sediment input. Out-sized clasts and boulders of
30 crystalline rocks are interpreted as dropstones derived from melting brash ice or icebergs. The
31 sediments of the poorly exposed I2 unit are primarily formed by glacialfluvial accumulation,
32 which can be derived from coeval deposits in neighbouring outcrops at the sea cliff.
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34 The (inaccessible) **M3** sedimentary complex includes a subglacial traction till. Parts of
35 the diamictic sediments, however, may have been formed by debris flows supplied from the
36 raised chalk ridges. This is indicated by the high amount of locally-derived materials such as
37 chalk and flint pebbles. The channel fills at the base of the unit are interpreted as (subglacial)
38 melt-out deposits.
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40 The M3 unit exposed at the upper cliff margin is preserved as an undisturbed,
41 horizontally stratified succession, whereas the older sedimentary record, cropping out below
42 the base-M3 disconformity, is structurally deformed (Fig. 2). In the NE part of the studied
43 cliff section, the chalk and the overlying record consisting of units M1 to I2 form a para-
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3 conform succession dipping to the SW. Its stratigraphic younging direction is upward and
4 towards SW. In the SW part of the cliff section, the succession from M1 to I2 is still dipping
5 to the SW but overturned (Figs. 2 and 3d) as indicated by inverted syn-depositional
6 sedimentary structures and other way-up criteria. In this part of the outcrop, the younging
7 direction is downward and towards NE, which is recognized by the lithostratigraphic order
8 and the fining-up of the lower I1 sequence. Consequently, the Cretaceous chalk and the
9 Pleistocene M1-to-I2 record display a NE-verging syncline that is truncated at the base of the
10 M3 unit. The fold closure is located within the I2 unit.

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16 The NE-verging Wissower Bach Syncline is very tight to isoclinal, moderately
17 inclined, and deforming both the Upper Cretaceous (Maastrichtian) chalk bedrock and
18 unconsolidated pre-M3 Pleistocene glacial deposits (Fig. 2). The northeastern limb is
19 orientated at c. 247/50 SW and is the right-way-up (Fig. 3) with the Pleistocene glacial
20 sequences resting paraconformably upon Maastrichtian chalk bedrock. Primary bedding
21 within the chalk is preserved by laterally extensive flint bands (Fig. 2) and dips to SW
22 (250/45 SW; Fig. 3b). On the southwestern limb of the fold (c. 203/44 SW; Fig. 3a), on
23 contrary, this sequence is overturned/inverted (Figs. 2 and 3d). The former lithostratigraphical
24 boundary between the chalk and the Pleistocene record has been modified by a SW/WSW-
25 dipping (260/50 WSW; Fig. 3c) reverse fault. This fault produced a sharp to wavy boundary
26 marked by a thin glacialite composed of chalk and streaks/stringers of the M1 diamicton
27 (see Fig. 2 inset a). The core of the syncline is largely obscured by debris (Fig. 2); the hinge
28 of this fold occurs below sea level. No small- and/or meso-scale parasitic folding of either the
29 chalk or glacial sediments have been recognised associated with the large-scale syncline at
30 Wissower Bach (see Fig. 2).

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41 The Wissower Bach Syncline is a NW-SE trending structure. It is located within the
42 southern structural domain of Jasmund, which is dominated by a series of SW-NE-trending
43 ridges (Fig. 1c) turning into a WNW-ESE trend close to the studied coastal cliff section (see
44 Fig. 1). These composite ridges reflect the “structural grain” of the underlying glacialite
45 Pleistocene sediments and chalk bedrock.

52 **Micromorphology and microstructural analysis**

53 Two samples of the M1 diamicton exposed on the overturned SW-limb of the Wissower Bach
54 Syncline were taken for micromorphological and microstructural analysis: (i) sample JA03
55 includes the faulted and tectonised contact between the chalk and the diamicton; and (ii) the
56 lower sample JA04 is located within the M1 diamicton approximately 10 cm below the fault
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3 boundary (see Fig. 2 inset b). A number of thin sections were prepared from each sample
4 (sample JA03: x4 vertical thin sections JA03.1, JA03.2, JA03.3, JA03.4 and x2 horizontal
5 sections J03.5, JA03.6; and sample JA04: x3 vertical sections JA04.1, JA04.2, JA04.3 and x1
6 horizontal section JA04.5) to enable the relationships between the various microstructures and
7 clast microfabrics developed within the diamicton to be examined in three dimensions. The
8 range of microstructures observed within the diamicton and chalk are shown in figures 5 and
9 6. Representative microstructural maps of a number of thin sections are illustrated in figures 7
10 to 12.

17 *Micromorphology of the M1 diamicton and chalk*

18 In thin section the M1 diamicton is composed of apparently massive, relatively fine-grained,
19 matrix-supported sand with a grey-brown silty-clay matrix (Fig. 5). The coarse silt to sand-
20 grade clasts (skeleton) are predominantly sub-angular to angular in cross-section with a low
21 sphericity (Fig. 5a, b c and d). However, subrounded to well-rounded grains are also present
22 (Figs. 5e and f) with the rounded nature of these polycyclic clasts probably being inherited
23 from the source rock/sediment. The clasts are mainly composed of monocrystalline quartz as
24 well as subordinate amounts of polycrystalline quartz and feldspar. The larger detrital grains
25 (>500 μm) also include plutonic igneous (granite) and sedimentary (limestone) lithic (rock)
26 fragments (see Figs. 5c to f).

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28 Arcuate and roughly circular alignments and clusters of sand grains are locally present
29 within the diamicton (Figs. 5a and b) and are interpreted as turbate structures formed in
30 response to ductile deformation (c.f. van der Meer, 1987, 1993; Menzies, 2000). Locally,
31 these structures enclose the larger lithic clasts (Figs. 5e and f); the latter forming a “core
32 stone” to these rotational deformation features. Other deformation structures present include
33 linear grain alignments and shears (Figs. 5c and d), and rare crushed grains (Fig. 6f); the latter
34 being relatively more abundant in the sample JA04. In general, the matrix to the diamicton
35 shows very little evidence of deformation. However, a weak plasmic fabric, defined by
36 optically aligned clay minerals, is locally apparent. The weak nature of this foliation may
37 simply reflect the low modal proportion of clay minerals and/or presence of very fine-grained
38 (micritic) carbonate (e.g. calcite) within the matrix to the diamicton, rather than the relative
39 intensity of deformation/fabric development.

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41 The boundary between the M1 diamicton and structurally overlying chalk is sharp, but
42 irregular in nature (Fig. 6a and b, also see Fig. 7). In detail this lithological boundary is highly
43 involute and deformed by small flame-like structures (Figs. 6a and b) as well as poorly
44 developed disharmonic folds (Fig. 6d). Thin stringers of fine-grained (micritic) carbonate
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3 were locally observed extending from the chalk-diamicton contact into the adjacent glacigenic
4 sediment (Fig. 6e) where they appear to be lining small-scale shears. Small, S-shaped to
5 sigmoidal augen of diamicton (Figs. 6a and b), possessing elongate tails in some places (Fig.
6 6c), can occur in the chalk. The shape of these structures locally records a dextral (top to
7 right) sense of rotation consistent with a northerly directed (in this plane of section) sense of
8 shear (Fig. 6b). The presence of augen of diamicton within the chalk as well as thin stringers
9 of carbonate within the M1 diamicton provide clear evidence that the deformation along this
10 lithological boundary led to the localised 'mixing' of these two lithologies. Although
11 deformed, the chalk immediately adjacent to the contact contains shell fragments, bryozoans,
12 echinoderm spines and foraminifera (50 to 100 μm size). Importantly the delicate, thin walled
13 tests of the foraminifera are intact (unbroken) suggesting that the intensity of deformation
14 accommodated by the chalk was relatively low. The chalk is mainly composed of very fine-
15 grained, dusty-looking grey-brown carbonate. However, immediately adjacent to the contact
16 with the M1 diamicton it also contains angular to subangular sand grains (Fig. 6c) providing
17 further evidence for at least some mixing of the chalk with the sandy diamicton during
18 deformation.
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30 *3D microstructural analysis*

