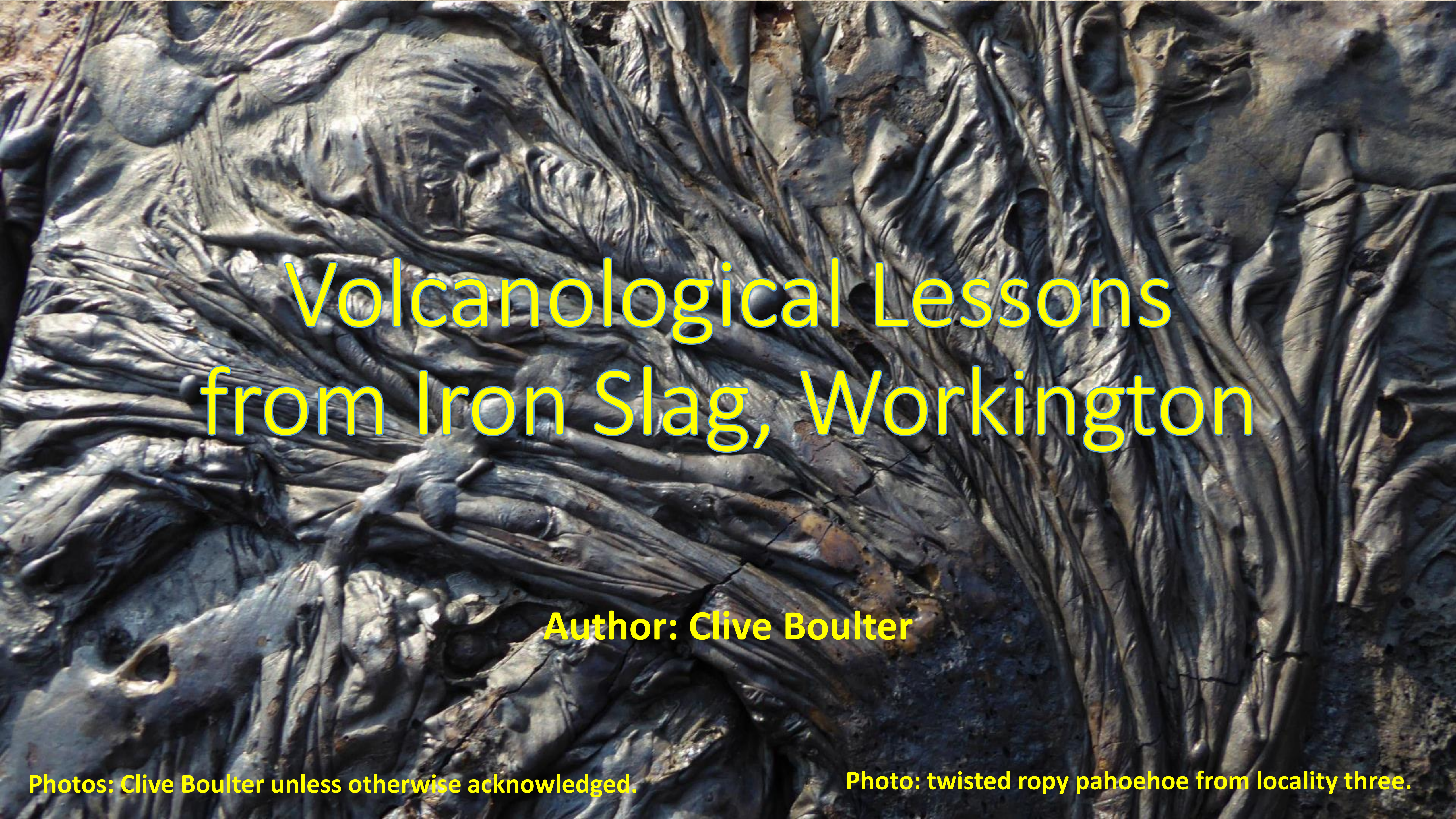
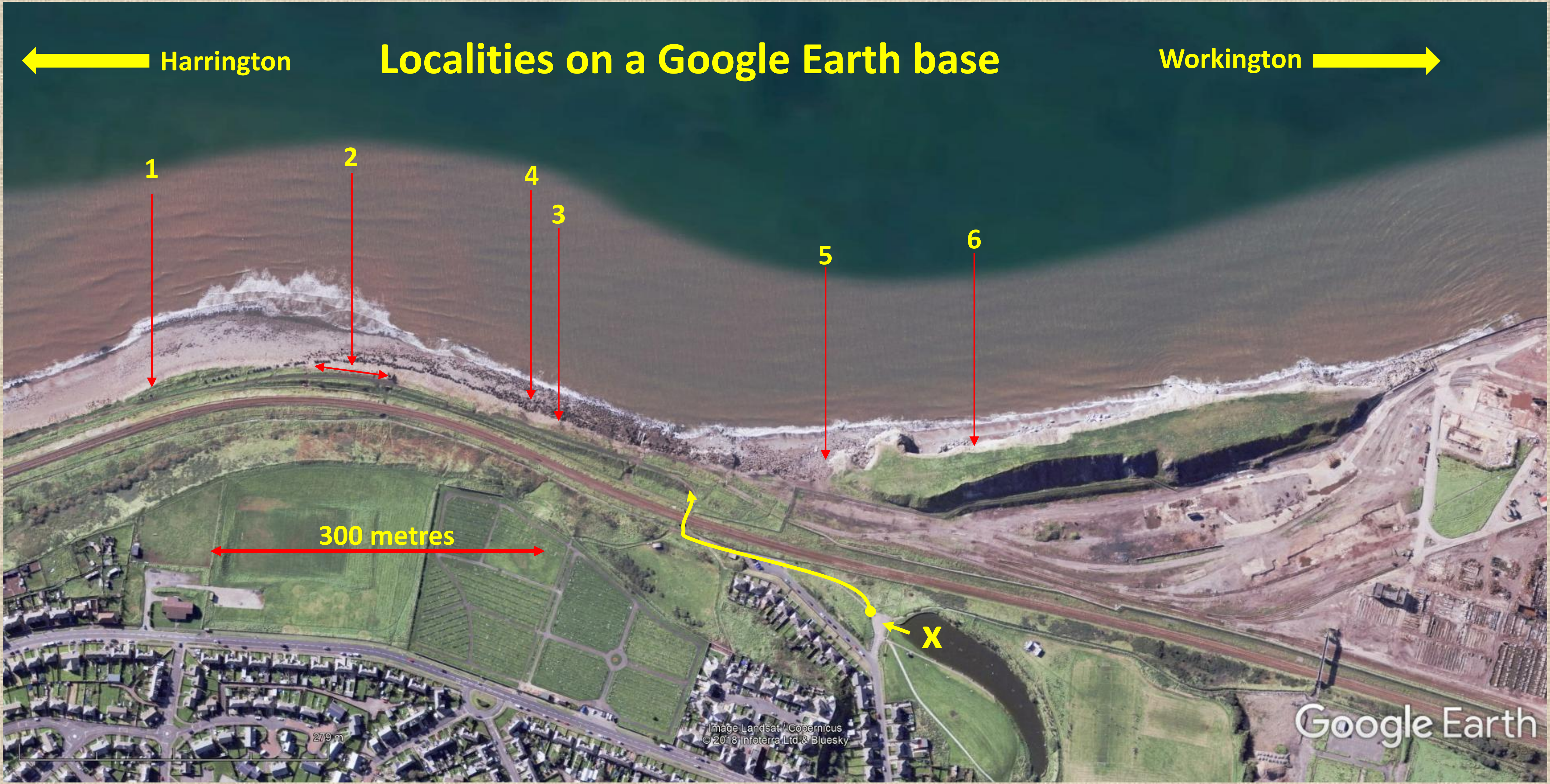
Volcanological Lessons from Iron Slag, Workington

