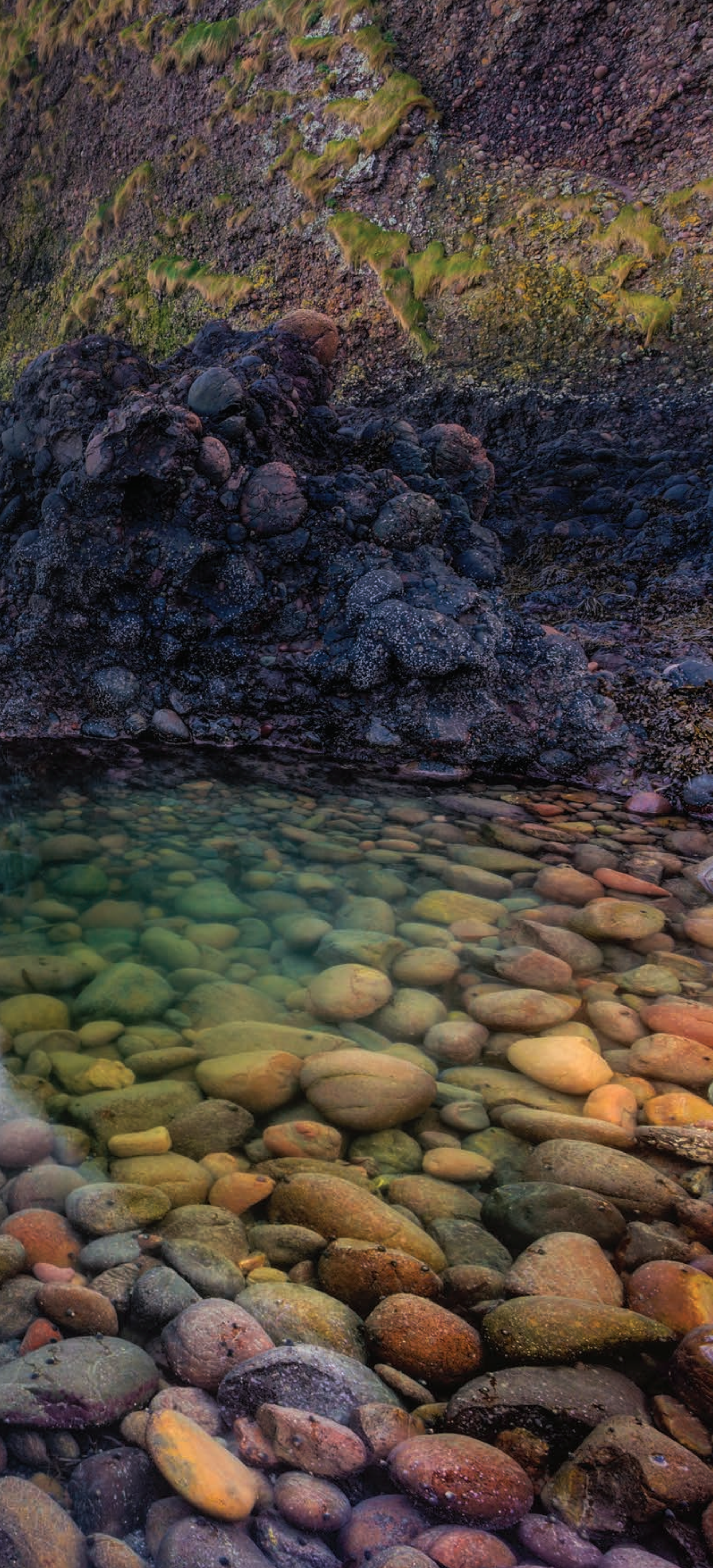
# CORE SURPRISE: WHAT'S INSIDE A PLATE BOUNDARY?

Digging to expose clay 'inside' the Highland Boundary Fault, **Lucy McKay**, **Zoe Shipton** and **Rebecca Lunn** discover a remarkable sequence of clay and microfossils within the core of an ancient plate boundary



Despite the fact that 90% of global seismicity occurs at plate boundary faults, our understanding of their internal structure is lacking. It's not easy to see inside a plate boundary fault – typically composed of a high-strain fault core surrounded by a fractured damage zone – and when we can, it often requires expensive drilling projects that yield limited information on the internal structure of the whole fault.

