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Fault core and damage zone fracture attributes vary along strike owing to interaction of fracture growth, quartz accumulation, and differing sandstone composition

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ABSTRACT

Small, meter-to decimeter-displacement oblique-slip faults cut latest Precambrian lithic arkose to feldspathic litharenite and Cambrian quartz arenite sandstones in NW Scotland. Despite common slip and thermal histories during faulting, the two sandstone units have different fault-core and damage-zone attributes, including fracture length and aperture distributions, and location of quartz deposits. Fault cores are narrow (less than 1 m), low-porosity cataclasite in lithic arkose/feldspathic litharenites. Damage zone-parallel opening-mode fractures are long (meters or more) with narrow ranges of lengths and apertures, are mostly isolated, have sparse quartz cement, and are open. In contrast, quartz arenites, despite abundant quartz cement, have fault cores that contain porous breccia and dense, striated slip zones. Damage-zone fractures have lengths ranging from meters to centimeters or less, but with distributions skewed to short fractures, and have power-law aperture distributions. Owing to extensive quartz cement, they tend to be sealed. These attributes reflect inhibited authigenic quartz accumulation on feldspar and lithic grains, which are unfavorable precipitation substrates, and favored accumulation on detrital quartz. In quartz breccia, macropores >0.04 mm wide persist where surrounded by slow-growing euhedral quartz. Differences in quartz occurrence and size distributions are compatible with the hypothesis that cement deposits modify the probability of fracture reactivation. Existing fractures readily reactivate in *focused* growth where quartz accumulation is low and porosity high. Only some existing, partly cemented fractures reactivate and some deformation is manifest in new fracture formation in *partitioned* growth where quartz accumulation is high. Consequences include along-strike differences in permeability and locus of fluid flow between cores and damage zones and fault strength.

1. Introduction

Faults are narrow zones of localized shear deformation typically composed of intensely deformed fault cores surrounded by a fault damage zone (Caine et al., 1996; Crider and Peacock, 2004; Shipton and Cowie, 2003; Shipton et al., 2006; De Joussineau and Aydin, 2007; Wibberley et al., 2008; Faulkner et al., 2010). Structural elements of brittle faults in low-porosity sedimentary rock include opening-mode fractures, also referred to as joints where barren, sheared opening-mode fractures, and smaller faults. Within fault cores, these elements coalesce to form cataclasite, gouge, and fault breccia. Differences between properties of deformed and undeformed rocks and the size, continuity, and porosity of structures in fault-core and damage-zone influence whether faults are barriers or conduits for fluid flow (Bense et al., 2013). Fracture attributes provide information about fault growth (Chester and Logan, 1986; McGrath and Davison, 1995), fault strength (Caine et al., 1996; Evans et al., 1997; Shipton et al., 2002), and earthquake processes (Sibson, 1985). The structure of fault zones has been the subject of intense study over the past several decades (Kim et al., 2004; Mizoguchi et al., 2008; Childs et al., 2009; Mitchell and Faulkner, 2009; Faulkner et al., 2010; Long and Imber, 2010; Manzocchi et al., 2010) and the role of cement accumulation in fault zones is increasingly recognized as modifying fluid flow conduits, strengthening faults, and providing evidence of fault history (Hippler, 1993; Fisher and Knipe, 1998, 2001; Foxford et al., 1998;

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Labaume and Moretti, 2001; Rawling et al., 2001; Fisher et al., 2003; Boles et al., 2004; Eichhubl et al., 2005, 2009; Woodcock et al., 2007; Laubach et al., 2010; Petrie et al., 2014).

Nevertheless, the extent to which cement precipitation and fracture growth interact to cause important differences in fault-zone properties over short distances is not fully appreciated. Fault studies have focused on faults in poorly to moderately cemented sandstones or sandstone-shale sequences, reflecting their relevance in conventional oil and gas reservoirs. Faults in well-cemented sandstones, on the other hand—including those representative of unconventional oil and gas reservoirs—have received less attention. While many aspects translate from one reservoir type to the other, greater cumulative burial and thermal exposure for unconventional gas and oil sandstone reservoirs (in the range of 80–200 °C) favor cement precipitation, which may occur at rates comparable to fracture opening rates (Becker et al., 2010; Fall et al., 2012; Lander and Laubach, 2014). Fracture-cement precipitation, and the interaction between chemical and mechanical processes in fracture formation is thus likely to be more pronounced in controlling fault permeability compared to rocks and for conventional reservoirs at lower thermal exposure or maximum burial temperature.

Here, for fracture arrays associated with small-displacement, oblique-slip faults formed under sedimentary basin conditions (moderate temperatures to ca. 100 °C) (Figs. 1 and 2), we show that, for the same faults, fault core and damage zone attributes vary markedly and abruptly from one well-cemented sandstone type to another (Table 1). Lithic arkose to feldspathic litharenite fault cores are matrix-rich cataclasite (indurated gouge) and probable flow barriers, whereas fault damage zones comprise long open fractures and are probable conduits. Quartz-arenite fault cores contain porous breccias that are conduits, whereas surrounding damage zones comprise mostly short, sealed fractures that are probable low fracture permeability zones or barriers. We account for these differences by inhibition of quartz accumulation on non-quartz substrates, particularly feldspar and lithic grains, and the large anisotropy in quartz growth among different accumulation-surface types, which tends to preserve fracture porosity under low-temperature conditions (Lander and Laubach, 2014). Differences in scaling of length and aperture size may arise if fractures have different propensities to reactivate and grow or to stagnate and seal, contingent on rock-type- and temperature-determined quartz-accumulation amounts (Hooker et al., 2012, 2013). At sub-metamorphic temperatures, small differences in rock type may lead to marked differences in structural style and permeability and to abrupt, but possibly predictable differences in fault strength.

