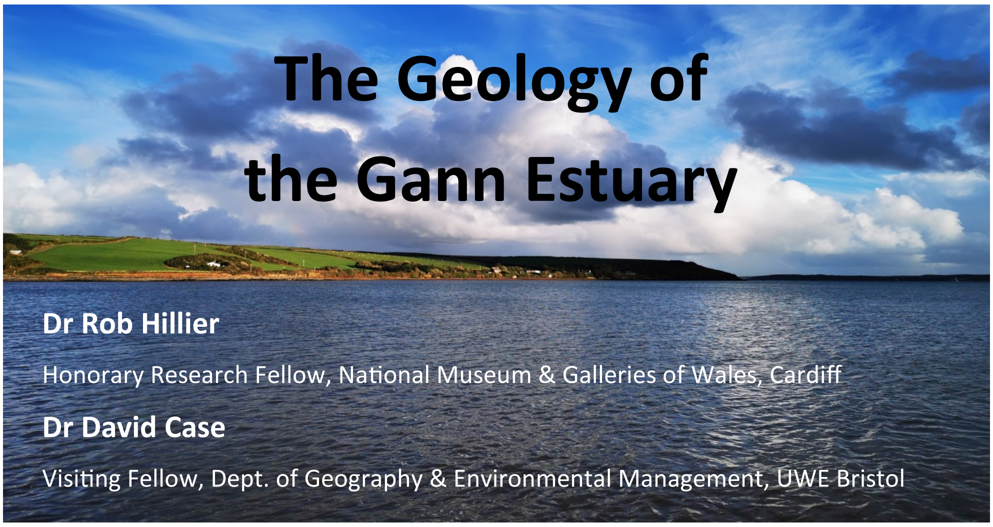

The Geology of the Gann Estuary

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Terra firma, the ground beneath our feet. We take it for granted in terms of its stability, endurance and longevity. However, over geological time (thousands to millions of years), processes operating at a variety of scales ensure that change is the mantra, with the rocks and softer surficial sediments that underlay the Gann Estuary and Dale Roads preserving significant environment, sea – level and climatic shifts throughout its geological history through to the very recent. Its record is a microcosm of Pembrokeshire's geological past, a heritage that has helped create an international recognised framework of geological building blocks, and to this day still unearths unprecedented treasures.

The rock cycle

On the Earth's surface, on land or beneath the sea, rocks are broken down by weathering (e.g. by temperature change or the effects of acid rain) often creating a thin veneer of soil, or are worn away by the action of erosion through the work of wind, water and ice. Sediment (gravel, sand, silt and clay) liberated by erosion is moved or transported. The mechanisms operating during this process are important for geologists, as they leave a fingerprint that is preserved as the sediment comes to rest from transportation by water (in rivers, lakes and the sea), by ice (often by glaciers) or by wind (everybody will know what it feels like to be sandblasted on the beach on a windy day!). This fingerprint may be in the form of a sedimentary structure (e.g. cross – bedding created by the movement of sand dunes in an estuary, or ripple marks moulded by waves on a beach). Also incorporated may be the evidence of former life, commonly the fossils of hard body parts such as shells or bones. Often preserved in large numbers are trace fossils, which record the former activity of plants, animals or as we will see, fungi. These may be the structure of burrows, trackways or roots. Geologists use all of this evidence to work out how the sediment was transported and deposited, and in which environment (e.g. a river, beach or deep sea) and importantly, under what climate conditions (cold, hot, wet or dry). Over time, the build – up, and subsequent burial of sediment layers (or beds) creates significant pressure, and the precipitation of minerals from groundwater eventually leads to cementation of the sediment and subsequent lithification.

This is the process of **sedimentary rock** creation, turning mud into mudstone, sand into sandstone, and gravel and pebbles into conglomerate. **Metamorphic rocks** are created when pre-existing rocks are changed by significant heat and or pressure. This often leads to deformation of original rock structures, the creation of new fabrics and the growth of new minerals. **Igneous rocks** are formed when molten rock (either magma within the earth, or lava at its surface) cools and finally solidifies. The rocks and surficial sediment at the Gann Estuary preserve all aspects of this, the rock cycle, and much more!

