Detailed Internal Structure and Along-Strike Variability of the Core of a Plate Boundary Fault: The Highland Boundary Fault, Scotland

Abbreviated Title: Internal Fault Core Structure of the HBF

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ABSTRACT

The Highland Boundary fault near Stonehaven, NE Scotland, provides a rare opportunity to study the internal fault structure of a well-exposed, along-strike section of an ancient plate boundary fault. As in many plate boundaries, serpentinite juxtaposes quartzo-feldspathic crustal rocks of distinct terranes. We report, for the first time, the complex internal structure of the Highland Boundary fault core, comprised of four structurally and chemically distinct clay-rich units that remain unmixed. Despite the evidence for internal strain, relatively intact clasts of wall rock and microfossils are preserved within the clay. The fault core clay minerology is consistent with a shallow, low temperature authigenesis derived from shear-enhanced chemical reactions between wall rocks of contrasting chemistry during sinistral strike-slip. The observed structure is comparable to those of other major weak-cored plate boundaries (e.g., San Andreas fault). Through detailed mapping, we demonstrate that the internal structure of a plate boundary fault core can vary in thickness and composition along-strike over centimetre to meter length scales.

Earthquake rupture mechanics critically depend on the physical properties of fault rock assemblages. Therefore, models that investigate rupture propagation at active plate boundaries should incorporate, or else assess tolerance and sensitivity to, variable fault core thickness and composition.

SUPPLEMENTARY MATERIAL: Further X-ray diffraction (XRD) analytical data are available at https://doi.org/xxxx'.

Understanding the internal structure of large faults is crucial because the chemical and mechanical properties of faults control how earthquakes rupture, nucleate and propagate (e.g., Caine *et al.* 1996; Wibberley *et al.* 2008; Faulkner *et al.* 2010). Geologists studying faults exhumed from depth have shown that they are heterogeneous along-strike and down-dip at a variety of scales (Faulkner *et al.* 2003; Heermance *et al.* 2003; Wibberley & Shimamoto 2003; Kirkpatrick *et al.* 2008, 2018; Barth *et al.* 2013; Lawther *et al.* 2016; Sosio De Rosa *et al.* 2018). Such internal variations in properties can influence how readily a rupture begins and terminates (Kirkpatrick & Shipton 2009), limiting the size of an earthquake (Cohee & Beroza 1994; Kirkpatrick *et al.* 2008) or the frequency of the radiated seismic energy (Ma *et al.* 2003; Madariaga *et al.* 2006) and consequently surface severity and damage (Lin *et al.* 2001; Heermance *et al.* 2003; Ma *et al.* 2003). Knowledge of the internal structure and rheology of seismogenic plate boundary faults is lacking as they are normally poorly exposed at the surface.

Recently, several drilling projects have been undertaken to explore how the internal structure of active plate boundary fault zones at-depth influences slip behaviour (e.g., at the San Andreas fault in California, Bradbury *et al.*, 2011; the Alpine fault in New Zealand, Toy *et al.* 2015; the Japan Trench, Kirkpatrick *et al.* 2015; the Nankai Trough offshore Japan, Ujiie & Kimura 2014; and the Chelungpu fault in Taiwan, Yeh *et al.* 2007). Scientific findings for each of these projects highlight the presence and importance of clay-rich fault rocks for influencing slip behaviour. However, drilling projects are expensive (e.g., $25M for SAFOD at the San Andreas; Winchester 2006) and effectively sample only one or two transects across a fault, limiting the ability to capture along-strike variability in fault zone properties.

In contrast, the Highland Boundary fault (HBF), NE Scotland, provides a rare opportunity to study the internal fault structure of a well-exposed, along-strike section of a major plate boundary fault. The HBF extends for >240 km along-strike separating Dalradian meta-sediments to the north from late Silurian to Early Carboniferous volcanics and siliciclastics to the southeast (Tanner 2008; Fig. 1). This study uses a field-based approach to characterise the along-strike variability in the internal structure of the HBF using an exceptional 560 m along-strike exposure of the fault near Stonehaven, NE Scotland. Whilst the HBF is well-characterised in terms of its regional tectonic importance (e.g., Tanner 2008), the only studies discussing mineralisation of the fault zone focus on the wall rocks (e.g., Parnell *et al.* 2000; Elmore *et al.* 2002) and do not address the internal fault zone structure.

The internal structure of a fault is typically comprised of a high-strain fault core bounded by a deformed damage zone. In turn, the fault core is surrounded by undeformed host rock (Chester & Logan 1986; Caine *et al.* 1996). It may consist of a single fault core (e.g., Chester *et al.* 1993) or multiple anastomosing fault cores that link and entrain lenses of fractured host rock between the branches (e.g., Faulkner *et al.* 2003). The fault core, which can range from a few centimetres up to tens of metres wide, accommodates most of the fault slip and consists of localised slip zones containing fault rocks such as clay-rich gouge, breccia or cataclasites (Faulkner *et al.* 2010). Few published data describe the spatial variation in fault core thickness and composition within a single fault (Barth *et al.* 2013; Lawther *et al.* 2016; Kirkpatrick *et al.* 2018; Sosio De Rosa *et al.* 2018). The damage zone, which can reach several hundred meters wide, may consist of fractured host rocks, subsidiary faults, small-displacement subsidiary slip surfaces, veins and folding at all scales (Faulkner *et al.,* 2010).