31 Detailed mapping of the microstructures within the thin sections taken from samples JA03
32 and JA04 has revealed that they possess three main generations of clast microfabrics (S1
33 (oldest) to S3 (youngest); Figs. 7 to 12) defined by the preferred shape alignment of elongate
34 coarse silt and sand grains present within the diamicton. Importantly, the orientation,
35 geometry and spatial relationships of these three microfabrics are broadly similar in both
36 samples indicating that they have encountered the same overall deformation history. The
37 mutually perpendicular thin sections taken from each of the samples (Sample JA03 - JA03.2,
38 orientation S-N (Fig. 7); JA03.3, orientation W-E (Fig. 8); and JA03.6, subhorizontal (Fig. 9);
39 Sample JA04 - JA04.1, orientation S-N (Fig. 10); JA04.3 orientation W-E (Fig. 11); and
40 JA04.5, subhorizontal (Fig. 12) have enabled these fabrics to be examined in three
41 dimensions. The resultant three-dimensional model of the microfabric system at the tectonic
42 chalk-diamicton contact is illustrated in Fig. 13.
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51 The dominant foliation in both JA03 and JA04 is the **S1 fabric** (see rose diagrams on
52 Figs 7 to 12), a discontinuous, heterogeneously developed (see Figs. 7 and 9) planar to
53 anastomosing fabric defined by short (JA03; Fig. 7) to elongate (JA04; Fig. 10), closely to
54 moderately spaced microfabric domains. In both JA03 and JA04, the northerly dipping S1 can
55 be divided into two sub-fabrics: (i) a gently inclined S1a foliation (dark blue on Figs. 7 to 12);
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3 and (ii) a more steeply dipping and more pervasively developed S1b fabric (pale blue on Figs.
4 7 to 12). In detail, the relative intensity of both these early foliations increases structurally
5 downwards from sample JA03 and into JA04 (compare Figs. 7 and 10, also see Fig. 13);
6 indicative of an apparent increase in the intensity of deformation, which led to the imposition
7 of S1 away from the chalk-diamicton boundary. 3D analysis of the microfibrics has revealed
8 that this increase in the relative intensity of S1 is accompanied by an anti-clockwise rotation
9 (c. 70° to 90°) in the direction of dip of this fabric (Fig. 13). Adjacent to the chalk-diamicton
10 boundary, in sample JA03, S1 dips at a moderate angle towards the NW (S1a - 307/48 NW;
11 S1b - 307/55 NW; Fig. 13). Furthermore, a comparable north-westerly dipping foliation,
12 coplanar to S1 within the adjacent diamicton, is developed within the adjacent chalk where it
13 is defined by the preferred alignment of elongated bioclasts (Figs. 7 and 8). In contrast, in
14 sample JA04 S1 dips to NE (S1a - 042/20 NE; S1b - 042/54 NE; Fig. 13).
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23 S1 is cross-cut, and locally deformed, by a later **S2 fabric** defined by variably spaced,
24 irregular to continuous domains (Figs. 7 to 12). The spacing of these domains is highly
25 variable, reflecting the heterogeneous/patchy development of S2 within the M1 diamicton.
26 The earlier S1 fabric is preserved within the microlithons separating the S2 microfabric
27 domains where it is deformed by small-scale microfolds or crenulations; the axial surfaces of
28 these folds appear coplanar to the adjacent S2 fabric. The relatively younger S2, therefore,
29 takes the form of a moderate to widely spaced, planar to anastomosing weakly developed
30 crenulation cleavage (e.g. JA03.2; Fig. 7). Locally the earlier formed S1 fabric is dislocated or
31 offset across the S2 fabric, implying an apparent normal sense of movement with downthrow
32 towards the south (Fig. 7 and 10). In both JA03 and JA04, the southerly dipping S2 can be
33 divided into two sub-fabrics: (i) a steeply inclined S2a foliation (dark green on Figs. 7 to 12);
34 and (ii) a more gently dipping S2b fabric (pale green on Figs. 7 to 12). The relative age
35 relationship(s) between these two sub-fabrics is uncertain. However, locally S2b appears to
36 cross-cut the potentially earlier S2a fabric (see Fig. 10). As with the S1 fabric, the relative
37 intensity of S2 increases downwards from sample JA03 and into JA04, away from the chalk-
38 diamicton boundary (compare Figs. 7 and 10). The S2 domains occur orthogonal to S1 and in
39 3D clearly define a southerly plunging linear fabric (Fig. 13). In sample JA03, adjacent to the
40 chalk-diamicton boundary, S2 is moderately inclined to SE (S2a - 136/49 SE; S2b - 136/31
41 SE; Fig. 13). Whereas, in sample JA04, S2 plunges towards the SW (S2a - 214/44 SW; S2b -
42 214/68 SW; Fig. 13). Consequently, as with S1, the S2 linear fabric shows a pronounced anti-
43 clockwise rotation in orientation with decreasing distance to the chalk-diamicton boundary
44 (see Fig. 13).
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3 Both S1 and S2 are cross-cut by the relatively younger **S3 fabric** (Figs. 7 to 12). This
4 widely to moderately spaced foliation is defined by steeply inclined to subvertical (JA03 -
5 176/85 S; JA04 - 181/90 S; Fig. 13), irregular to anastomosing, discontinuous domains (Figs.
6 7 to 13). In contrast to both S1 and S2, the relative intensity of S3 appears to increase towards
7 upwards the chalk-diamicton boundary (compare Figs. 7 and 10) and shows a relatively
8 consistent orientation in both samples.
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13 14 **Discussion and Interpretation**

15 The results of the detailed microstructural mapping and 3D analysis of the deformation
16 structures developed within the M1 diamicton presented here clearly demonstrate the
17 potential benefits of this type of analysis when applied to glacitectonically deformed
18 sequences. The presence of a large scale syncline and associated thrust fault deforming the
19 chalk and overlying glacial sediments exposed at Wissower Bach has been known for
20 some time (e.g. Steinich, 1972). The present 3D microstructural analysis has now provided
21 further information regarding the development of these glacitectonic structures, which are not
22 recognisable in the field. This includes: the partitioning of deformation into the relatively
23 weaker unconsolidated diamicton during folding leading to the development of Riedel shears
24 (stage 1); followed by the imposition of a second (S2) crenulation fabric as deformation
25 continued (stage 2); the anti-clockwise rotation of the S1 and S2 microfabrics (stage 3); and
26 finally the dewatering of the diamicton and imposition of S3, which apparently accompanied
27 the localised reactivation of the earlier formed S2 fabric to form small-scale normal faults and
28 extensional shears (stage 4).
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38 Several previous studies have demonstrated that the combination of macro- and
39 microstructural analyses enable a detailed model of the complicated deformation histories
40 recorded by glacial sediments to be established (e.g. van der Meer *et al.*, 2003; Menzies,
41 2000; Phillips and Auton, 2000; van der Wateren *et al.*, 2000; Menzies *et al.*, 2006; Phillips *et*
42 *al.*, 2007; Lee and Phillips, 2008; Denis *et al.*, 2010; Vaughan-Hirsch *et al.*, 2013; Narloch *et*
43 *al.*, 2012, 2013). However, these studies have been carried out on orientated thin sections cut
44 parallel to the regional ice movement direction and are therefore only 2D in nature, different
45 from this study.
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51 Two different evolutionary models were considered to describe the microstructures
52 developed within the M1 diamicton and the chalk. The macroscopic basis of the first model is
53 an antiformal stack produced by SW-directed thrusting, while the second model considers the
54 already established syncline as part of a proximal imbricate fan that requires NE-directed
55 thrusting and subsequent gravitational relaxation.
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3 The **first evolutionary model** for the glacitectonism at the Wissower Bach is discussed
4 in Fig. 14. The development of an antiformal stack in the southern structural complex of
5 Jasmund is assumed, which evolved from an ice push from NE. In the first stage (Fig. 14a) a
6 fault-bend fold is formed along a primary ramp, dipping to NE. The second stage (Fig. 14b) is
7 characterised most likely by a continued push from NE and progressive deformation. This
8 leads to another fault-bend folding along a new ramp resulting in an antiformal stack (Fig.
9 14b). On the southwestern side of the stack, the thrust sheet is moved downwards along a
10 normal fault dipping to SW, which may represent the fault at Wissower Bach.

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12 This model could explain the normal faults at micro-scale (Fig. 10). Additionally, the
13 macroscopic S-inverted folds within the chalk north of the Wissower Bach (Fig. 2, profile
14 meters 200 to 250 in the cross section) may indicate an antiformal stack, due to a sort of drag
15 folding along another SW-dipping normal fault in the lower part of the stack.

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17 The **second evolutionary model** considers the formation of an imbricate fan by ice
18 push from SW as shown in Fig. 15. The documented Wissower Bach Syncline is interpreted
19 as part of a footwall-thrust sheet below a SW-dipping ramp (Fig. 2). The SW-dipping fault
20 bounding the syncline at its southwestern limb may represent one of the successive thrust-
21 fault splays that branched up from a décollement surface at some depth below sea level.

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23 Based on this model, the microstructural evolution of the M1 diamicton at the
24 southwestern limb of the Wissower Bach Syncline can be explained by a series of events
25 resulting from glacitectonically induced reverse- to thrust-faulting as outlined in more detail
26 below. The youngest microfabric, on contrary, is attributed to normal faulting (inversion) due
27 to gravitational relaxation and pore-water escape.

