AGS

Geological Field Excursion Guide for

Tod Head, Aberdeenshire

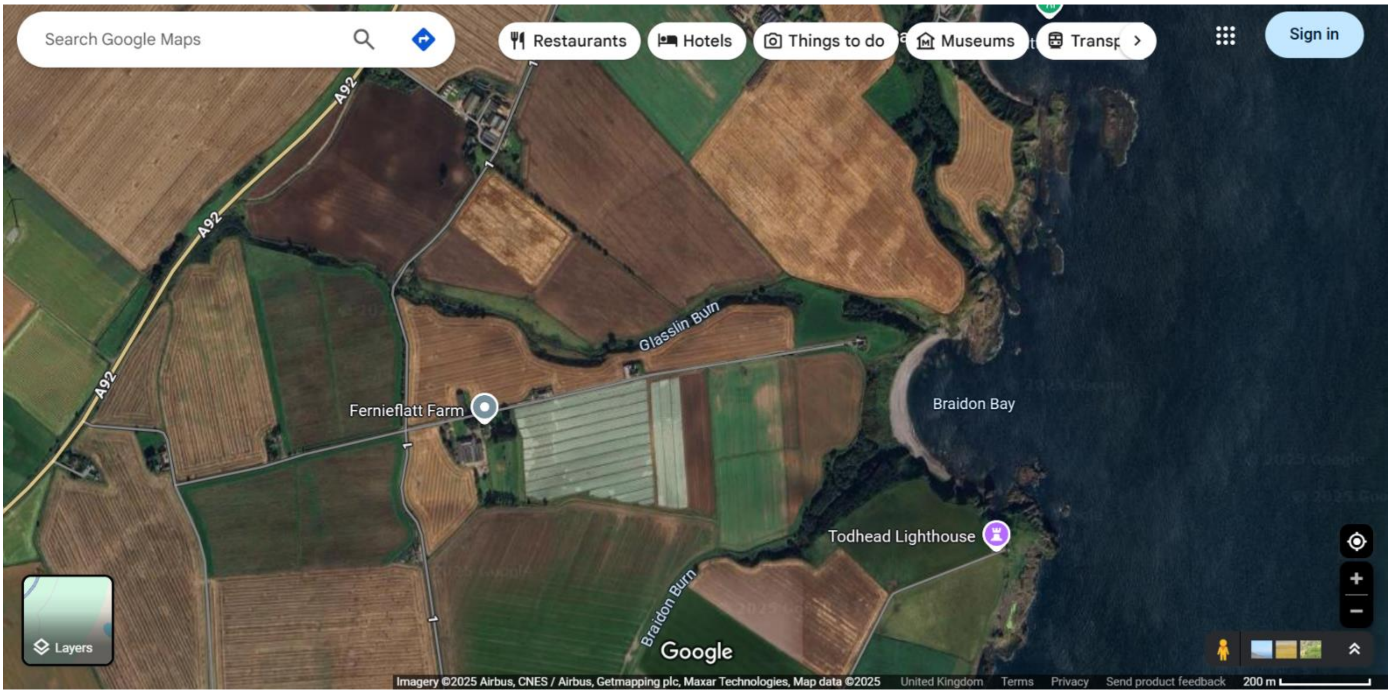
Tod Head Lighthouse - built and first lit in 1897

Stuart Archer and Martin Forster

Introduction

Tod Head is on Scotland's east coast, south of Stonehaven, between Crawton and Kinneff. Coastal outcrops provide good exposure immediately south of Catterline Bay and Braidon Bay.

Parking at the lighthouse is limited and so for larger groups it's advised to car-pool at the large arcuate layby on the southbound side of the A92, close to the Fernieflatt turnoff (see map below).



General location map using Google Earth

The rocks are situated in the northern portion of the Midland Valley, ca 12 km south of the Highland Boundary Fault (HBF). They were deposited near the end of the Caledonian orogenic phase and now lie near the axis of the strongly asymmetrical Strathmore syncline.

