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Fault zone permeability structure evolution in basalts

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ABSTRACT

A combination of field, microstructural and experimental static permeability characterization is used to determine fault permeability structure evolution in upper crustal basalt-hosted fault zones in the Faroe Islands. The faults comprise lower strain fracture networks, to higher strain breccias that form tabular volumes around a principal slip zone hosting gouge or cataclasite. Samples representative of these fault zone components are used for static experimental permeability measurement. Results indicate that within the appropriate effective pressure (depth) range (10–90 MPa: ~0.3 to ~3.0 km), basalt-hosted faults evolve from low strain (< 1m displacement), relatively low-permeability (<10–17 m^2) structures, to high strain (≥ 1m displacement), relatively high-permeability (>10–17 m^2) structures. Sample analyses reveal that static permeability is controlled by the development of: a) fault-parallel clay alteration (decreasing permeability); and b) porous zeolite vein connectivity due to hydrofracture (increasing permeability). Fault-parallel permeability is increased relative to the host rock, while fault-normal permeability is low throughout fault rock evolution. This configuration will tend to promote across-fault compartmentalization and along-fault fluid flow, facilitating migration between relatively high-permeability horizons (e.g. vesicular flow unit tops and siliciclastic horizons), bypassing the bulk of the stratigraphy.

INTRODUCTION

The need to understand subsurface fluid flow and sealing potential in basaltic sequences is becoming increasingly important with the rising economic significance of intra- and sub-volcanic hydrocarbon plays (Schutter, 2003), conventional and enhanced geothermal systems, and the growing need to find suitable sites for geological carbon sequestration or storage (Hawkins, 2004; Oelkers and Cole, 2008). The efficacy of geological CO_2 storage is dependent on the retention time, the dynamic reservoir stability (the risk of leakage), and/or the mineral storage potential of the host rock (Gislason et al., 2010). Sealing potential in basaltic sequences is also important to intra- and sub-basaltic hydrocarbon plays, particularly in passive margin continental basins that are active targets for hydrocarbon exploration. In volcanic geothermal systems, the methods used for geothermal exploration and resource development are highly dependent on whether heat is lost by convection or conduction, and so fault permeability is critically important.

Faults are a key component in the sealing potential of any subsurface storage system, yet little is known about the hydraulic structure of basalt-hosted faults. Here we focus on part of the European North Atlantic margin (Fig. 1A; *Appendix 1*), which is covered by variable thicknesses of basaltic lavas and volcaniclastic rocks related to the North Atlantic Igneous Province. Several recent onshore and offshore studies in the Faroe-Shetland Basin (e.g., Ellis et al., 2009; Moy and Imber 2009; Walker et al. 2011a,b) have shown that faults cut part, or all of the Palaeocene lava sequence together with the rocks in the underlying sedimentary basins. It is important, therefore, to determine the permeability characteristics of such lava-hosted faults since they will likely influence fluid flow in the sub-surface.

Fluid flow in upper-crustal brittle fault zones is dependent on the permeability of the fault rock assemblage and its architecture (e.g., Faulkner and Rutter, 2001). Models for clastic sedimentary sequences and crystalline basement rocks typically refer to a low-permeability *fault core* surrounded by a higher-permeability *damage zone*, relative to the intermediate permeability of the undeformed host rock (e.g., Caine et al., 1996; Evans et al., 1997). In this paper, we detail the permeability structure of basalt-hosted fault zones using examples of widely distributed brittle fracturing in the Faroe Island Basalt Group (FIBG) on the NE Atlantic Margin. This study uses experimental permeability measurements to quantify fault zone static permeability structure in basalts. Qualitative field- and microstructural characterization of the same fault rock assemblages are used to rationalize measured permeability, and to infer dynamic permeability associated with fault events. The results indicate that permeability during faulting is important in fluid migration, and, at stages in fault evolution low-strain zones can act as a barrier to fluid flow, whereas high-strain zones act as conduits.