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29 Concerning our current data base, we **favour the second evolutionary model** (Fig. 15).
30 The Pleistocene sediment record indicates a syncline, which must have been cut by a thrust
31 fault at the southern limb. All faults along the coastal transect of the southern sub-complex
32 dip south-westward or southward. In case that all these faults would represent a foreland
33 dipping ramp, as assumed for the model 2, an extremely thick pile of an antiformal stack
34 might be the consequence. The glacitectonic complex must have had a height of about 2 km,
35 which is enormous and less realistic. Furthermore, there is a clear trend from south to north
36 favouring model 1: the faults show a decreasing inclination (see Steinich, 1972), which can be
37 interpreted as a stepwise steepening of the older faults (proximal, SW) due to the propagation
38 of the active fault towards the foreland (distal, NE) as described by Pedersen (2005) for
39 glacitectonic complexes. Consequently, an ice push from a southern source forming the folds
40 and faults of the southern structural complex (Fig. 1c) is much more plausible than the
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3 formation of an antiformal stack by a straight push from NE. In addition, the digital elevation
4 model (Fig. 1c) shows two arcuate sub-complexes that point to two deformation events
5 including an ice push from both NE and SE. Thus, especially the southern sub-complex
6 concave to SE has a much more complicated deformation history than the northern one. This
7 makes the interpretation of the Wissower Bach structure to a bigger challenge.
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13 Based on the interpretation that the faulted Wissower Bach Syncline is part of an NE-
14 verging imbricate fan (model 2), the **microstructural evolution** of the M1 diamicton at the
15 southwestern limb of the syncline can be divided into four stages. This reconstruction takes
16 into account, that the sediment preferentially records the processes of the last deformation
17 events (see Phillips et al. 2011). Thus, all the previous fabrics, in this case formed during the
18 Saalian glaciation and superimposed during the ice advance of the Brandenburg/Frankfurt
19 phase (W1), have been erased.
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24 The **first evolutionary stage** led to the imposition of the **S1 fabric** (dip to NE) (Fig.
25 15a). The microfabric domains represent a downward movement of clasts into a general
26 northerly direction on planar tracks. The geometry of this clast-fabric can be interpreted as
27 Riedel shears with the S1 fabric representing the synthetic *R shears* recording narrow zones of
28 extension and kinematically corresponding to normal “faults” (Fossen, 2010). It has to be
29 taken into account that the S1 domains represent planes (cf. Fig. 13) that are generated by the
30 clast long axes whose orientation can vary in two dimensions (more or less freely). In
31 contrast, in a linear fabric system, the clast long axes are more restricted (axes are more or
32 less sub-parallel), which is typical of the *P shears* (cf. Fig. 15a) that correspond to reverse
33 “faults” (Fossen, 2010) and represent zones of compression. Such P shears, in this case
34 perpendicular to S1, could also be established by microstructural mapping. Apparently, these
35 are shear lines (**S2 fabric**) built together with the S1 domains, when the compressional stress
36 acted from a general southerly direction.
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41 During the **second evolutionary stage** (Fig. 15b), continued deformation led to the
42 crenulation of **S1** (dip to NE) and imposition of **S2** (dip to SW). The S1 fabric has been turned
43 into folds with axial surfaces coplanar to the adjacent S2 fabric.
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48 Continued deformation during the **third evolutionary stage** led to the modification
49 and reorientation of the microfabrics present within the M1 diamicton (Fig. 15c). This
50 reactivation led to the anti-clockwise rotation of both S1 and S2 within the fault zone so that
51 the dip of S1 was changed from NE into NW and the plunge of S2 from SW into SE (see Fig.
52 13).
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3 The **fourth evolutionary stage** is characterised by the development of the sub-
4 vertical, planar **S3 fabric** (Fig. 15d). The domains defining this foliation could be interpreted
5 as steeply inclined shears, or alternatively as an anastomosing sub-vertical foliation developed
6 in response to dewatering of the diamicton. If we consider the steep shears to be a part of the
7 Riedel shear zone, they can be interpreted as *R'*-fractures. However, the irregular to
8 anastomosing nature of S3 is considered to be more consistent with this foliation having
9 developed in response to the flow of escaping pore water and dewatering of the diamicton
10 during the later stages of deformation. In this interpretation the S3 domains represent
11 anastomosing conduits or fluid pathways taken by the escaping pore water. This can be
12 confirmed by the character of the contact between the chalk and the diamicton at both macro
13 and microscale, which shows a ductile structure and interfingering of both depositional units
14 by porewater movement (see Fig. 6).
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23 Also during the fourth stage, the S2 foliation has been reactivated and enhanced.
24 Locally, it displays normal (extensional) faults which cross-cut and dislocate the earlier
25 developed S1 domains (Fig. 15d; see Figs. 7 and 10). This microstructural relationship
26 records a generally south-directed extension during possibly the later part of the proposed
27 polyphase deformation history recorded by the M1 diamicton.
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33 The results of the microfabric analysis outlined above have **implications** for late
34 Weichselian ice-sheet dynamics and the development of regional-scale faulting during
35 glacitectonism of the Jasmund Peninsula. After the ice advance of the Brandenburg/Frankfurt
36 stage (W1), the Baltic Ice Stream advancing from NE is considered to have split into northern
37 and southern branches around a topographic high or nunatak in the area now occupied by the
38 Jasmund Peninsula (see Panzig, 1995; Ludwig, 2011). The southern branch of this ice stream
39 is thought to have been responsible for the large-scale glacitectonic folding and thrusting on
40 the southern side of the peninsula (southern structural complex, see Fig. 1c), including the
41 Wissower Bach Syncline. The series of NE-SW trending ridges seen on the DEM of the
42 region represents the surface expression of this folded and thrustured imbricate fan, and clearly
43 demonstrates that the ice responsible for this glacitectonism advanced onto the Jasmund
44 Peninsula from SE (Fig. 1c) (see Steinich, 1972). Compression directed from SE to NW
45 generated by the advancing ice resulted in the folding and thrusting of both the chalk bedrock
46 and overlying glacial sediments, leading to the early stages of the development of the
47 Wissower Bach syncline (**first stage** with local pressure directed to NE, Fig. 15a). These
48 initial stages of the development of the syncline were accompanied by flexural slip along the
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3 lithological boundary between the chalk and the diamicton, and the imposition of the S1
4 microfibrils within M1 (sample JA04). Movement along the boundary between the chalk and
5 adjacent glacial deposits appears to have been partitioned into the relatively weaker,
6 unconsolidated M1 diamicton; a conclusion supported by the preservation of delicate
7 microfossils (e.g. foraminifera) within the chalk (sample JA03) exposed immediately adjacent
8 to this glacitected contact.
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12 The progressive development of the Wissower Bach Syncline in response to continued
13 compression (**second stage**, Fig. 15b) is thought to have led to the further tightening of this
14 syncline. The tightening of the fold may have accompanied the overturning and localised
15 thrusting on the southern limb of the syncline. On a smaller scale, continued deformation
16 resulted in the microscale folding (crenulation) of the earlier developed S1 fabric and
17 imposition of the second foliation (S2) within the M1 diamicton.
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23 During the **third stage**, ice is interpreted to have overridden a part of the Jasmund
24 Peninsula, indicated by the erosional unconformity and the overlying sediment complex M3
25 (see Fig. 2, Fig. 15c). The orientation of the axial surface of the Wissower Bach Syncline
26 coupled with the dip and strike of the S1 and S2 microfibrils developed within the M1
27 diamicton are consistent with a SW compression during at least the first and second stages of
28 the proposed deformation model. However, the results of the 3D microstructural study clearly
29 demonstrate that both S1 and S2 appear to have rotated (Fig. 15c) as deformation progressed,
30 suggesting that there was a change in the orientation in stress regime being imposed by the
31 overriding ice. Even though in general S1 dips towards the north and S2 to the south, there is
32 a marked change in the orientation of these fabrics between sample JA03, located
33 immediately adjacent to the chalk-M1 contact, and sample JA04, which occurs 10 cm below
34 this tectonised boundary. In sample JA03, S1 is inclined to NW, whereas in JA04 it dips
35 towards the NE. A similar apparent anti-clockwise rotation in the orientation of the clast
36 microfibrils close to the chalk-M1 boundary is revealed by S2 (JA03: dip to SE, JA04: dip to
37 SW). This rotation is thought to record a change in local ice-movement direction as the
38 southern part of the Baltic ice stream progressively overrode the Jasmund Peninsula.
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49 During the **fourth stage** (Fig. 15d) the final ice retreat from the Jasmund Peninsula led
50 to a large-scale relaxation in the glacitected complex, which was probably accompanied by
51 dewatering of the M1 diamicton. The consistent orientation of S3 in both samples JA03 and
52 JA04 indicates that dewatering of the sediment post-dated the rotation of S1 and S2 during
53 stage 3. The localised reactivation of S2 and southerly directed extension across these R²-type
54 Riedel shears and associated normal faulting within the M1 diamicton are thought to record
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3 the late-stage reactivation of the thrust cutting the southwestern limb of the Wissower Bach
4 Syncline due to the gravitational relaxation caused by the retreat of the ice.

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6 The model proposed here to explain the structural development of this syncline
7 involves progressive deformation of the chalk bedrock and glacial sediments during ice
8 advance and subsequent retreat, thereby relating deformation to changes in ice dynamics
9 during the glaciation of the Jasmund Peninsula.
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12 13 **Conclusions**

14 Within the M1 diamicton bounding the main fault (dip to SW/WSW), three different main
15 fabrics were distinguished. The planar S1 fabric (oldest) dips to NW/NE and is split up into
16 the two sub-fabrics S1a (gently inclined) and S1b (steep). S2 is linear and dips to SE/SW
17 (always perpendicular to S1). Here a separation into a steeper and more gently inclined sub-
18 domain (S2a and S2b) could be observed, too. The youngest fabric S3 is nearly vertical,
19 planar and can be interpreted as either steeply inclined shears or anastomosing sub-vertical
20 foliation (dewatering).
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23 The microstructural evolution of the M1 diamicton at the southwestern limb of the
24 Wissower Bach Syncline can be divided into four stages. It starts with an overall sense of
25 compressional movement to the NE (S1, S2) leading to progressive folding (microscale
26 crenulation). This is followed by an anti-clockwise rotation of the microfabric in a narrow
27 shear zone along the tectonic contact between the diamicton and chalk, when the ice partly
28 overrode Jasmund. The evolution ends in dewatering (S3) and a late-stage reactivation
29 (normal faulting due to gravitational relaxation) at the southwestern limb of the Wissower
30 Bach Syncline as the ice retreated.
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33 The results of the present 3D microstructural study, when combined with the
34 macrostructural (field) data, has the potential to provide a more robust dataset on which to
35 interpret the structural evolution of the Wissower Bach Syncline. Moreover, this strategy
36 helps us to better make up the evolutionary model of glacitectonic complexes like Jasmund.
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3 **Fig. 1** Maps of the investigation area showing **a)** the island of Rügen in the southwestern
4 Baltic Sea adjacent to the North Sea region, **b)** the Jasmund peninsula as the northeastern part
5 of Rügen island, and **c)** the digital elevation model of Jasmund with a separation into the
6 northern and southern structural complex, including the regional ice flow directions and the
7 exact study area Wissower Bach (DEM5, visualised as a hillshade relief model, 10 times
8 vertical exaggeration; data provided by the LAiV MV).

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14 **Fig. 2** Panoramic image and geological cross section of the Wissower Bach Syncline. At the
15 southwestern limb of the syncline there is a SW-dipping thrust fault between the Cretaceous
16 chalk and the Pleistocene M1 diamicton below. This area has been sampled for the
17 microstructural analysis of orthogonal thin sections. The abbreviations of the Pleistocene
18 lithostratigraphic units M1, I1, M2, I2 and M3 have been adapted from Jaekel (1917); **a)**
19 tectonic contact between the chalk and the M1 diamicton in detail; **b)** sample blocks JA03 and
20 JA04 at the thrust fault.

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28 **Fig. 3** Lower hemisphere stereographic plots showing **a)** the southwestern limb of the
29 Wissower Bach Syncline with an average inclination to SW, **b)** the northeastern limb of the
30 Wissower Bach Syncline dipping to SW, and **c)** the orientation of the thrust fault at the SW
31 limb of the syncline with general dip to SW/WSW; **d)** the structural map illustrates the entire
32 structural conditions at the Wissower Bach.

