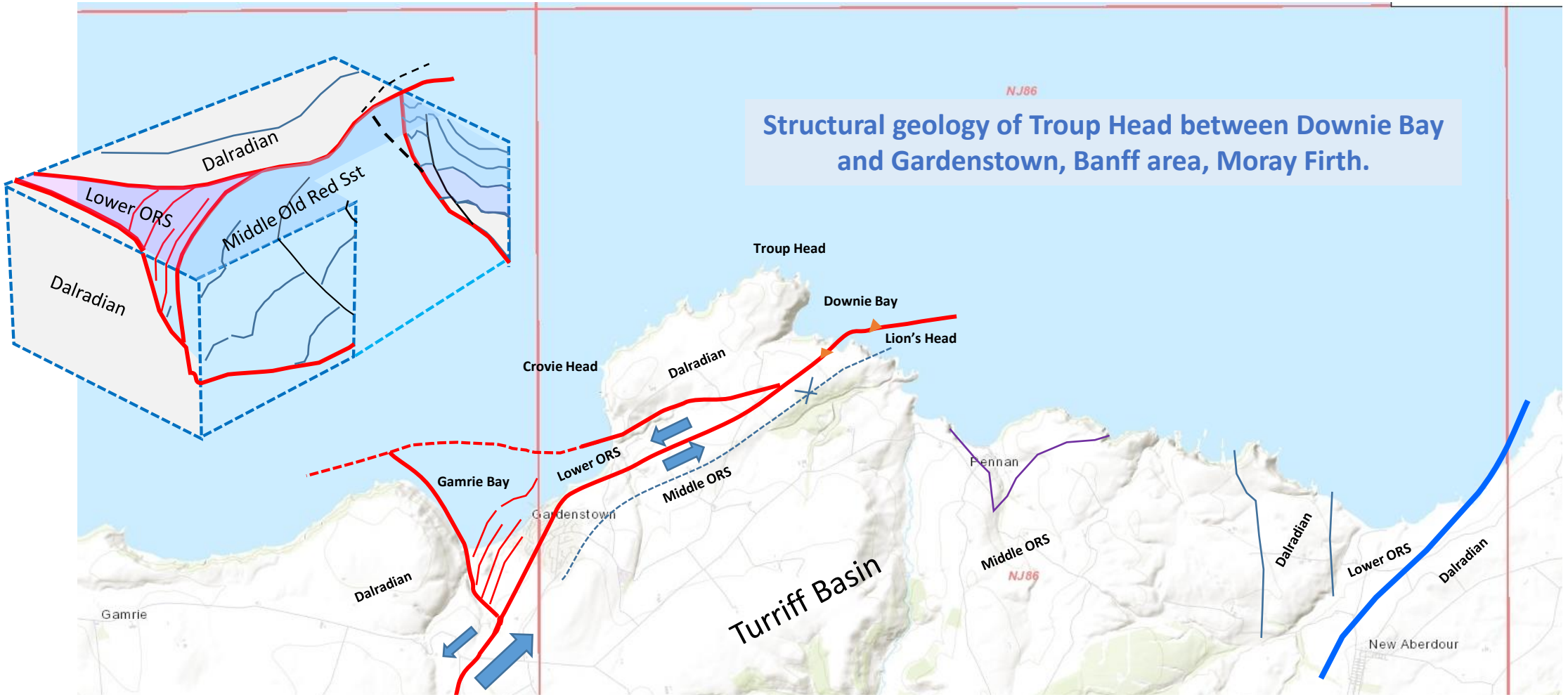
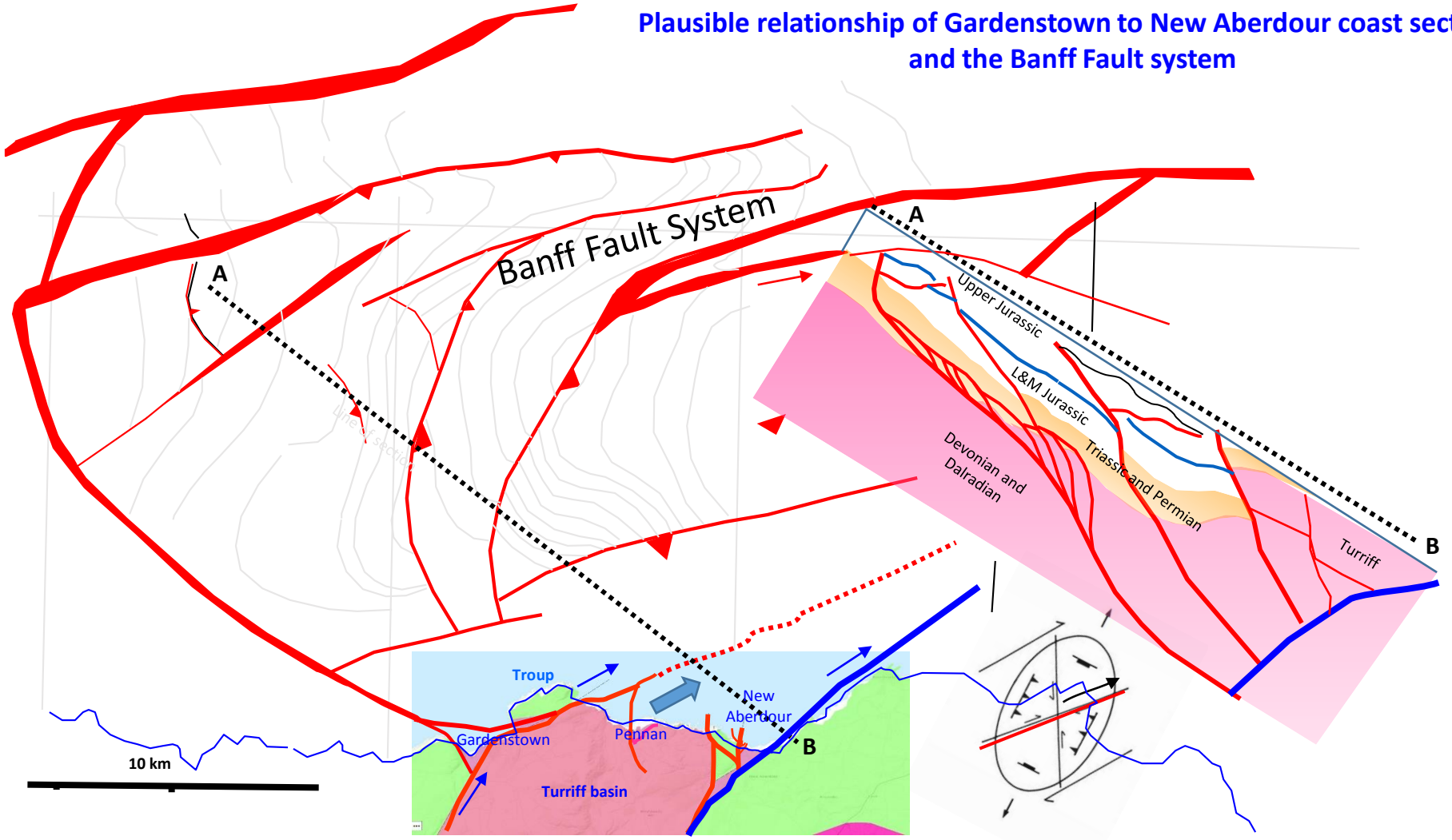