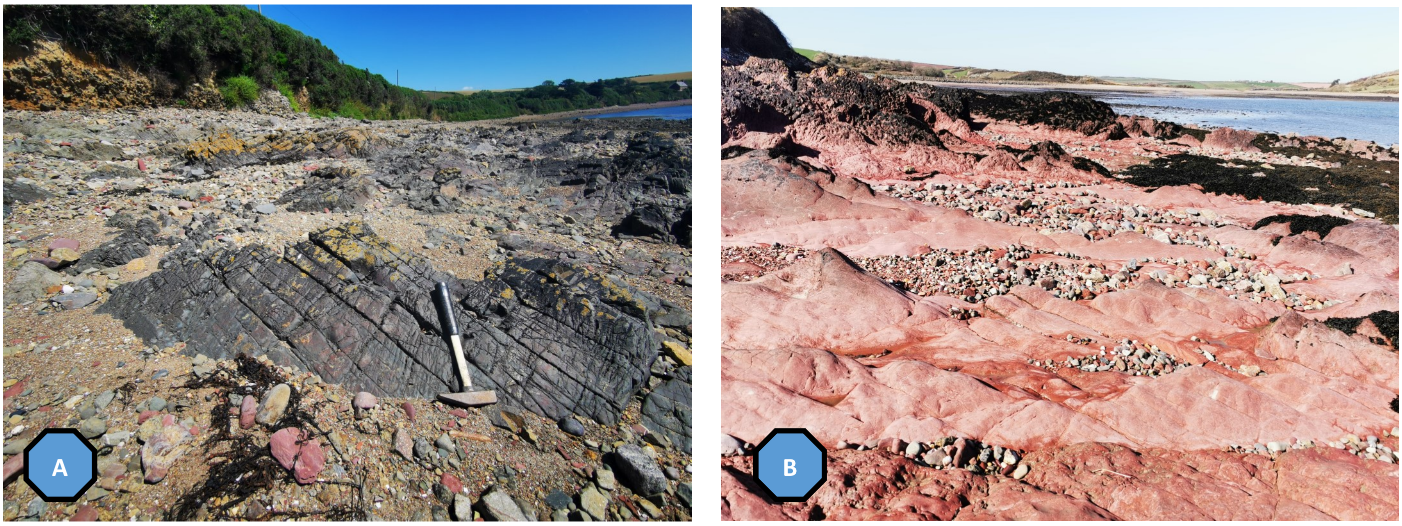

Figure 1. A). Shore platform on northeastern side of the estuary exposing igneous lava flows of the Skomer Volcanic Group. The cliff line exposes more recent Quaternary deposits that contain evidence that the sediments were deposited under extreme cold climate conditions during the Last Glacial Period.

B). Shore platform on the southern side of the estuary with view towards Pickleridge beach. The red rocks comprise mudstones of the Old Red Sandstone that were deposited in a dryland environment subject to tropical wet and dry seasons. The mudstones preserve evidence of tropical rivers and soils as well as containing fossils of the animals and plants that existed during Silurian times.