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38 **Fig. 4** Detailed sediment log of the Wissower Bach Syncline with representative photos from
39 selected depositional units. The abbreviations of the Pleistocene lithostratigraphic units M1,
40 I1, M2, I2 and M3 have been adapted from Jaekel (1917). **a)** M3 sediment complex on the top
41 of the cliff comprising the gravel- and boulder-rich channel at the unit's base and the light
42 brown to whitish sandy diamicton. **b)** Lowermost part of the I1 unit starting with the gravel
43 layer at the bottom, which is followed by white to light brown sands. **c)** M1 diamicton at the
44 base of the cliff.

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51 **Fig. 5** Microstructures within the M1 diamicton: **a)** round clast alignments without a core
52 stone (JA03.3); **b)** interpreted version (JA03.3); **c)** lineations (JA04.5); **d)** interpreted version
53 (JA04.5); **e)** limestone clast involved in a comet structure (JA03.4); **f)** interpreted version
54 (JA03.4).

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4 the M1 diamicton within the chalk (JA03.1); **b**) interpreted version (JA03.1); **c**) augen-shaped
5 diamicton “clast” in the chalk (JA03.4); **d**) ductile, wavy boundary between the chalk and the
6 diamicton below (JA03.2); **e**) thin chalk veins in the M1 diamicton (JA03.3); **f**) crushed
7 quartz grains in the diamicton (JA04.3).
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13 **Fig. 7** Microstructural maps of the thin section JA03.2 showing the tectonic boundary
14 between the chalk on top and the M1 diamicton below. The left map displays the fabrics S1 to
15 S3, including the sub-fabrics of S1 and S2. The right map is the interpretation of the three
16 fabrics. The S1 fabric is locally dislocated by normal faults along the S2 fabric. The rose
17 diagrams illustrate the strength of the individual microfabrics in both depositional units. The
18 northerly inclined fabric in the chalk and the S1 fabric are most dominant.
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24 **Fig. 8** Microstructural maps of the thin section JA03.3 showing the tectonic boundary
25 between the chalk on top and the M1 diamicton below. The left map displays the fabrics S1 to
26 S3, including the sub-fabrics of S1 and S2. The right map is the interpretation of the three
27 fabrics. The rose diagrams illustrate the strength of the individual microfabrics in both
28 depositional units. The westerly inclined clast microfabric in the chalk and the S1 fabric are
29 strongly dominant.
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36 **Fig. 9** Microstructural maps of the horizontal thin section JA03.6 showing the three fabrics S1
37 to S3 in the M1 diamicton. The top map displays the fabrics S1 to S3. The bottom map shows
38 the interpretation of the microfabrics. The folded S1 fabric within the microlithons separating
39 the S2 microfabric domains is easily visible. The rose diagram illustrates the strength of the
40 individual microfabrics.
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46 **Fig. 10** Microstructural maps of the thin section JA04.1 showing the M1 diamicton. The left
47 map displays the fabrics S1 to S3, including the sub-fabrics of S1 and S2. The right map is the
48 interpretation of the three fabrics. The northerly inclined S1 fabric is dislocated along the
49 southerly inclined S2 fabric ending up in local normal faults. The rose diagram illustrates the
50 strength of the individual microfabrics.
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56 **Fig. 11** Microstructural maps of the thin section JA04.3 showing the M1 diamicton. The left
57 map displays the fabrics S1 to S3, including the sub-fabrics of S1 and S2. The right map is the
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3 interpretation of the three fabrics. The rose diagram illustrates the strength of the individual
4 microfabrics with the S1 microfabric representing the most dominant one.
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8 **Fig. 12** Microstructural maps of the horizontal thin section JA04.5 showing the three fabrics
9 S1 to S3 in the M1 diamicton. The top map displays the fabrics S1 to S3. The bottom map
10 shows the interpretation of the microfabrics. The folded S1 fabric within the microlithons
11 separating the S2 microfabric domains is easily visible. The rose diagram illustrates the
12 strength of the individual microfabrics.
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18 **Fig. 13** 3D model of the microfabric system at the chalk-diamicton contact (samples JA03,
19 JA04) including the results from the orientation analysis of all thin sections. The lower
20 hemisphere stereographic plots show the orientation of the microfabrics S1, S2 and S3, their
21 shape (linear/planar) and their spatial relationship to each other.
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26 **Fig. 14** First suggested model for the Wissower Bach structure developed by the push of an
27 ice stream advancing from NE; **a)** stage 1: ramp thrusting of a chalk sheet over another chalk
28 sheet, directed from NE towards SW; **b)** stage 2: formation of an antiformal stack, probably in
29 the same progressive dynamic event, or alternatively in a readvance of the NE ice.
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34 **Fig. 15** Deformational model of the Wissower Bach Syncline including the four evolutionary
35 stages; **a)** stage 1: incipient imposition of the large-scale folds which leads to the development
36 of the microfabrics S1 (dip to NE) and S2 (dip to SW) as part of a Riedel shear zone; **b)**
37 second stage with the continuation of large-scale folding and thrusting leading to progressive
38 deformation (crenulation) of S1 and S2 at microscale; **c)** stage 3 comprising the anti-
39 clockwise rotation of the microfabrics S1 and S2 within the narrow shear zone (10 to 20 cm)
40 of the thrust fault presumably by the partial overburden of the glacitectonic complex by the
41 proceeding ice; **d)** stage 4: retreat of the ice and associated relaxation, which ends in local
42 microscale normal-fault movements along the S2 microfabric and dewatering of the M1
43 diamicton, which produces a ductile deformation of the tectonic boundary and the evolution
44 of the S3 microfabric.
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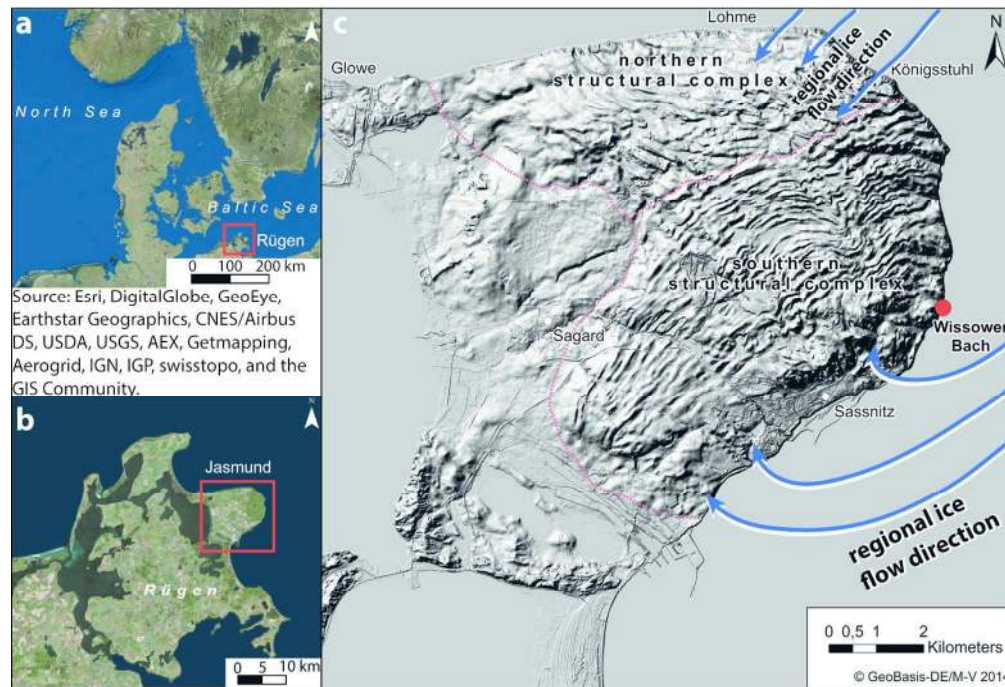


Fig. 1 Maps of the investigation area showing a) the island of Rügen in the southwestern Baltic Sea adjacent to the North Sea region, b) the Jasmund peninsula as the northeastern part of Rügen island, and c) the digital elevation model of Jasmund with a separation into the northern and southern structural complex, including the regional ice flow directions and the exact study area Wissower Bach (DEM5, visualised as a hillshade relief model, 10 times vertical exaggeration; data provided by the LAiV MV).
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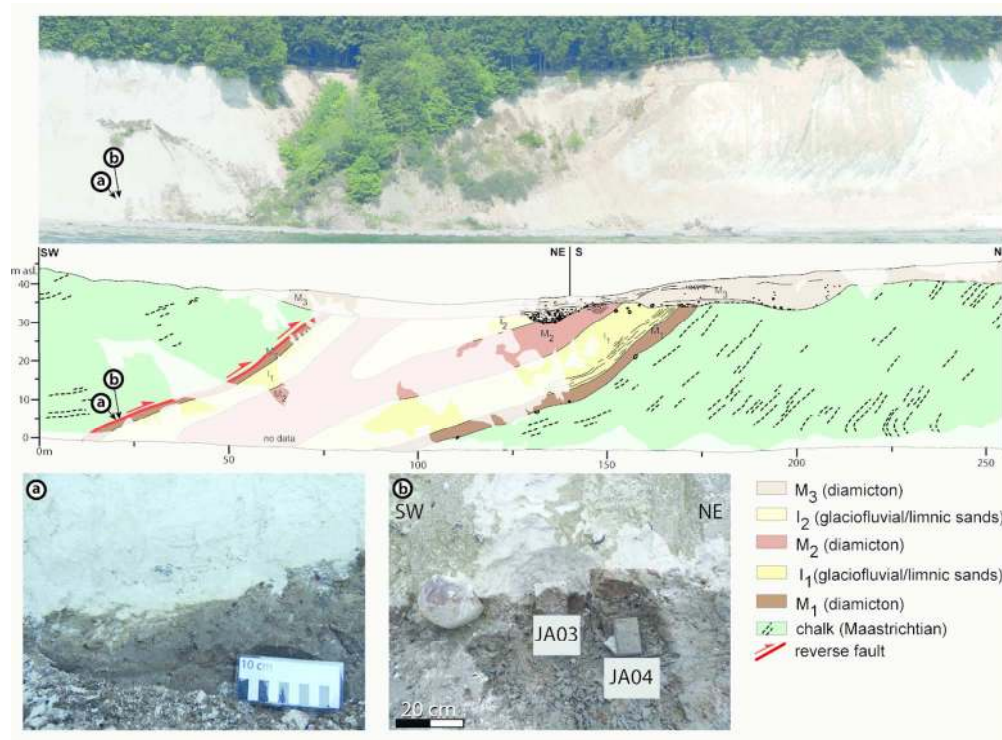


Fig. 2 Panoramic image and geological cross section of the Wissower Bach Syncline. At the southwestern limb of the syncline there is a SW-dipping thrust fault between the Cretaceous chalk and the Pleistocene M₁ diamicton below. This area has been sampled for the microstructural analysis of orthogonal thin sections. The abbreviations of the Pleistocene lithostratigraphic units M₁, I₁, M₂, I₂ and M₃ have been adapted from Jaekel (1917); a) tectonic contact between the chalk and the M₁ diamicton in detail; b) sample blocks JA03 and JA04 at the thrust fault.