Author: Clive Boulter

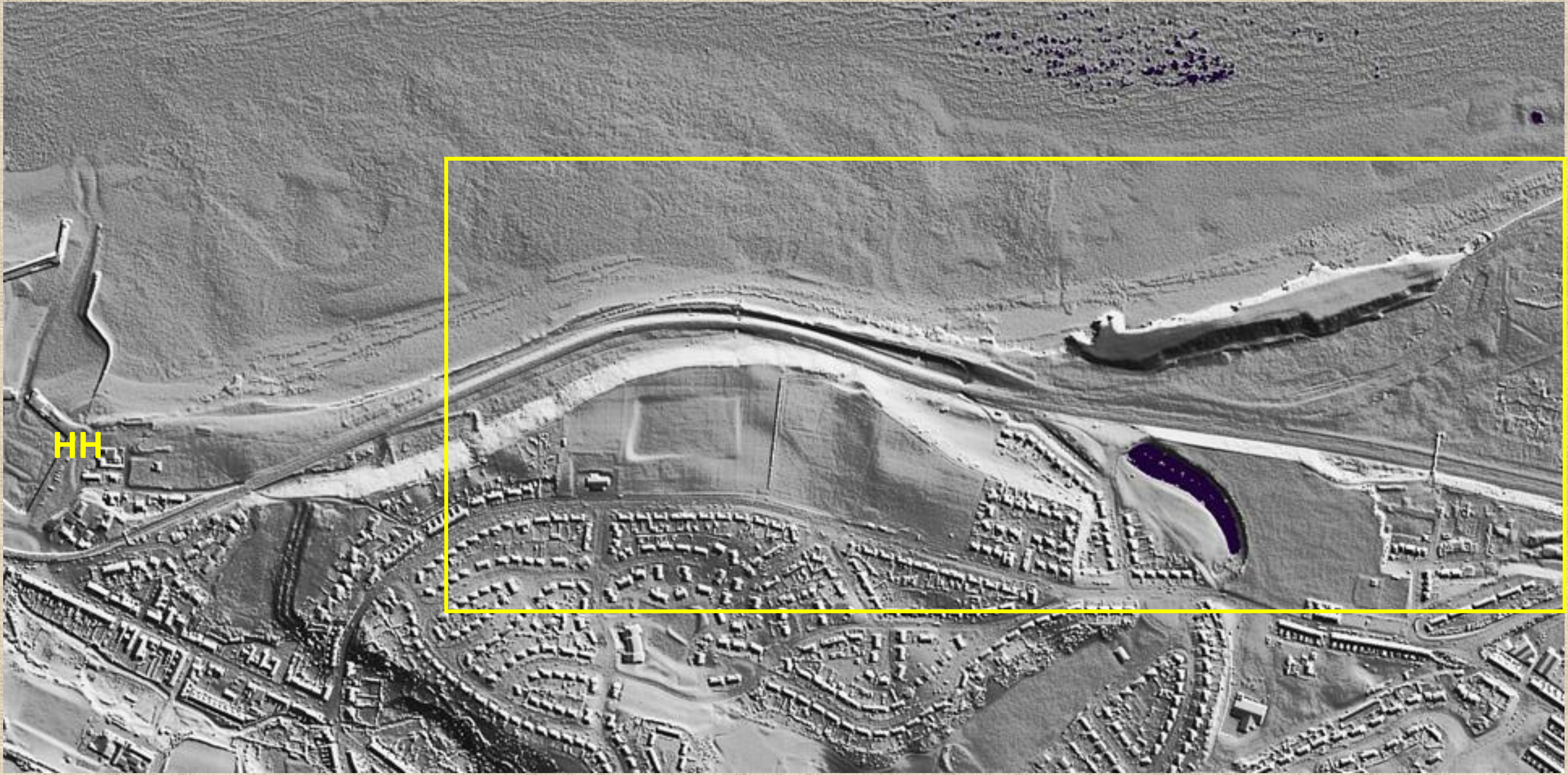


Photos: Clive Boulter unless otherwise acknowledged.

