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Multiscalar 3D temporal structural characterisation of Smøla island, mid-Norwegian passive margin: an analogue for unravelling the tectonic history of offshore basement highs

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S1 Geophysical and remote sensing data and lineament mapping

The geophysical data used in this study was supplied by the Norwegian Geological Survey (NGU) and stems from three different airborne magnetic surveys (in 2011, 2012, and 2013) flown with line spacings between 250 m and 1000 m (60 m-200 m flight altitude), with the flight lines being oriented NW-SE (315°/135°) or N-S (0°/180°) depending on the survey flown. The data from the different surveys was subsequently merged and levelled to produce single geophysical grids over the Smøla region. Prior to the lineament mapping and structural interpretation, the merged geophysical data was processed into different transformations and filter products (Nasuti et al., 2015). The geophysical products used in this study include the total magnetic intensity (TMI) product, the reduce to pole (RTP) transformation, and derivative filter products, which include first vertical derivative (1VD), analytical signal (AS), total horizontal derivative (THD), and the tilt derivative (TDR). All the products are sun-shaded from the NE (045°). A full description of the geophysical data processing and merging methodology is available in Nasuti et al. (2015). The DTMs used were also provided by the NGU and are greyscale sun-shaded imagery generated from high-resolution LiDAR surveys (1m/pixel) previously flown over the mid-Norwegian region. The DTMs are sun-shaded from the NW (315°).

The lineament mapping following techniques from White, (2014) and Scheiber & Viola (2018) within a geographic information systems (GIS) software platform. The magnetic filters and transformations used in the mapping were based on scale: while at the smaller scales, the TMI and RTP products were used, at larger scales the 1VD, THD, and TDR products were used. The lineament mapping was undertaken manually at variable scales, identifying magnetic fabric truncations, offsets, linear features, and magnetic domain contacts that exhibit lateral continuity. Possible intrusive contacts and metamorphic foliation were ignored for the lineament mapping where no visible structural offset could be interpreted. Zones of evident negative magnetic signal (possible remnant magnetism), suggesting depletion of magnetic minerals owing to major fluid-flow (e.g., Grant, 1985), were also used to identify higher order lineaments (which may correspond to major fault structures). As a continual process during the lineament mapping, topographical features on the DTM (if over onshore areas of Smøla) were used to identify surface traces of the magnetic lineaments, and thus the exact placement and extent of the lineament polyline.

S2 Drill hole logging and field methods

Geological features in the drill core (Figure 3) were systematically documented downhole (for a total investigated length of 364.9 m of diamond drill core with a focus on recording lithology and rock alteration, deformation types, fracture/fault characteristics, mineral infill, and cross-cutting relationships.

The measuring of structural data in drill core followed the methods outlined by both Holcombe (2013) and Blenkinsop et al. (2015). Both planar and linear structural data measured in drill core were first measured using the α, β, γ angle system whereby features are measured relative to both the ‘bottom of core’ (BOC) line and the core axis (line parallel to the length of the drill hole). To accomplish this, two different instruments were used: a kenometer (HQ-size in this study) for the α, β angles (describing a plane cutting through the drill core), or a rotating protractor for the γ angle (describing a line within a plane cutting through the drill core). The α, β, γ angles were then converted into dip and dip direction data for the planar features, and trend and plunge data for linear data, making use of the downhole survey (which provides the downhole trend and plunge orientation of the core axis line).

S3 K-Ar dating and X-ray diffraction (XRD)

Seven fault gouge and breccia samples were collected from fault and deformation zones in both drill core and outcrop and were then processed at the dedicated NGU laboratory in Trondheim, Norway. Initially, all the samples were gradually disintegrated through repetitive freeze-thaw cycles in a ‘cryostat’ system. This process avoids any mechanical grinding or comminution of the particle sizes and therefore prevents possible contamination of the finer size fractions by fragmented potassic-bearing mineral phases. Following this, the samples underwent separation into <0.1 µm, 0.1-0.4 µm, 0.4-2 µm size fractions using high-speed centrifugation and 2-6 µm, 6-10 µm size fraction separation in distilled water using Stoke’s law. Each of these size fractions then underwent quantitative analysis for both potassium (K) and argon (Ar) using total digest ICP-OES for K, and a Isotopx NGX multi collector noble gas mass spectrometer system for Ar. A full description of the K-Ar analysis methodology is available in Viola et al. (2018).