FAULT ZONE ARCHITECTURE

Fault zones in the Faroe Islands cut volcanic and volcaniclastic strata of the Palaeocene-age Faroe Islands Basalt Group (FIBG: 59–56 Ma; Passey and Jolley, 2009), and are representative of faulting at depths between 1 and 3 km (Walker et al., 2012), formed before, during and immediately after North Atlantic break-up in the early Eocene (Walker et al., 2011a). Basaltic host units display joints and microfractures formed during cooling, which range in length from <1 mm up to ~30 m (i.e., the thickness of the host unit). Fractures and joints of this type increase in density toward the top of lava units, and toward the margins of dykes. Fault-related damage represents an increase in fracture density, relative to the host lithology. Slip is accommodated on a surface or zone of cataclasite or gouge, defining the *principal slip surface* or *zone* (PSS or PSZ respectively: Figure 1A, D). These are contained within the *fault core*, which is defined here as the zone that accommodates the majority of shear displacement, and can be characterized by mosaic and chaotic breccias (Fig. 1A, C) (breccia definitions following Woodcock et al., 2006). Surrounding the fault core is a zone of damage, which is characterized by crackle to mosaic breccias (Fig. 1A, B).

Calcite and zeolite mineralization are ubiquitous in syn-magmatic Faroe Islands fault zones, indicating that they acted as conduits for the passage of hydrous fluids. Early-formed veins are filled with zeolite that grows inwards from the fracture walls as hemiradial fibers, indicating mineral growth into fluid-filled cavities. In thicker veins (>1–2 mm thick), calcite is typically the dominant mineral fill. In most fault zones, zeolites are also observed lining the euhedral terminations of individual calcite crystals. Textural relationships suggest that zeolite and calcite mineralization were accompanied by the generation of authigenic clays at all stages of fault zone evolution (Walker et al., 2012).

METHODS

Host rock and fault zone assemblages were sampled in transects across representative fault zones in the Faroe Islands, to characterize fault zone heterogeneity. The experimental static permeability measurements detailed below have sample volumes on the scale of cubic centimeters. Since mesoscopic open fractures have not been sampled explicitly, measured permeabilities may only provide a lower bound to the bulk fault zone permeability. Cores were taken to measure fault-parallel and fault-normal permeability, but, in most cases, the fault-parallel samples broke along fractures and veins, and could not be loaded into the high pressure fluid-flow apparatus. Static permeability was measured experimentally under simulated subsurface reservoir pressures (0.3 to 3.0 km) using the Transient Pulse Decay (TPD) technique (Brace et al., 1968): a detailed methodology is provided by Armitage et al. (2011). Argon was used as the permeant, and all experiments were conducted at a maintained room temperature of

~22ºC. The resolution of the pressure measurements is ± 0.3 MPa, and permeability can be measured accurately within the range 10^{-16} to 10^{-23} m^2 using our set-up for the TPD technique.

STATIC PERMEABILITY RESULTS

The bulk permeability structure of a fault zone is a composite of the properties of the architectural elements and their spatial arrangement in three dimensions (e.g., Caine and Forster, 1999). Permeability measurements of the key fault zone components provide an indication of in situ permeability. On the assumption that low-strain fault rock components represent early stages of high-strain zones, these data can be used to infer the evolution of static permeability through time.

Pressure cycling within the study range (i.e., 10–90 MPa effective pressure) was used here to close any stress-relief micro-fractures (see *Appendix 2* for details). Our data reveal that at a simulated depth of ~3 km (90 MPa), permeability spans over four orders of magnitude, ranging from 1.32×10^{-20} m^2 (L03; Fig. 2) to 1.44×10^{-16} m^2 (L05; Fig. 2). For samples with fault-parallel (k_V) and fault-normal data (k_H), k_H ranges from 1.51×10^{-20} m^2 (IB07b; Fig. 2) to 2.81×10^{-18} m^2 (IB13a; Fig. 2); k_V ranges from 6.54×10^{-19} m^2 (IB07a; Fig. 2) to 2.97×10^{-17} m^2 (IB13a; Fig. 2). The permeability anisotropy ratio (k_V/k_H) at 90 MPa effective pressure ranges from 11 to 43, with the maximum anisotropy in the lower-strain zone.