This note describes the geology of Troup Head, for people visiting on foot and using the boat trips available from Macduff harbour.

For geologists working on carbon capture, its interesting as a model fracture zone, for comparison with onshore CCS candidate structure trends in the Carboniferous basins of England and Wales. Its good to see what fractured rocks actually look like, in more detail than seismic can show. The focus is the Dalradian basement rocks of Turriff Basin's north flank, well exposed along the Gardenstown to Downie Bay fault which is a strike-slip zone established in Devonian times and reactivated at intervals to present day in Moray Firth Banff Fault development.

And if you just want to watch dolphins and gannets close-up, it's a marvellous place!

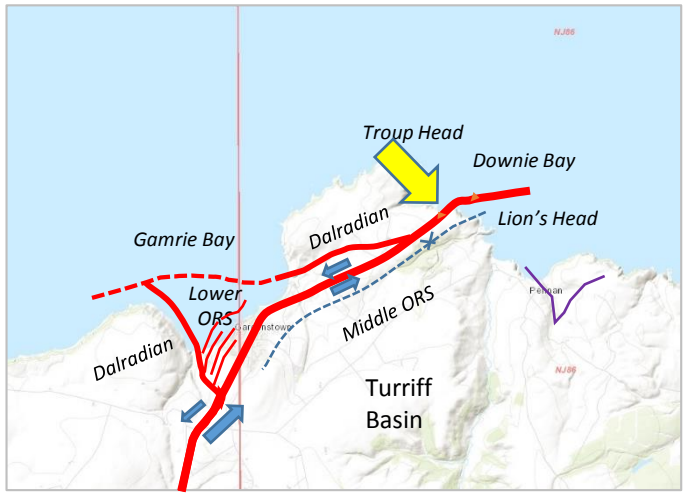
Plausible relationship of Gardenstown to New Aberdour coast section, and the Banff Fault system