The layers of time

Before we look at the rocks, just a note on the geological timescale and the concept of stratigraphy. Geologists arrange the array of rock types they observe using a hierarchical structure starting with individual beds or layers (that may be of centimetre or metre thickness), scaling up to formations of similar beds (of tens or possibly hundreds of metres thick) which they can map from place to place. Formations are in turn arranged into groups (usually hundreds of metres or even kilometres thick), which usually preserve features that may have been common over time and influenced the formation of beds and formations. Beds, formations and groups are each given a name, conventionally linked to the place where they were first observed or where they are currently best exposed or developed. Geologists use radiometric dates from isotopes in minerals held within igneous rocks or ash falls to work out an absolute date of when the rock was created. This is a bit like a chemical ticking clock that starts as soon as the minerals are created; the clocks tick for a very long time however, and record dates since creation measured usually in millions of years before present (Ma). More recent sediments are dated using radiocarbon methods, the carbon present in fossils and other materials. Fossils are also used to provide relative dates, by comparing similarities or differences between formations for example to say which formation is older or younger. These, and features observed within the rocks such as colour, or sedimentary structures are used to link or correlate rocks from place to place, a process that usually brings more certainty when making interpretations of for example the environment or climate under which the sediments were originally deposited.

Geologists have used these concepts of stratigraphy to identify a series of distinct time periods in which to group rocks. The rocks at the Gann Estuary were created during the Palaeozoic era (between 448 and 416 Ma), with a large time - gap in the preserved record before deposition of sediments in the Quaternary Period which started 2. 6 Ma. The mud, sand and gravel that comprises the shifting bed of the current estuary is part of the Holocene Epoch (that began 11. 7 thousand years before present, BP), but some geologists now suggest the Holocene has ended, and we have entered the Anthropocene Epoch characterised by the impacts of humans (e.g. microplastics in beach sediments and human – induced extinction). The large time gap seen at the Gann Estuary doesn't mean that nothing interesting was happening here, just that nothing is preserved. The large breaks in time create geological surfaces known as unconformities in the rock record. These may have multiple causes, such as folding or faulting of the rocks or significant changes in sea – level and /or climate.

Evidence of a drifting, deforming and shaking past

Over this vast expanse of geological time, the earth's surface has not remained static. The continents and plates in which they reside are constantly on the move albeit at small speeds and rates. The oldest rocks at Dale were deposited during late Ordovician to early Silurian times when the plate that contained southern Britain was in sub – tropical latitudes south of the equator. Naturally, sediments deposited at this time preserve evidence of the climate of these latitudes. Since then, the UK has steadily migrated northwards, initially through equatorial climates (associated with deposition of the Carboniferous Coal Measures in tropical rainforest deltas, for example at Broad Haven). We are currently moving away from North America at a rate similar to the growth of our fingernails, a process linked to the extension of the Atlantic Ocean. As the plates move, they jostle with each other and significant pressures build up leading to deformation of the earth's crust usually at the plate margins. Such deformation takes the form of tears or faults in the crust, which enable rocks on either side of the fault planes to move past each other. The Gann Estuary and Dale Roads have three significant fault planes running through them, each trending roughly west - east (Dunne 1983).   The most significant is the Ritec Fault that runs from Westdale Bay through to Dale, then onwards to Pembroke and Tenby (Fig. 2).