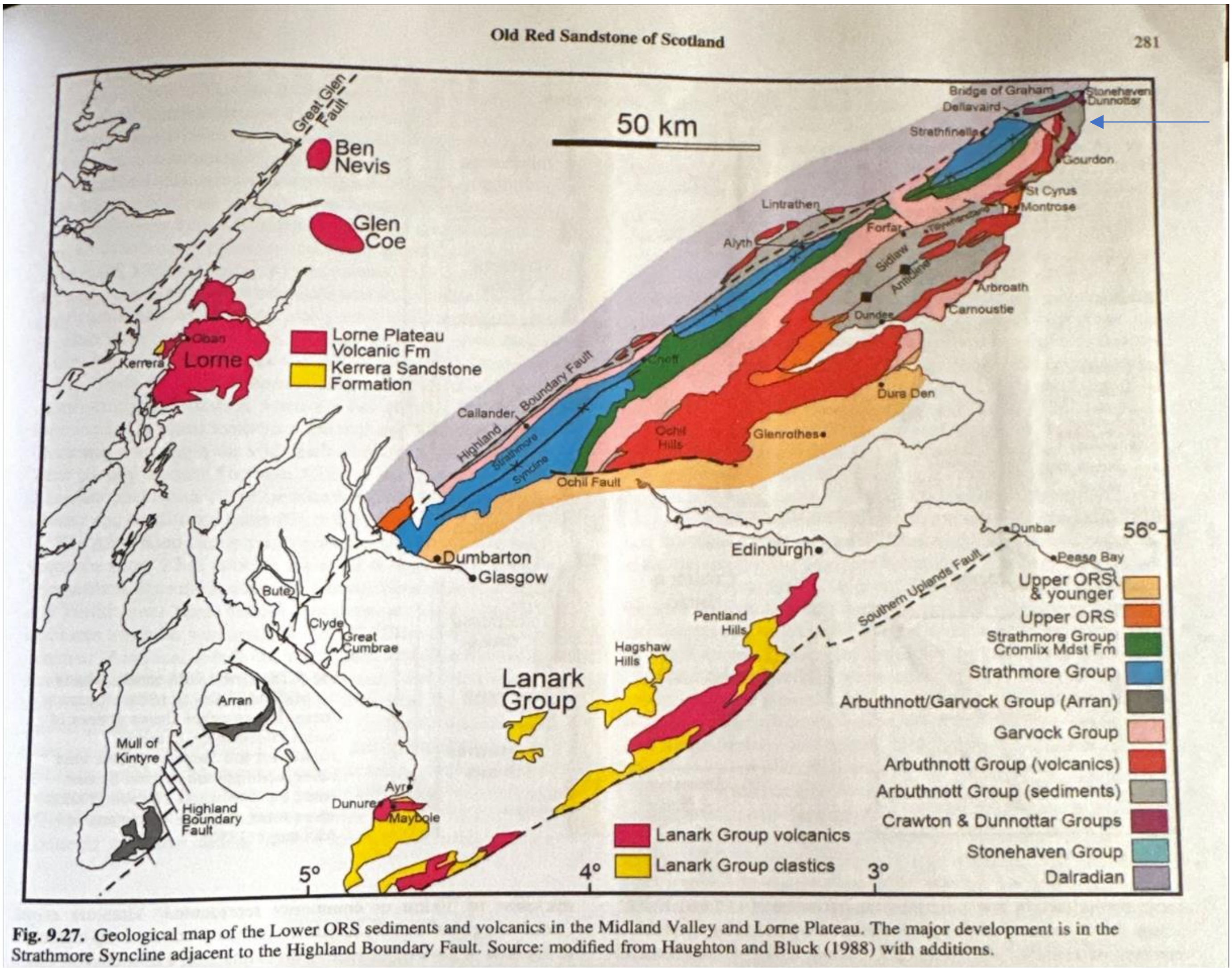


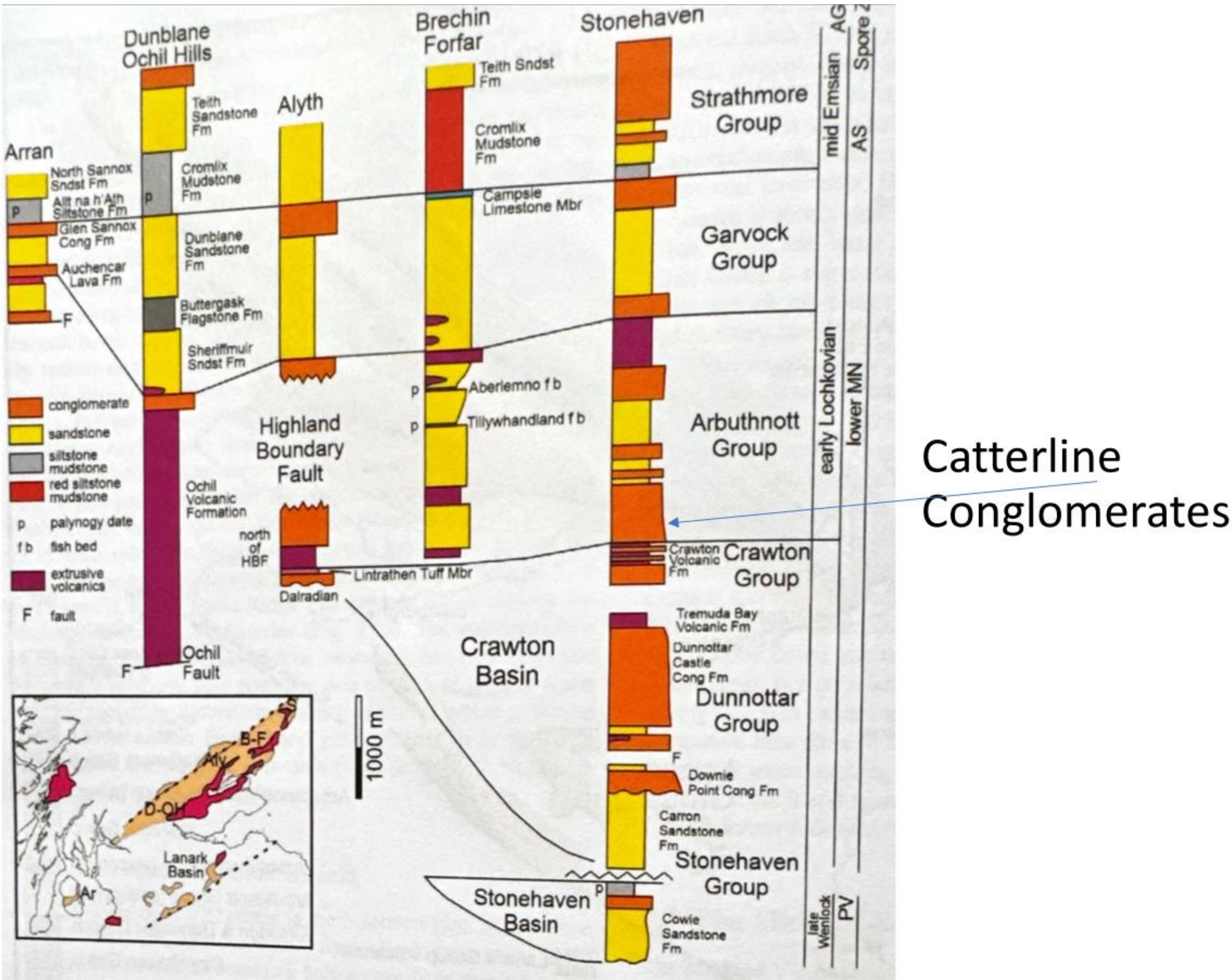
Fig. 9.27. Geological map of the Lower ORS sediments and volcanics in the Midland Valley and Lorne Plateau. The major development is in the Strathmore Syncline adjacent to the Highland Boundary Fault. Source: modified from Haughton and Bluck (1988) with additions.

Map is modified from Haughton and Bluck (1998) and copied from Marshal (2024)

The strata here are Lower Devonian in age and are younger than those many will be familiar with around Cowie, Stonehaven and Dunnottar. This trip assesses Old Red Sandstone conglomerates and lavas which are interbedded in a very similar way to those, just up the coast, at Crawton. However, there are a few interesting aspects at Tod Head that distinguishes this outcrop as a rich and unique geo-scientific laboratory. Namely, columnar joints, lava lobes, vesicular and amygdaloidal basalts, zeolite minerals, faulting and mineralisation of several types, intriguing peperite fluidisations in the lavas, conglomerates providing an opportunity for detailed textural analysis (size, shape, type, imbrication, cementation etc.) and "pitted pebble" burial related features

Lastly, there is a 'curiosity or teaser' geological feature, termed here, in good humour...