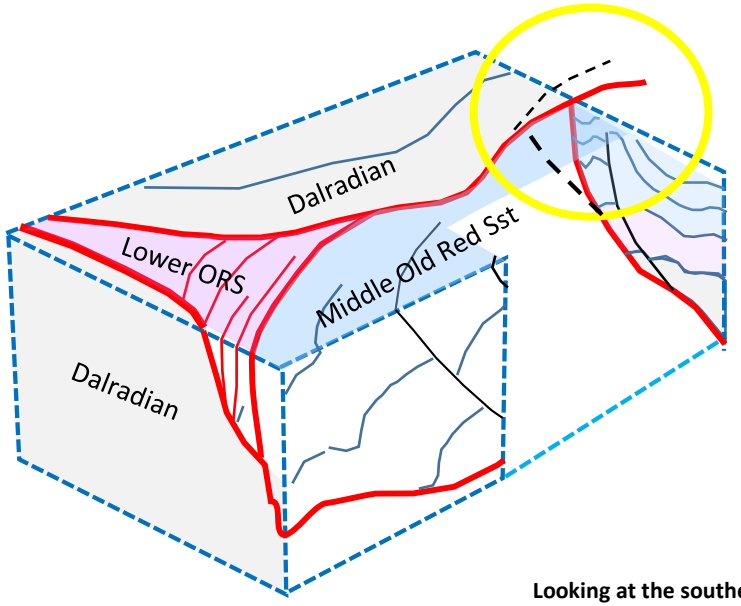


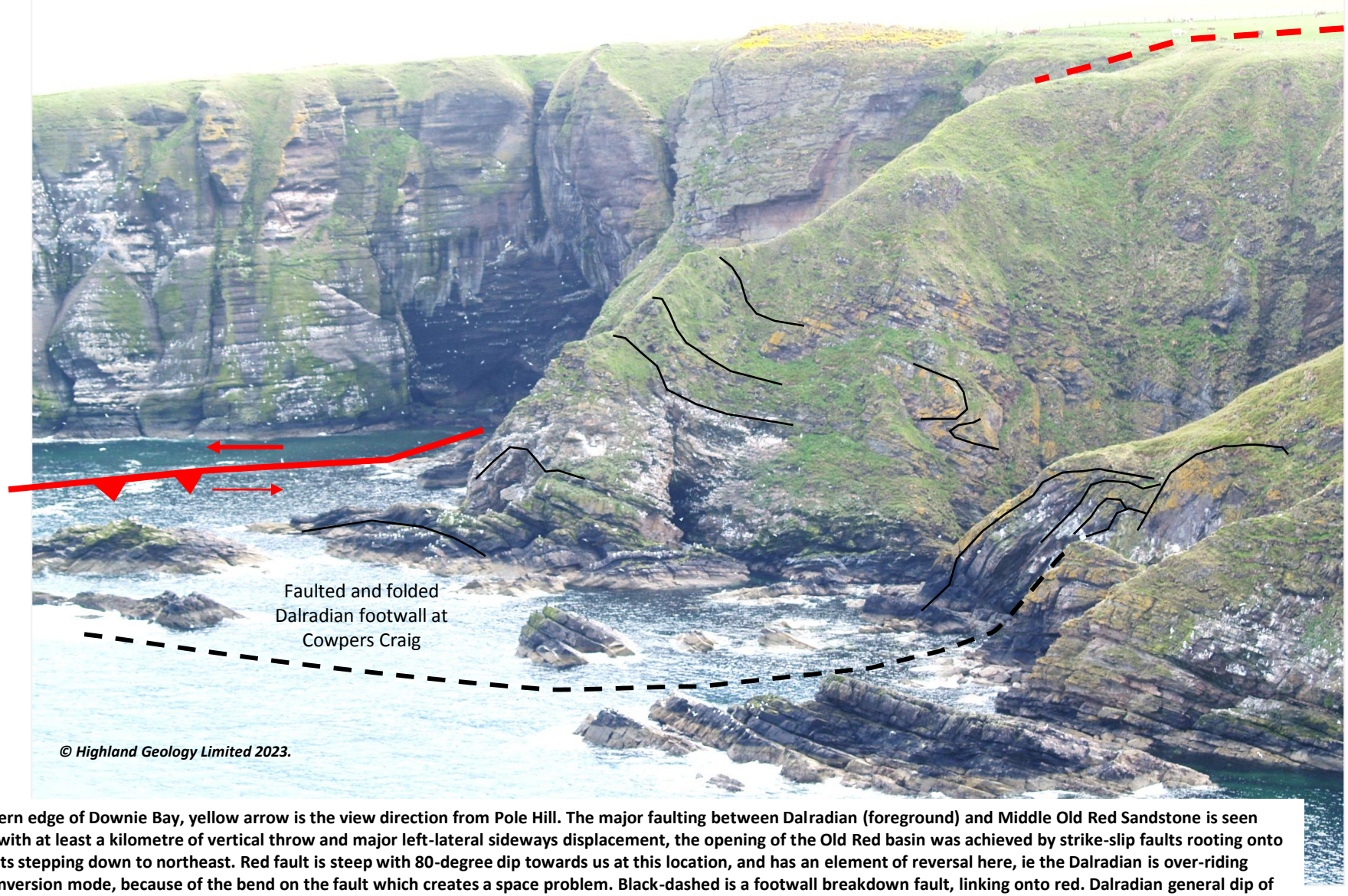
Offshore seismic profiles shot for oil exploration show that major faults in the Inner Moray Firth basins are arcuate surfaces linked together by steep wrench faults which have both vertical and sideways displacement, and its those northeast-trending wrenches which controlled the history of the Old Red. They were established in Ordovician and Silurian crustal compression, when plates collided to form the Himalayan-scale Caledonian thrust-fold belt, and they were instrumental in the collapse and huge erosion which followed. The sediment piles resulting are the Old Red Sandstone. Strike-slip faults in the Moray Firth have continued moving for nearly 450 million years, first in Devonian rifting and later in the opening of the North Sea, and the Alpine collision of Europe and North Africa.

Here we suggest Turriff Basin and the Troup Head faults are part of that system. The underlying idea for all this, is that the major faults are linked by even bigger ones, which drive the opening of the basin.