The studied basaltic host rocks are generally low permeability, within the range of 10^{-20} to 10^{-19} m^2, with the exception of the compound lava unit sample (L01; Fig. 2). The two sample suites (aphyric basalt lava unit and aphyric to plagioclasephyric basalt dyke) show a varied evolution pathway from host rock to evolved fault rock (Fig. 2). In the lava sample suite, permeability initially increases by about two orders of magnitude (from host to crackle breccia), but then decreases by a comparable amount into the higher-strain mosaic breccias. By contrast the dyke sample suite shows an initial decrease in permeability from the host rock into the low strain fault rocks, followed by a near reciprocal increase toward the fault core. That permeability increase continues in the dyke suite into the fault core chaotic breccia, which records the highest permeabilities of this study (Fig. 2). A permeability increase is also recorded from the lava unit mosaic breccia (IB07) into the PSS cataclasite samples (IB13) (Fig. 2). Overall the sample suites show lower permeability in low strain zones, and higher permeability in high strain zones.

FAULT ROCK ASSEMBLAGES

Microstructural characterization of the host and fault rock assemblages is important as it gives insights into the controls of the static permeability laboratory measurements. Furthermore it gives a qualitative indication of the likely evolution in syn-faulting dynamic permeability with increasing deformation.

Sample suite host rocks are generally fine crystalline basalt, dominated by plagioclase and pyroxene, and display very minor mineral alteration to clays (Fig. 3A). This clay development appears to be authigenic, occurring along microfractures and crystal boundaries. Longer and wider fractures, where present, are typically clay-lined, and no zeolite or calcite mineralization is observed (Fig. 3A).

Low strain (<1m displacement) fault rocks (Fig. 3B) show increased alteration relative to the host, with discrete zones of clay minerals developed immediately adjacent to - and parallel with - fractures and veins (Fig. 3B). In samples L03 and IB07, zeolite veins are clay-lined and poorly connected in the section plane, whereas in samples S02 and L04, zeolite veins are interconnected. Blue-stained zeolite veins in thin section (Fig. 3B-C) indicate that these veins remain porous.

High strain (fault core) rocks that have accommodated m-scale displacements or greater (Fig. 3C) show intense zeolite and calcite veining that forms a connected network. Authigenic clays developed during host alteration appear to be absent in the crystalline groundmass, with zeolite fill in their place. PSS cataclasite samples that have accommodated ~30 m displacement (Fig. 3D) comprise chaotic, generally matrix-supported basalt, zeolite and calcite clasts set in a cataclasite matrix formed of the same components. Established vein networks are cut by, and incorporated into, the cataclasites.

Thin sections of measured samples show a strong correlation between clay development, section plane vein connectivity, and static permeability results. Where low strain fault rocks display poor zeolite-vein connectivity, permeability is higher than for samples with segmented veins. In the most permeable, high strain zones, clays are absent or dissected by zeolite/calcite (veins or continuous clasts of veins).

IMPLICATIONS FOR PERMEABILITY STRUCTURE EVOLUTION

The measured experimental static permeabilities when combined with field- and microstructural-characterization of the fault rocks show that faults in basalt generally develop through stages of low-strain, lower-permeability assemblages, to high-strain, higher permeability assemblages. This contrasts with most clastic-hosted fault zone models, where high strain fault cores are generally thought to exhibit lower permeabilities due to grain comminution effects (e.g. Caine et al., 1996). Microstructural evidence here indicates that the evolution of static permeability in basalt-hosted faults relates to the interplay between clay sealing versus zeolite vein connectivity, and cataclasis and vein dissection. The presence of pervasive mineral vein networks and authigenic clays within fault zones also indicate that there was significant transient permeability development during rock fracture episodes (i.e., dynamic permeability).