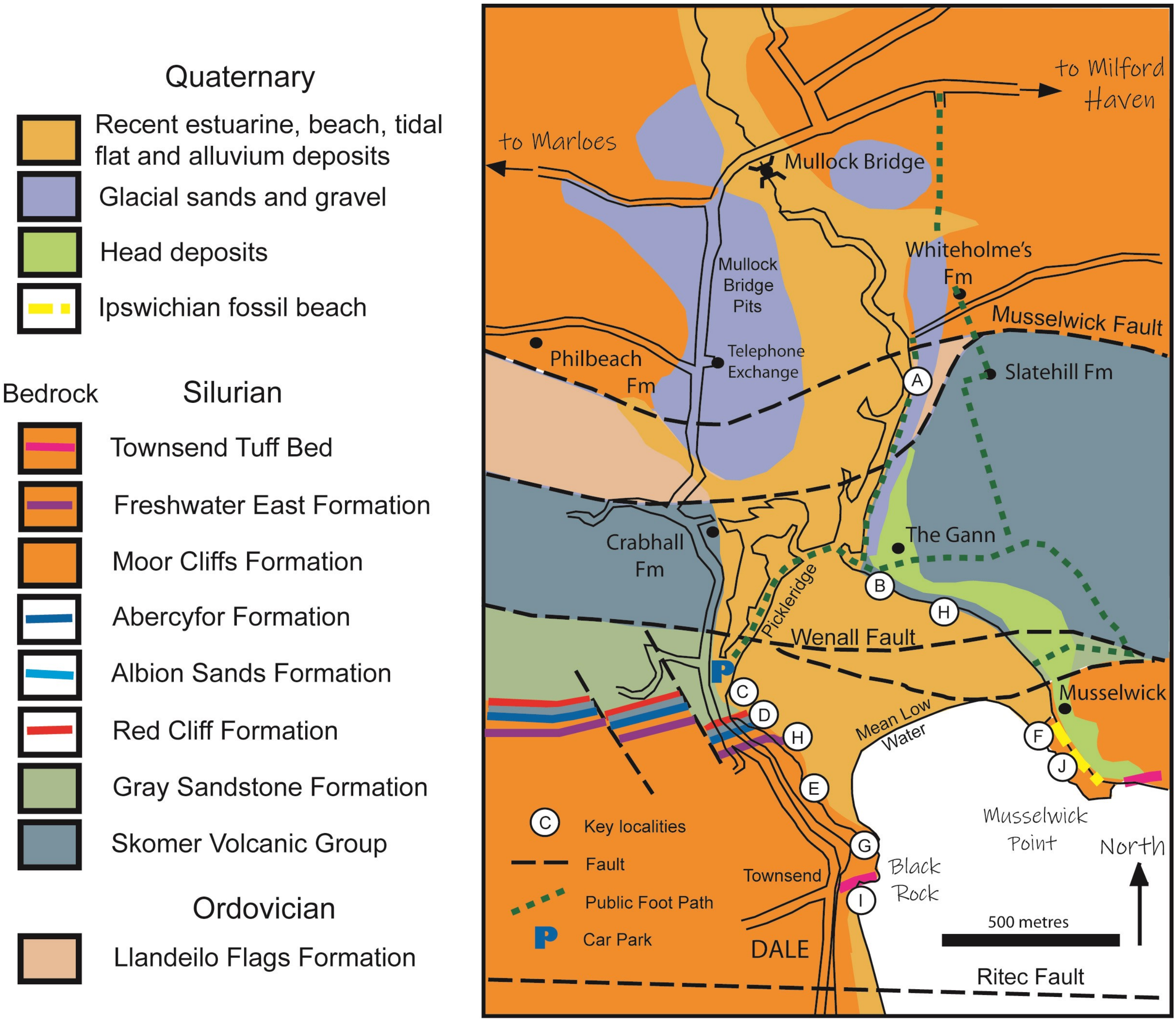

Figure 2. Geological Map of the Gann Estuary and Dale Roads modified after BGS (1978).

Rocks have been moved along the Ritec Fault repeatedly through geological time, and there are displacements of several kilometres of rocks on both sides of it. It influenced sedimentation significantly during the Palaeozoic era. As the displacements occurred, rocks close to the fault plane would have become broken up and deformed. Over time these weakened rocks would have been more susceptible to erosion, and the Westdale valley and wider Milford Haven owe their origins to the relative ease of erosion compared to rocks further away from the fault plane. The Wenall Fault is more localised, running from Musselwick on the eastern shore of the estuary, continuing westward beneath Pickleridge onto the Airfield (Fig. 2). The closely associated Musselwick Fault trends from St Ishmael's to Slatehill and Philbeach Farms then northwestward beneath Marloes and onto Musselwick Sands. These faults have all had a part to play in influencing the preserved geology at the Gann Estuary. During times of significant fault movement in the geological past, rocks in between the fault planes have been deformed, most noticeably into large scale folds that tilted the originally near horizontal strata into upward and downward closing anticlines and synclines respectively.