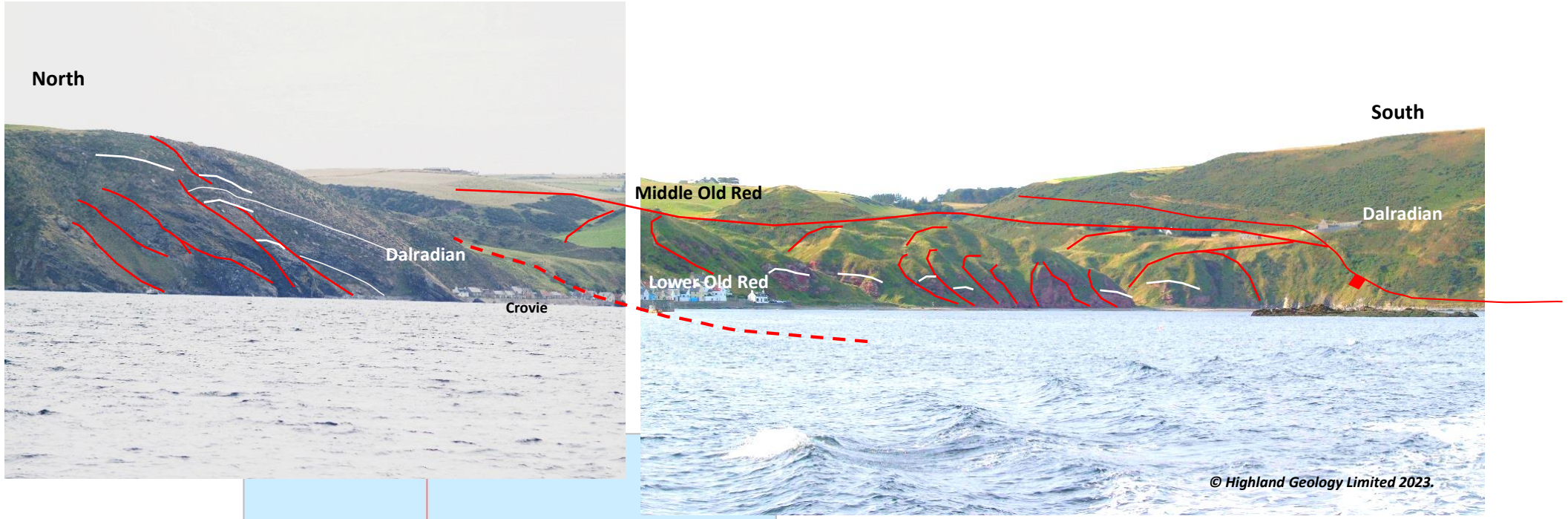
Looking SE across Downie Bay from Pole Hill, the foreground cliffs are Dalradian and those in background are Middle Old Red Sandstone, Devonian: the south boundary of the Troup Head block runs between them, drawn in red.