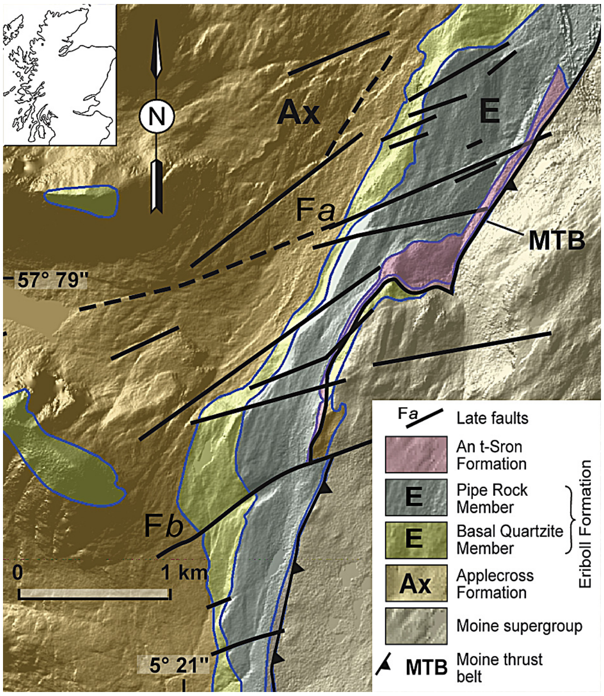

Fig. 1. Location map and fault traces. Bedrock geology and hill-shaded digital surface model (British Geological Survey). Geology and fault traces adapted from Peach et al. (1907), Goodenough et al. (2009), this study. *Fa*, Corrie Hallie and Gleann Chaorachain faults; *Fb*, Brathan fault. Inset: location of field area in Scotland.

2. Setting

In NW Scotland west of the ESE-dipping Paleozoic (Caledonian) Moine Thrust Zone (MTZ), red sandstones of the Proterozoic Torridonian succession are unconformable on the Archean Lewisian Gneiss Complex and are unconformably overlain by sandstones and carbonate rocks of the Cambro–Ordovician Ardvreck and Durness Groups (Johnstone and Mykura, 1989; Trewin and Rollin, 2002) (Fig. 1). The youngest part of the Torridonian, the early Neoproterozoic Torridon Group, was deposited ca. 1000 Ma (Kinnaird et al., 2007), and the four constituent units are up to 5 km thick (Stewart, 1993, 2002; Williams and Foden, 2011). In our study area, the Applecross Formation, the youngest unit of the Torridon Group, is dominantly reddish-brown, medium to coarse lithic arkose to feldspathic litharenite with pebble beds (Ellis et al., 2012). Beds are nearly flat lying. The overlying lowermost Cambrian unit, the Eriboll Formation, includes quartz arenite of the 75–125-m-thick Basal Quartzite Member and the younger 75–100-m-thick Pipe Rock Member (Park et al., 2002). Beds dip ca. 12 degrees ESE.

Despite histories that probably involved deep (>10 km) and possibly protracted burial before and during emplacement of the Moine Thrust (Johnson et al., 1985; Hall and Bishop, 2002), Applecross and Eriboll Formation sandstones are indurated but unmetamorphosed sedimentary rocks. Owing to erosion of younger units, post-Caledonian exhumation is not closely constrained, but apatite fission-track data suggest multiple phases of cooling interpreted to record regional Triassic, Cretaceous, and Cenozoic exhumation (Holford et al., 2010), rather than monotonic cooling and denudation (Macdonald et al., 2007). Inferred Mesozoic temperatures of ca. 80–90 °C are compatible with sparse fluid inclusion homogenization temperature observations of ca. 70–100 °C from the youngest fracture sets in the Eriboll Formation (Laubach and Diaz-Tushman, 2009).

Faults that cut both Applecross and Eriboll Formations and that postdate the Moine Thrust were recognized and mapped by Peach et al. (1907) and their contemporaries, and these faults have recently received more attention (Laubach and Marshak, 1987; Stewart, 1993; Knipe and Lloyd, 1994; Holdsworth et al., 1997, 2001; Roberts and Holdsworth, 1999; Beacom et al., 2001; Wilson et al., 2010; Elmore et al., 2010) (Fig. 1). Wilson et al. (2010) recognized a faulting sequence for northern Scotland that they attribute to regional events superposed on basement fabrics. Devonian rifting resulted in N–S to NNW–SSE striking faults. Permo-Triassic faults strike NE–SW and accommodated NW–SE extension. An ESE-striking strike-slip fault system is also present. Paleomagnetic studies of some red fault breccias ascribed to Mesozoic extension contain Triassic and Jurassic chemical remanent magnetization (Elmore et al., 2010) consistent with the inference that some faulting occurred in the Mesozoic era (Roberts and Holdsworth, 1999; Wilson et al., 2010). Jurassic sedimentation patterns in western Scotland could reflect episodes of footwall uplift on NE-striking faults (Roberts and Holdsworth, 1999; Hudson, 2011).