The Marloes peninsula is underlain by the northwest to southeast trending Marloes – Lindsway Anticline that was formed during significant plate collision (the Variscan Orogeny) during the Late Palaeozoic. The rocks in the Gann Estuary are on the southern flank of this fold, with the oldest in the north, progressively becoming younger southwards towards the mouth of the estuary. The fault and fold related deformation also led to numerous small – scale faults that are commonly observed, together with the creation of a cleavage as the rocks were subject to low grade metamorphism (see below).

Although the UK generally is not considered to have frequent earthquakes, one of its largest recorded events took place on August 18th 1892 when a magnitude 5.1 earthquake had its epicentre close to Pembroke, most likely associated with the Ritec Fault. Detailed records reveal small shocks, and "rumbling noises" in the run up to the principal earthquake in the early hours of August 18th (Davison 1897). There were hundreds of records of shocks, lasting up to 20 seconds at Cresselly. A murmuring sound resembling that of sea waves was heard at Lamphey, changing to a deep, short thunder-like boom continuing after the shock for several seconds. A tsunami was generated in Milford Haven, being felt by the engineer of a steamboat at Langwm: *"The water, although perfectly calm before, became suddenly swelled as with a heavy breeze. The boat seemed as if passing over a swell, and then another, and then another*". The waves lasted for between 15 to 20 seconds, being felt elsewhere as far away as the Scilly Isles. The quake had effects on local groundwater levels up to eight weeks afterwards, with springs at Marloes running dry in the upper parts of the village, and overflowing in the lower reaches. Significant aftershocks were felt across the area, with one of note at Dale on August 18th.

The following sections describe each of the major rock and sediment units observed at the Gann Estuary, together with a brief summary of how geologists have interpreted their formation.

The Ordovician Llandeilo Flags Formation (c. 451 to 467 Ma). The oldest rocks exposed at the Gann Estuary comprise grey and yellow silt- and mudstones with some thin volcanic ash layers. They are poorly exposed, and best seen below Slatehill Farm at the eastern edge of the estuary (Fig.2, Locality A). These sediments were deposited beneath shallow seas that covered much of Wales, becoming deeper in central Wales in an area known as the Welsh Basin. There is good evidence that major faults controlled the transition from shallow into deeper water at this time, and the Ritec and other faults formed the southwestern splay of a line of faults that extend through Carmarthenshire northeastward into the Welsh Borders. The Llandeilo Flags Formation at the Gann Estuary have yielded wonderful specimens of the trilobite *Trinucleus* (Fig. 3; Cantrill et al. 1916). Trilobites are an extinct group of marine arthropods having a hinged exoskeleton with a segmented body, and paired, jointed legs. Modern arthropods include lobsters, crabs and millipedes.