Photo: twisted ropy pahoehoe from locality three.



You can either park at Harrington Harbour [see next slide] or at X which is just off Shore Road. **Locality 6 is tide dependent and is inaccessible for an hour or so around high tide.**

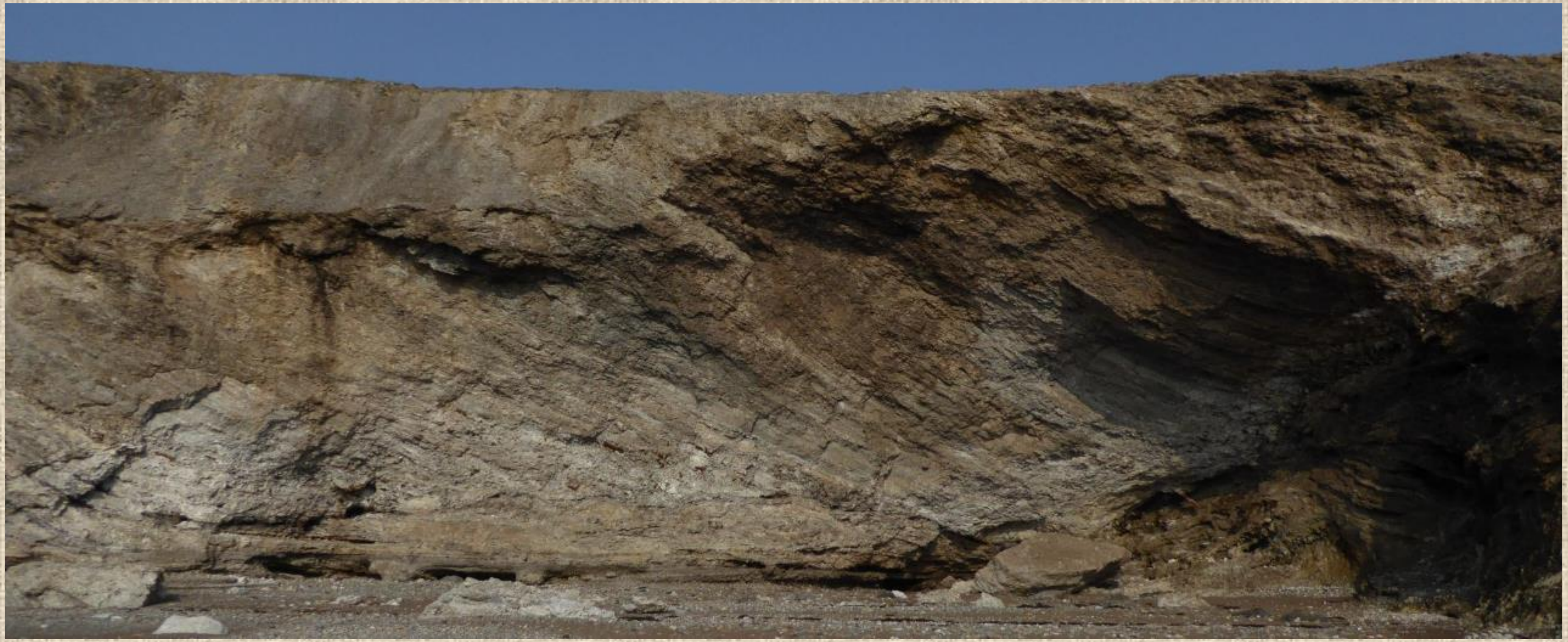


An expanded view on a LIDAR image to show the relationship between the Google Earth image on the previous slide [yellow box] and Harrington Harbour [HH].

https://houseprices.io/lab/lidar/map

Tipped slag from iron working is full of physical volcanology and studying slag has provided invaluable information for our understanding of some volcanological systems. Around the coast of Cumbria we still have many opportunities to examine this style of effusive activity though remedial operations have meant some classic sites have been lost.