237x176mm (150 x 150 DPI)

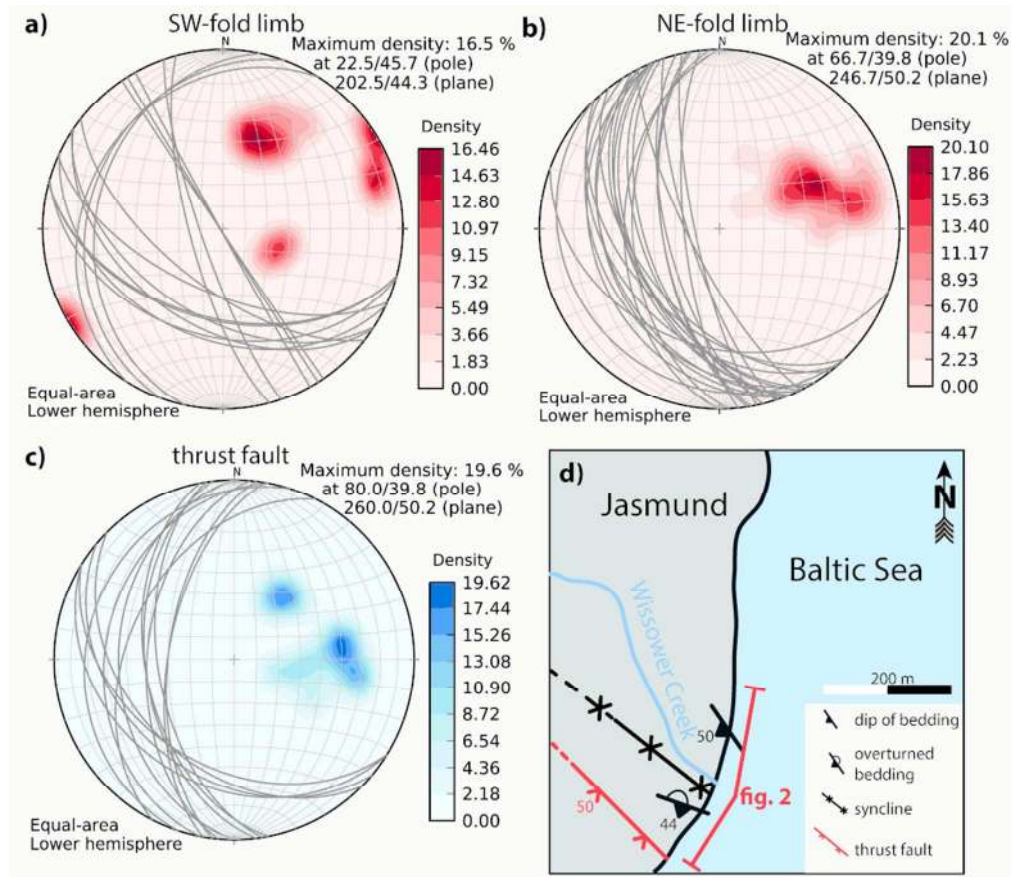
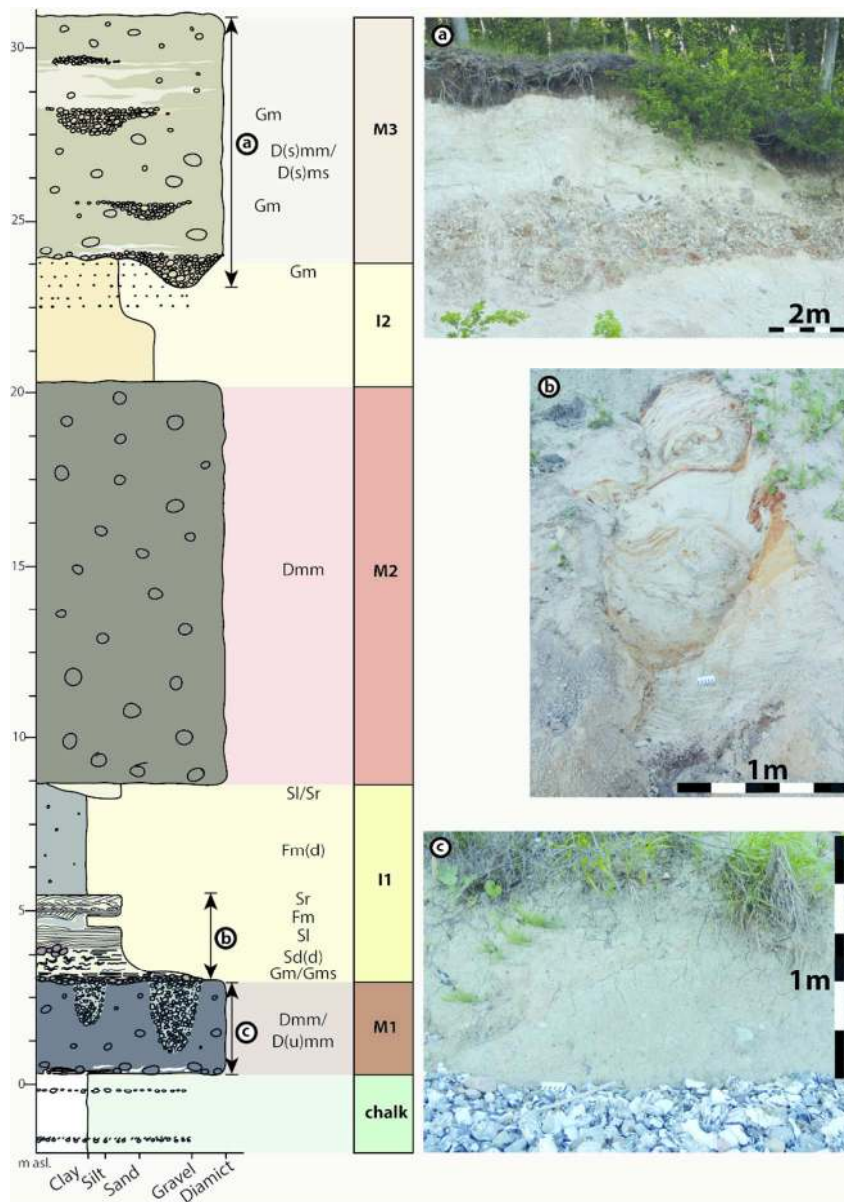


Fig. 3 Lower hemisphere stereographic plots showing a) the southwestern limb of the Wissower Bach Syncline with an average inclination to SW, b) the northeastern limb of the Wissower Bach Syncline dipping to SW, and c) the orientation of the thrust fault at the SW limb of the syncline with general dip to SW/WSW; d) the structural map illustrates the entire structural conditions at the Wissower Bach.
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Fig. 4 Detailed sediment log of the Wissower Bach Syncline with representative photos from selected depositional units. The abbreviations of the Pleistocene lithostratigraphic units M1, I1, M2, I2 and M3 have been adapted from Jaekel (1917). a) M3 sediment complex on the top of the cliff comprising the gravel- and boulder-rich channel at the unit's base and the light brown to whitish sandy diamicton. b) Lowermost part of the I1 unit starting with the gravel layer at the bottom, which is followed by white to light brown sands. c) M1 diamicton at the base of the cliff.