Understanding the internal structure of large faults is crucial, because their chemical and mechanical properties control how and where earthquakes rupture, nucleate and propagate. This in turn limits the size of the earthquake or the amount of radiated seismic energy, and consequently the severity of surface damage. The 1999 magnitude 7.7 earthquake along the Chelungpu plate boundary fault, for example – the second deadliest earthquake in Taiwan's recorded history – saw significant variations in slip and ground motion at different locations along the fault which resulted in large local variations in casualties and damage. Subsequent field investigations related these variations to changes in the fault's structure (i.e., clay width, geometry), which in turn controlled how the fault moved.

## Seeing inside

Opportunities to directly study the internal structure of plate boundary faults are few, since they are normally poorly exposed at the surface. One alternative is to drill into the plate boundary to collect geological data. Several drilling projects have recently been undertaken at active plate boundaries in order to explore their internal structure at depth, including at the San Andreas fault in California, the Alpine fault in New Zealand, the Japan Trench, the Nankai Trough offshore Japan and the Chelungpu Thrust in Taiwan.

Such projects, though, are expensive – the bill for the San Andreas Fault Observatory at Depth (SAFOD) project alone was $25M. They are also limited in what they can tell us, effectively ▶

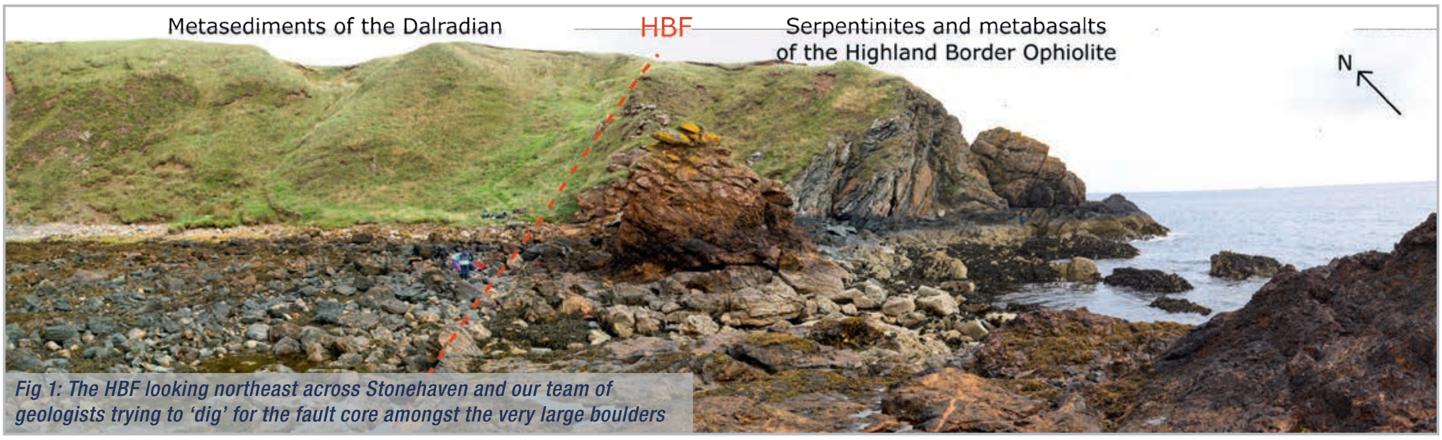



Fig 1: The HBF looking northeast across Stonehaven and our team of geologists trying to 'dig' for the fault core amongst the very large boulders