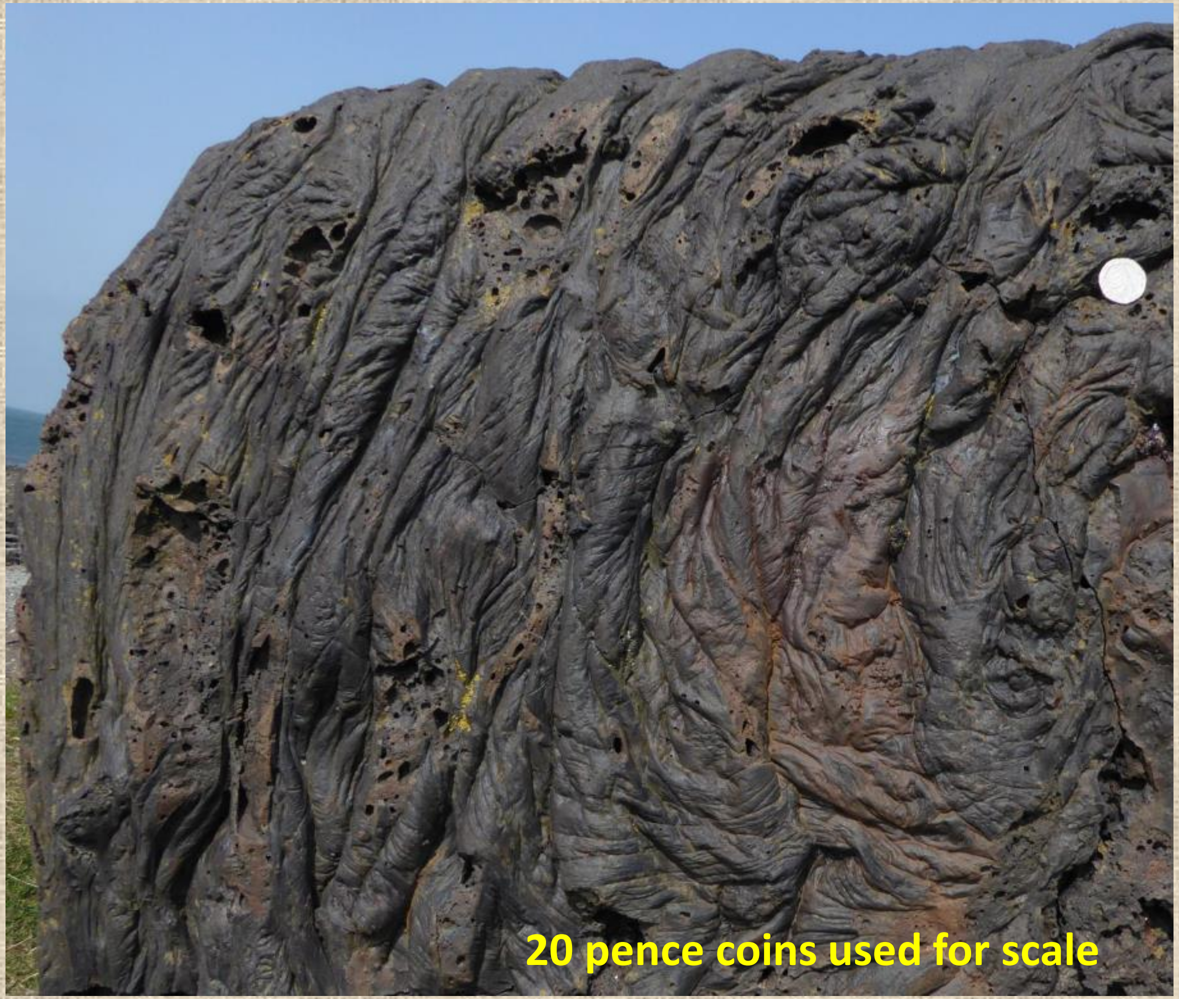
Iron oxide is reduced in a blast furnace to metallic iron. The furnace is charged with iron ore and coke, together with limestone as a flux to reduce the melting temperature. All of these are impure. Even the purest limestone has a few weight percent of impurities such as quartz, iron oxides, micas, and other minerals. Similarly rock forming minerals are present in iron ore. In the blast furnace the molten iron sinks to the bottom and the impurities float forming a silicate liquid which is equivalent to a natural magma but very different in composition. As an example of slag chemistry, samples from Corby Steel Works have around 34 wt % CaO in their chemical analyses and, as would be expected, a Ca-rich mineralogy is the result including exotic minerals in terms of igneous petrology e.g. fassaitic diopside, gehlenite-rich melilite, and oldhamite; an assemblage more common in some meteorites than Earthly materials. Most slag magmas are more akin to carbonatites than any calc-alkaline magma but there are interesting variants including Fe-rich compositions with komatiitic textures.