'Sid's Sandstone Surprise'



Stratigraphic chart adapted from Mykura (1991) and copied from Marshal (2024)

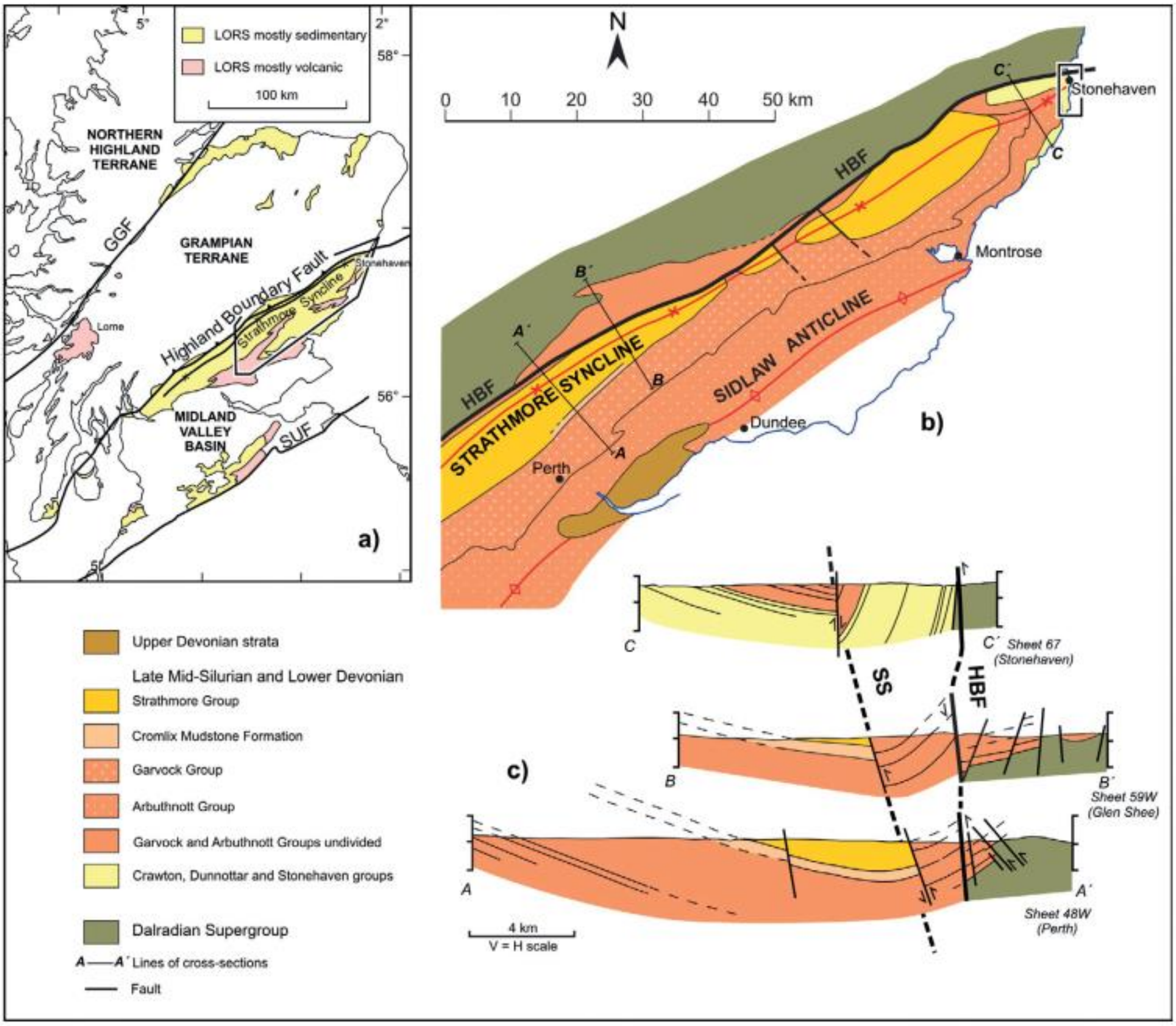
The conglomerates at Tod Head are part of the Catterline Conglomerate Formation which sit at the base of the Arbuthnott Group (early Lochkovian). In regional terms, the Catterline Conglomerates are roughly time equivalent to the Rhynie Cherts and the Ochil Volcanics.

The Crawton lavas are slightly older in terms of age and so are not correlative with the Tod Head lavas (BGS interpretation). It may be tempting however to correlate the Tod Head lavas with the Crawton lavas based on lithological similarities and the relatively shallow dip of the strata between the two areas. In addition, the Crawton lavas have also been mapped to the south of Tod Head by the BGS. On reflection, the igneous/sedimentary stratigraphy at Crawton does seem more highly interdigitated and so may indeed be a different age. The counter interpretation, that the lavas are the same age would need a model that invoked lateral facies changes. Future mapping of units on this coastline would be assisted by use of a boat and/or a drone and would have to take careful account of faulting.

LORS Structure

The steep dips observed at Cowie and Dunnottar Castle reduce to the south and relax out into the centre of the Strathmore syncline. This is a large-scale SW-NE trending fold that dominates the structure of the northern part of the Midland Valley. The rocks at Tod Head are relatively flat as the outcrop location is just to the south of the axis of the syncline.

Their position, near the base of the syncline means that the strata here are largely viewed in the sea cliffs as sub-horizontal (strike direction is along the coast), with a general structural dip of 10- 20 deg or so to the west (landward). This syncline was likely folded during uplift and shortening associated with the Acadian phase of deformation (end Middle Devonian), eroding the Middle Devonian from the Midland Valley but may also have been structured during the Carboniferous.



Note that the axis of the Strathmore syncline (SS) sits 2-5 km south of the Highland Boundary Fault (HBF) and is a 'faulted fold', with displacement flipping polarity along strike which is suggestive of strike slip faulting - likely during the Acadian inversion phase. From Hartley and Leleu (2015).