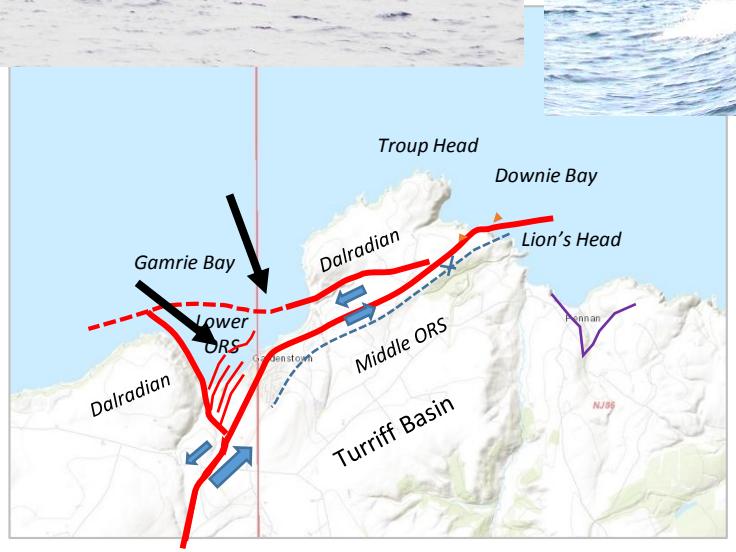




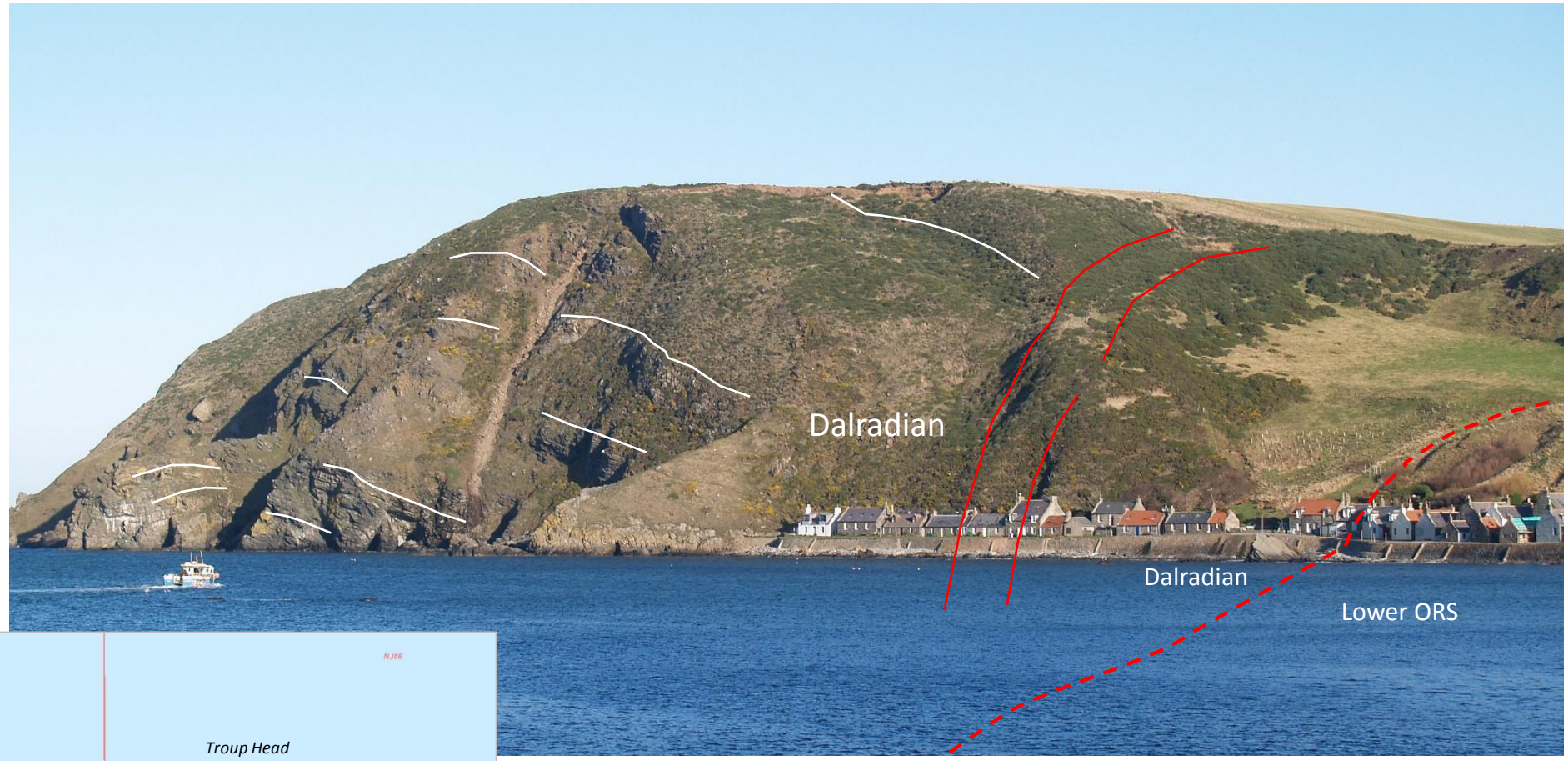


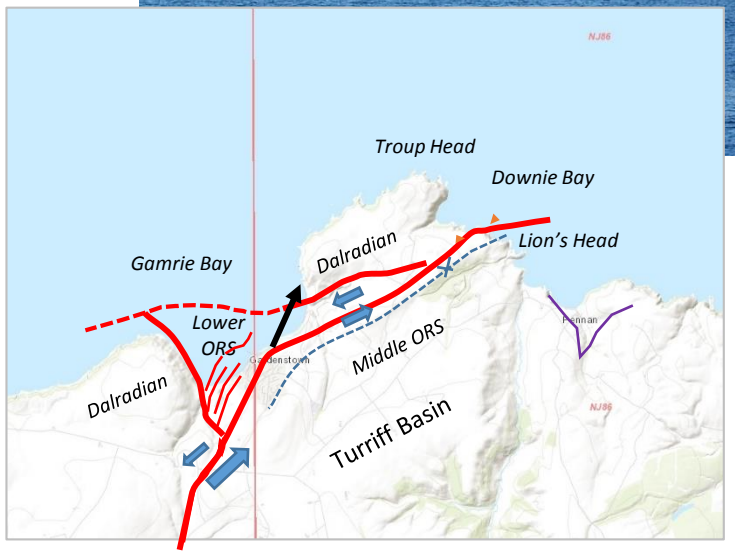
Looking at the southern edge of Downie Bay, yellow arrow is the view direction from Pole Hill. The major faulting between Dalradian (foreground) and Middle Old Red Sandstone is seen and its a huge fault, with at least a kilometre of vertical throw and major left-lateral sideways displacement, the opening of the Old Red basin was achieved by strike-slip faults rooting onto deep flat detachments stepping down to northeast. Red fault is steep with 80-degree dip towards us at this location, and has an element of reversal here, ie the Dalradian is over-riding south-eastwards in inversion mode, because of the bend on the fault which creates a space problem. Black-dashed is a footwall breakdown fault, linking onto red. Dalradian general dip of Troup block is southeast, here between the red and dashed black its southward, with local folding in the 50-75 metre wide inter-faulting compression zone.



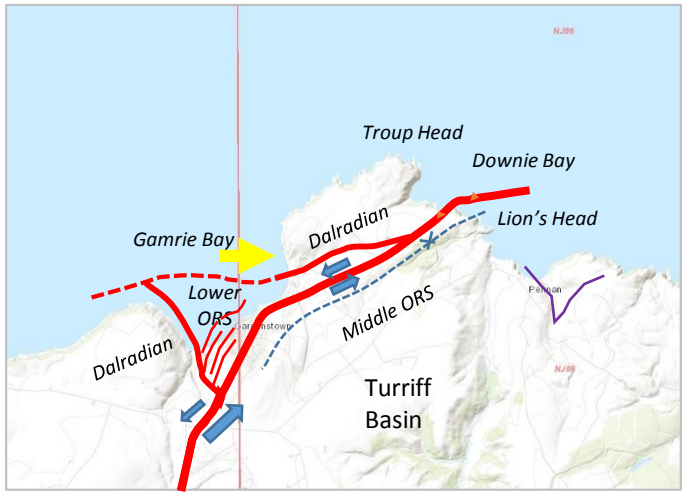


Western end of the Crovie to Downie Bay fault zone, two photos from Gamrie Bay, direction of black arrows. Crovie cottages seen centrally, Gardenstown is behind the reef, Craigandargity. Faults are red, bedding dips white. Note how the wedge of west to southwest-dipping Lower Old Red is closely-faulted, the dip is twice that seen in the Dalradian.