176x249mm (150 x 150 DPI)

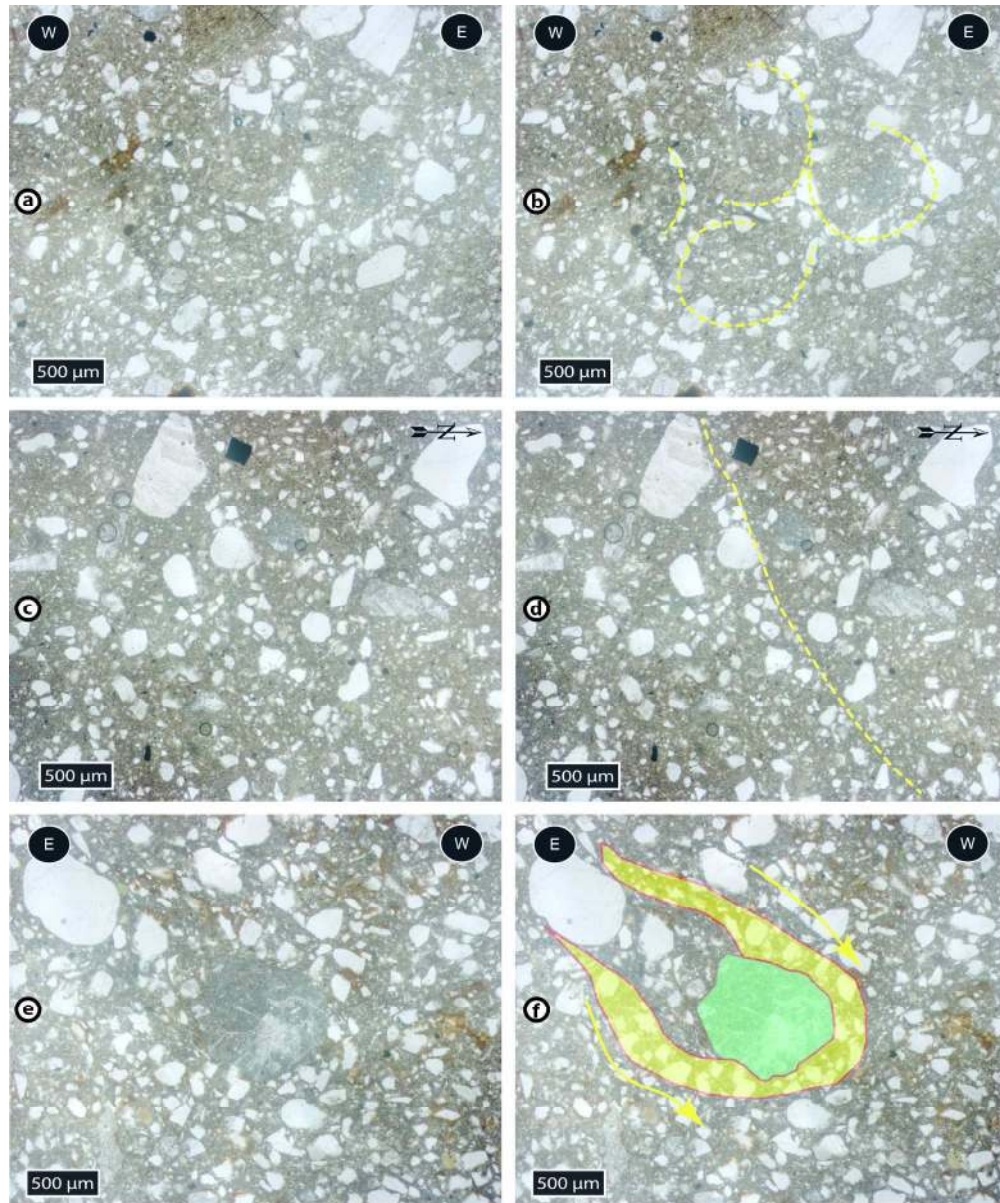


Fig. 5 Microstructures within the M1 diamicton: a) round clast alignments without a core stone (JA03.3); b) interpreted version (JA03.3); c) lineations (JA04.5); d) interpreted version (JA04.5); e) limestone clast involved in a comet structure (JA03.4); f) interpreted version (JA03.4).
 176x211mm (300 x 300 DPI)

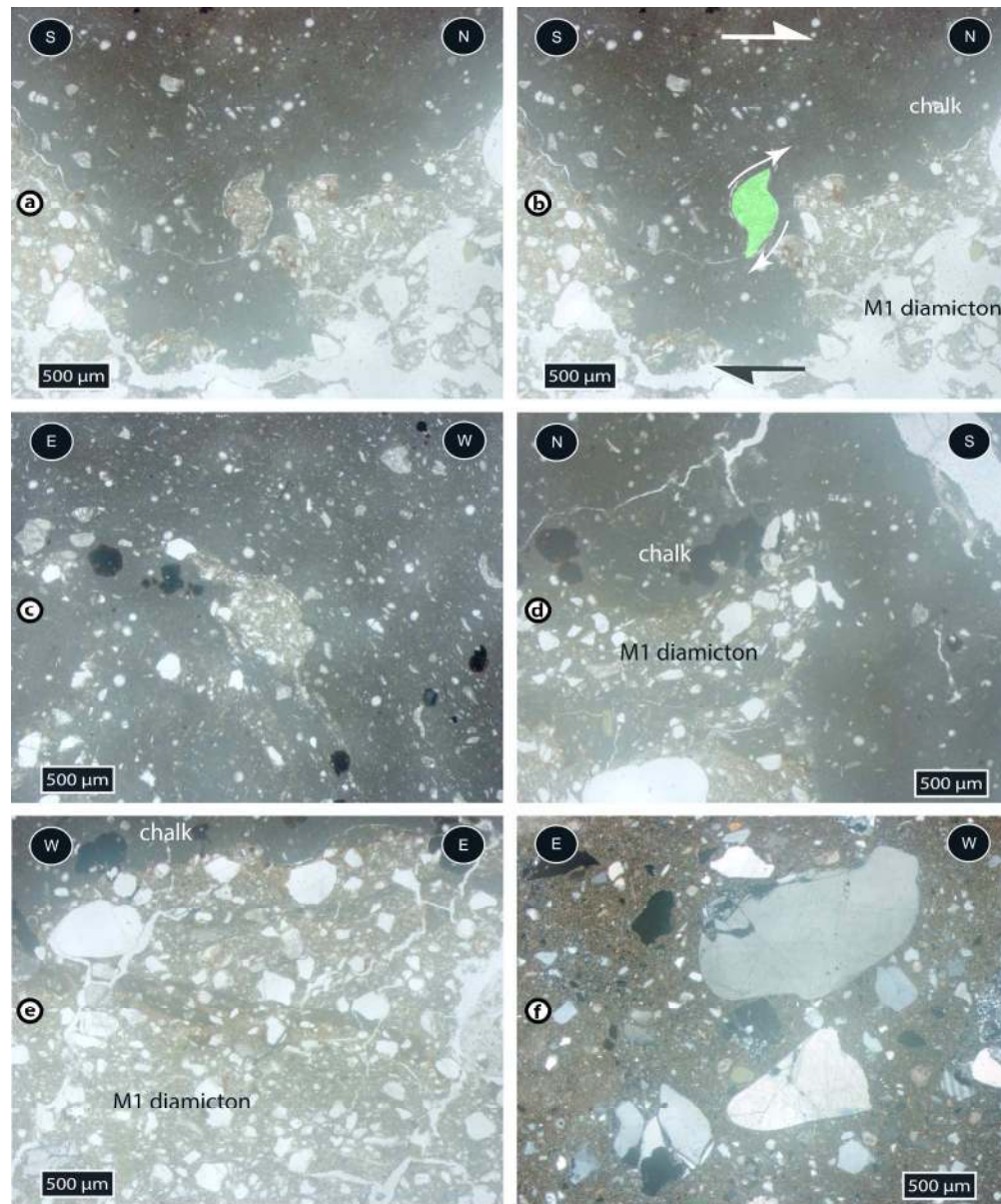


Fig. 6 Microstructures within the M1 diamicton and the chalk: a) deformed augen structure of the M1 diamicton within the chalk (JA03.1); b) interpreted version (JA03.1); c) augen-shaped diamicton "clast" in the chalk (JA03.4); d) ductile, wavy boundary between the chalk and the diamicton below (JA03.2); e) thin chalk veins in the M1 diamicton (JA03.3); f) crushed quartz grains in the diamicton (JA04.3).
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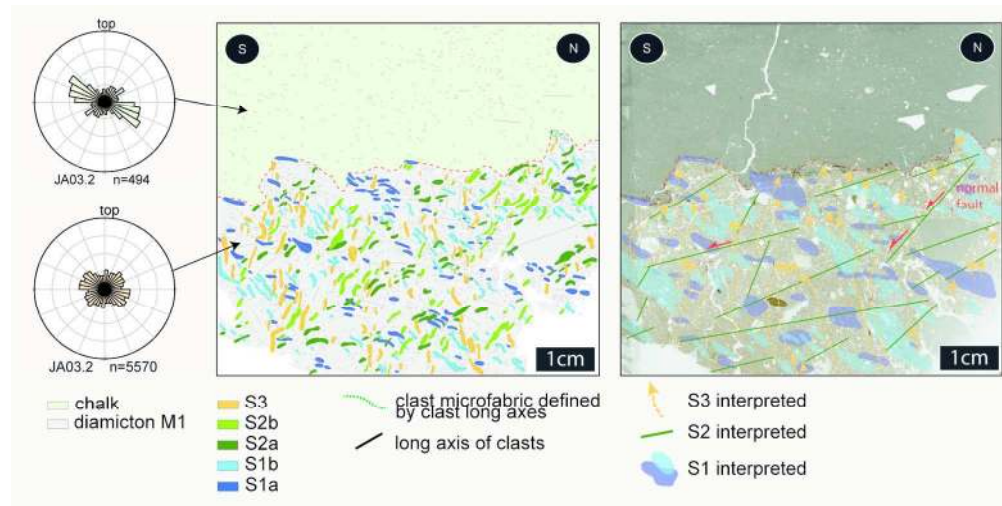


Fig. 7 Microstructural maps of the thin section JA03.2 showing the tectonic boundary between the chalk on top and the M1 diamicton below. The left map displays the fabrics S1 to S3, including the sub-fabrics of S1 and S2. The right map is the interpretation of the three fabrics. The S1 fabric is locally dislocated by normal faults along the S2 fabric. The rose diagrams illustrate the strength of the individual microfabrics in both depositional units. The northerly inclined fabric in the chalk and the S1 fabric are most dominant.
297x149mm (150 x 150 DPI)