In this study we present the first field observations of the internal structure and fault rock lithologies of the HBF, and show that they are comparable to other major weak-cored plate boundaries such as the San Andreas fault in California. By dissecting the physical and chemical properties of the fault (e.g., thickness, fault structures and mineralogy) we demonstrate the Stonehaven section of the Highland Boundary fault core is internally composed of four distinct structurally and mineralogically variable clay-rich units that vary in thickness along-strike over different length scales. As well as contributing to the understanding of the sequence of events at the Highland Boundary fault system, these observations of variable along-strike fault core internal structure, composition and thickness have implications for modelling earthquake ruptures at active plate boundaries.

GEOLOGICAL SETTING

The HBF is a mature, ancient plate boundary fault with a long and complex history. Today, the remarkably straight surface trace extends for over 240 km NE to SW across Scotland, with possible along-strike extension into western Ireland (Chew 2003; Tanner 2008). The fault separates two distinct geological terranes (Fig. 1a): Neoproterozoic to Cambrian, crustal, quartzo-feldspathic metasedimentary rocks (Dalradian Supergroup) of the Grampian terrane to the north from Lower Devonian, volcano-sedimentary rocks of the Midland Valley terrane (e.g., Stonehaven Group) to the south. The easternmost exposures of the Dalradian near Stonehaven experienced low pressure greenschist facies metamorphism (0.4 to 0.55 GPa) with peak temperatures of c. 375 °C (Vorhie & Ague 2011). The maximum burial depth of the Stonehaven group was 3-5 km as determined from vitrinite reflectance (Monaghan 2014). Adjacent to the fault near Stonehaven (Fig. 1b), intermittent serpentinite exposures with impersistent low-alteration zones represent the dismembered Highland Border Ophiolite (see Leslie, 2009; Henderson *et al*., 2009 for detailed reviews). Such juxtaposition of quartzo-feldspathic crustal rocks with a serpentinite zone (Fig. 2) has been observed along active plate boundary faults (e.g., sections of the San Andreas fault in California [Moore & Rymer 2012] and the Alpine fault in New Zealand [Barth *et al.* 2013]) making the HBF a potential field analogue for the internal structure of these plate boundaries.

The HBF is considered to have been active during two events of the Caledonian Orogeny: the early Ordovician Grampian Orogeny (480 to 460 Ma) and the mid-Devonian Acadian Orogeny (420 to 390 Ma) (Chew & Strachan 2014). Early fault motion was believed to be reverse, inheriting the subduction interface and emplacing the Highland Border Ophiolite immediately prior to the Grampian Orogeny (Ramsay 1962; Chew *et al.* 2010). The Highland Border Ophiolite is a mixture of both collisional (Penrose) type sequences (Chew *et al.* 2010) and Ligurian-type ophiolites, including seafloor supporting latest stages of Dalradian sedimentation in an extensional ocean–continent transition environment (Henderson *et al.* 2009; Leslie 2009; Dilek & Furnes 2014). It probably also incorporates more allochthonous ocean crust, especially proximal to the HBF zone (Chew *et al.* 2010; Chew & Strachan 2014). Overprinting by Grampian metamorphism and deformation occurred ca. 465 to 461 Ma (Viete *et al.* 2013). Following the Grampian Orogeny, the continental collision of Laurentia with Avalonia was accommodated by partitioned transpressive, sinistral strike-slip movement on the HBF and related faults (McCarthy *et al.* 2015) during the Acadian Orogeny ca. 420 Ma (Chew & Strachan 2014). The magnitude of strike-slip displacement is debated. Based on palaeogeographical reconstructions and detrital zircon data from both the hangingwall and footwall of the fault, Dewey & Strachan (2003) and Cawood *et al.* (2012) support significant sinistral offset of up to several hundreds of kilometres; whereas, Tanner (2008) compiles the case for an alternative minimum offset of <30 km. The HBF was probably reactivated during late Acadian orogenic collapse as a result of regional crustal extension (Chew & Stillman 2009; Mendum & Noble 2010). Other terrane-bounding, crustal-scale Caledonian faults in Scotland were reactivated with dextral and normal offset in the Mesozoic during North Sea extension and in the Cenozoic as Scotland exhumed regionally on the flanks of North Atlantic opening (e.g., Le Breton *et al.* 2013). It would not be surprising if the HBF accommodated minor motion at these younger ages.

STRUCTURAL FRAMEWORK

The HBF near Stonehaven is marked by a relatively straight, steep (dip: 66 ± 7°; n=70), north-west dipping contact (strike: 059 ± 8°; n=70) between the fault core and Highland Border Ophiolite (footwall damage zone) (Fig. 2a). A major splay of unknown offset, and with no development of clay gouge, is observed trending east to west towards Garron Point (Fig. 1b). New mapping as part of this study highlights numerous small offset (~5-10 m), sinistral and dextral strike-slip faults within the Highland Border Ophiolite (footwall damage zone) towards Garron Point (Fig. 1b). Kinematic markers, primarily slickenfibres recorded on calcite mineralised slip surfaces, enable these faults to be grouped into one dextral and two sinistral sets that are subdivided based on orientation with respect to the mean HBF (Fig. 2c). The dextral set has a mean strike of 144 ± 18° (n=20) and a north-easterly dip of 77 ± 11° (n=20) developing ~80° anticlockwise from the mean HBF. The first sinistral set has a mean strike of 038 ± 11° (n=12) and a north-westerly dip of 67 ± 19° (n=12) developing ~19° anticlockwise from the mean HBF. The second sinistral set has a mean strike of 92 ± 24° (n=16) and a northernly dip of 69 ± 14° (n=18) developing ~30° clockwise from the mean HBF. Several small-scale (<1 m offset) thrust faults are also observed below the scale of mapping. In places, these thrust faults sole onto strike-slip faults. No consistent cross-cutting relationships are observed, suggesting they all formed concurrently. If these faults represent Reidel shears to the main fault, they fit with sinistral strike-slip motion on the HBF (Fig. 2d). We see no field-scale evidence for late-stage dextral or normal offset that would be consistent with Mesozoic and Cenozoic reactivation.