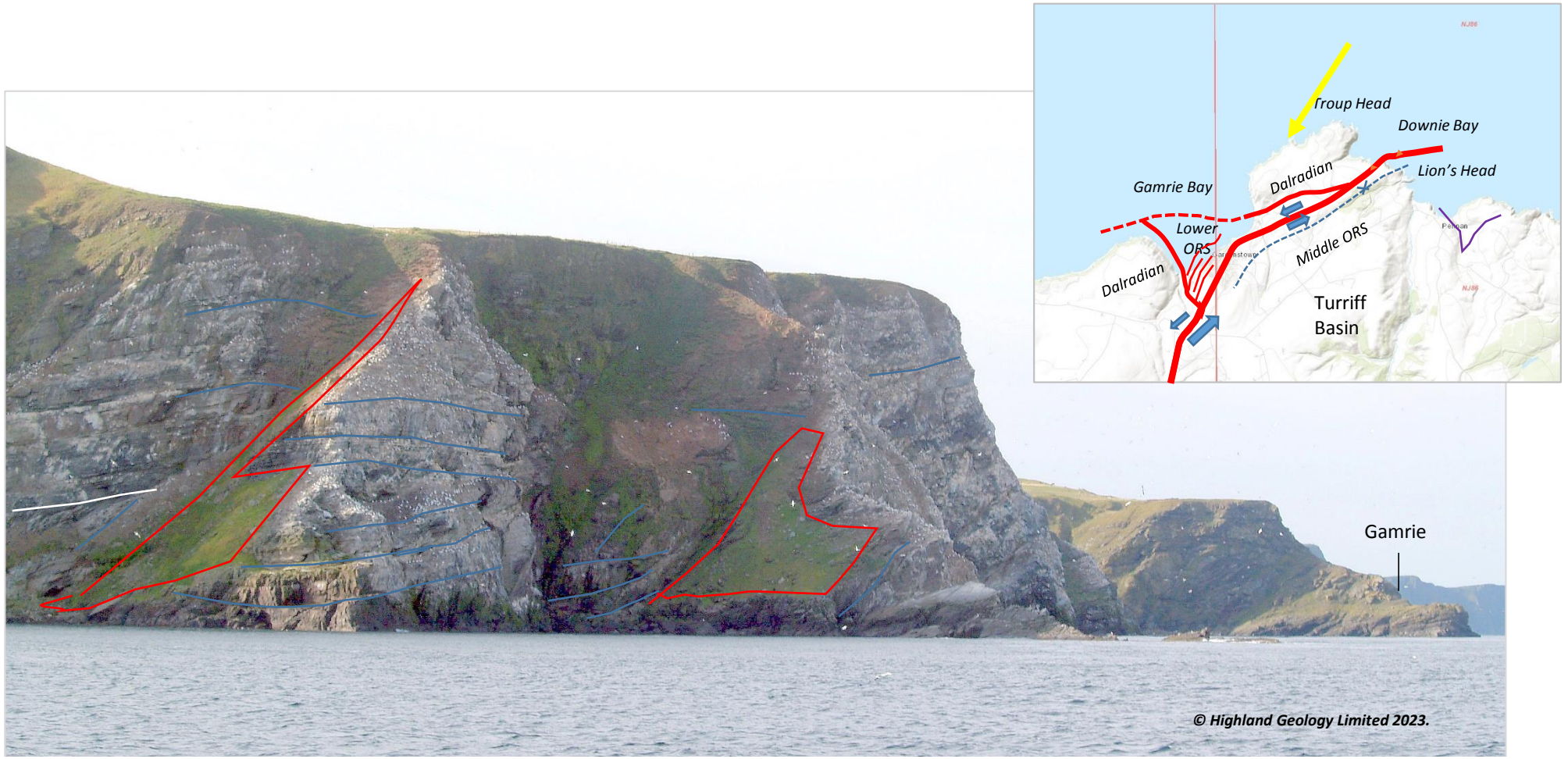


View from Gardenstown harbour towards Crovie, black arrow, strong fracturing at the left end of the walkway along the Crovie cottage front, and poor outcrop in the hill behind is attributable to intense fracturing at the fault between Dalradian and Lower Old Red.



Dalradian strongly fractured footwall rocks about 250 metres north of the Crovie-Downie boundary fault, just north of the Crovie cottages. The old 6-inch geological map notes made in the late 1800s described the sequence as "very shattery".

Upper Dalradian quartzites and slaty shales at Black Craig, north of Crovie Head, some 800m north of the Crovie-Downie Fault: highly jointed but not so smashed as in the previous photo near Crovie, closer to the fault.