Although the host rocks from the sample suites are low-porosity fine crystalline basalts, microfractures related to cooling and/or distributed strain demonstrably facilitated transient, low fluid-flux, as is evidenced by the occurrence of minor alteration to clays. Depending on fluid chemistry (i.e., CO_2 concentration), pH and temperature, alteration of the basaltic mineralogy to clays within the study depth range (i.e., 0–3 km) can occur in a matter of years (Gysi and Stefánsson, 2008), i.e., at a rate comparable to aseismic fault creep. During initial meso- to macro-scale rock fracturing, fluid flow was increased locally, leading to the precipitation of zeolite and calcite as veins. In these low strain fault rocks, veins and fractures may remain locally statically permeable, but are lined by low-permeability clays and are poorly-interconnected (Fig. 3B). The development of clays acts to decrease permeability relative to the host rocks (Figs. 3A, B, 4). Such lowered permeabilities could help promote pore fluid trapping, ultimately resulting in pressure elevation and hydrofracture.

As fault displacement accumulates, the zeolite/calcite veins link to form through-going, transient high permeability pathways. Zeolite veins retain porosity following crystal growth (Fig. 3B,C), maintaining high permeability after faulting. If these veins are interconnected, fault rock static permeability will remain high; if they are not connected, static permeability will be low (e.g., Figures 2, 3).

Larger displacement (>1 m) fault core samples principally comprise interconnected zeolite-calcite mineral-fills, with minor clay content only (Fig. 3C); hence static permeability is high. Further slip leads to static permeability reduction in the fault core through cataclasis, clay gouge development and dismemberment of existing zeolite/calcite veins. Nevertheless, the static permeability of the PSS (Figs. 2, 3D) remains over an order of magnitude higher (both k_V and k_H) compared to low strain fault rocks, despite fragmentation of the relatively high-permeability veins, and development of a fine-grained matrix (cataclasite and/or gouge). Inspection of hand specimens suggests that this could be due to out of section-plane connectivity of permeable vein fragments (Fig. 3D).

The high-permeability, high strain zone, low-permeability low strain zone model presented here will promote lateral compartmentalization, and along-fault fluid migration. However, since the low strain zone forms a barrier to flow, fluids will only be able to migrate from and to relatively high permeability horizons (e.g., lava unit vesicular flow tops), bypassing the bulk of the lava flow stratigraphy via an 'insulated' fault core.

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FIGURE CAPTIONS

Figure 1. A: Overview of a dip slip normal fault in a columnar-jointed basalt unit (after Walker et al., 2012), showing idealized strain distribution. Map shows the location of the Faroe Islands and North Atlantic Igneous Province (NAIP). B: Low strain zone crackle and mosaic type fault breccias that accommodate mm- to cm-scale displacements. C: High strain (fault core) mineralized mosaic and chaotic breccias that accommodate about 5 m net slip. D: Principal slip zone chaotic breccia and cataclasites that accommodate >10 m displacement. Breccia styles defined following Woodcock et al. (2006).

Figure 2. Measured permeability data for host rock and fault rock assemblages at effective pressures ranging from 10 to 90 MPa (static fluid pressure of 10 MPa). Fault-parallel (k_V) and fault-normal (k_H) values are shown for anisotropic samples (IB07 and IB13). Host rock and chaotic breccias do not exhibit a clear fabric: k_V and k_H values are assumed equal within the experimental uncertainty. Within the sub-100 MPa confining pressure range, the high permeability of the dyke fault core sample (L05) is at the limits of the TPD technique using our experimental set-up; successful analysis at higher effective pressures (110–190 MPa; *Appendix 2*), and down-pressure extrapolation indicate that fault core permeability ranges from ~$2.5x10^{-15}$ m^2 at 10 MPa, to $1.44x10^{-16}$ m^2 at 90 MPa.