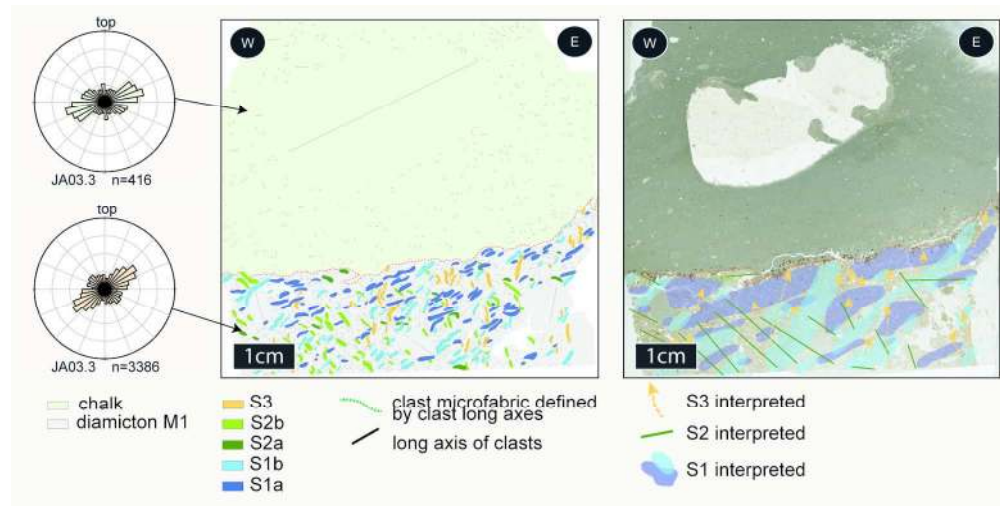
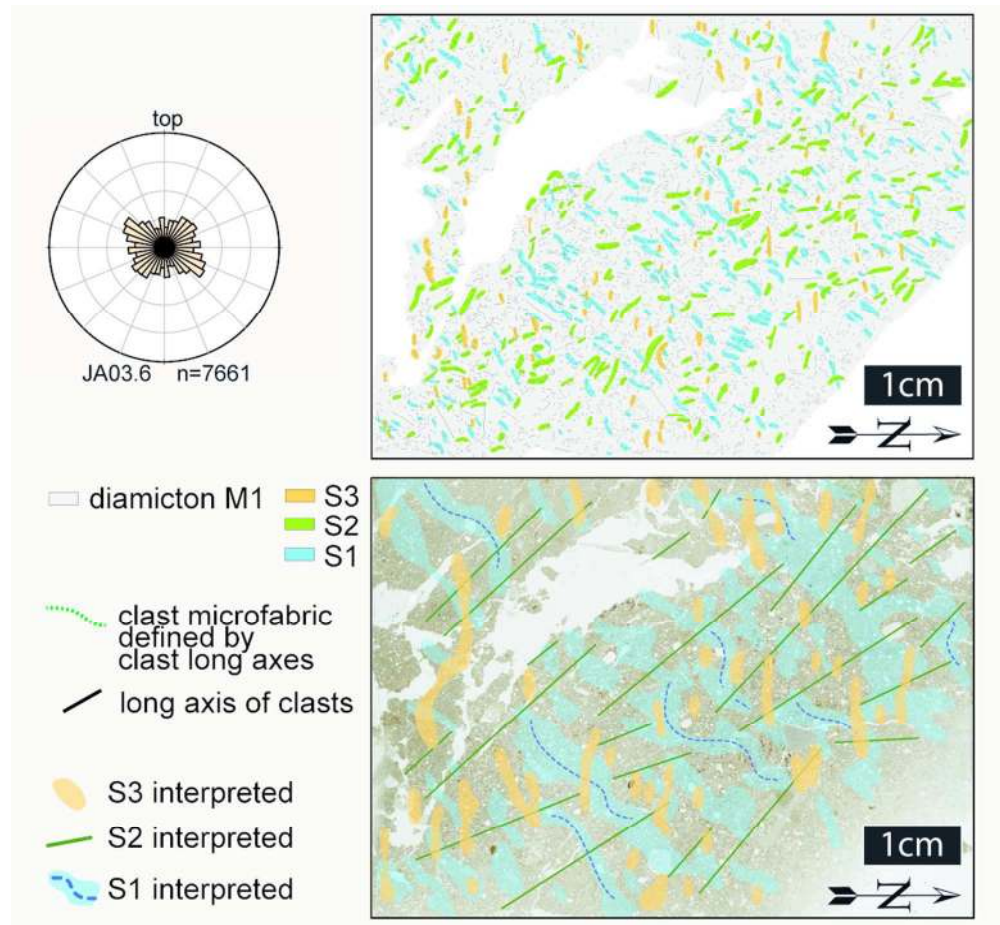


Fig. 8 Microstructural maps of the thin section JA03.3 showing the tectonic boundary between the chalk on top and the M1 diamicton below. The left map displays the fabrics S1 to S3, including the sub-fabrics of S1 and S2. The right map is the interpretation of the three fabrics. The rose diagrams illustrate the strength of the individual microfabrics in both depositional units. The westerly inclined clast microfabric in the chalk and the S1 fabric are strongly dominant.

297x149mm (150 x 150 DPI)



38 Fig. 9 Microstructural maps of the horizontal thin section JA03.6 showing the three fabrics S1 to S3 in the
39 M1 diamicton. The top map displays the fabrics S1 to S3. The bottom map shows the interpretation of the
40 microfabrics. The folded S1 fabric within the microlithons separating the S2 microfabric domains is easily
41 visible. The rose diagram illustrates the strength of the individual microfabrics.
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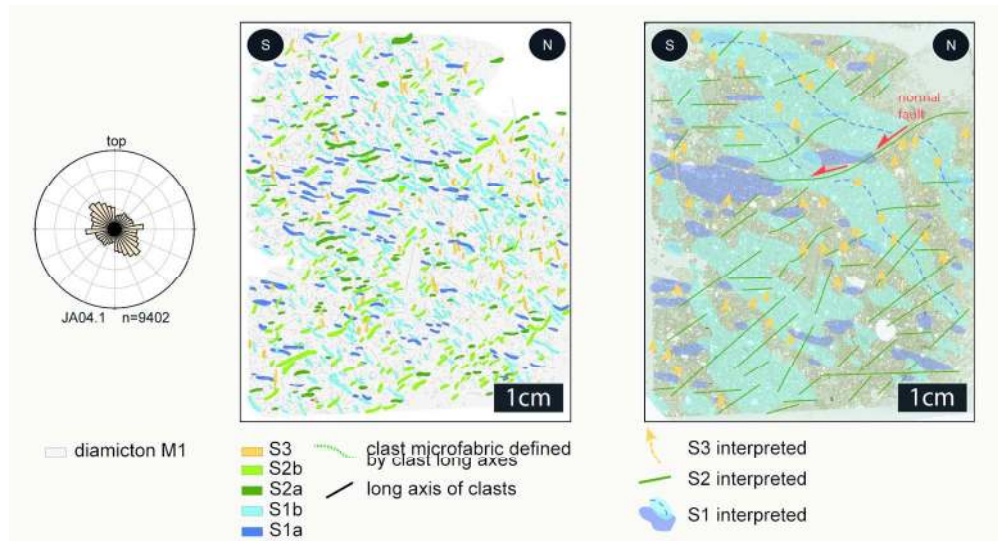


Fig. 10 Microstructural maps of the thin section JA04.1 showing the M1 diamicton. The left map displays the fabrics S1 to S3, including the sub-fabrics of S1 and S2. The right map is the interpretation of the three fabrics. The northerly inclined S1 fabric is dislocated along the southerly inclined S2 fabric ending up in local normal faults. The rose diagram illustrates the strength of the individual microfabrics.
297x161mm (150 x 150 DPI)

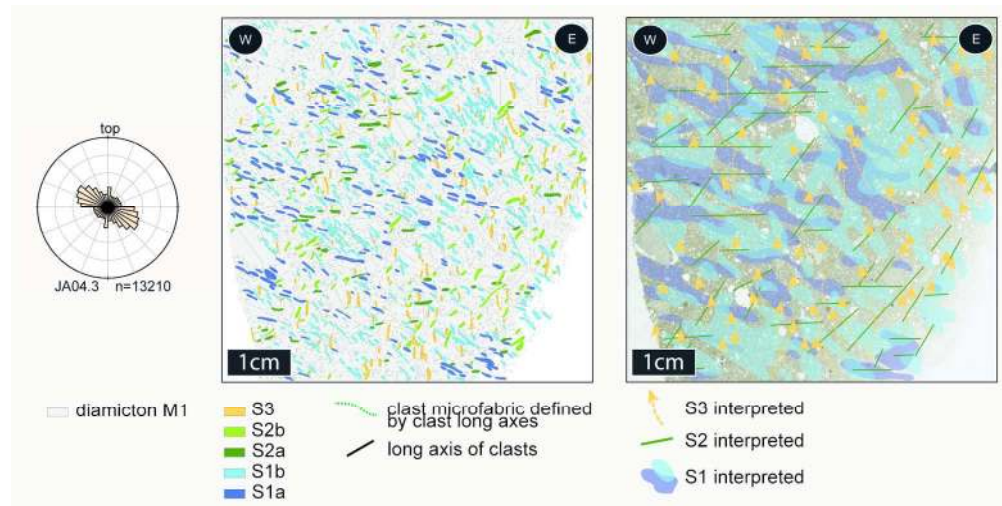


Fig. 11 Microstructural maps of the thin section JA04.3 showing the M1 diamicton. The left map displays the fabrics S1 to S3, including the sub-fabrics of S1 and S2. The right map is the interpretation of the three fabrics. The rose diagram illustrates the strength of the individual microfabrics with the S1 microfabric representing the most dominant one.