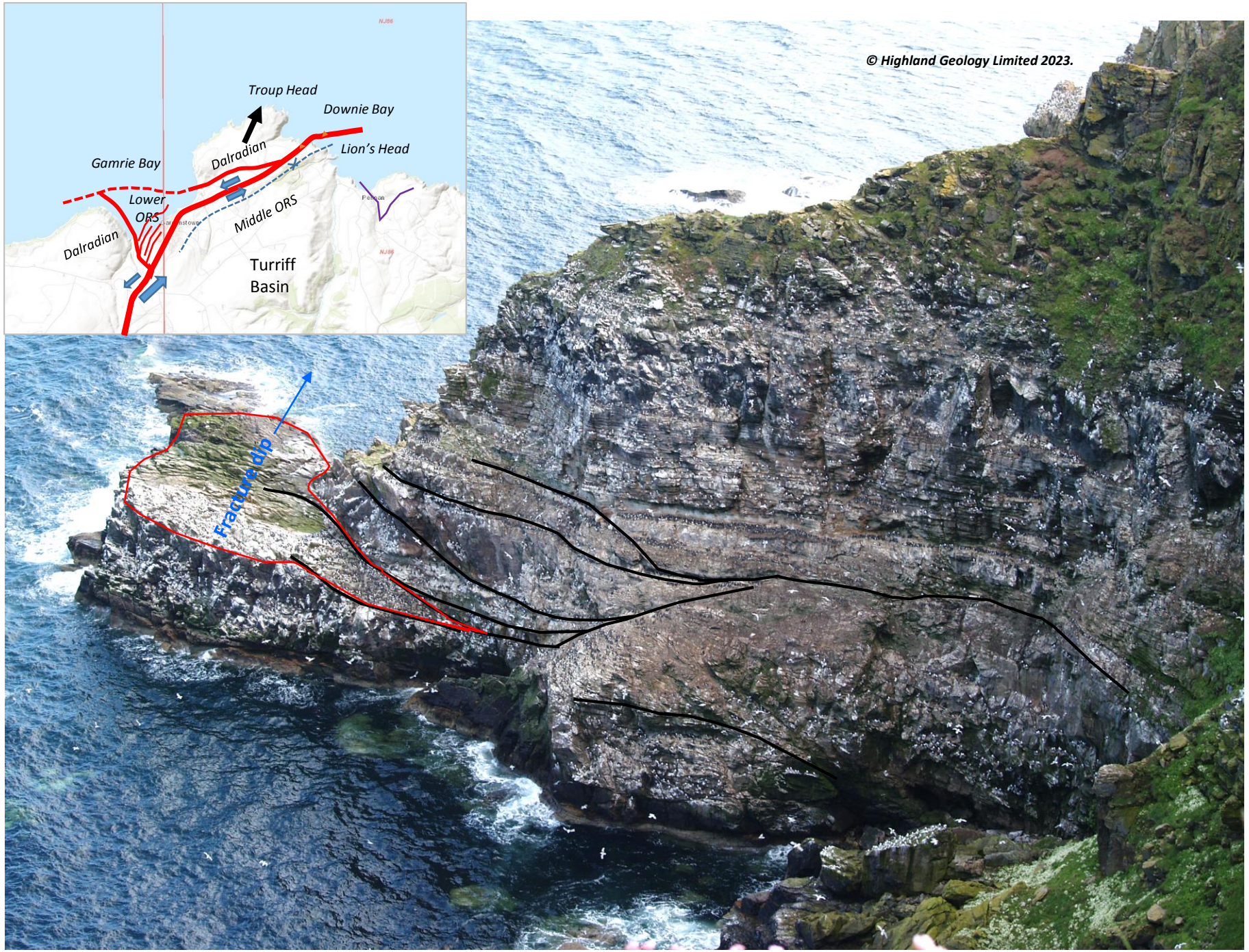
At Collie Head in the main Troup cliff section, which is about 80-90m high, looking SSW the Dalradian dip is into the plane of the photo, away from us at about 30 degrees, which is consistent for the whole Troup block. Some very large fractures cut through the section (grass areas mark the planes of displacement), dipping around 45 degrees northeast: these are extensionals dipping in the same direction as the Devonian basin was opening.

