This 1-day field excursion will introduce key aspects of the structural geology, geomechanics and rock physics of faults and deformation bands in Permian age aeolian sandstones (Hopeman Sandstone) that is exposed on the Moray coast. Cataclastic deformation bands are found in many North Sea reservoirs, and these outcrops have been used as analogues for fields in the Southern North Sea gas basin. The outcrops should inspire discussions on fault zone processes and fault rock properties, and the implications for fault stability and fluid flow in deformed porous rocks. The highlight of the excursion is the Clashach Fault but spectacular outcrops of deformation bands will precede this to set the scene and promote discussion on how specific patterns of deformation band arrays may influence in subsurface hydrocarbon reservoirs. The Clashach Fault is believed to be a normal fault of Jurassic age (as are the deformation bands throughout the Hopeman Sandstone), and related to the main phase of extension in the Inner Moray Firth. A larger displacement normal fault (the Lossiemouth Fault) runs parallel to the Clashach Fault a few kilometres inland, and acts as the southern margin to the Inner Moray Firth basin.

The margins of the Inner Moray Firth basin are largely coincident with the modern coastline, with marginal sedimentary veneers continuing onshore. The basin contains arrays of normal faults that broadly trend ENE-WSW (there are significant thicknesses of Jurassic strata: well in excess of 3 km along the flank of the Helmsdale Fault). As elsewhere, these structures are sealed stratigraphically by the Base Cretaceous Unconformity, but subsidence and secondary faulting continued after this. This subsidence culminated in the regional blanket of chalk that covered Scotland (along with the rest of the British Isles). However, regional uplift has stripped this chalk off the Inner Moray Firth, which has greatly assisted in seismic imaging! Figure 1 provides a geological map while Figure 2 a larger-scale basin context for the excursion. Details follow on individual stops.
The cross-section (Fig 2) provides some regional context for the outcrops in terms of the basins immediately offshore. All these basins have their origins in the Devonian with the accumulation of the continental Old Red Sandstone (ORS) system in a wide variety of settings. These ORS basins developed on top of a Caledonian metamorphic basement that reached shallow crustal levels by c. 430 Ma. The ORS basins contain the detritus from the denuding orogenic belt. It is likely that this deposition occurred across much of the northern Highlands with just a few outliers remaining (Watson 1984).
Stop 1 – St Aethans

UK Grid Reference: NJ 128 692

Fault zones in high porosity sandstones are commonly related to sub-parallel arrays of cataclastic deformation bands. The foreshore at St. Aethans provides superb exposures of these features in plan form, and in sectional view on the flanks of a large sea stack. The deformation bands weather proud of the rock bedding planes, and form resistant seams. Gullies through the foreshore provide excellent exposures of deformation band arrays and small fault zones. Multiple cements are present in these rocks, including calcite, quartz, barite and fluorite. The relationship between these episodes and the brittle deformation is not clear! Some questions to discuss here include:
• Is the Aydin model for fault zone formation from deformation bands valid for these rocks?
• Can we find field evidence consistent with either strain hardening or strain weakening behaviour?

Figure 3. Locations of stops for the Clashach field excursion. The grid square are 1 km across. For location see Fig. 1.

Figure 4. Array of closely spaced cataclastic deformation bands in the sea stack at St. Aethans.
Stop 2 – Cabrach How

UK Grid Reference: NJ 133 693

The cataclastic deformation bands here display a restricted range of orientations, and mutually crosscut each other. A mean strike orientation is approximately East-West, but a simple average hides a significant spread in strikes of +/- 25 degrees either way. This means that the Hopeman Sandstone is compartmentalised by polymodal (non-conjugate) deformation bands into 3D rhomb shaped units; as these deformation bands show reduced permeability with respect to the host rock, this effectively destroys the bulk permeability of the unit as a whole. In contrast, if the deformation bands show a classical conjugate (or bimodal) pattern, there would be significant remaining bulk permeability in a direction parallel to the intersection direction of the two sets. Small faults are also exposed in the cliffs at the back of the beach, and provide a contrast to the structures to be seen earlier at St. Aethans, and provide a link to the next stop at Clashach Cove.

Fig. 5. Variably cemented Hopeman Sandstone either side of a narrow zone of cataclastic deformation bands at Cabrach How.

Stop 3 – Clashach Cove

UK Grid Reference: NJ 159 702

The Clashach Fault is exposed in outcrops of the Hopeman Sandstone (Permian) and trends E-W, with a steep dip (~70°) to the South. Cataclastic deformation bands are found throughout the unit, and are exposed along the shoreline for several kilometres in either direction. Shallow N-dipping joints and other steep iron-stained fractures cut across the deformation bands and the fault. Laboratory analyses reveal porosities of > 20% in samples taken several metres away from faults and deformation bands. The anisotropy of permeability in the fault zone has been quantified by Farrell et al. (2014). The permeability measured in the down-dip direction is up to 5 orders of magnitude greater than the permeability measured either along strike or across the fault.

Some questions for discussion are:

- Do faults in high porosity sandstones evolve from arrays of deformation bands? Or do these faults propagate upwards from deeper basement structures?
- Is there a distinct architecture of fault core and flank damage zones?
- Is there any asymmetry in the fault zone?
- What is the strength of the fault core relative to the wall rocks?