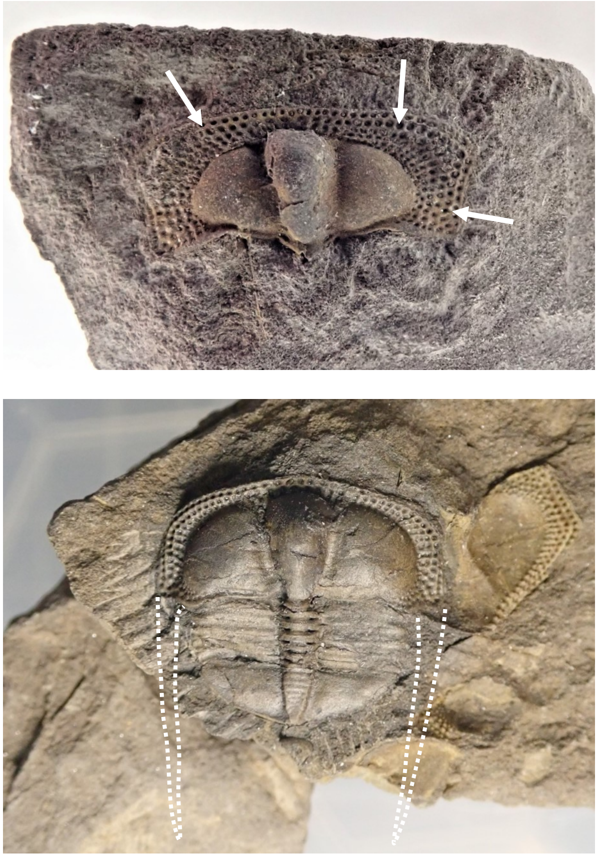

Figure 3. Specimens of *Trinucleus* courtesy of Dr. R Owens. Note series of fringe pits on periphery of the head (arrowed), segmented body, and position of genal spines

Trilobites evolved complex eyes, being one of the earliest of all well – developed sensory systems. What's remarkable about *Trinucleus* though is that it did not possess eyes (it was blind), and this is likely due to its life habit. Trace fossils inferred to have been made by *Trinucleus* show that they made shallow plough – like burrows in the muddy sediment that they lived in (Fortey & Owens 1999). This soupy environment had much suspended mud with little visibility potential; it is likely that the ancestor of *Trinucleus* evolved to capitalise on life in this harsh environment. The head of *Trinucleus* is fringed by a series of pits; geologists have speculated that these may have had a sensory function possibly to detect current direction, food sources or acting as a filter system linked to feeding habit. Well – preserved specimens also have very long genal spines that extend backwards from the head well beyond its body (Fig. 3).

These may have acted as supports to the body as it rested on the muddy sea floor (a bit like a snow shoe), and also have acted in a protective role against predators. On an historical note, the eminent Welsh naturalist Edward Lhwyd illustrated a *Trinucleus* along with the trilobite *Ogygiocarella* (as 'flat fish'), both from the Llandeilo area, in correspondence with Martin Lister in August 1698. These were the first illustrations of trilobites to be published anywhere in the world.

The Skomer Volcanic Group (c. 440 Ma) is of Llandovery (Silurian) age, and is best exposed in the rock platform at high-tide mark on the eastern side of the estuary (Fig. 2 Locality B). Here are found grey volcanic lava flows (metafelsites). These are speckled with large white feldspar crystals, a feature known as a porphyritic texture (Fig. 4). This tells us something about how the igneous rock was formed, as the feldspar crystals originally developed

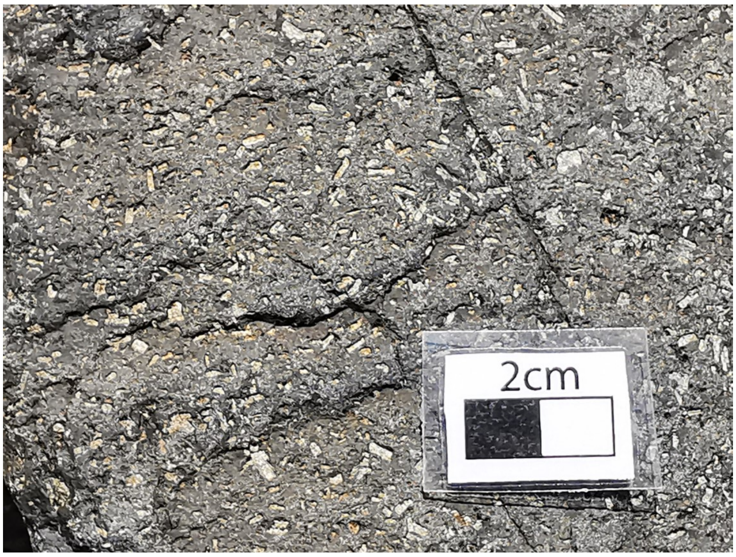

Figure 4. White feldspar crystals set in porphyritic lava flow of the Skomer Volcanic Group.

within the magma chamber of a volcano that was most likely centred to the west of Skomer Island (Fig. 6a; Ziegler et al. 1969). Feldspar crystals grew as the liquid magma began to cool in the magma chamber beneath the volcano. The volcano erupted however before other minerals could crystallise from the melt; the molten rock was erupted to the earth's surface, forming flows of molten lava that were shed away from the volcanic centre. Lava flows are also well – preserved at Skomer Island, Wooltack Point, and Marloes Sands.