METHODS

To characterise the internal structure of the HBF and its along-strike variability we collected six across-fault transects (structural logs) perpendicular to the fault plane (locations given in Fig. 1b). All logs except Log 3 mapped the fault core. Log 3 investigated the folding and maximum extent of the Dalradian damage zone. To expose the fault core for mapping and sampling, the shingle below the high tide mark was scraped back using spades and trowels along as linear a transect as possible, avoiding large boulders. The shingle was subsequently replaced after sample collection to maximise the conservation of this SSSI (Site of Special Scientific Interest). A series of eighteen logs 1 m apart were also collected between Logs 5 and 6 to capture the smaller, metre-scale variability of the fault core. We describe the fault breccias following the classification of Woodcock & Mort (2008).

Twelve samples from Log 4 [grid reference NO 388914 787493] were analysed by X-ray diffraction (XRD). These include one representative sample from each of the three fault core units, two samples of the clasts within the red foliated chaotic breccia, six damage zone samples from the Highland Border Ophiolite and Dalradian and one from the Dalradian host rock. ~10 g of each sample was oven dried before grinding to a fine powder with a mean particle diameter of 5 to 10 microns before analysis. Randomly-oriented samples were analysed for whole-rock mineralogy. Highland Border Ophiolite and Dalradian powders were analysed using a Bruker D8 Advance Diffractometer, scanning from 5° to 60° at 0.02° 2Θ step-size intervals at 40 kV and 40 mA (Cu-Kα radiation). Clay powders were analysed by X-Ray Minerals Ltd. using a PANalytical X'Pert3 Diffractometer and scanned from 4.5° to 75° at 0.013° 2Θ step-size intervals at 40 kV and 40 mA (Cu-Kα radiation). An intensity-based quantification analysis was performed where the maximum intensity of each mineral identified was measured and compared to a standard intensity for a pure sample of that mineral. The results were normalised to 100% based on the assumption that the complete mineral content of the sample is accounted for in the diffractogram.

Additionally, the <2 μm fraction was separated, to identify clay mineral phases following Moore & Reynolds (1997). Samples were placed on orientated mounts and analysed before and after treatment with ethylene glycol and heating to 380°C and 550°C using a Philips PW1730 Generator Diffractometer. Air-dried and glycolated samples were scanned from 3° to 35° at 0.05° 2Θ step-size intervals at 40 kV and 40 mA (Cu-Kα radiation). The untreated sample was also analysed between 24 to 27° at 0.02° 2Θ step-size intervals to further define kaolinite and chlorite peaks. Chlorite, illite, and mixed-layer illite-smectite determination was based on the comparison between air-dried and glycolated samples and a peak intensity quantification process. Specific peak widths indicate clay crystallinity. Relative intensities of the chlorite 001 and 003 peaks determined Fe occupancy in the six octahedral sites.

STRUCTURE OF THE FAULT ZONE

The internal structure of the HBF can be described as a single high-strain fault core bounded by damage zones of contrasting lithology. From south to north in an across-fault transect, the HBF consists of: (1) a footwall damage zone (FW DZ) comprising faulted and veined metabasalt and serpentinite sequences of the Highland Border Ophiolite; (2) a structurally and lithologically variable fault core (FC) comprising four distinct units, and; (3) a hangingwall damage zone (HW DZ) developed in chlorite- to biotite-grade Dalradian metasedimentary rocks (Fig. 3).

The footwall damage zone of the Highland Border Ophiolite is characterised by three distinct units. In logs 1-5 the footwall damage zone adjacent to the fault core (footwall damage zone 1) is characterised by an intensely faulted, fractured and veined, buff coloured dolomitised serpentinite properly termed ophicarbonate. Veins in this unit are ~2 to 10 cm thick and are filled by multiphase carbonate including very fine-grained, massive dolomite in the centre with isopachous, sparry calcite lining the vein wall (Fig. 3d). The calcite displays a dog-toothed epitaxial texture, indicative of crack-seal growth and extensional opening mode fractures. The veins are typically aligned sub-parallel to the HBF but can be split into two distinct sets based on dip and cross-cutting relationships (set 1: 062/67NW, n=67, crosscut by set 2: 111/21NE, n=11). The second unit (footwall damage zone 2), adjacent to the HBF in Log 6, is a carbonated serpentinite displaying a chaotic network of cross-cutting calcite veins. This unit is cut by localised, sub-horizontal fractures with an alteration halo (Fig. 3c). The fractures have an anastomosing, conjugate geometry comprised of curvy, cross-cutting, brittle cracks. Orange to brown, calcitic alteration halos extend ~3 cm either side of the fractures, where the alteration is symmetrical around the aperture. The alteration follows the same geometry as the fractures and can be traced into the ophicarbonate unit. The third unit (footwall damage zone 3) is a fractured metabasalt lava sequence with interbedded ferruginous chert and siliceous siltstone/shale, sporadic pillow lavas and a localised shear zone with evidence of reverse motion and ductile deformation (Fig. 3b). Damage zone alteration decreases away from the HBF with the ophicarbonate unit displaying the most fault-related deformation (i.e., subsidiary faulting, fractures and veining).

The Dalradian north of the HBF is composed of a succession of competent (e.g., metagreywacke) and less competent (e.g., pelite) beds. Beds within the hangingwall damage zone are folded into a series of open, plunging folds (wavelength ~5 m) with the axial plane sub-parallel to the HBF (079/86NW; Fig. 2b), and display evidence of fault-related deformation such as alteration, subsidiary fractures and brecciation. Fault-related deformation is absent beyond approximately 45 m. We consider this the extent of the hangingwall damage zone.