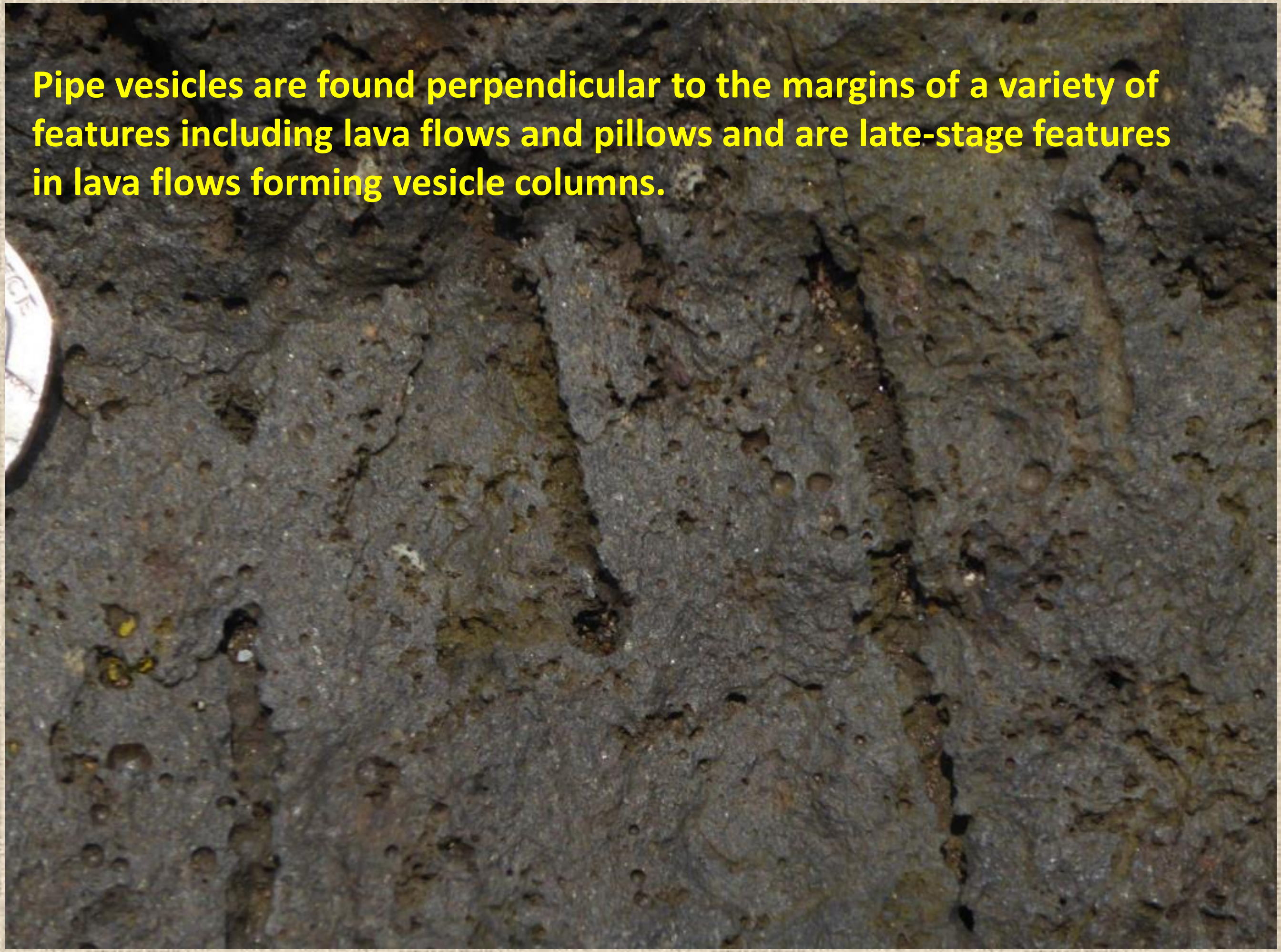


Locality 6: cross-stratification created by multiple thin pahoehoe lavas from tipped slag. Cliff height approx. 10 metres.

Locality 1 NX 98743 25915 Pipe vesicles & lava dribbles

The slag that formed this large block [skull] was poured into a railway-mounted ladle and held until it was almost all solidified before tipping. The top surface of the skull has a ropy pahoehoe surface structure indicative of a very fluidal, low viscosity, flow of liquid slag. The outer surface of the flow becomes chilled and solid but, in the case of pahoehoe, the crust is initially thin and flexible deforming into wrinkles when it is impeded but the lava beneath is still moving. The uncertainty here is when did the pahoehoe form? Was it formed whilst appreciable amounts of liquid slag were present or does it represent small amounts of still-molten slag that escaped at the time of tipping – a dribble? Dribbles are very common in slag deposits on the Cumbrian coast.





Locality 2 Traverse from NX 98707 26060 to NX 98708 26132

Here an old railway embankment has been constructed from tipped slag. In early operations only manually charged blast furnaces were used which, because of their lower temperatures, produced viscous slag that could be transported by rail in slag boxes sealed to waggon bogies by fireclay. At the slag tip, the box sides were lifted off and the solid block of slag could be tipped. Box shape evolved from octagonal through rectangular to circular. Clearly the aim was not to have too much liquid in the box at the time of tipping. The nature of the slag deposits reflects varying lengths of cooling. Advanced cooling led to abundant fractures because the slag contracted as it cooled; such materials would break into many small pieces when tipped. Shorter cooling periods with less pervasive fracturing left intact blocks known as puddings in some places and skulls in others.

A rectangular pudding with dribbles on its current top – did it flip during tipping?

A round pudding.