Additionally, each size fraction underwent X-ray diffraction (XRD) analysis for mineral composition characterisation using a Bruker D8 Advance (Da Vinci System). Randomly oriented samples were prepared by side-loading and analysed with a Bruker D8 Advance X-ray diffractometer operating with a Cu X-ray tube (40 kV/40 mA) and Lynxeye XE detector. The XRD scan was performed from 3 to 75° 2q with a step size of 0.02° 2q, a measurement time of 0.5 s per step, and rotation speed of 30 per minute. Fixed divergence had an opening of 0.6 mm and primary and secondary soller slits were 2.5°. A knife edge was used to reduce scatter radiation. Mineral identification was carried out with the automatic and/or manual peak search-match function of Bruker's Diffrac.EVA V6.1 software using both Crystallographic Open Database (COD) as well as the PDF 4 Minerals database from the International Centre for Diffraction Data (ICDD). For further clay minerals study, oriented mounts of fractions 2-6 µm were prepared by letting 1 ml of sample suspension dry out on a glass slide. These slides were measured from 2 to 40° 2q at room temperature, after treatment with ethylene glycol for 24 h, and after heating at 550°C for 1 h.

Mineral quantification was performed on randomly prepared specimens using Rietveld modelling with TOPAS 5 software. Refined parameters included crystallite size, unit cell dimensions, sample displacement, preferred orientation as well as background coefficients. The lower detection limits are mineral-dependent and estimated to be 1-2 wt% with an approximate uncertainty for the Rietveld modelling (i.e., quantification) of at least 2-3 wt%.

S3.1 Locations of field and drill hole samples, and mesoscale/microscale deformation image

The table (Tables S1) below provides the GPS locations (UTM) and down-hole depth (where relevant) associated with each of the images, and the samples used for the K-Ar and petrography work, as referred to in the main body of text:

Table S1. Locations for each of the images are provided below, either as sample site ID with UTM coordinates (Projected coordinate system UTM-WGS 1984, 32N)

Mesoscale deformation features						
Image ID	**Site ID**	**Sample ID**	**X**	**Y**	**Drill hole ID**	**Depth (m)**
A	1001	N/A	447053	7025827	BH1	97.95
B	1029	N/A	445432	7025769	BH2	15.5
C	1024	N/A	447264	7027955	BH2	108.3
D	1033	N/A	454471	7023250	N/A	N/A
E	1020	N/A	447104	7027930	N/A	N/A
F	1019	N/A	446969	7027950	BH2	93.4

Microscale deformation features						
A	N/A	125602	N/A	N/A	BH1	15.655
B	N/A	125612	N/A	N/A	BH1	92.74
C	N/A	125611	N/A	N/A	BH1	92.63
D	N/A	125644	N/A	N/A	BH2	108.27
E	N/A	125644	N/A	N/A	BH2	108.27
F	N/A	125622	N/A	N/A	BH2	79.735
G	1033	SP1033_1b	454471	7023250	N/A	N/A
H	N/A	125616	N/A	N/A	BH2	20.105
I	N/A	125628	N/A	N/A	BH2	91.65

K-Ar samples						
A	N/A	SK2012	N/A	N/A	BH2	108.3
B	N/A	SK2015	N/A	N/A	BH2	109.9
C	N/A	SK2008	N/A	N/A	BH2	79.7
D	N/A	120714	N/A	N/A	BH4	31.3
E	1024	SK1024_1	447264	7027955	N/A	N/A
F	1029	SK1029_1	445432	7025769	N/A	N/A
G	1033	SK1033_1	454471	7023250	N/A	N/A

S3.2 Supplementary material: K-Ar geochronology and X-ray diffraction

In addition to the K-Ar sample geochronology and XRD results in the main body of text, the following more detailed descriptions are provided for the seven fault gouge samples (Table 2, Figure 9) collected from drill holes BH2 (SK2008, SK2012, SK2015), BH4 (120714) (Figure 4), and fault core outcrop exposures on Smøla Island (SK1024_1, SK1029_1, SK1033_1). Please refer to the dated sample compositions by X-ray diffraction (XRD) results as shown in Figure 10 by weight percent (wt%), with the K-Ar dating results in Table 3 and Figure 11A, with the dating results relative to structure geometries in Figure 11B. The samples are characterised below, and are ordered by interpreted deformation episode (D2 to D4):