FAULT CORE LITHOLOGIES

The fault core, which is between 2.95 and 10.7 m thick, is comprised of four structurally and chemically distinct units with sharp, fault-parallel contacts. Adjacent to the HBF, observed at Log 4 only, is a zone of green foliated gouge (fault core 1a) that is relatively homogenous and free of obvious clasts (Fig. 3e). This is in sharp contact with a zone of a blue gouge (fault core 1) of high plasticity (Fig. 4a). In places this blue gouge unit is internally foliated, the foliations being sub-parallel to the HBF (070 ± 15°; n=17) (Fig. 4b). Small (typically <5 cm diameter), sub-rounded clasts of wall rock are observed within this unit altered to a bleached white colour. Occasionally larger, fragmented, altered clasts are observed (Fig. 5a).

Towards the hangingwall damage zone the blue gouge has a distinct fault-parallel contact with a red foliated chaotic breccia unit (fault core 2) (Fig. 4a). A localised zone of mixing (10 to 50 cm thick) is observed against the sharp contact, where the zone of mixing extends into both units either side of the contact (Fig. 3f, Fig 5a). This zone consists of distinct patches and stripes of red and blue clay. The foliated chaotic breccia unit has a grey silty texture with red, hematitic foliations that define a clear structural fabric. The compositional (colour) foliations are generally aligned parallel to the HBF with a mean orientation of 060 ± 23° (n=101) (Fig. 4c) but anastomose and wrap around variably altered, sub-angular, centimetre-scale, metasedimentary clasts of the Dalradian. In places the foliation is internally folded (Fig. 5b). Clast size, aspect ratio and abundance increase towards the hangingwall (Fig. 4a). For example, clasts within the blue gouge have a mean long axis of 1 cm (n=8) and a mean aspect ratio of 1.7 (n=8). Within the red foliated chaotic breccia, the clasts have a mean long axis of 19 cm (n=65) elongate parallel to the HBF and a mean aspect ratio of 2.8 (n=65). Several clasts can be described as lens-shaped boudins with the long axis (orientation 076°) parallel to the HBF, indicating asymmetric shear fractures parallel to the HBF (Fig. 4a).

At Logs 5 and 6, the transition zone between the fault core and hangingwall damage zone comprises a red crackle breccia with large, fragmented, metasedimentary lenses of Dalradian up to 2.3 m long. Thin (< 5 cm and typically < 1 cm) zones of foliated clay (clay content 5 to 10%) are observed between, and wrapping around the lenses (Fig. 5c). The clay zones are interpreted as high strain zones and can be observed cutting through some of the larger lenses. The lenses have a mean long axis of 81 cm (n=32) and a mean aspect ratio of 3.3 (n=32). All clasts and lenses within the fault core have a preferred orientation and are elongate in the direction parallel to the HBF with a mean apparent long axis orientation of 067 ± 15° (n=97) on a sub-horizontal exposure (Fig. 4d), and clasts observes to be dipping parallel to the dip of the footwall damage zone contact. The clay content generally decreases away from the HBF with a concomitant increase in size and angularity of clasts/lenses.

FAULT CORE VARIABILITY

Not every unit is laterally continuous along-strike, and each fault core unit varies in thickness over different length scales (Fig. 6, Fig. 7). Observations from the six structural logs reveal the total thickness of the fault core varies from 2.95 to 10.7 m over an along-strike distance of 560 m (Fig. 6). Every unit is internally variable. For example, the green gouge is only observed in Log 4 and is 0.3 m wide. The blue gouge is continuous along-strike and varies from 0.65 to 2.65 m thick over 560 m. The red foliated chaotic breccia is continuous along-strike and varies from ~1.5 to 5.4 m thick. The red crackle breccia is only present between Logs 5 and 6 so varies in thickness from 0 to 4.65 m.

Mapping of the fault core at Garron Point between Logs 5 and 6 reveals the smaller, meter-scale variability over an along-strike section of 50 m (Fig. 7). Over this 50 m section, the blue gouge varies from 0.7 to 2.6 m thick with a mean of 1.1 ± 0.7 m (n = 20). The red foliated chaotic breccia varies from 2.3 to 5.4 m thick with a mean of 4.1 ± 0.8 m (n = 20). The red crackle breccia varies from 0.35 to 4.65 m thick with a mean of 2.6 ± 1.5 m (n = 20). These observations demonstrate that, in addition to the smaller, centimetre-scale variability in each unit (Fig. 4), the total thickness of the fault core, and each unit within the fault core, can vary considerably over relatively short distances of 50 m.

MINERALOGY

XRD results are summarised in Fig. 8. Surrounding the fault core are damage zones of contrasting mineralogy: the Fe-, Mg- and Ca-rich ferromagnesian serpentinites of the Highland Border Ophiolite to the south from K- and Al-rich quartzo-feldspathic crustal rocks of the Dalradian to the north. The Highland Border Ophiolite in the footwall damage zone is characterised by two mineralogically-distinct units. Ophicarbonate (footwall damage zone 1) is characterised by serpentinite (lizardite polymorph), carbonate (primarily dolomite) and quartz, despite serpentinite and quartz not commonly co-existing (although see Streit *et al*., 2012). Carbonated serpentinite (footwall damage zone 2) is comprised of serpentinite (lizardite polymorph), calcite, dolomite, and silicates such as chlorite, prehnite, wollastonite, tremolite, talc and diopside (see Frost & Beard, 2007). The hangingwall damage zone units are characterised by quartz and K- and Al-rich felsic minerals such as white mica and feldspar, presumably derived from the Dalradian. Chlorite and biotite are also present indicative of low-grade, greenschist facies metamorphism supporting previous studies on the Dalradian (e.g., Vorhie and Ague, 2011).