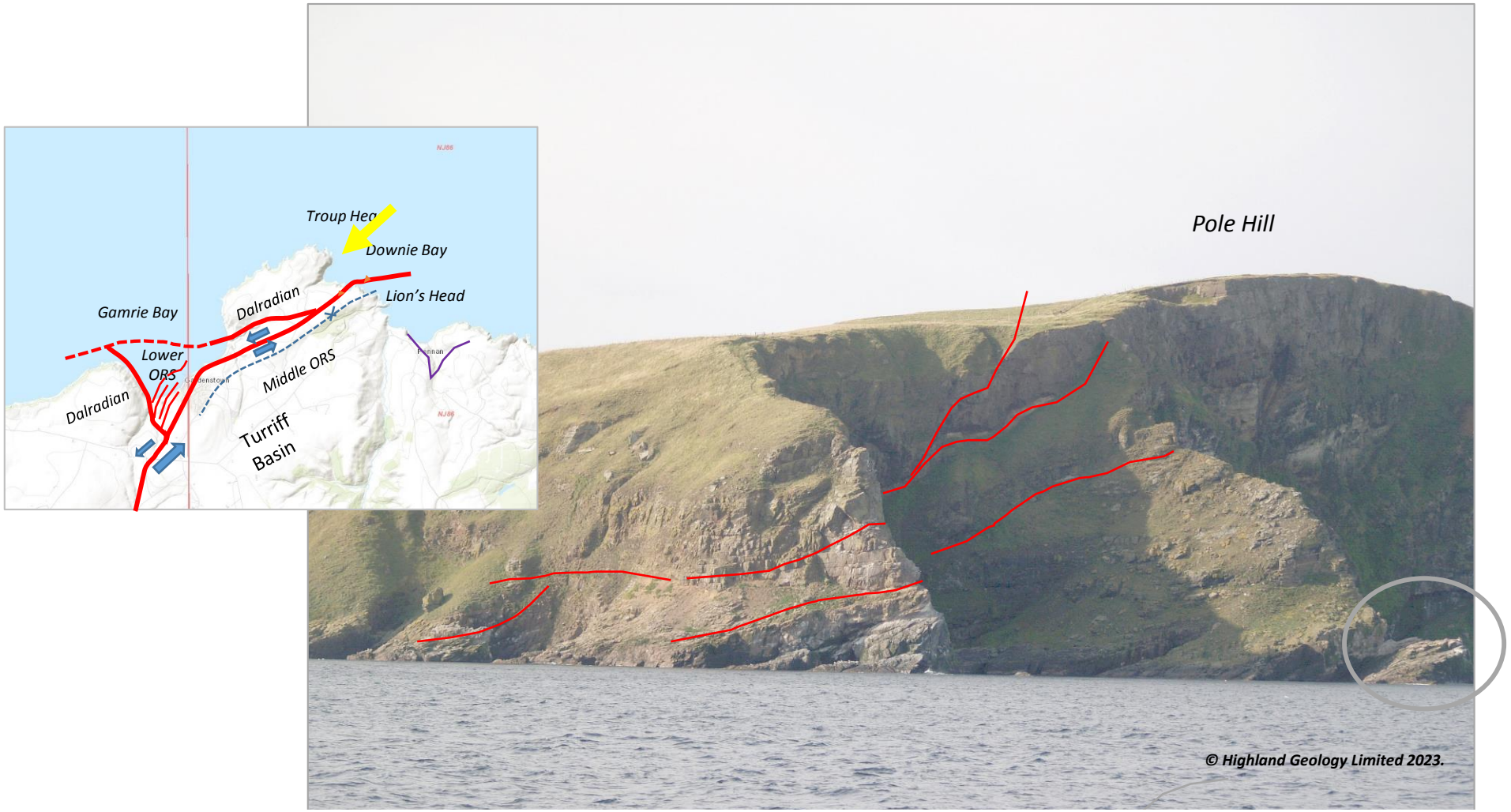
Fracture surfaces like these can be visible on seismic, provided there are velocity changes associated with them to give an impedance contrast, making a seismic reflector: in very hard, formerly deeply-buried and well-cemented rocks that means the fracture has to be open with water or hydrocarbon charge. For example they may be routes towards ground surface, for pore water being expelled, and they interconnect smaller-scale fracturing in the rock between them.

Looking northeast off the top of Troup Head, we see another of the major northwest-trending, NE-dipping extensionals, red-outlined surface, showing close-spaced breakage and what looks like a sidewall fault-set in photo centre, drawn in black. Some of these surfaces were re-activated in compression.

The upper half of the section is very broken, and locally red-stained, this could be the result of Devonian beds being removed by erosion which opened-up the fracture fabric close to the Dalradian-Old Red unconformity.

(There are many hundreds of birds in the view, mainly guillemots and fulmars, making use of the ledges and cavities for nesting. Gannets numbering several thousand raise chicks on Troup too, they prefer the steeper, higher cliffs just to west of here. A lot of birds had gone back to sea at the time of these photos, September-October. Its been a bad year for them, with avian flu).





Looking SW our boat is heading westwards and about to round Troup Head. Dips are about 25 degrees SSE. Pole Hill is 112m amsl. The ringed extensional of the previous photo is at lower right. The extensionals in the Upper Dalradian quartzites and micaceous schists are evidently rooting into the Crovie-Downie Bay fault zone: the sideways movement opening the Old Red basin is what drove the big fractures in the Dalradian.

Pinch-points where faults converge, like this one at Troup, need not show dislocation of overlying sequence if movement is wholly sideways, but there can be intensive fracturing due to space problems at such locations.

Comparing Lancaster and Troup

Lancaster oil field in the West of Shetlands Rona Ridge granites is an informative comparison for Troup fracturing.

The original Lancaster wells were inconclusively drilled and tested. Based on subsequent development using 3-D seismic data and long deviated and horizontal well drilling with cores, the fault zones at Lancaster are now known to comprise a surprising 30-40 percent of the gross rock volume in closure. Storage space in the main fracture zones ranges 2/5/8 percent of gross rock volume with average "porosity" 4.8 percent.

At Lancaster highly-connected matrix fracturing, between the main fault zones, is proved by the abundant core and by production logging, and it is critically important additional storage space for oil. The granite "pseudo-matrix" has lower fracture volume than the main fracture zones but its pervasive, just as we see at Troup, and this inter-main fracture matrix makes up about 60 percent of gross rock volume.

So Troup lets us appreciate that high volumes of bicarbonate slurry made with carbon dioxide could be held in this type of reservoir. Also that a huge percentage of fractures are sub-seismic in scale and we should apply geological modelling as well as seismic interpretation, in selecting potential sequestration sites.

There are a lot of cross-basin fracture zones in UK's onshore basins, where CO2 could be efficiently and safely stored in slurry form, we don't need to spend huge sums pumping CO2 offshore to old oil and gas fields!