SK2012

Sample from BH2 at 108.3 m, from a 25 cm-wide foliated gouge/phyllite to cataclasite interval (Figure 9A), within monzogranite, with strong chlorite and sericite D2 mineralisation and host rock fragments. The sampled interval strikes NE-SW with a shallow NW dip and exhibits no clear kinematics. XRD results (Figure 10) show that the K-Ar dates are provided by K-bearing illite/muscovite and smectite. In the sample, illite/muscovite (muscovite involves mostly sericite from the petrography work) increases with decreasing grain size fraction, with the highest abundance for the <0.1 μm size fraction (63 wt%). Smectite similarly increases in abundance within the smaller size fractions. The mineralogy of the sample is consistent through the size fractions, except for the quartz component within the coarser size fractions (0.4-2 to 6-10 μm), which derives from either the crystalline groundmass or host rock fragments. This sample yielded an age of 196.1 ± 2.8 Ma for the <0.1 μm size fraction, potentially authigenic, and 290.7 ± 4.4 Ma for the 6-10 μm (Table 3) fraction, potentially a protolithic/inherited component (e.g. Viola et al., 2016). The age results for the intermediate fractions, particularly 0.1-0.4 to 0.4-2 μm, are mixed authigenic-protolithic ages. Overall, the results for SK2012 indicate an inclined age spectra curve on Figure 11A.

SK2015

Sample from BH2, at 109.74 m, from a 20 cm-wide well-milled foliated clay-rich gouge zone, striking E-W, moderately S-dipping (Figure 9B), and is 3D modelled on Figure 8A as Zone IV. The sampled interval is set within highly fractured monzogranite, representing a well-defined damage zone. Within the gouge interval there are abundant host rock and quartz-calcite vein fragments. XRD results indicate the K-Ar ages derive from illite/muscovite, smectite, and potassium feldspar (Figure 10). Like SK2012, illite/muscovite (sericite) content increases in the finer grain size fractions. The coarser size fractions are quartz-dominated, with minor components of calcite, and potassium feldspar (limited to the size fractions 2-6 to 6-10 μm), potentially representing an inherited potassium source. Chlorite is present throughout the size fractions. The <0.1 μm size fraction yielded an age of 201.4 ± 2.9 Ma, and the 6-10 μm size fraction an age of 287.0 ± 4.7 Ma (Table 3), indicating a similar inclined age spectra curve as SK2012 (Figure 11A). Both the samples SK2012 and SK2015 returned similar ages for the 4-6 and 6-10 μm fractions, even though they from different structures with unique orientations (Figure 11A, B). This implies that there is an inherited component (potentially inherited illite/muscovite) present in both samples from an earlier tectonic episode.

SK1029_1

The field sample, collected from a ~5 cm-wide well-developed gouge, chlorite, and clay-rich zone, hosted in monzodiorite (Figure 9F). The sampled zone extends >10 m, striking ENE-WSW and dipping steeply SE, with no observable kinematics. The sampled zone is proximal and inclined to a major E-W structure, mapped as a 2nd order L3 lineament (Figure 2). XRD results show K-Ar ages derive from smectite, illite/muscovite, and zeolite. Overall, the sample is dominated by chlorite-smectite mixed clay (tosudite) and is the only mineral phase in the <0.1 µm size fraction. Illite/muscovite is present in the size fractions 0.1-0.4 to 6-10 µm and absent in the finest fraction. Zeolite is similarly present in the coarser size fraction, being particularly abundant in 2-6 µm, and 6-10 µm size fractions (Figure 10). In the coarser fractions, quartz, plagioclase, and amphibole are all present, representing host-rock fragments. The sample's finest fraction (<0.1 µm) yielded an age of 204.1 ± 3.7 Ma, which derives from authigenic smectite, with the largest fraction (6-10 µm) yielding and age of 218.2 ± 3.8 Ma (Table 3). The oldest age however come from the size fraction 0.4-2 µm (314. ± 5.4 Ma). The younger ages for the coarser fractions can be attributed to zeolite, which both mineralised at a later stage and while providing K to the system, potentially experienced radiogenic 40Ar loss from the crystal structure, leading to lower age results (e.g. Levy and Woldegabriel, 1995). The convex-upward age spectra curve on Figure 11A for SK1029_1, indicates that only the finest fraction provides a reliable age result.

SK2008

This sample, collected at 79.7 m in BH2, is from an 8 cm-wide indurated gouge to micro-vein breccia (Figure 9C), striking NNE-SSW, and dipping shallowly WNW, and exhibits no kinematic indicators. The sampled zone has typical D3 chlorite-hematite mineralisation, in altered monzogranite, defining a ~5 m wide damage zone. XRD results indicate that illite/muscovite, potassium feldspar, and smectite (a significantly lower source of K compared to the other minerals) contribute towards the K-Ar ages. Hematite, which is the distinguishing feature of the sample, is present in all the size fractions (0.1-0.4 to 6-10 µm), except for the finest fraction. The illite/muscovite component is present in all size fractions but becomes a minor component in the <0.1 µm fraction (2 wt%). Smectite increases in abundance towards the finest fraction (80 wt% in the <0.1 µm fraction), while chlorite remains consistent through the size fractions. The coarser size fractions (2-6 to 6-10 µm) contain potassium feldspar, calcite, and quartz (with quartz also present in 0.4-2 µm fraction), representing host rock fragments. The <0.1 µm fraction returned a K-Ar age of 99.6 ± 1.8 Ma, with illite/muscovite and smectite potentially authigenic. The largest fraction provided a 195.2 ± 3.1 Ma age (Table 3), which with potassium feldspar present in the size fraction, could be a protolithic age. Overall, the age spectra curve for SK2008 on Figure 11A shows a plateau trend for the fractions 0.4-2 to 6-10 µm corresponding to ~200 Ma, which coincides with the finest fraction ages for samples SK2012, SK2015, and SK1029_1, also suggesting D2 inheritance within the coarser fractions.