The whole rock (Fig. 9a) and the fine grained (<2 μm fraction; Fig. 9b) mineral assemblages of the three fault core units demonstrate variable clay content as summarised in Table 1 and Table 2. Bulk mineralogy of the green gouge (FC 1a) is comprised of 48.8 weight % (wt%) clay (24.3 wt% illite + mica, 1.4 wt% mixed layer illite-smectite (I–S) and 23.1% chlorite), with additional quartz, dolomite and anatase. The mixed layer illite-smectite and chlorite clays expand whereas illite does not. The <2 μm fraction suggests the clay minerals are poorly to moderately crystallised and Fe-rich (Table 2). Similarly, the blue gouge (FC 1) is comprised of 45.3 wt% clay (15.6 wt% illite + mica, 6.1 wt% I–S and 23.6% chlorite), with additional quartz, dolomite and anatase. Despite comparable mineralogy, subtle differences exist between the green and blue gouge units. For example, the blue gouge is finer-grained with a higher % of the <2 μm fraction and contains more mixed layer illite-smectite and dolomite.

The red foliated chaotic breccia (FC 2) is comprised of 37.5 wt% clay (23.6 wt% illite + mica, 5.6 wt% I–S and 8.1% kaolinite), with additional phases of quartz, dolomite, hematite and anatase. Compared to the blue gouge, the red foliated chaotic breccia contains non-swelling clays such as kaolinite and illite, chlorite is absent and has a higher percentage of quartz. The <2 μm fraction suggests the clay minerals within the red foliated chaotic breccia are moderately to well-crystallised (Table 2). In addition to a change in colour and structure, a distinct mineralogical change therefore occurs between the blue gouge and red foliated chaotic breccia. In the <2 μm fraction (Table 2), the green and blue gouge are comprised primarily of chlorite, which is Fe- and Mg-rich. Whereas, the red foliated chaotic breccia is comprised primarily of kaolinite and illite assemblages, which are K- and Al-rich.

Optical microscopy reveals the presence of microfossils within the clay-rich fault core (Fig. 10). These include relatively intact fragments of ancient bryozoans, possibly belonging to the order Fenestrata (as identified by P. D. Taylor, pers. comm. 2018) (Fig. 10a-c), brachiopods and an echinoid spine (Fig. 10b).

Both primary fabrics and secondary recrystallisation/growth textures are observed. Despite the fossils being preserved within a high-strain fault gouge, there is no evidence of internal strain (e.g., microfracturing or shear indicators) within the fossil fragments.

DISCUSSION

Origin of the Clay-rich Fault Core

The mineralogical composition of the fault core matches the wall rocks. From the distinct chemical change between the blue gouge and red foliated chaotic breccia, it can be assumed the Mg- and Fe-rich green and blue gouges are chemically derived from the Mg- and Fe-rich Highland Border Ophiolite serpentinite wall rocks (footwall damage zone 1 and 2). In contrast, the K- and Al-rich red foliated chaotic breccia is chemically derived from the quartzo-feldspathic Dalradian wall rocks. These units remain surprisingly unmixed: there are a limited number of clasts of weathered host rock within the clay units, but there are no clasts of one clay unit within another that would be indicative of mixing. Similarly to other plate boundary settings where serpentinite and quartzo-feldspathic wall rocks juxtapose (e.g., Moore and Rymer, 2012), the HBF clay likely formed through fluid-assisted, shear-enhanced chemical reactions between wall rocks of contrasting chemistry (the serpentinite of the Highland Border Ophiolite provides the Mg and Fe, while the Dalradian provides K, Al and some of the Si). The green gouge is only observed at one location (Log 4; Fig. 6) so could either represent a zone of localised alteration, or a remnant fragment of a reworked, previously extensive, fault core lithology. The blue gouge and red foliated chaotic breccia are continuous along-strike, albeit varying in thickness, suggesting that for this 560 m along-strike section, there has been continuous processing of both wall rocks. It remains unclear why the red crackle breccia is not laterally continuous along-strike. However, this may be controlled by the rheological variation within the Dalradian or by stress heterogeneities along the fault.

The mineralogical composition of the clays provides constraints on the temperature of clay authigenesis. With increasing temperatures, smectite transforms to illite. The reaction is complete by ~120-150°C, which suggests an increasing proportion of illite within mixed layer illite-smectite with increasing temperature and depth (e.g., Hower *et al.* 1976; Vrolijk 1990). Hower *et al.* (1976), show that the degree of smectite transformation to illite can be used to gauge temperature. In all observed HBF fault core units, the smectite to illite reaction has progressed to 70-80% illite (Table 2) equating to a reaction temperature of 100 and 110°C, corresponding to <3 km depth (<1 kbar) assuming a high geothermal gradient setting. Mineral assemblages of chlorite, illite, smectite, kaolinite, as well as serpentinite and talc have been associated with fluid flow and brittle deformation under low temperature conditions (~100°C) at other plate boundary settings where the clays have formed through strike-slip deformation (e.g., the San Andreas fault; Moore and Rymer, 2007; Schleicher *et al.*, 2009).