Local LORS Stratigraphy

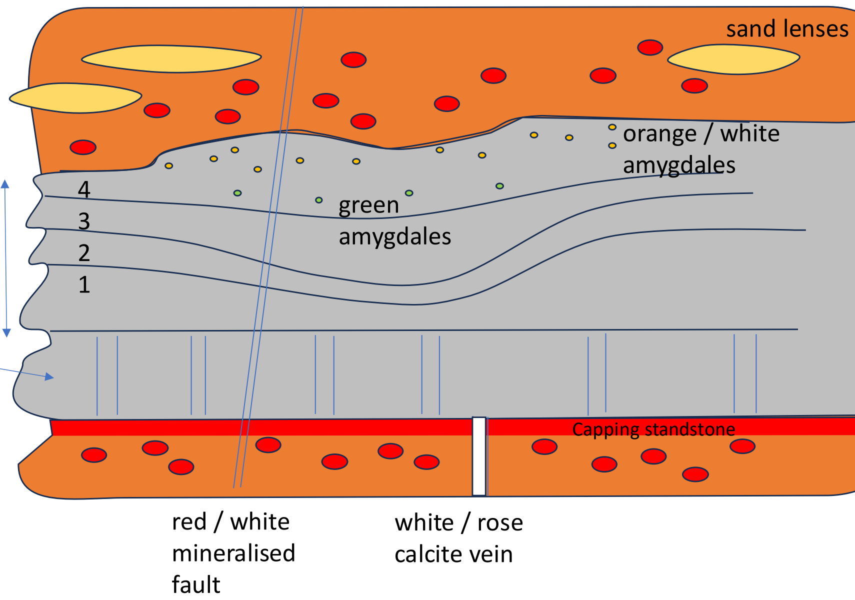
The strata at Tod Head can be informally broken into three main units:

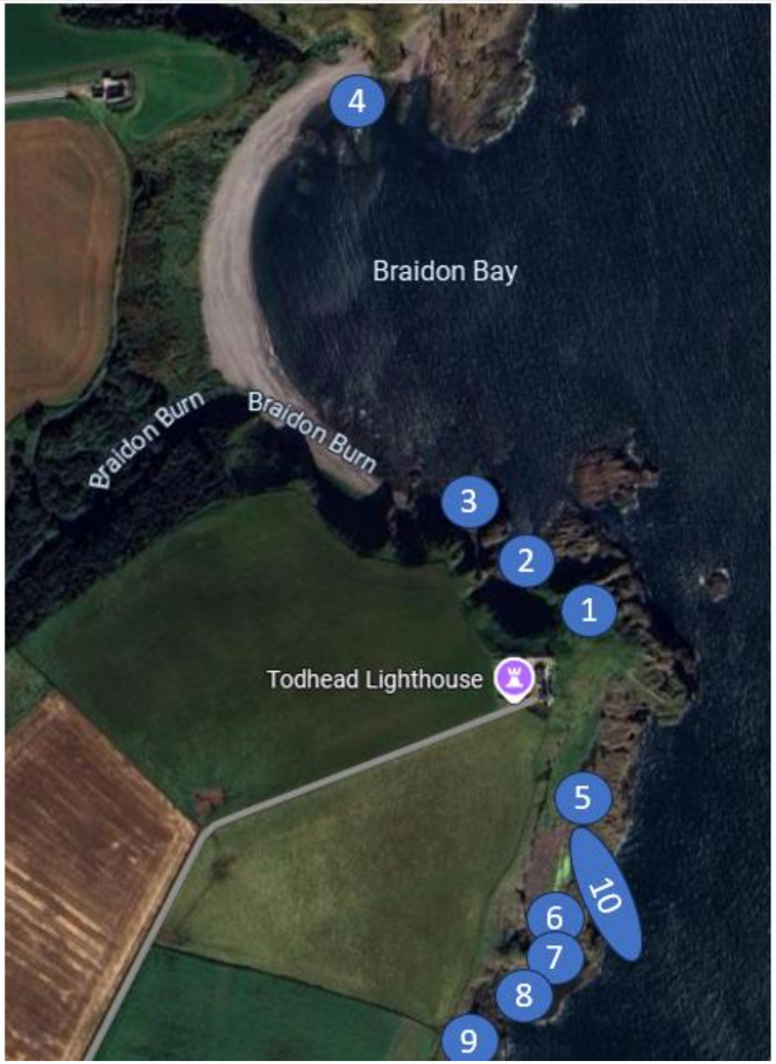
- Upper Conglomerate
- Basalt
- Lower Conglomerate

The conglomerates are crudely bedded with rare sandstone lenses up to 1 m thick and 10 m across. The volcanics are around 5 m thick and within the basalt pile there is an obvious layering system that can be observed. The lower volcanic unit is a columnar basalt. The upper volcanics are lensoid and tend to vary in thickness. In places, four separate lava flows can be split out in the upper 'lensing' basalt lavas.

Tod Head ORS Stratigraphy

- Upper Conglomerate
- Basalt
  - Upper Lensing Basalts
  - Lower Columnar Basalt
- Lower Conglomerate