SK1033_1

A field sample from a ~25 cm-wide possible weathered gouge zone within a saprolite horizon (Figure 9G), bound by chloritic-hematite slickenside surfaces adjacent to the zone. The plane adjacent to the zone, oriented with low confidence owing to poor preservation, strikes ENE, dipping steeply SE, with dip-slip oriented slickenlines (too subtle to accurately measure). XRD results show a mineralogy dominated by smectite with minor illite/muscovite both contributing towards the K-Ar ages (Figure 10). Illite/muscovite is only present in the coarsest size fraction 6-10 µm, with minor abundance of chlorite also present within the fractions 0.4-2 to 6-10 µm. The finest fraction returned an age of 128.1 ± 11.8 Ma, with the large uncertainty associated to the low K wt % (Table 3) for the size fraction (<0.1). The coarsest fraction yielded an age of 263.3 ± 5.4 Ma (Table 3). The finest fraction K-Ar age, deriving entirely from smectite, may represent authigenic clay growth during saprolite formation or hydrothermal activity, or a mixture of the two processes. On Figure 11A, the age spectra curve for SK1033_1 is overall inclined from the finest to the coarsest fractions, however the youngest age is 126.0 ± 9.2 Ma corresponding to the 0.1-0.4 µm size fraction.

120714

Sample collected at 31.3 m in BH4, from a 40 cm-wide friable clay-rich gouge within a shear band, with cross-cutting zeolite veins, in diorite (Figure 9D). The sampled zone strikes NW-SE, with a moderate NE dip. XRD results show that the K-Ar dates derive from smectite, illite/muscovite, and potassium feldspar. The sample overall is smectite-dominated, and becomes more abundant in finer size fractions, with the finest fraction <0.1 µm composed entirely by smectite. Illite/muscovite is present in the two coarsest fractions, 2-6 to 6-10 µm, and the fraction 0.1-0.4 µm. The two coarsest fractions also have minor amounts of potassium feldspar, plagioclase, and calcite (which also occurs in the fraction 0.4-2 µm), representing potential host rock fragments. Chlorite is moderately abundant in all fractions except the finest fraction. The finest size fraction <0.1 µm yielded an age of 74.7 ± 1.7 Ma, the youngest age for all the samples collected from Smøla Island (Table 3). The coarsest fraction 6-10 µm returned an age of 153.6 ± 2.7 Ma, which may represent an inherited age owing to the presence of host rock potassium feldspar, and illite/muscovite. The zeolite veins, not present in the XRD results, crosscutting the sampled gouge, would have mineralised after these ages, indicating a possible upper limit on the timing of D4. Overall, the age spectra curve for 120714 is inclined from the finest to the coarsest size fraction (Figure 11A).

SK1024_1

This field sample, from a ~8 cm-wide foliated chloritic gouge zone (Figure 9G) within an 8 m wide damage zone. The sampled gouge zone, a D2 to D3 feature, strikes E-W, dips sub-vertically to steeply south, with crosscutting by zeolite veins, and is adjacent to hematite fractures. Due to insufficient material in the finest fraction (<0.1 µm), both XRD and K-Ar dating analysis could not be undertaken for this size fraction. This sample is therefore included for demonstrative purposes only. For the other size fractions, the XRD analysis indicates that smectite, illite/muscovite, and zeolite all contributed to the K-Ar ages. The size fractions 0.4-2 to 6-10 µm have similar mineral compositions, with major amounts of smectite, chlorite, and zeolite, and lower abundances of quartz and illite/muscovite. The 0.1-0.4 µm has much lower abundances of zeolite, quartz, and illite/muscovite. The K-Ar ages for the size fractions range from 162.1 ± 3.1 Ma to 163.5 ± 3.0 Ma for the coarsest fraction (Table 3), with the oldest age (180.5 ± 3.4 Ma) associated with the 0.4-2 µm fraction. The age spectra curve on Figure 11A is a convex-upward shape, with zeolite presence in the coarser fractions resulting in a lower age, similar to sample SK1029_1.

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