Figure 5. Onion skin or spheroidal weathering at top of Skomer Volcanic Group lava flow; Locality B, Fig. 2. Note grey core stone and red spheroids. Lens cap 8 cm wide.

The lava flows cooled quickly when they were exposed at the Earth's surface, too quickly for the formation of any other large crystals. As a result, the grey "groundmass" that surrounds the feldspar crystals in the metafelsites contains minute crystals that are only visible under the microscope. We know that the lava flows were erupted at the earth's surface as the tops of the flows preserve evidence that they were weathered by the atmosphere. At the Gann Estuary, there is very well – developed spheroidal or "onion skin" weathering phenomena observed (Fig. 5). Here weathering of the lava flow tops loosened and fragmented them into ball – shaped grey "core-stones" with successions of red and buff coloured concentric saprolite layers several mm thick. These superficially resemble the inside of a sliced onion, hence the name. These features may preserve important evidence about Silurian weathering processes and are subject to ongoing studies.

The Gray Sandstone Formation (c. 430 Ma). The Wenlock (Silurian) age Gray Sandstone Formation is sporadically exposed only at low tide in the rock platform immediately south of Pickleridge (Locality C, Fig. 2), and also in a very few small exposures on the eastern side of the Gann Estuary. It contains thin beds of buff coloured sandstone and grey mudstones. The interval is very well exposed at Marloes Sands and to the north of Gateholm Island. Here it has been demonstrated to be the deposits of an extensive tropical delta system that covered southern Pembrokeshire some 430 Ma (Hillier & Morrissey 2010). Large-scale tidal channels are preserved that drained a landmass to the south and west opening into deeper marine environments to the northeast in the Welsh Basin (Fig. 6a). In this tide – influenced setting, lots of small ripples are preserved in sandstones that reflect working by tidal currents. Thin mudstone layers and beds were deposited at slack tide during periods of reduced tidal current activity. The tidal channels and its associated mudflats preserve a range of trace fossils including *Arenicolites* which is a U – shaped burrow identical in form to those produced by modern Arenicola lugworms at the Gann Estuary.

The Old Red Sandstone (ORS) comprises the deposits of rivers and floodplains forming the red cliffs on both sides of the Gann Estuary. Despite the name, here they are mainly mudstones of late Silurian age and document an extremely important episode in the earth's history as they preserve the record of early life on land. This process of "terrestrialisation" occurred when Wales was in subtropical latitudes south of the equator (Hillier & Williams 2006). We can infer this from the style of preserved deposits (see below), with additional important evidence coming from frequently observed "fossil" soils called calcretes within the ORS (Allen 1986). Calcretes contain nodules of white or pink, spherical or rod shaped calcium carbonate nodules (Fig. 7a) that grew at shallow depths (tens of centimetres) below the Earth's surface, sometimes within burrows created by animals, or cracks that were present in the soil at the time. Modern calcretes form in tropical soils where the climate is warm, with well – defined wet and dry seasons. The ORS is red as iron present within it was oxidised at the earth's surface at the time of deposition. The environment would have appeared alien to us. Despite the tropical climate, there were no trees, shrubs or grass (none of these had evolved yet); the land plants were very small and comprised "Lilliputian forests" at the margins of rivers and floodplain ponds. The largest organisms were probably fungi, and rocks in south Pembrokeshire contain an internationally significant record of early land plants and trace-making animals, mainly arthropods (millipedes, extinct scorpion – like hexapods and eurypterids; Morrissey et al. 2012).