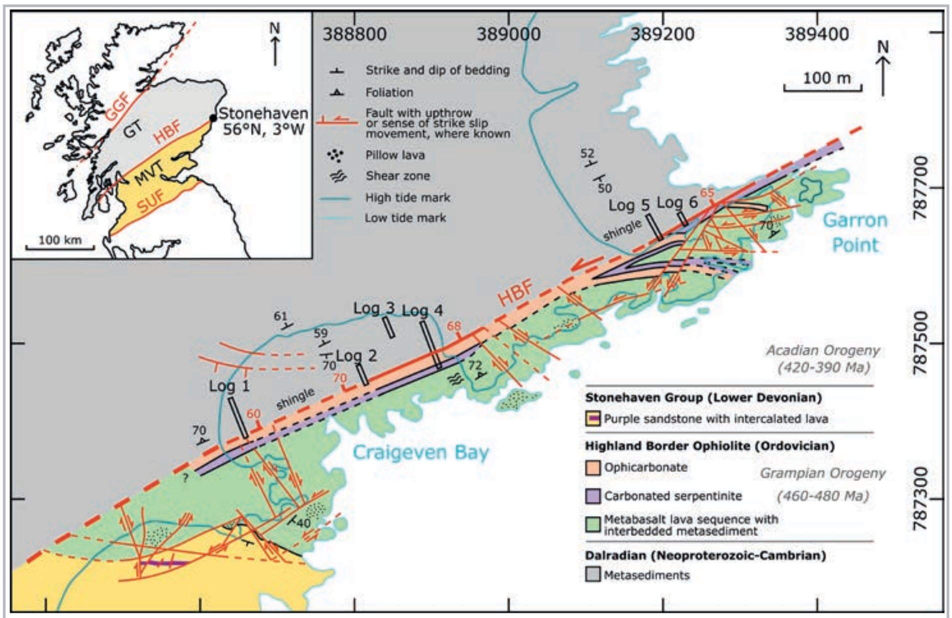
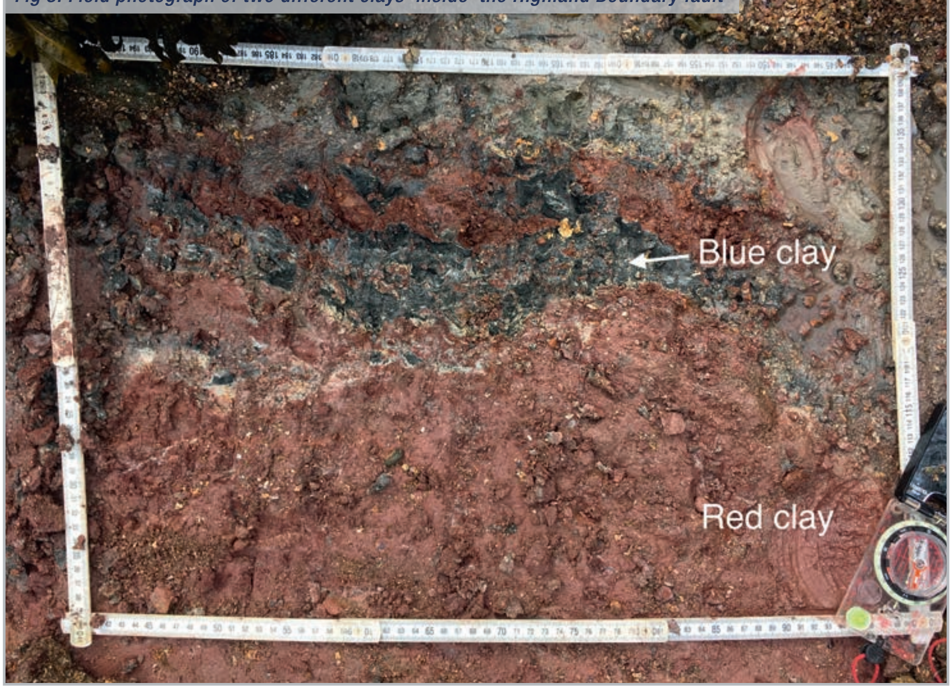



Fig 2: Our geological map of the HBF near Stonehaven. The fault cuts across Craigeven Bay and is only observed and mappable at low tide. The location of the structural logs are indicated with black rectangles

Fig 3: Field photograph of two different clays 'inside' the Highland Boundary fault




sampling only spatially limited '1D' transects across a fault, which limits the ability to capture the variability in the internal structure at different locations along the fault.

Luckily, a rare opportunity to study the variability of the internal structure of an ancient plate boundary fault exists closer to home – and without the need for expensive drilling projects – in the form of the Highland Boundary Fault (HBF).

## The Highland Boundary Fault

The HBF is an important terrane boundary in UK geology which has been the subject of many regional tectonic studies. It separates the Scottish Highlands from the Midland Valley, extending for over 240 km NE-SW from Stonehaven on the northeast coast to the Isle of Arran in the west. It is also exposed at Comrie, Loch Ard Forest, Loch Lomond and the Cowal and Rosneath peninsulas. We explored several of these locations but found the best exposure along a coastal section ~1km north of Stonehaven.

On a rare, dry, late summer's day in August 2017, our team of geologists from the University of Strathclyde's Faults and Fluid Flow research group travelled from Glasgow to Stonehaven, having applied for and been granted permission from the Scottish Natural Heritage to 'dig' out the fault at several locations at the Stonehaven site.