Figure 3. Plane polarized light photo-micrographs of host rock and fault rock assemblages representative of samples used for experimental permeability measurement (i.e., Fig. 2). All samples were prepared using blue-stained resin to show porosity. See text for description and

discussion. A: Host rocks; B: Fault damage crackle (left) and mosaic (right) breccias; C: Fault core chaotic breccia; D: Principal slip zone comprising chaotic breccia and cataclasite and/or gouge. Disp.: displacement.

Figure 4. Summary model for the evolution of fault-parallel and fault-normal permeability, based on experimental data combined with microstructural characterization of fault zone assemblages.

[1]GSA Data Repository item 2012xxx, Appendix 1: Location maps for the study fault zones, Faroe Islands, N. Atlantic European continental margin; Appendix 2: Experimental method description, including table of results and graphs for all data, is available online at www.geosociety.org/pubs/ft2012.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.

Figure 1
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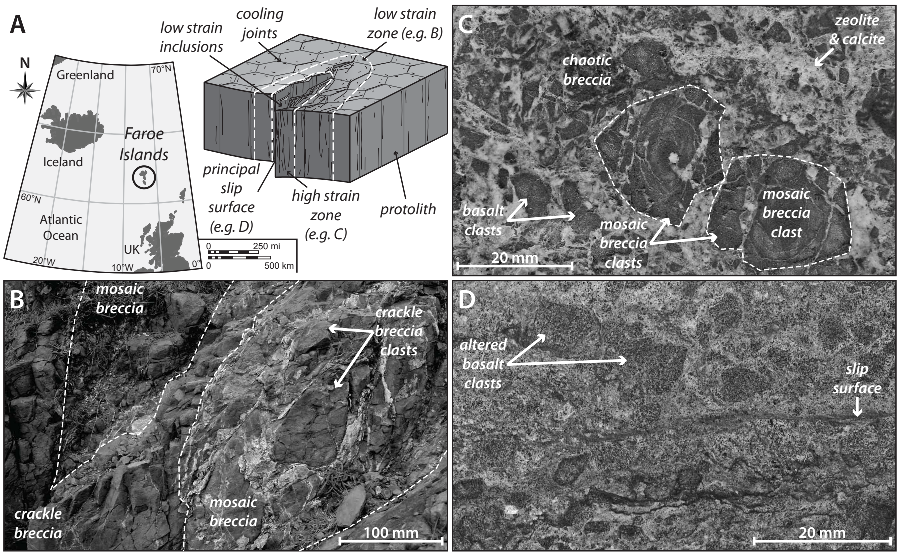

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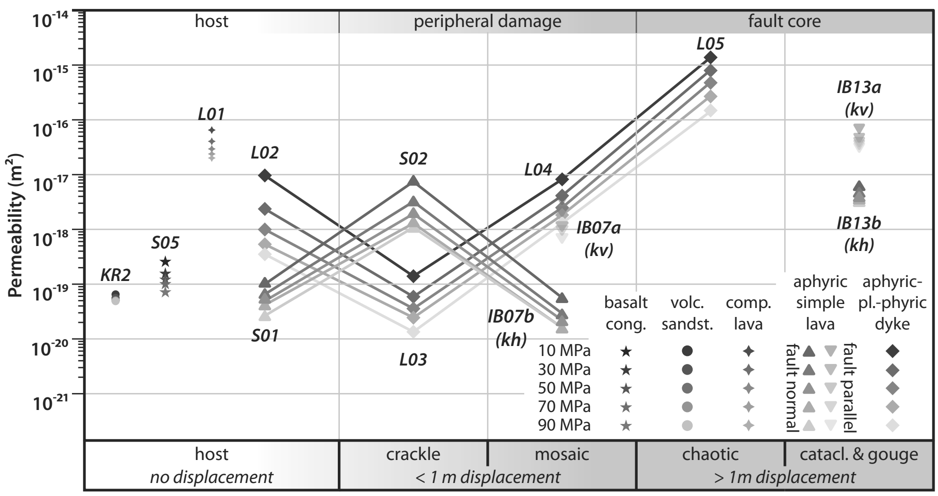