The low temperatures of formation of the clay (~100°C, palaeodepth of ~3 km) implies that this clay-rich fault core must form late in the evolution of the HBF as such a shallow formation depth would mean it would likely have been exhumed if it formed earlier. Based on the kinematics in the footwall damage zone (Fig. 2c) and field-scale observations of the clay (e.g., fault-parallel foliations, incorporation of orientated wall rocks clasts, foliations wrapping around clasts, elongation of the clasts parallel to the HBF and the smectite-illite mineralogy) (Fig. 4, 5, Table 2) we propose the clay has a syn-faulting origin and formed as a result of shallow, low temperature, shear-enhanced chemical reactions between wall rocks of contrasting chemistry during latest sinistral strike-slip motion of the HBF. Unfortunately, there are no clear field-scale kinematic indicators within the clay that would help to constrain the kinematics either to motion in the Carboniferous to Permian or related to crustal-scale exhumation in the Cretaceous to Palaeogene (c.f. Andersen *et al.* 1999).

Since the strike-slip faults (i.e. Reidel shears) offset previously deformed units of the Highland Border Ophiolite (Fig. 2), clay authigenesis must be younger than the emplacement and deformation in the Highland Border Ophiolite and associated reverse motion on the HBF. Based on palaeomagnetic results, Elmore *et al.* (2002) suggest the dolomitisation of serpentinite in footwall damage zone 1 occurred in the Permian at 260 Mya. Clay growth must also be younger than the fossils, which assuming the bryozoans belong to the order Fenestrata (as identified by P. D. Taylor, pers. comm. 2018), are Ordovician to Permian in age. The presence of these ancient fossils within the clay therefore constrains the age of clay authigenesis to younger than Ordovician-Permian. To our knowledge this is the first time that the age of fossils preserved within a fault gouge have been used to constrain the relative age of that fault. Further microstructural and isotopic analyses (e.g., ^{40}Ar-^{39}Ar radiometric dating) are needed to fully constrain the absolute timing and nature of fluids controlling clay authigenesis and slip behaviour on this plate boundary fault.

Both wall rocks are incorporated into the fault zone through chemical and mechanical alteration spanning the entire range of chemical and physical processes responsible for grain size reduction and wall rock comminution in a fault zone. In addition, the preservation of fragile fossils within the clay suggests strain within the units remain highly localised despite the fault having accumulated between 30-100 km of lateral offset (the exact magnitude of slip is debated in the literature). From the preservation of the textures in the clay, and the remarkable preservation of delicate fossil fragments it is clear that strain localisation by grain size reduction is principally concentrated on the margins of the fault core.

How representative is the HBF of Active Plate Boundary Faults?

The rocks on either side of the HBF are similar lithologies to those cut by the $25M SAFOD (San Andreas Fault Observatory at Depth) drilling project through creeping sections of the strike-slip San Andreas fault (SAF). SAFOD drill core revealed the presence of a clay gouge 2.6 m thick (Bradbury *et al.* 2011).

Comparable to the red foliated chaotic breccia of the HBF, the SAFOD clay is composed of a dark greyish-black to greenish-black, highly-sheared, foliated matrix that wraps around centimetre-scale clasts of serpentinite and sedimentary wall rocks that are elongate parallel to the foliation (Bradbury *et al.* 2011). Structurally foliated fault rocks with clasts derived from the wall rocks are common along many strike-slip plate boundary faults (e.g., Faulkner *et al.* 2003; Barth *et al.* 2013). The SAFOD clays have been interpreted as the product of fluid-assisted, shear-enhanced, metasomatic reactions between serpentinite, tectonically emplaced from a source in the Coastal Range Ophiolite (cf. the HBO), and quartzo-feldspathic crustal wall rocks (cf. the Dalradian) of contrasting chemistry (Bradbury *et al.* 2011; Moore & Rymer 2012).

Laboratory friction experiments involving SAFOD gouge at hydrothermal conditions (temperature $\geq$ 200°C) have demonstrated that due to the chemical contrast between the rock types, aseismic slip (creep) is initiated as soon as serpentinite and quartzo-feldspathic crustal rocks are sheared against each other (Moore and Lockner, 2013). This is attributed to a solution transfer process, modifying the chemistry of the pore fluids within serpentinite, thereby promoting creep along serpentinite-bearing crustal faults at otherwise seismogenic depths (Moore and Lockner, 2013). Long-term shearing of these two chemically different rocks results in the authigenesis of mechanically weak minerals such as clay and talc, considered important in the mechanical behaviour of a fault. Laboratory experiments on the mechanical properties of clay mixtures suggest they would locally promote creep rather than stick-slip (i.e., the clay would retard fault rupture propagation and act as a barrier to earthquake propagation) (Scholz 1998; Ikari *et al.* 2009; Behnsen & Faulkner 2012). These comparable observations on the SAFOD gouge may have implications for understanding palaeo-slip behaviour and clay authigenesis at the Stonehaven section of the HBF.

Along-Strike Variability and Its Implication for Rupture Propagation

By necessity, drilling projects at active plate boundary faults such as the SAFOD and the Japan Trench Drilling Project, effectively sample one only or two transects across a fault, limiting the ability to capture along-strike variability in fault zone properties. Whilst along-strike variability is commonly observed on small-scale faults (e.g., Sosio De Rosa *et al.* 2018), our field observations demonstrate that seismogenic plate boundary faults can also vary in thickness, structure and composition along-strike over different length scales (Fig. 6, 7). This variability effect will likely be larger down-dip for strike-slip boundaries as fault geometrical variability is smoothed in the direction parallel to slip (Sagy *et al.* 2007).