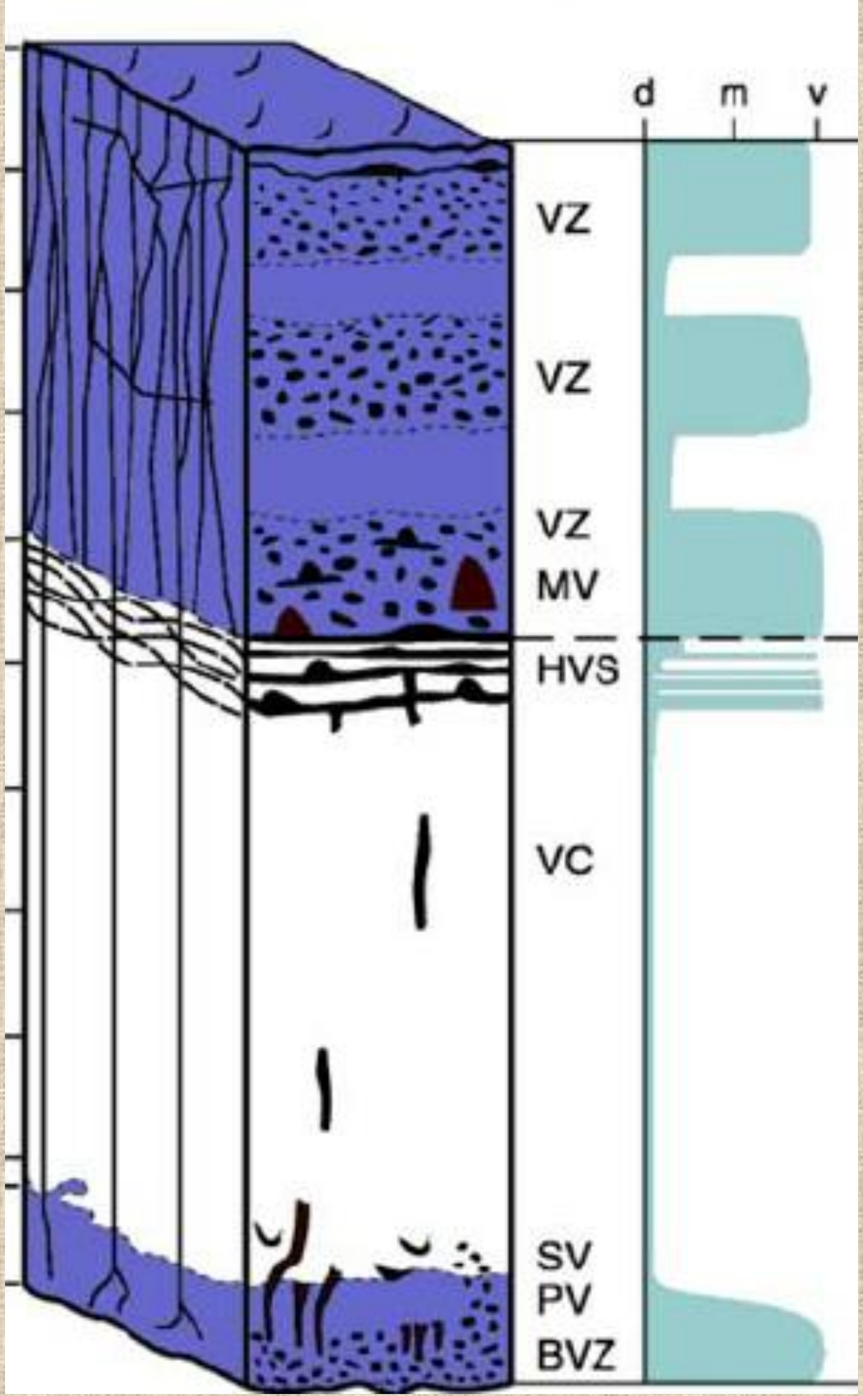
Locality 2 Traverse

A pudding which appears to have cracked open a bit on tipping. The block has not moved further since it was tipped as shown by the vertically-hanging lava stalactites on the roof of the cavity from a little residual liquid in the pudding. Up to three similar cavities are seen in a stacked sequence at the top of many large pahoehoe lava flows and they were crucial in the realisation that these enormous flows were emplaced by inflation [the SWELL hypothesis].

Stacked cavities with lava stalactites in a pahoehoe lava flow, Las Cañadas, Tenerife, demonstrating emplacement by inflation. Each time the lava flow front extends by a lobe bursting out, pressure reduction creates vesiculation and in some cases the volatiles gather together to form a gas cavity. As in lava tubes magma on the cavity roof can drip into the open space making stalactites [always wear a hard hat in a lava tube!].

Judging by the size of the cavity, this pudding seems to have arrived at the tip with quite a bit a liquid present. The cavity has a surround of vesicles and the present-day top has lava stalactites formed as the last of the liquid drained. The movement of vesicles will have been arrested at the inward-migrating solidification front and the relationships seen in various complete puddings indicate complex cooling patterns. Many puddings/skulls were formed by discrete slag pouring events at variable time intervals. Some patterns in individual "flow" events are simple and mimic what you see in lava flows but others are much more complex and will no doubt stimulate discussion on the day.

Closeup of the large cavity on the left showing lava stalactites and vesicle distribution in the encasing slag.



SWELL HYPOTHESIS

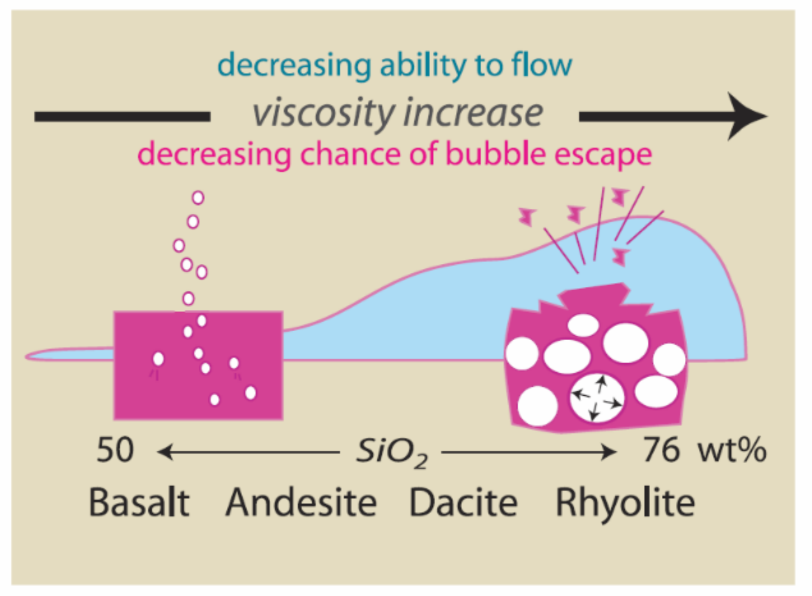
A graphic log through a typical pahoehoe sheet flow showing the Upper Crust and Basal Crust in blue. The green on the graph roughly shows degree of vesiculation. The Upper Crust will have up to three discrete vesicle zones each one created as a lobe burst out and the flow advanced – cavities can be formed by vesicle amalgamation in any or all of the zones. More zones are not generated because the distance to the flow front meant that depressurisation associated with further lobe outbursts was not sufficient to disturb the magma pressure this far into the flow. The **S**tandard **W**ay to **E**mplace **L**arge **L**avaflows [SWELL] hypothesis was developed from such data as well as from direct observations of inflating pahoehoe lava flows in modern settings [Self et al. 1998, The Importance of Pahoehoe, Ann. Rev. Earth Sci., vol. 26, pp. 81-110].

Vesicular slag at Workington. The vesicles are mainly between 5 to 10 mm.

Volatiles in Magmas

This is an important topic because the behaviour of volatiles in magmas is a critical control on eruptive mechanisms. It is not a trivial topic which is something brought home when you look at mathematical treatments of the subject. Besides complex physics, intricate chemistry is at play mainly involving the chemical species created by the volatiles reacting with magma. For example, CO_2 in silica poor magmas reacts with the melt, dissolves as carbonate groups [CO_3^{2-}], and is dependent on Ca, K, and Na, cation concentration making it far more soluble in alkaline basalt than tholeiitic basalt. In contrast CO_2 does not react with felsic magmas hence it dissolves in molecular form in rhyolite. Another major volatile, H_2O, dissolves in melts as OH^- groups when total concentrations are low and, as total H_2O increases, molecules of H_2O progressively become the dominant species. Other influences of volatiles are significant including the depolymerisation caused by H_2O in silicate melts which breaks Si-O-Si bonds and leads to marked decreases in viscosity and melting temperature. Within a silicate melt Si^{4+} shares coordination with four O ions and joins to Al^{4+} to make rings and this polymerisation can be up to 15 tetrahedral lengths [more SiO_2 more polymerisation].