Tod Head Localities

1. The overlook
2. 'Smuglers Cove'
3. The stacks

4. The waterfall

5. Main face
6. Mineralised fault
7. Lava lobes
8. Fault terrace
9. Long face
10. Calcite vein

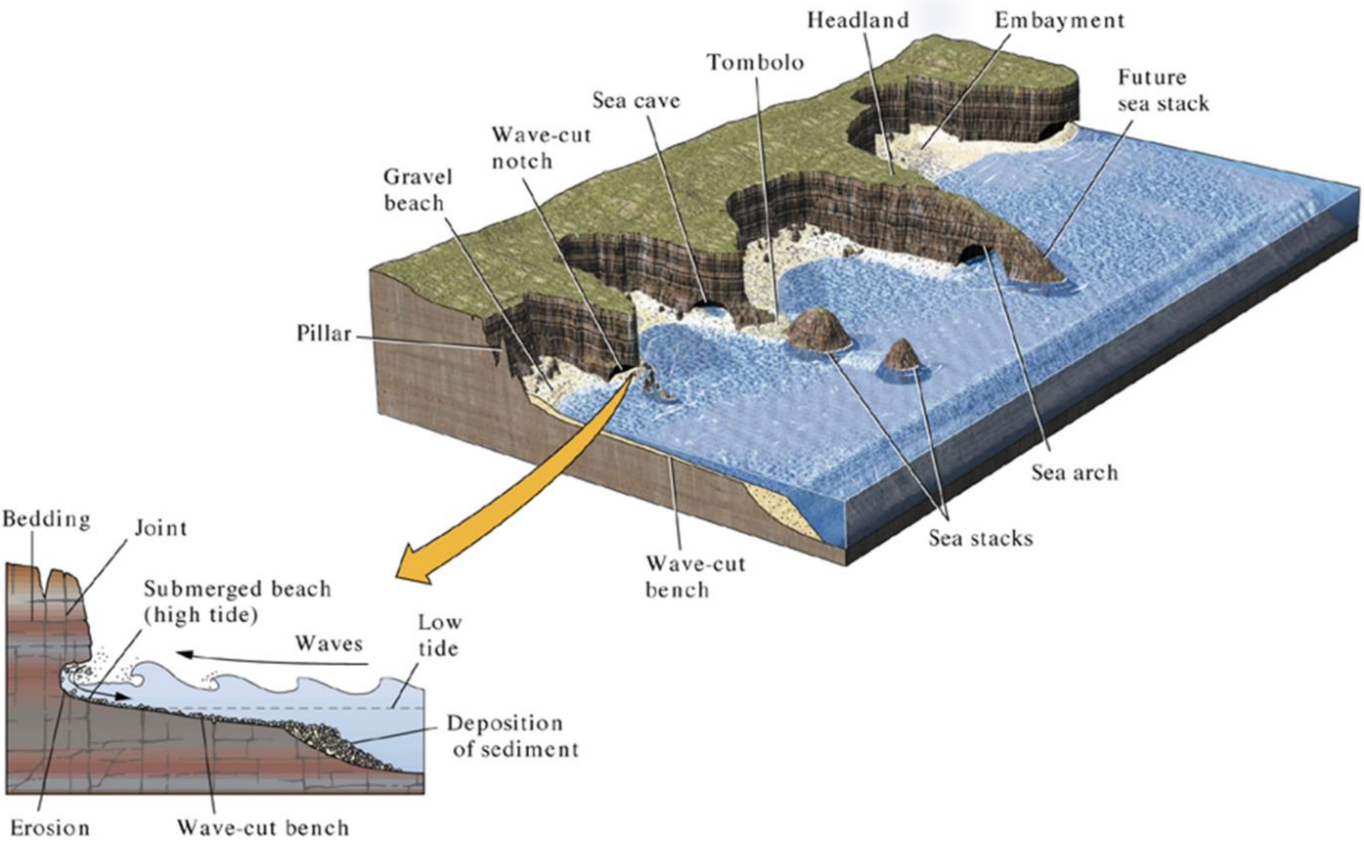
Locality Details

A good morning can be spent north of the light house (Localities 1-4) and the afternoon to the south (Localities 5-10).

Locality 1 (The Overlook)

- Coastal Geomorphology from the Overlook

This coastline is famous for its picturesque ruggedness and the coastal physiography is strongly related to the relative hardness of the ORS strata, with conglomerates appearing harder than the surrounding sandstones and basalts. The Bullers of Buchan are the best-known example on this coast, but geos, caves, arches, blowholes, sea stacks and skerries are all observed here in sedimentary rock too. Even though the ORS is largely sedimentary in nature, the rocks are sufficiently old, cemented and resistant for this coast to reveal classic 'hard rock coastal erosion' features.



Erosional landscape elements associated with hard rock coastal geomorphology

(from the Online Geophile Pages)

Locality 2

- "The Smugglers Cove"

This locality is accessed by a set of small concrete steps that descend north of the lighthouse. The cove reveals the basic stratigraphic organisation of lower conglomerates, volcanics and upper conglomerates.

Smuggler's Cove from the Overlook

The lower conglomerate here is capped by a thin (20 – 30 cm) sandstone. The contact between the conglomerates and the sand can be debated to be sharp or gradational depending on what section is observed. It's concluded here that these are separate flows, one high energy (the conglomerate) and one lower energy (the sandstone) rather than the record of a gradually waning flow.

Conglomerate / sandstone boundary

– gradational waning flow signature or two separate flows?

Mineralogically, these are Olivine Basalts although locally other lavas are andesitic. Within the basalts there is a simple bi-partite breakdown that can be made between the lower columnar jointed basalts (that are less vesicular) and the upper basalts that are very heavily vesicular and often amygdaloidal.

The 'Leprechauns Causeway'

Person sized columnar structures

The columnar basalts are made up of relatively crude, irregular polygons that appear ca 1.5 - 2 m high and roughly 40 cm in diameter. It could be possible to interpret the columnar basalts as a sill rather than a lava flow, but the unlikely coincidence of a sill intruding a lava pile means these igneous rocks are likely all volcanic extrusives.

There is a colourful, symmetrical cement fill that can be observed at the top of the columns, filling the joints between the columns. The outer edge cement is red/brown and the inner is a light emerald green, more fibrous and slightly softer (possibly talc or epidote or chlorite??).

'Fry's Peppermint Cream' structure – two toned joint filling mineralisation

(early oxidised cement and later reduced cement as the section gets buried?)

Vesicular basalts are common here in Smuggler's cove. In some basalt lobes the vesicles remain open but as one works up section, the vesicles tend to be filled making these lavas amygdaloidal basalts.

The amygdales of the upper basalts exhibit a range of zeolite fills. Zeolites are aluminosilicates composed of (Si, Al) O4 tetrahedra and geochemically are part of the feldspar family. The net negative charge of the framework is balanced by the presence of cations, in most cases Ca, Na or K.

In the lower part, the amygdales are green coloured and slightly resistive to weathering such that its common to find a whole ball like fill rather than a cross section. Often in cross-section, the green colour only forms the outer-rim.


"Wasabi peanut structures" where vesicles are filled by zoned green minerals (epidote?).

Higher in the section, many of the amygdales have multi-fills, that could be described as zoned (but are actually probably better described as layered). The lower cement fill is orange Stellerite(?) and the upper fill is white calcite? On occasion, the lower orange cement fill can exhibit a fan-like structure with needle like growth radiating out from the base of the vesicle.

There is commonly a gap between the top of the white zeolite and the top of the vesicle which is partially filled and may reflect the lack of mineral rich fluids?

Intriguingly, the green amygdales appear to sit stratigraphically lower than the red and white and it's possible that these formed in a waterlogged setting below the water table, whereas the red and white formed in the vadose zone with the variability exhibiting 'REDOX' behaviour.

There are two opposing Zeolite deposition models: 1. warm hydrothermal groundwater from below or 2. cooler meteoric waters from above. Both models will require further investigation to discern the root cause and relative timing of the many zeolite minerals here at Tod Head.