Plate boundaries are bi-material interfaces bringing together materials of different mechanical and chemical properties (e.g., the Highland Border Ophiolite and Dalradian). However, studies that investigate rupture propagation at plate boundaries typically assume constant fault properties along-strike and down-dip (e.g., Cochard & Rice 2000; Aochi & Madariaga 2003; Shi & Ben-Zion 2006; Ampuero & Ben-Zion 2008). Structural and compositional fault properties spatially impact how and where earthquakes rupture, nucleate and propagate (e.g., Aochi & Madariaga 2003; Heermance *et al.* 2003; Wibberley *et al.* 2008; Kirkpatrick & Shipton 2009). Dynamic weakening processes and energy loss during earthquake slip is dependent on the physical properties of the fault core (Shipton *et al.* 2006; Kirkpatrick & Shipton 2009). Kirkpatrick *et al.* (2018), demonstrated that due to the along-strike variation in slip zone thickness, slip-weakening mechanisms such as thermal pressurisation must have been spatially variable during seismic slip. Most slip-weakening mechanisms are triggered by frictional heating. Therefore, if the units within the fault core have variable thickness, then the heating effect and consequently the lubrication effect that determines the size of the rupture, will also be variable (the thinner the unit the faster the heating) (Kirkpatrick *et al.* 2018). Along-strike thickness variations is expected to be a common feature of all faults (Kirkpatrick *et al.* 2018). Therefore, earthquake models for seismogenic plate boundaries must consider, or else assess tolerance and sensitivity to, along-strike variation in the thickness of units within the fault core, as well as the composition (e.g., the localised green gouge in Log 4).

CONCLUSION

This study delivers a level of detail on the along-strike internal fault core structure of a major plate boundary fault that has rarely been seen before. The well-exposed Stonehaven section of the Highland Boundary fault core is composed of four structurally and chemically distinct clay-rich units. Field and mineralogical observations suggest clay authigenesis occurred as a result of shallow, low temperature, shear-enhanced chemical reactions between wall rocks of contrasting chemistry during sinistral strike-slip motion of the HBF.

The internal structure and mineralogy of the Highland Boundary fault is comparable to other major weak-cored segments of plate boundary faults (e.g., the creeping section of the San Andreas fault in California). Whilst along-strike variability is commonly observed on small-scale faults, our field observations demonstrate that the core of seismogenic plate boundary faults can also vary in thickness and composition along-strike over centimeter and meter length scales. Earthquake rupture mechanics critically depend on the physical properties of fault rock assemblages. Therefore, models that investigate rupture propagation at active plate boundaries should incorporate, or else assess tolerance and sensitivity to, variable fault core thickness, structure and composition.

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Table 1. *XRD results of the whole (bulk) rock fraction (5-10µm) from three clay-rich fault core units of the HBF (FC1a: green gouge; FC1: blue gouge; FC 2: red foliated chaotic breccia). See Fig. 6 for sample locations. Modal % was determined via peak intensity quantification.*

Sample	Illite/ Smectite (I-S)	Illite + Mica	Kaolinite	Chlorite	Qtz	K Feldspar	Plagioclase	Dolomite	Anatase	Hematite
FC 1a	1.4	24.3	0	23.1	44.6	TR	0	3.3	3.3	0
FC 1	6.1	15.6	0	23.6	41.4	TR	0	11.2	2.1	TR
FC 2	5.6	23.8	8.1	0	57.7	TR	TR	1.7	0.4	2.7

Table 2. *XRD results of the fine-grained <2 µm fraction from three clay-rich fault core units of the HBF (FC1a: green gouge; FC1: blue gouge; FC 2: red foliated chaotic breccia). See Fig. 6 for sample locations. Modal % was determined via peak intensity quantification.*

Sample	Wt. %	Illite/smectite			Illite		Kaolinite		Chlorite			Qtz	Dol
	<2µm	%	Order*	% illite	%	Crys†	%	Crys†	%	Crys†	Y‡	%	%
FC 1a	12.5	11.6	O	70-80	25.2	P	0		45.4	M	2	17.8	0
FC 1	51.1	11.9	O	70-80	19.9	P	0		46.1	M	2	13.5	8.5
FC 2	19.6	28.7	O	70-80	39	H	21.2	M	0		-	11.1	0

* Order: O = ordered interstratification

† Clay crystallinity: H = highly crystalline; M = moderately crystalline; P = poorly crystalline

‡ Y = number of Fe atoms in six octahedral sites

FIGURE CAPTIONS

Fig. 1. Geological map of the HBF near Stonehaven, NE Scotland. (**a**) Simplified geological map of Scotland indicating the location of the study site near Stonehaven. GT, Grampian Terrane; MVT, Midland Valley Terrane; GGF, Great Glen fault; SUF, Southern Uplands fault. (**b**) The Highland Boundary fault along the coastal section ~1 km north of Stonehaven. The location of the six structural logs are indicated.

Fig. 2. Damage zone deformation of the HBF. (**a**) Field photograph of the HBF at the northern end of Craigeven Bay looking northeast [grid reference NO 8870 8740]. (**b**) Stereographic projection of poles to Dalradian bedding showing the mean bedding planes and the interpreted fold axis (Kamb contours of interval 2 sigma and confidence level 3). (**c**) Stereographic projection of field data on small faults associated with the HBF consistent with strike-slip faulting. Poles to all faults in the Highland Border Ophiolite and the mean planes of sinistral, dextral and thrust faults interpreted into a strike-slip strain ellipse for sinistral motion of the HBF (separated based on kinematic markers in the field). Mean planes were determined from contour maps. There are numerous faults where the sense of motion cannot be determined (unfilled), however, they are not outliers and can be grouped into one of the three sets. The principal stress axes are inferred from kinematic data. (**d**) Ideal strike-slip strain ellipse for comparison assuming symmetry of the Reidel shears around a fault with the same dip as the HBF and pure strike-slip. All stereonet plots were created using Stereonet 10 software.