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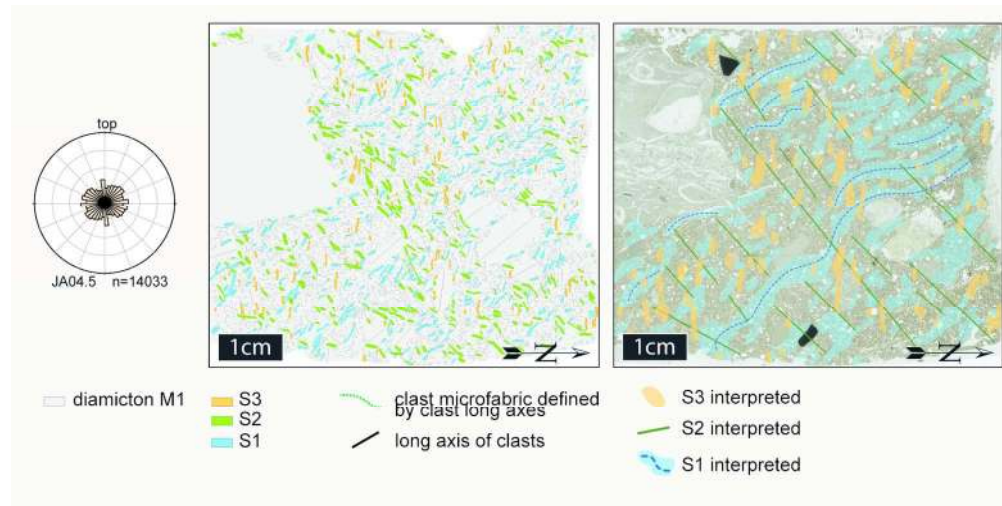


Fig. 12 Microstructural maps of the horizontal thin section JA04.5 showing the three fabrics S1 to S3 in the M1 diamicton. The top map displays the fabrics S1 to S3. The bottom map shows the interpretation of the microfabrics. The folded S1 fabric within the microlithons separating the S2 microfabric domains is easily visible. The rose diagram illustrates the strength of the individual microfabrics.
297x149mm (150 x 150 DPI)

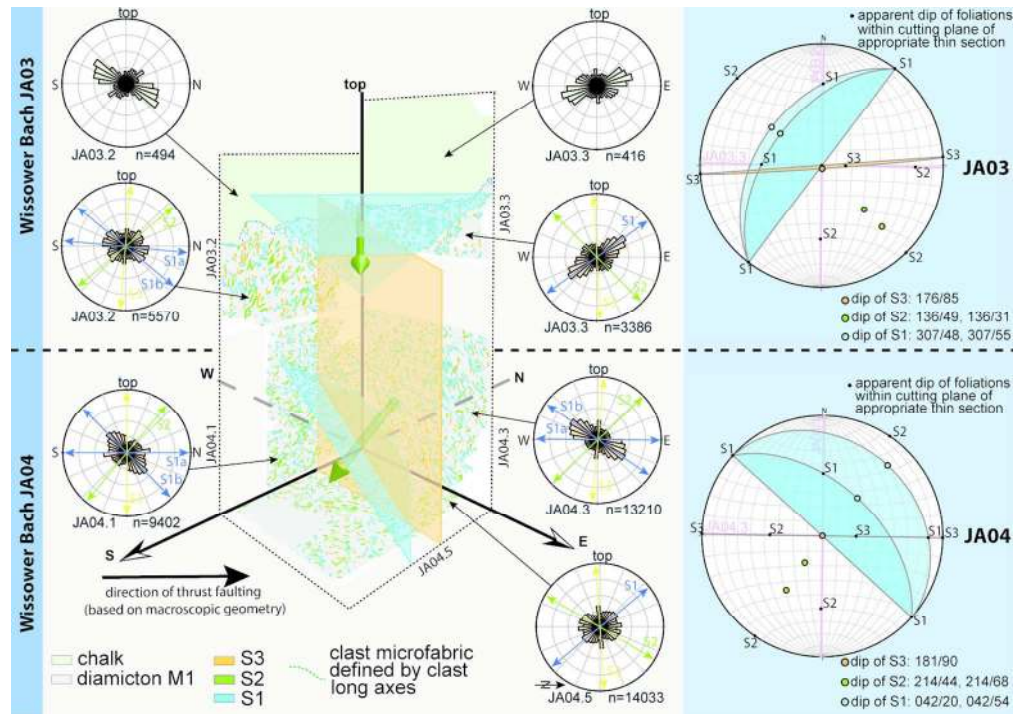


Fig. 13 3D model of the microfabric system at the chalk-diamicton contact (samples JA03, JA04) including the results from the orientation analysis of all thin sections. The lower hemisphere stereographic plots show the orientation of the microfabrics S1, S2 and S3, their shape (linear/planar) and their spatial relationship to each other.

248x175mm (150 x 150 DPI)

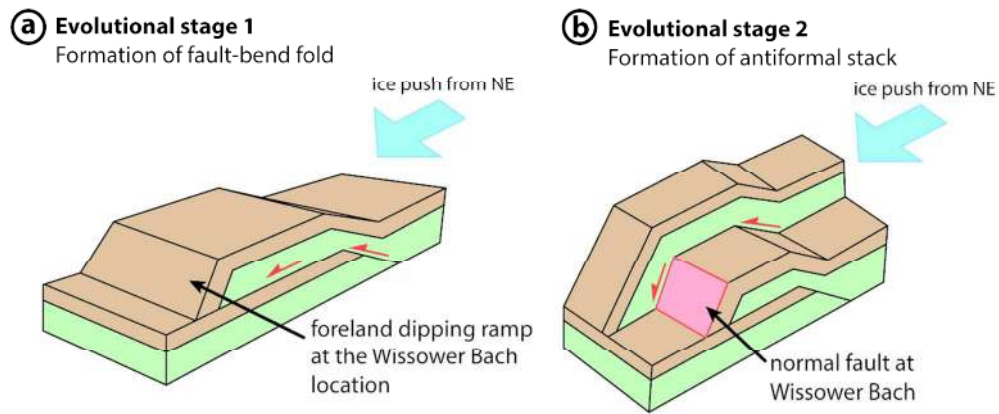


Fig. 14 First suggested model for the Wissower Bach structure developed by the push of an ice stream advancing from NE; a) stage 1: ramp thrusting of a chalk sheet over another chalk sheet, directed from NE towards SW; b) stage 2: formation of an antiformal stack, probably in the same progressive dynamic event, or alternatively in a readvance of the NE ice.

209x93mm (150 x 150 DPI)

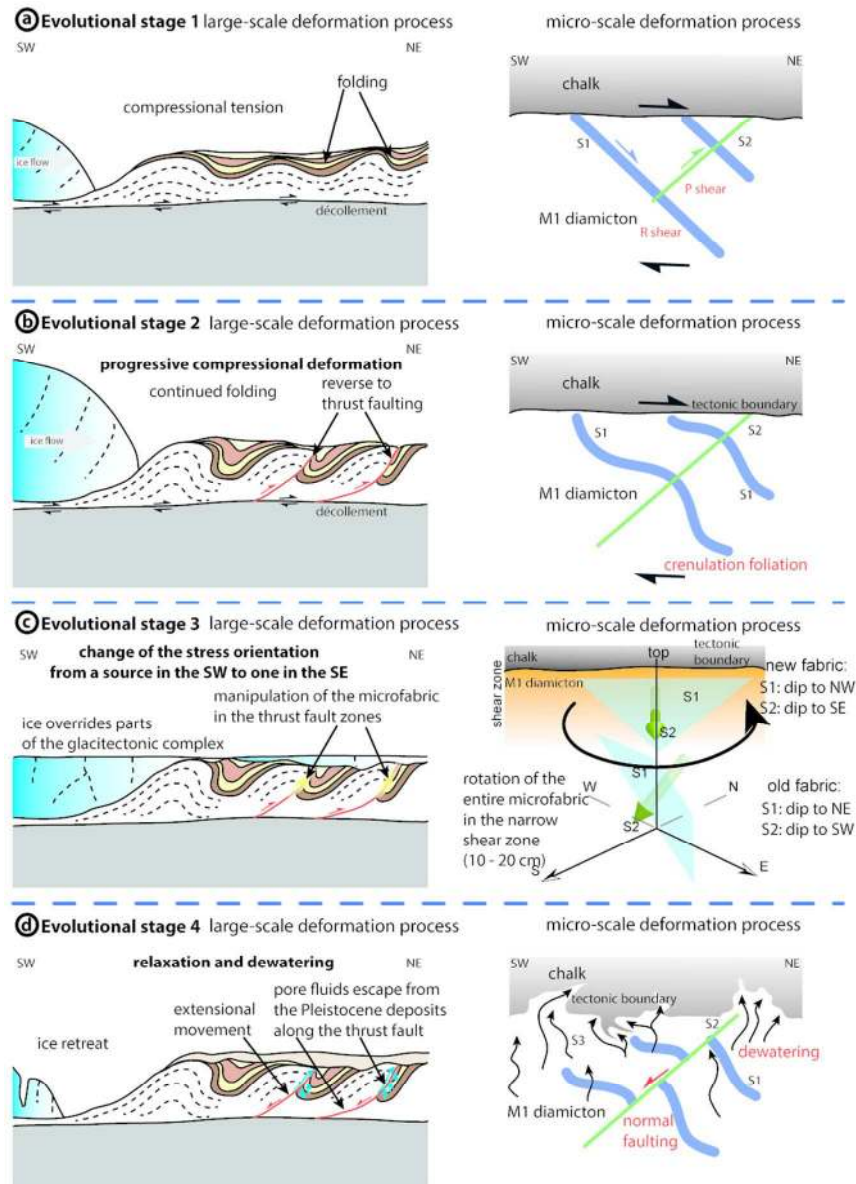


Fig. 15 Deformational model of the Wissower Bach Syncline including the four evolutionary stages; a) stage 1: incipient imposition of the large-scale folds which leads to the development of the microfabrics S1 (dip to NE) and S2 (dip to SW) as part of a Riedel shear zone; b) second stage with the continuation of large-scale folding and thrusting leading to progressive deformation (crenulation) of S1 and S2 at microscale; c) stage 3 comprising the anti-clockwise rotation of the microfabrics S1 and S2 within the narrow shear zone (10 to 20 cm) of the thrust fault presumably by the partial overburden of the glacetectonic complex by the preceding ice; d) stage 4: retreat of the ice and associated relaxation, which ends in local microscale normal-fault movements along the S2 microfabric and dewatering of the M1 diamicton, which produces a ductile deformation of the tectonic boundary and the evolution of the S3 microfabric.

176x247mm (150 x 150 DPI)