Stellerite is a rare zeolite mineral with the general formula $Ca_4[Al_8\ Si_{28}\ O_{72}]28H_2O$. It is very similar in chemical composition and physical appearance to Stilbite ($NaCa_4[Al_9\ Si_{27}\ O_{72}]30H_2O$) – just without the Sodium. Laumontite and Mordenite also occur here at Tod Head (Dyer et al., 1992)

Some of the vesicles appear elliptical rather than spherical and this is due to the gas attempting to escape while the lava was still flowing and then the gas bubbles were fossilised as the lava cooled and froze - these strained gas bubbles retain their stretched-out appearance. In the photo above-left these elliptical vesicles have layered amygdaloidal fill. Way up was likely to the left.

Locality 3

- The Stacks

Can you detect imbrication? What's the largest clast size? Are these deposits clast supported or matrix supported? Random and chaotic or organised? Can you imagine the energy in these flows and what the landscape would have looked like?

The deposits here are crudely bedded with a bed thickness of 2-3 m. Clast supported conglomerates dominate with cobbles and boulders that get up to ~60 cm across in the long axis. The clasts in the conglomerates are not randomly positioned but organised. Imbrication should be checked for in the stacks. It appears to point generally southwards with a range that suggests sediment dispersal in an unconfined alluvial plain setting. The understanding of imbrication and palaeoflow in the conglomerates is made more complex here by clast shape. Recognition of imbrication is easy with strongly elliptical clasts but much harder in clasts that are spherical to sub-spherical. In terms of clast shape, the a, b and c axes often exhibit similar dimensions and this demonstrates that the clasts are spherical to sub-spherical. The clasts are all well rounded and percussion dents can be observed suggesting high energy transport and numerous clast to clast impacts during sediment transport.

Clast size is smaller at Tod Head and rounding and sphericity appear higher than further to the north. These Tod Head deposits are also younger on account of the Strathmore syncline, making 'proximal to distal time equivalent observations' very difficult in these Devonian sections. The matrix is generally medium grained sand and is strongly cemented.

Clast size tends to diminish slightly upwards within bedsets, suggesting waning stream flows. The internal bedding with dip is likely to reflect accretion in a bar form (possibly medial braid bars). These deposits are likely the products of very high energy, turbulent, flash floods with deposition taking place in alluvial fan or proximal braidplain environments.

In the early Devonian, Scotland was in the southern hemisphere at latitudes that had a semi-arid dryland climate. There are a few small erosional scours but no major unconformity surfaces have been observed. This suggests that conglomerate deposition was largely unconfined with both sediment supply and accommodation 'in phase' and plentiful.

Clast types are variable but include andesite, psammite, feldspar porphyry, quartzite, granites, felsite and vein quartz. The quartzites are particularly intriguing as there is no quartzite in the current Highland provenance area, suggesting that there may have been a carapace of mature sandstone that rested on the Dalradian and was metamorphosed during Caledonide deformation and mountain building. This topic has been termed 'the enigmatic, lost quartzite unroofing problem'.

A photo of a quartzite clast. The conglomerate clasts often appear sheared and the splitting process leaves smooth and regular planar surfaces. Is there directionality and a dip to these planes? This shearing appears to occur along fault and fracture planes leaving clusters of sheared clasts.

Are the faults that shear the clasts normal, reverse or strike slip?

- Stack Internal Faulting and Fracturing

Faulting of the sea stacks and associated cliffs at Locality 2 is clearly seen from Locality 1. Assess the throw on the fault between the outer and inner stack by looking at the displacement of the basalt with the upper conglomerate. The throw looks to be around 3 m and the fault strikes roughly SW-NE. To the south of the inner stack, in the alcove, another couple of faults can be picked out by noting the position of the basalt/conglomerate boundary, which steps up to the south. The faults create well vegetated, soft gullies on the upper slopes. One SW – NE fault in particular creates an obvious step just above beach level.

Internally, the stacks are also disturbed by faulting and shearing which is not straight forward and would require detailed work to decipher but some clasts are fractured and faulted by the structuration. The 3D nature of the exposed stack faces would help this analysis. The continuation of the faults and shears into the competent basalt beds below is not clear. Can you trace the faults and shears visible in the ORS conglomerates into the basalts below. Is there a detachment?

Faulting and shearing of the Upper ORS Conglomerates overlying amygdaloidal basalt. The contact between the Upper Conglomerates and the basalt is not simple. In places a sandstone lies between and the nature of the contact appears irregular.

Looking back towards the sea from The Stacks, and onto the Lower Conglomerate and thin sand. These cracks in the 'bedding plane' are all normal faults with displacement down to the left (north). The largest of the faults is on the right in shadow and has about 3 m of throw.

Locality 4

- Braidon Bay and the Glasslin Waterfall

It should be of interest to participants that neither of the two burns in Braidon Bay reach the ocean which is likely due to infiltration of overland flow into the coarse storm beach. The river water from the Braidon Burn and the Glasslin Burn enters the sea as ground water using the porosity and permeability that exists between the cobbles on the beach.

Lunch stop at the waterfall and discussion of sandy interbeds and their faulting in a terrace style, synthetic fault network that throws down to the north east

Locality 5

- The main cliff face above the perched platform

Is the stratigraphic story from Smugglers Cove is also applicable here? Can a correlation be made even though there is no outcrop directly below the Lighthouse? Is a fault required (a conceptual 'Lighthouse Fault') to bring the basalt up from sea level or are the beds continuous and just steeply dipping?

The bedding plane that participants stand on to view the main face is the top of the Lower Conglomerate. Note a thin capping sand exists on top of the conglomerate. What is the thickness variability of this sand? Are the columnar basalts as extensive here as they are at Smugglers Cove? This vertical face exposes the contact between the basalts and the Upper Conglomerates. What is the nature of this contact?

This picture was taken looking onto the perched platform (top bedding plane of the lower conglomerate). Two joint or fracture sets can be seen that are roughly orthogonal to each other.

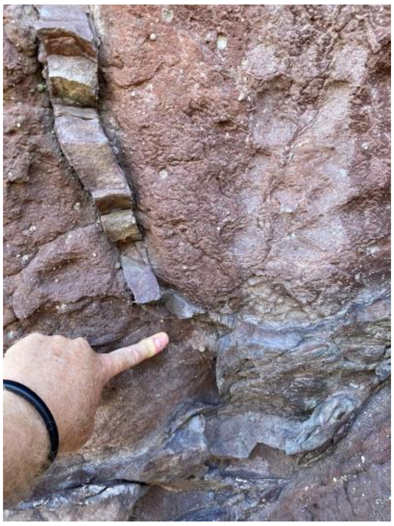
Locality 6

- Mineralised fault

What is the azimuth and attitude of this fault? What type of fault is it?