## Tectonic history

The HBF has a long and complex tectonic history. It hasn't always been considered a plate boundary, nor were the rocks on the southern side of the fault, formerly referred to as the Highland Border Complex, considered to be part of an ophiolite sequence (a sequence commonly associated with plate boundaries.)

These rocks include a diverse assemblage of altered serpentinites, metabasalt, amphibolite, basaltic pillow lava, conglomerate, arenite, black graphitic mudstone, limestone and chert. Recent reappraisal by Tanner & Sutherland (2007) suggests this assemblage belongs to an ophiolite sequence that lies in stratigraphic and structural continuity with the Dalradian, and not an exotic terrane as previously suggested (Bluck 1985). Field observations of the 'Highland Border Ophiolite (HBO)' from the British Geological Survey's Highland Workshop in 2008 (see Leslie et al. 2009 for detail), support Tanner & Sutherland's hypothesis.

Importantly, the orange-brown-weathered carbonated serpentinite (termed ophicarbonate) shows remarkable similarities to rocks from modern Iberia-type ocean-continent transitions and Ligurian-type ophiolites in northern Italy (not the classic Penrose-type ophiolite sequence).

All this suggests that the HBO represents a slice of exhumed serpenitised sub-continental mantle and associated sedimentary rocks, that formed part of the seafloor of an extended Dalradian basin, and was thrust onto the Dalradian block immediately before the start of the Grampian Orogeny and associated metamorphism 490 million years ago (Leslie et al. 2009).

At Stonehaven, as at many plate boundaries, oceanic serpentinite juxtaposes quartz and feldspar-rich crustal rocks of distinct terranes: the now termed Highland Border Ophiolite and Dalradian group, respectively (Fig. 1). We remapped this section of the HBF, focusing on its fault structure (Fig. 2). While the HBF is well-characterised in terms of regional tectonic importance, the only studies discussing mineralisation of the fault focus on the rock walls (on both sides), and do not address the internal fault zone structure.

## Exposing the fault core

Using spades and trowels, we scraped back the shingle from below the high tide mark, along as linear a transect as possible. This was easier said than done; in places the shingle layer was very deep, and we had to avoid some very large boulders.

We were surprised to unearth not one but several distinct clay-rich units. After our initial amazement, we mapped and collected samples, then replaced the shingle to maximize conservation before the tide covered our study area. The site is an important Site of Special Scientific Interest, and it was important to make sure our work left no permanent mark. We returned after six weeks to confirm that the area we had excavated was indistinguishable.

Fig 4: Modelling a fish out of the blue clay

In order to characterize the variability of the internal structure at different locations, with further permission from the Scottish Natural Heritage, we returned to the site and collected a total of five across-fault transects (structural logs) through the fault core (locations given on the geological map; Fig. 2).

## What is 'inside' the HBF?

By digging to expose the fault core at five different localities, we are able to deliver a level of detail on the variability of an internal fault core structure of a major plate boundary fault that has rarely been seen before. Each log delivers structural detail equivalent to that revealed via drill core, but with the advantage of being able to trace the variation in fault zone structure through multiple logs hundreds of meters apart.

This work reveals the Stonehaven section of the HBF is composed of a remarkable sequence of fault rocks (Fig. 3). The fault core, which is between 2.95m (Log 4) and 10.7m (Log 5) wide, is composed of four structurally and chemically distinct units – a localized green clay, a blue clay, a red foliated clay with structural fabrics and a unit consisting of large, lens-shaped clasts broken off the Dalradian wall rock (see McKay et al. 2020).

These fault core units are very different to each other and remain surprisingly unmixed, despite having accommodated offsets between 30 to 150 km. For instance, the blue clay is of high plasticity that feels exactly like modelling clay. In fact, one member of our team even managed to model a fish in the field (Fig. 4). The red foliated clay has a grey, silty texture with compositional (colour) foliations that wrap around wall rock clasts elongated parallel to the HBF. Surprisingly, despite the evidence of internal strain, relatively intact clasts of wall rock and ancient microfossils are preserved within the clay.