Exsolving volatiles to form bubbles and vesicles is an intricate process. Exsolution should begin soon after vapour pressure exceeds confining pressure but a degree of supersaturation is required because of the energy needed to create bubbles and in a pure liquid [no tiny impurities or crystallites], where there are few bubble nucleation sites, a much greater degree of supersaturation is needed. Growth of vesicles is then controlled both by the rate at which volatiles can diffuse through the magma and by intrinsic variables such as magma density, viscosity, and surface tension. Because it is a dynamic system we have to remember that processes, like water loss from the magma, increases its viscosity and yield strength during ascent and eruption.



Despite the potential complexities some generalities hold such as bubbles can pass through basaltic magmas 100s to 1000s of times more readily than through siliceous magmas. For this reason it was once thought that ultramafic [komatiitic – see Locality 4] magmas would never preserve vesicles but some do. Vesiculation is widely developed in slag showing that bubble escape was prevented in many cases perhaps by rapid skinning over of the melt.

Miller & Wark,2008, Supervolcanoes and their Explosive Supereruptions, Elements, vol. 4, pp. 11-16.

This block of spinifex-textured slag is intermittently exposed about 20-30 metres south of locality three depending on storm frequency, etc. Walking north from locality two the natural line is along the sandy strip of beach between the tipped slag and the head of the beach. It is on the seaward side of this strip that I noticed the block shown in photos here. Bladed spinifex is well developed and random spinifex is exposed in 3D [?grown into a cavity??].

Small blocks in beach sand and gravel can readily be covered by storms so keep an eye out for good examples – see Locality 4 for other locations.

←Location 3 NX 98749 26320

A fine example of twisted ropy pahoehoe though the most impressive examples in Cumbria are to be found at the end of Askam Pier where there are flow fields of pahoehoe lava.

Askam →

At Askam it would appear that most of the slag ladles were delivered to the tipping location either totally molten or with very little solid. The pier was build up by multiple thin flows rarely thicker than ten cm. Rather than the sectional views provided by the main slag tip at Workington, Askam allows you to walk over the tops of sheets of lava poured onto nearly horizontal surfaces.

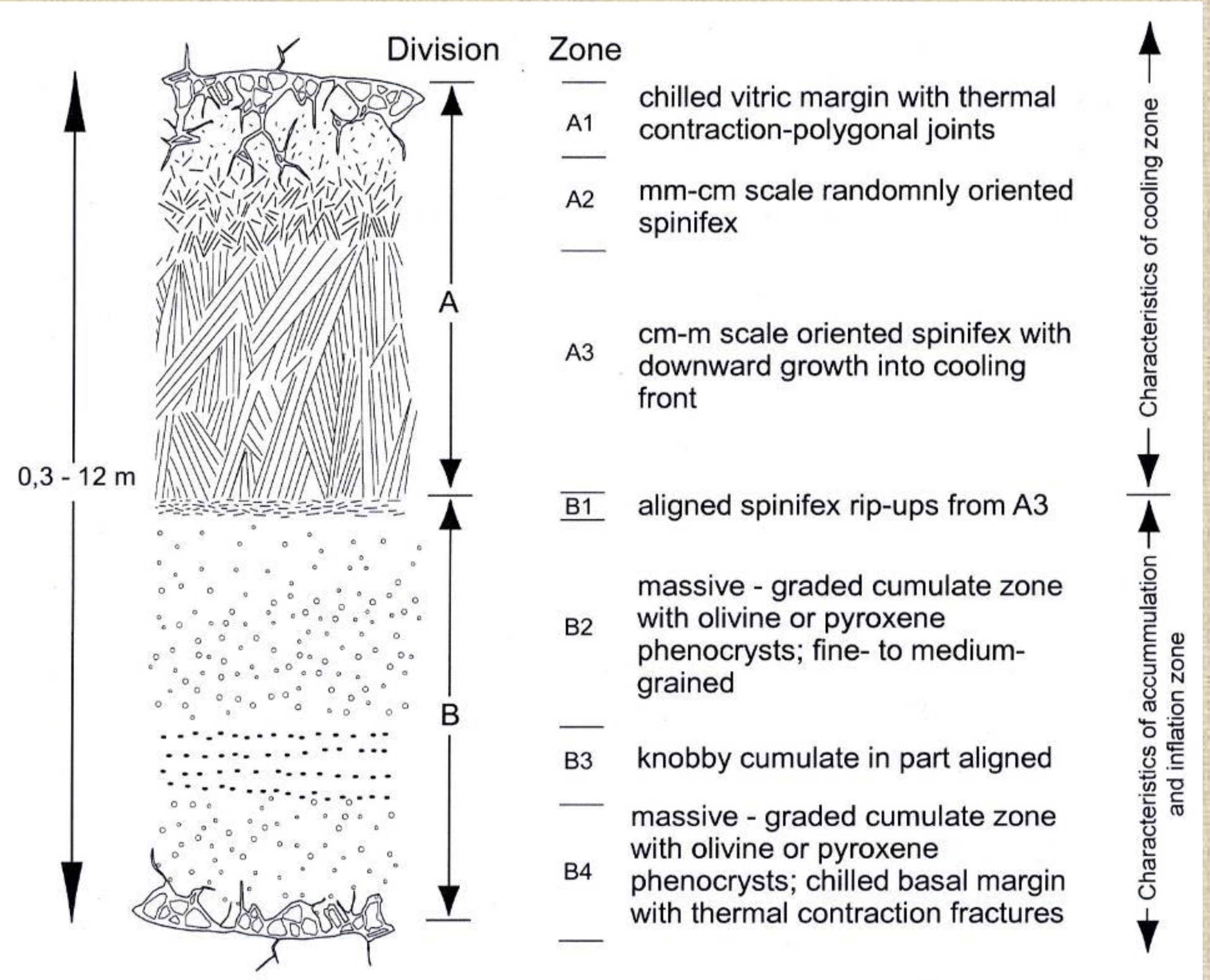
Locality 4 NX 98727 26289 Spinifex textured slag