Both bright orange and white veining fill the fault and the veins in associated fractures and damage zones. In the grassy slope above where the conglomerates outcrop there is a subtle but detectable raised ridge area that is the extension of the mineralised fault upwards.

Picture of the mineralised fault, and also an image of fwo faulted then mineralised cobbles with evidence for dextral strike slip movement.

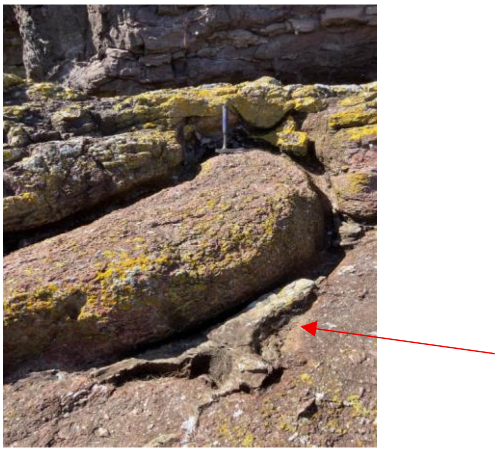


Intriguingly, there are also fine sandstone 'saucers and wings' in the lavas on the corner of the lava face in the south of the outcrop area. These appear injected, and this is confirmed in plan view on the top of the lavas where triangular junctions can be seen. Although the origin of the sandstone motherlode is not easy to detect it's possible the sand is sourced from the matrix of the lower conglomerate below. Is the volume of injected matrix sufficient to alter the texture of the conglomerate to matrix supported to clast supported?

The capping sandstone bed which is present in Smugglers Cover and thickens up below the lighthouse tends to thin to the south. The thinning may be related to the re-mobilisation of the sands into injectites in the south? In places, injected sandstone fins and wings appear to wrap around pillow like lava lobes, introducing the idea that hot lavas may have interacted with wet sediments, creating pillows and 'steam forced injections' - hypothesised as a linked process where hot lavas poured onto a damp, sandy alluvial plain.

Examples of injected sandstones, into lavas - seen as fins around 5-10 cm in width and in places forming triple junctions – suggestive of a 3D network of saucers and fins.

These injected sandstones are thought to be associated with Peperites. Peperites are rocks formed when magma intrudes and mingles with unconsolidated, typically wet sediment (Skilling et al. 2001). They are also formed by similar processes operating at the contacts of lavas and other hot volcaniclastic deposits with such sediments. Peperites commonly exhibit sedimentary dyke injections – seen in the host magma. They occur in a wide range of geological environments and have been described from the contacts of lavas in sub-aerial environments which is especially relevant to the outcrops seen at Tod Head.



This photo shows are some of the white sandstone veins (interpreted as fluidised sand injections) which we looked at localities 8 and 9 (hammer for scale)

In this general area, there appears to be a prevalence of bedding parallel 'laminar' cement fills. These are usually only a cm or two thick but can be up to 1 or 1.5 m long. Separation of cements from sandstone sills or saucers needs careful examination.

- Pitted Pebbles

The dip slope below the cliffs exposes indurated ORS conglomerate clasts on or near the bedding plane surfaces. Pitted pebbles can be observed where the pebbles indent each other with no intervening matrix. Silica released by pressure solution redistributes into the matrix giving a highly indurated cemented conglomerate. Some clasts on the bedding surfaces have been dislodged revealing the pressure solution cements around the clasts. This occurs at temperatures above 80 °C (ND Shaw personal communication.) implying a minimal 3 km of burial.

Conglomerate showing pitted pebbles formed by pressure solution of indenting pebbles (example boundaries highlighted in red). Redistribution of silica rich fluids causes cementation of the highly indurated matrix.

Locality 7

- Lava lensing, infill and topographic healing

How many lava flows do you see here? Name them using numbers from bottom to top please.

Here on the southerly nose of the main cliff face there are some interesting changes in bed thickness - compare the thicknesses of the flows you have named across the outcrop.

Do you think there is sufficient evidence here to suggest this is compensational stacking of lava lobes?

Are the conglomerates isopachous here or not? Is there a residual topographic low that gets used by the conglomerates in their early phase of deposition?

Locality 8

- Fault terracing

Are these faults post or syn-depositional? What evidence should we look for to distinguish models?

Two well exposed faults can be seen at the southern end of the perched platform. This exposure provides critical information regarding the nature of the normal faulting here and helps the interpretation conclusion that Tod Head is a horst block.

An obvious fault terrace between two synthetic normal faults. Neither of the fault sets continue very far and tend to change angle downwards, suggestive of a relay zone or relay 'lozenge'.

Locality 9

- The long face (The Slainges)

Can you break this seismic scale outcrop into key sequences?

This south-westerly extending coastal cliff offers rare, extensive and high vertical exposure. The upper conglomerates and sand lenses form resistive relief and rest on top of recessive, softer grey basalts.

The basal contact between the conglomerates and the basalt is generally sharp and flat but to the south there is an erosive step that needs more analysis, considering two options - either an erosive, channelised edge or the infilling of a low in the top of the basalt, maybe between lobes, as can be observed elsewhere at Tod Head.

The long face with lavas at the base and conglomerates higher up.

Note that in detail, there are two distinctive conglomeratic sequences in the upper conglomerates here in the south of the field area. The upper one could be Devonian or could be Quaternary. This needs further consideration but there is certainly an abundance of clasts locally in the Devonian to create a clast rich boulder clay / till. The top conglomerate is recessive, more vegetated and appears less favourable for gulls nests....maybe as this area is in play for the Tods to steal eggs from!

In the conglomerates here Kittiwakes have used the protrusion of the largest clasts from the cliff face as nesting sites which are now picked out in white, creating the new sub-discipline of 'Seagull Stratigraphy'.

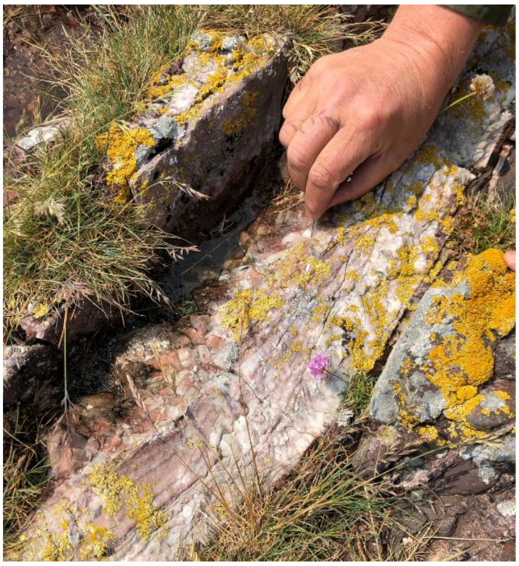
Beds here in 'the nook' appear steeper than usual and this may be due to the change in orientation of the cliff face relative to the long face to the south. There might also be some fault drag in the hanging wall of a south dipping normal fault (fault in the bottom right of this field photo and faces left).