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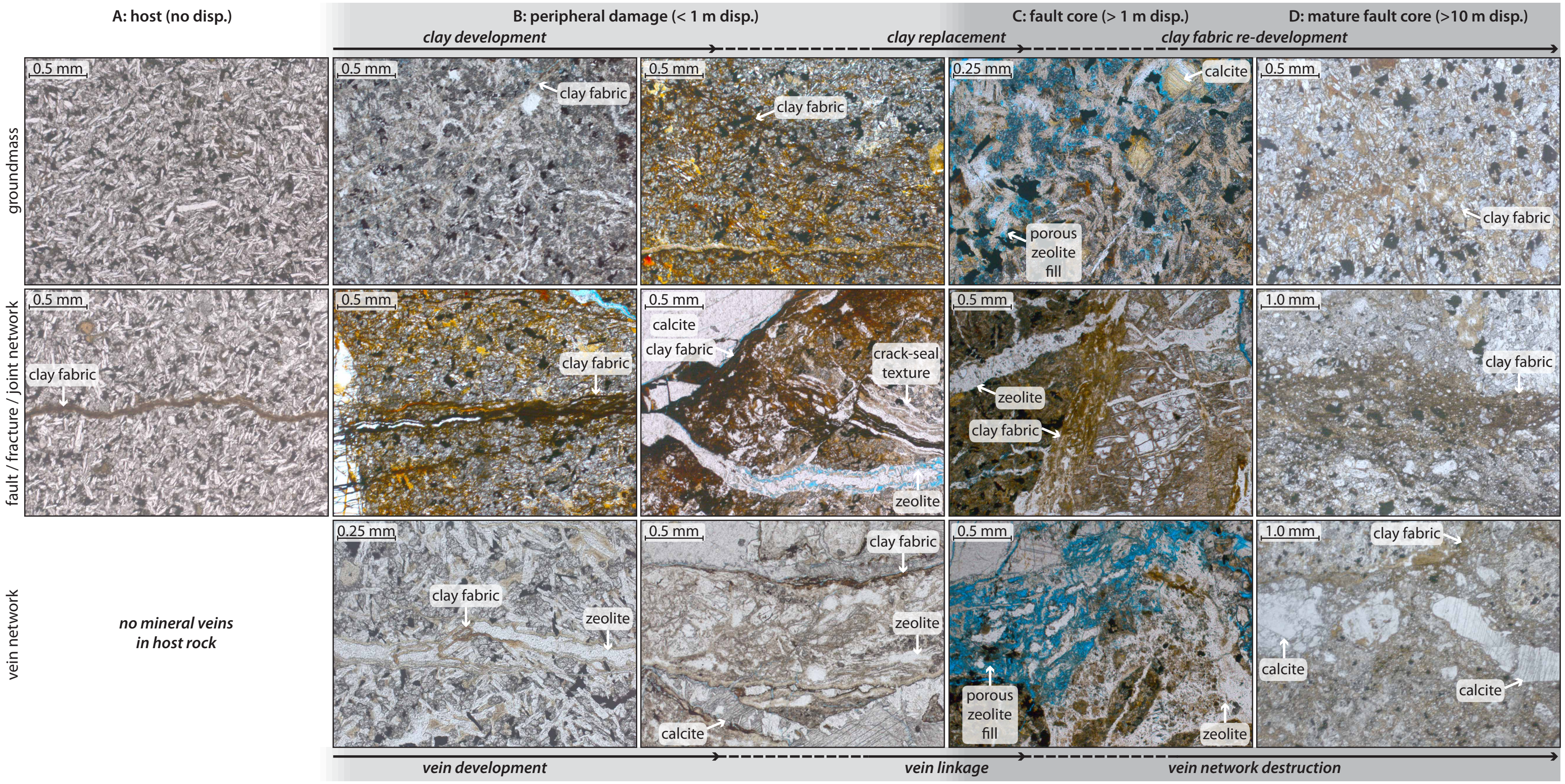

Figure 4
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