At this locality there is a fine example of spinifex texture [bladed olivine crystals] which has rarely formed in nature since the Archaean [details in the next slide]. It is possible that it might be covered by sand following storms but if this has happened there is plenty of the same feature to be seen from NX 98715 26575 to NX 98661 26847.

Illustrated to the left is a block that is buried by sand from time to time. It is the longest set of bladed olivine crystals I have seen at Workington [the coin is 21.4 mm in diameter]. In komatiite lava flows the equivalent crystals are Mg-olivine but in the slag environment they are Fe-olivine.

Random and oriented olivine blades.

Prior to 2,500 million years ago, lavas with less silica than basalts were commonly erupted on the Earth's surface at temperatures up to 1650°C. Many of those unfamiliar with very old rocks believe that effusively erupted magmas range from silica-poor basalt to silica-rich rhyolite but, with even less silica than basalt, komatiite extends the compositional range as they have at least 18 wt % MgO in their chemical analyses ranging up to 32%. Komatiites have distinctive mineralogies and textures as shown in the diagram where blades of olivine criss-cross. This texture is named spinifex after a similar looking desert grass found in Western Australia; once thought to be the product of quenching it is now regarded as forming by rapid crystallisation in a magma with few impurities that could have acted as nucleation sites. Its presence in slag shows the crystallisation time-scale is no more than a few days and probably much less. It also shows that you have to be careful in applying grainsize alone to determine cooling rate e.g. granites versus rhyolites; factors like the abundance of crystal nucleation sites are equally important. Olivine is a very common mineral in the mantle where it is a magnesium silicate. In slag the iron silicate fayalite [Fe_2SiO_4] takes the place of forsterite [Mg_2SiO_4] because iron and magnesium are easily interchangeable in the same crystallographic lattice site. Fayalite at 4.39 g/cm^3 is much denser than the continental crust average.



A typical profile through a komatiitic lava flow [instruct.uwo.ca] but not all flows are this regular. In a slice through the rock the olivine grains appear to be needles but they are cuts through blades as can be seen if the surface is a bit irregular. Closer to basalts in composition, pyroxenitic komatiite has needles of pyroxene instead of olivine blades.

Locality 5 NX 98756 26533 Volcanic Glass

Volcanic glass is scattered all along the excursion route but this pudding gives us the chance to see the original setting that produced this chilled/quenched magma. Within lava flows cooling rates are typically around one degree Celsius per hour whereas quenching involves rates 100s to 1000s times more rapid. Slag box material commonly has glass around the pudding margins whilst in the skulls glass is mainly from the portion in contact with the ladle base. The right-hand photo shows conchoidal fracturing which is very characteristic of volcanic glass – better than steel as a cutting edge! Some glass seen on the traverse has a greenish tinge.

Locality 6 NX 98729 26664 Thin pahoehoe lava flows **[you need a hard hat to examine this locality safely]**

Very thin lava flows form most of the slag tip. Many of the flows are around 5 to 10 cm thick and have two to three internal subdivisions. The white components have pahoehoe structures on their upper surfaces which means they represent the top of these flows. Because the cliff face presents lava sections the pahoehoe top surfaces are rarely exposed but some steps in the weathered face give limited opportunities to examine the ropy structure. The blue notebook is 10.5 cm wide.

Many of the lava flows have a glassy bottom layer and a white upper layer. Some flows have a three-fold structure with a rusty [Fe-rich] layer [F] in between the white and glassy parts [G]. The pronounced topography on the white top of the central flow may have been an hornito/driblet spire where a weakness in the lava crust allows magma and volatiles to escape. The next/uppermost flow has a glassy base, an iron enriched layer, and a white top. Small fingers of the brown component penetrate upwards into the white pahoehoe part showing the linkage in time between the two.

A Miscellany of Features, the Best Examples of Which Are Covered From Time to Time by Sand

If iron is tapped along with the slag its density means it will sink to the bottom of the box/ladle and this provides a way-up criterion for puddings/skulls that have tumbled down a slag bank and partially broke up. If tapping was done at discrete intervals the patterns may be complex.

Cooling joints in puddings are geometrically related to cooling surfaces. Many puddings are so heavily jointed that they broke into a myriad of fragments upon tipping. Others develop crude columnar cooling joints.

PJBs & Similar Features.

The relationship between the margins of rock fragments and cooling joints provides crucial volcanological information.

In the **top left photo** the pale fragment has crude radial cooling joints at high angles to the block margins [**prismatic jointed block**]. This shows it was the magma that was responsible for the explosivity in this [accretionary-lapilli bearing] ignimbrite – Caldera del Rey, Tenerife.

Top right is a lava ball that detached itself from a lava flow on the steep slopes of Teide, Tenerife, and at some time has split open. The crude radial joints show it was hot whilst the snowball shape was being moulded as it rolled downhill.

To the right is a cracked open skull from Workington and again it has a good radial pattern of cooling joints.

Blisters approx. one centimetre in size on a slag lava flow surface.