Similarly to other plate boundary settings where oceanic and crustal wall rocks juxtapose, our field and mineralogical observations (see McKay et al. 2020) suggest the HBF fault core likely formed through shallow, low-temperature, shear-enhanced, chemical reactions between the wall rocks of contrasting chemistry. In other words, the green and blue clay are derived from the HBO wall rocks, whereas the red foliated clay and lens unit are derived from the ▶

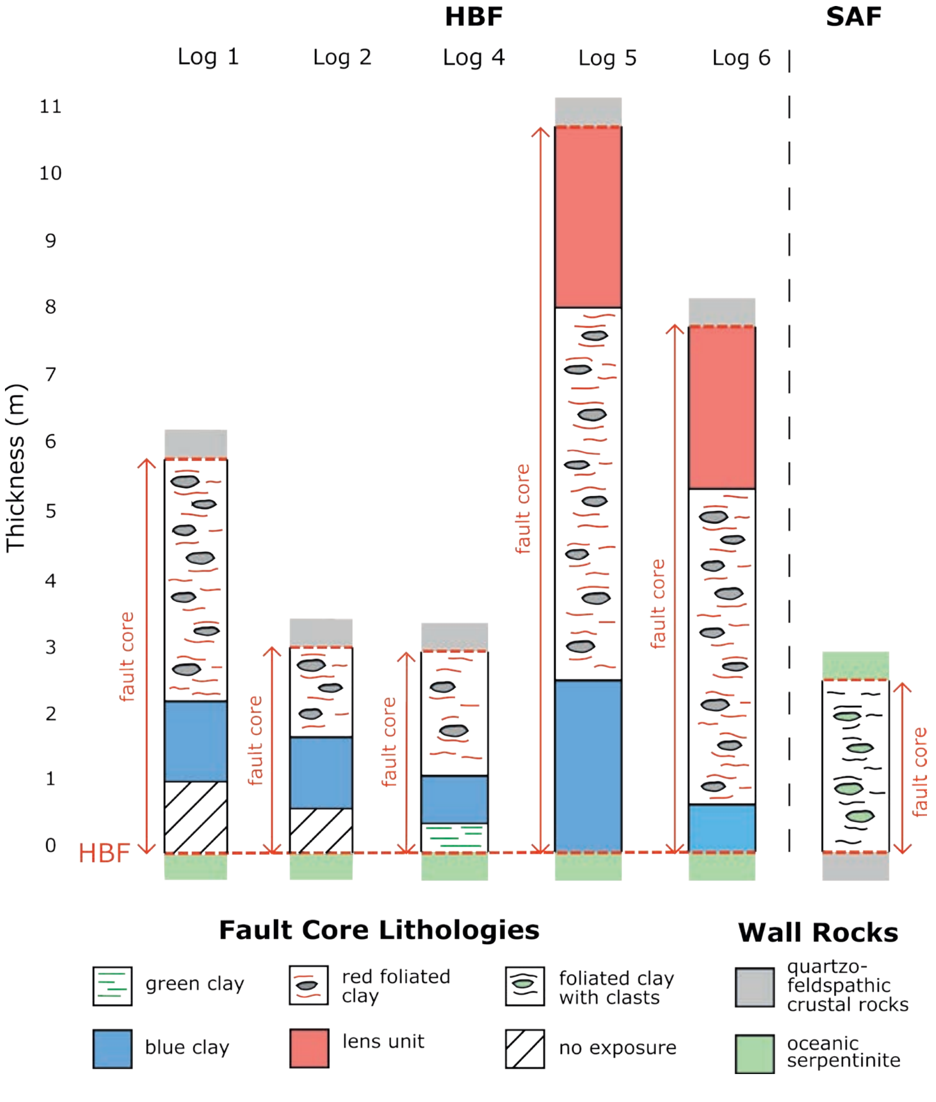



*Fig 5: Structural logs highlighting the along-strike variability in the thickness of the Highland Boundary Fault (HBF) core in comparison to the San Andreas Fault (SAF)*

*The University of Strathclyde's Fault and Fluid Flow research group 'digging' for the Highland Boundary Fault*

Dalradian wall rocks. Our field observations confirm the HBF has dominant sinistral strike-slip, but also reveal that the thickness and composition of the HBF core is variable at different locations i.e. not every unit is continuous, and each unit has variable thickness (Fig. 5).

## Fault zone palaeontology!

One of the most surprising (and puzzling) discoveries was the preservation of relatively intact, ancient microfossils within the blue clay (Fig. 6). Initially, and rather disappointedly, we thought these were just modern-day fossils, and hence modern-day clay found on a beach. However, after discussion with Paul Taylor at the Natural History Museum it was confirmed that these fossils were indeed ancient bryozoans, possibly belonging to the order Fenestrata. They were found alongside brachiopods and echinoid spines.

