Supplement for:

Multiscalar 3D characterisation of the Mid-Norwegian passive margin evolution, Central Norway: A multi-technique approach to unravelling the structural characteristics and tectonic history of offshore basement highs

Hodge Matthew, Sotheron[1]*, Venvik, Guri[2], Knies Jochen[2], van der Lelij, Roelant[2], Schönenberger, Jasmin[2], Nordgulen, Øystein[2], Brønner, Marco[2], Nasuti, Aziz[2], & Viola Giulio[1]

1: Department of Biological, Geological and Environmental Sciences, University of Bologna, Italy

2: Geological Survey of Norway (NGU), Trondheim, Norway

Correspondence to: Matthew S. Hodge (matthew.hodge@unibo.it)

1 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.

2 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).

3 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%.

References

Blenkinsop, T., Doyle, M., & Nugus, M. (2015). A unified approach to measuring structures in orientated drill core. In Geological Society Special Publication (Vol. 421, Issue 1, pp. 99–108). Geological Society of London. https://doi.org/10.1144/SP421.1

Clauer, N., Zwingmann, H., Liewig, N., & Wendling, R. (2012). Comparative 40Ar/39Ar and K–Ar dating of illite-type clay minerals: A tentative explanation for age identities and differences. Earth-Science Reviews, 115(1–2), 76–96. https://doi.org/10.1016/J.EARSCIREV.2012.07.003

Grant, F. S. (1985). Aeromagnetics, geology and ore environments, I. Magnetite in igneous, sedimentary and metamorphic rocks: An overview. Geoexploration, 23(3), 303–333. https://doi.org/10.1016/0016-7142(85)90001-8

Holcombe, R. (2013). Oriented Drillcore: Measurement, Conversion and QA/QC Procedures for Structural and Exploration Geologists. Http://Www.Holcombe Coughlinoliver.Com/Downloads/.

White, N. C. (2014). Geological Interpretation of Aeromagnetic Data (David J. Isles and Leigh R. Rankin). Economic Geology, 109(5), 1495–1496. https://doi.org/10.2113/econgeo.109.5.1495

Nasuti, A., Olesen, O., Baranwal, O., & Dumais, M. (2015). Compilation of aeromagnetic data. In O. Olesen, O. Baranwal, M. Brönner, E. Dalsegg, M., A. Dumais, J. Gellein, L. Gernigon, T. Heldal, B. , E. Larsen, T. Lauritsen, O. Lutro, Y. Maystrenko, A. Nasuti, D. Roberts, H. Rueslåtten, J. S. Rønning, T. Slagstad, A. Solli, & A. Stampolidis (Eds.), Coop Phase 2 - Crustal Onshore-Offshore Project. NGU confidential Report (Vol. 063, pp. 11–24). Norges Geologiske Undersøkelse.

Scheiber, T., & Viola, G. (2018). Complex Bedrock Fracture Patterns: A Multipronged Approach to Resolve Their Evolution in Space and Time. Tectonics, 37(4), 1030–1062. https://doi.org/10.1002/2017TC004763

Zwingmann, H., & Mancktelow, N. (2004). Timing of Alpine fault gouges. Earth and Planetary Science Letters, 223(3), 415–425. https://doi.org/https://doi.org/10.1016/j.epsl.2004.04.041