Fig. 3. Summarised fault zone structure. (**a**) Schematic structural log illustrating the units within the fault core (FC) and footwall and hangingwall damage zones (FW DZ and HW DZ, respectively) of the HBF. The structural log schematically highlights the typical fabrics in each unit. The tick marks and other ornamentation within the units correspond to foliations. The ± symbol indicates that the unit may or may not be present in all structural logs. (**b**) Shear zone in metabasalt lava sequence (footwall damage zone 3, FW DZ 3) [grid reference NO 388953 787474]. (**c**) Fractures with alteration halos in carbonated

serpentinite (footwall damage zone 2, FW DZ 2) [grid reference NO 388939 787494]. (**d**) Multiphase carbonate veining in ophicarbonate (footwall damage zone 1, FW DZ 1) [grid reference NO 388931 787496]. (**e**) Green gouge (fault core 1a, FC 1a) between ophicarbonate wall rock to the SE and the blue gouge unit to the NW (Log 4 only) [grid reference NO 388914 787493]. (**f**) The contact between the blue gouge (fault core 1, FC 1) and the red foliated chaotic breccia (fault core 2, FC 2) indicating localised mixing [grid reference NO 389201 787640].

Fig. 4. Centimetre-scale variations in the fault core units. (**a**) Detailed sketch of the fault core from Log 4. Clast sizes and foliation thicknesses are exaggerated (x2) for illustration purposes. The variation in clast composition (colour) is also shown with sandier wall rock clasts depicted in yellow. (**b**) Rose diagram of the foliations from the blue gouge (fault core 1) (all logs). (**c**) Rose diagram of the foliations from the red foliated chaotic breccia (fault core 2) (all logs). (**d**) Rose diagram of the orientation of the long axis of the clasts and lenses from both the red foliated chaotic breccia (fault core 2) and the red crackle breccia from the fault core - hangingwall damage zone transition (all logs).

Fig. 5. Photographs and detailed sketches of the fault core units. The fault core clays were wet and sticky meaning that attempts to clean the outcrop resulted in smearing of the clays across the surface. The internal structure was therefore exposed by lifting out sections of the clay with a shovel-tip. This left an irregular surface that did not photograph well, but which could be logged and sampled in the field. (**a**) Blue gouge (fault core 1). The indents in the photograph represent the spade marks from digging [grid reference NO 388914 787494]. (**b**) Red foliated chaotic breccia with clear structural fabrics (fault core 2) [grid reference NO 388914 787495]. (**c**) Red crackle breccia with large, fragmented lenses of Dalradian in the fault core - hangingwall damage zone transition zone [grid reference NO 389238 787664]. The ‘clasts’ that are white are shingle.

Fig. 6. Structural logs highlighting the along-strike variability in the thickness of the HBF fault core units over the well-exposed 560 m Stonehaven section (refer to Fig. 1b for the location of each log). The thickness of the fault core units is to the same scale (that on the left), whereas the horizontal axis is only schematically to scale to indicate the approximate position along-strike of the structural logs beginning at 0 m for Log 1 (significant across-fault exaggeration 25:1). Each log mapped a patchy shoreline with large boulders in places, thus the contacts between each unit are inferred by the dashed line. The Dalradian is a mix of polyphase metamorphic- and fault-related folding so the units are not correlated along-strike. Key as in Fig. 3. The stars in Log 4 represent the location of the fault core samples used for XRD analysis (Table 1; Table 2). Green gouge [grid reference NO 388914 787493]; blue gouge [grid reference NO 388914 787494]; red foliated chaotic breccia [grid reference NO 388914 787495].

Fig. 7. Smaller-scale structural logs at Garron Point highlighting the along-strike, metre-scale variability of the HBF fault core over a 50 m section (refer to Fig. 1b and Fig. 6 for location). The horizontal and vertical axes are not to the same scale with significant across-fault exaggeration (5:1). The tick marks on the horizontal axis shows the density of mapping. Each log mapped a patchily exposed shoreline, thus the contacts between each unit are inferred by the dashed line. We have only mapped the exposure, thus the units between the logs are not inferred. Key as in Fig. 3 (the lithological variations in the Dalradian hangingwall are not shown). The red numbers refer to the dip of the faults bounding the fault core, while the grey ‘lentils’ represent the size and orientation of the Dalradian clasts/lenses. The clast size generally decreases away from the Dalradian with a concomitant increase in clay content. Boxplots highlight that each unit within the fault core varies in thickness over the 50 m section. The thick black line represents the median, while the cross represents the mean. The same length scale applies to all three boxplots.

Fig. 8. Summary schematic log of the HBF architecture with associated mineralogy determined via x-ray diffraction (XRD) analysis. The samples used for analysis were from Log 4 only [grid reference NO 388914

787493]. The ± symbol indicates that the unit may or may not be present depending on the location of structural log. For the mineralogy of the metabasalt lava sequence (footwall damage zone 3) refer to Ikin (1983).

Fig. 9. X-ray diffraction (XRD) diffractograms for (**a**) the whole (bulk) rock and (**b**) <2 μm size fractions of the three clay-rich fault core domains of the Highland Boundary Fault. I, Illite; I-S, Illite-Smectite; C, Chlorite; K, Kaolinite; A, Anatase; Q, Quartz; D, Dolomite; H, Hematite. For the <2 μm size fraction, the diffractograms for the four clay treatments are overlain to identify the clay mineral assemblages present.

Fig. 10. Fault zone palaeontology - shallow marine microfossils in the blue gouge. (**a**) Fan-shaped, bryozoan, possibly of the Fenestrata order displaying both primary and secondary recrystallisation textures. (**b**) A bryozoan and echinoid spine. (**c**) Fan-shaped, bryozoan, possibly of the Fenestrata order. All images are in cross-polarised light (XPL).