Locality 10

- Calcite vein

How many phases of cementation can you see in this vein? Is it all the same mineral?

The vein reaches 50 cm in width and extends for 100 m or so. The edges of the vein possess laminar calcite but the central cavity was filled with coarser, triangular spar crystals of white and rose-coloured calcite (78 deg rhombic angles).



The vein has no obvious extension up stratigraphy into the lavas or the conglomerates and so may provide evidence that it is an early mineralised fault or joint that may have been eroded by an unconformity at the end of the lower conglomerate deposition, before the eruption of the basalts? This topic of timing of mineralisation requires more work.

Appendix - 'Sid's Sandstone Surprise'

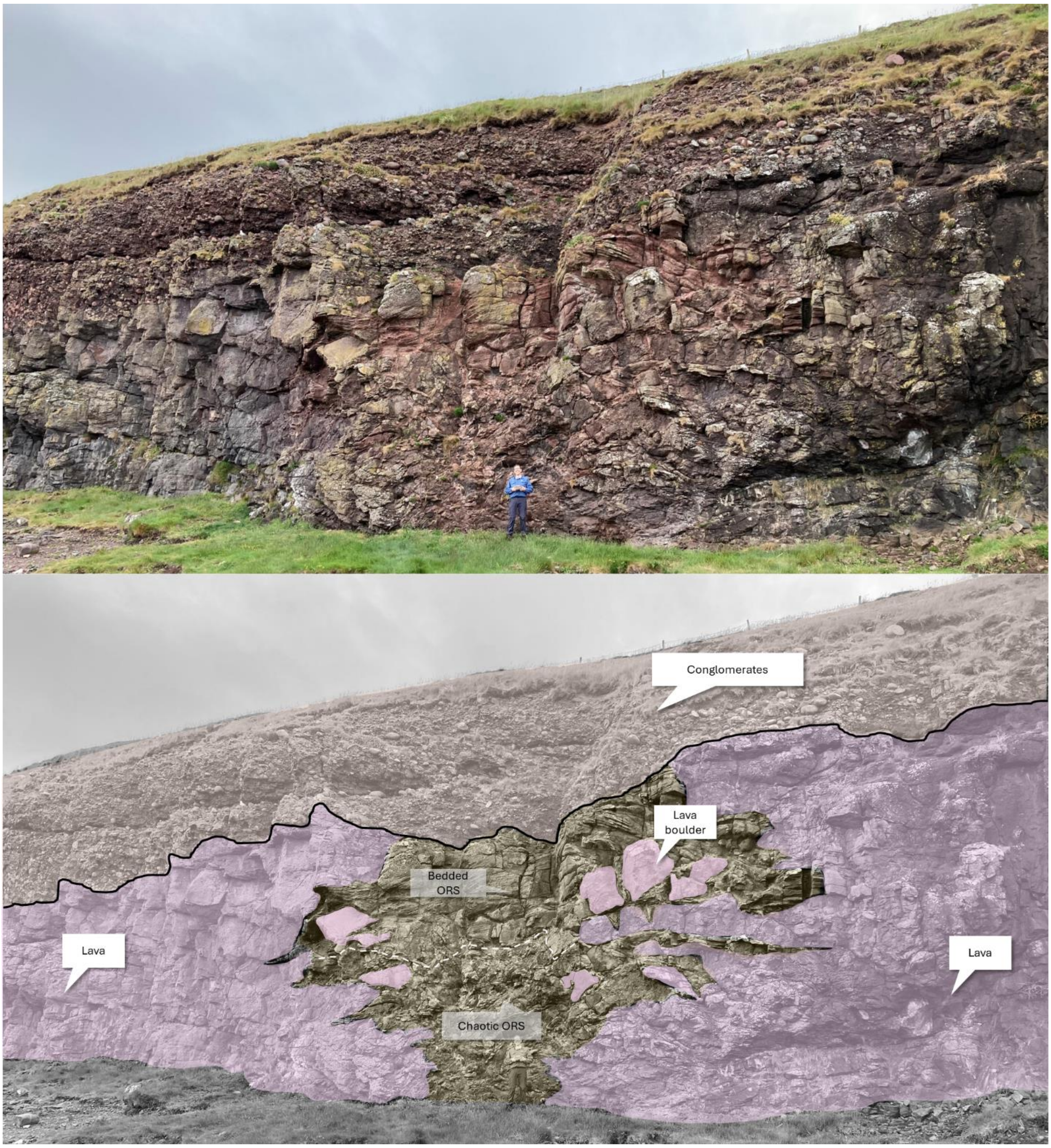
Special 'teaser' locality to finish...a red sandstone/lava 'curiosity' on the main face at Locality 5.

'Sid's Sandstone Surprise'

Start simple by asking how many lithotypes can we see? Then undertake a description of the field relationships between these rock types. Only then should an interpretation of this complex be countenanced.

Interpretative options for the complex:

1. Fissure fill (Neptunian Dyke)?
2. Lava tunnel - then roof collapse and filled by sandstone?
3. Sand injection structure?
4. Fault zone with disruption?
5. Wadi river valley?...
   ....answers on a postcard!



Photograph of Sid's Sandstone Surprise with lithological interpretation and Sid for scale!

The main lithotypes are 1. conglomerate, 2. lava, 3a. bedded sandstones and 3b. less bedded / chaotic sandstones.

Our interpretive preference is a 'wadi river' with the early 'chaotic' sandstones potentially being deposited at the same time the lavas were erupting. The upper, more bedded sands are better organised and may have been deposited once the lava was cool and brittle, ripping large lava clasts into the stream flow. Large scale 'peperite' injection of sandstone into the margins of the lava field are observed. The sands didn't quite fill all of the channel topography as the conglomerates are thicker over the channel, finally filling the wadi before overspill of the wadi margins in a wide, conglomeratic alluvial plain setting.

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Photo Credits

All photos were taken by AGS members