Since we think that the blue clay is derived from the HBO, one hypothesis is that these shallow, marine fossils are derived from the sedimentary cover of the ophiolite sequence. Regardless of their origin, it is impressive that these delicate fossils remain relatively intact within a high-strain fault clay and show no evidence of internal strain (e.g. microfracturing or shear indicators). Strain within the clay must have been highly localized and principally concentrated on the margins of the fault core.

Clay growth must be younger than the fossils which, assuming the bryozoans belong to the order Fenestrata, are Ordovician to Permian in age but reached their largest diversity during the Carboniferous. The presence of these ancient fossils within the clay therefore constrains the age of the clay to younger than Ordovician-Permian. Obviously this does not provide a very tight age constraint, but to the best of our knowledge this is the first time that the age of fossils preserved within a fault clay have been used to constrain the relative age of that fault.

## How representative is the HBF of active plate boundary faults?

Our maps are the first time anyone has seen 'inside' this iconic plate boundary fault that is such an important part of UK geology. As well as contributing to the understanding of the sequence of events at the HBF system, our maps show the

HBF has remarkable similarities in thickness and composition with other plate boundary faults.

All plate boundary faults appear to have similar fault core thicknesses. For example, the San Andreas fault (SAF) clay as revealed by the $25m SAFOD project has a fault thickness of 2.5m (similar in thickness to Log 2 and 4). It is composed of a dark greyish-black to greenish-black, highly-sheared, foliated clay that wraps around wall rock clasts that are elongated parallel to the foliation (similar to the red clay). Structurally foliated fault rocks with clasts derived from the wall rocks are common along many strike-slip plate boundary faults. In both the HBF and SAF, the clay formed as a result of fluid-assisted, shear-enhanced chemical reactions between wall rocks of contrasting chemistry.

## What can we learn from the Highland Boundary Fault?

The remarkable similarity between the HBF and other plate boundary faults confirms that our results are applicable to the growing number of studies into how fault structure controls earthquake ruptures. The magnitude and speed of rupture propagation and the frequency content of radiated seismic energy all affect how damaging an earthquake is, so understanding the internal structure of plate boundary faults is crucial if we are to better understand and mitigate damage.

If the thickness and composition of the fault changes at different locations along the fault, which we have demonstrated they do for the HBF, then models of structural control on earthquakes must take this thickness variation into account. For instance, if the units within the fault core have variable thickness, then the effect of shear heating or lubrication by thermal pressurisation is likely to vary (the thinner the unit the faster the heating). Therefore, it is crucial to understand the controls on the presence and thickness of such units along the length of the fault. Drilling a few boreholes at a particular section of the fault is not enough to fully characterize the internal structure, and hence earthquake properties, of the entire plate boundary – variable fault core thickness and composition have to be accounted for.

## What next?

The next stage of this work, which forms part of my PhD, involves detailed microstructural (thin section) analysis and laboratory work on the blue and red clay. Not only will this help to unravel the history of this iconic UK tectonic structure, but it will provide new data on the interplay between fault processes and earthquake mechanics. Look out for a forthcoming publication with these observations!

We have also received funding from the Geological Society to attempt to constrain the timing and nature of fluids responsible for the growth of the blue and red clays. Any suggestions for further work that will help understand the puzzling fault zone palaeontology will be most welcome…

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### FURTHER READING

Bluck, B.L. (1985). The Scottish paratectonic Caledonides. *Scottish Journal of Geology*, 21, 437-464.

Leslie, A. (2009). Border Skirmish. *Geoscientist*, 19, 17-19.

McKay, L. et al. (2020). Detailed Internal Structure and Along-Strike Variability of the Core of a Plate Boundary Fault: The Highland Boundary Fault, Scotland. *Journal of the Geological Society*, 177, 283-296.

Tanner, P.W.G. & Sutherland, S. (2007). The Highland Border Complex, Scotland: a paradox resolved. *Journal of the Geological Society*, 164, 111-116.

*Fig 6: Fossils in the blue clay*


*Panorama of a cliff with ancient castle in a bay with blue sky and white clouds in Dunnottar Castle, near Stonehaven, Aberdeenshire*