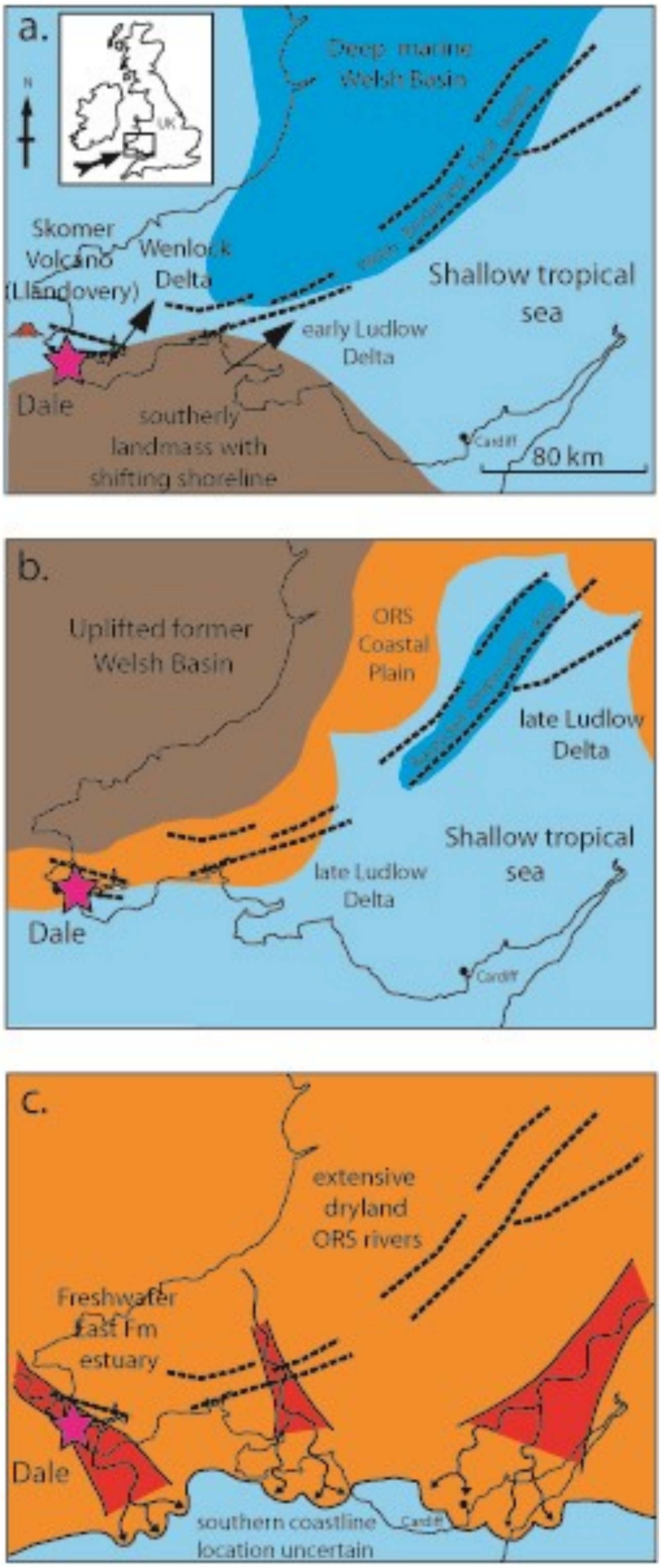

Figure 6. Simplified palaeogeography maps of southern Wales during a). Llandovery to early Ludlow times with deep marine areas of the Welsh Basin; b). Late Ludlow times when the Welsh Basin was uplifted, shedding ORS rivers and sediment southwards; c). Pridoli age ORS valleys (in red) including that containing the Freshwater East Formation at the Gann Estuary. Modified after Hillier et al. 2019.

The Silurian was the first episode in Earth's history when there was significant amounts of mud on land, and it is believed that the primitive vegetation cover promoted the generation and the preservation of mud (Davies & Gibling 2010), since lithified as mudstone which is easily observed at the Gann Estuary. The ORS here is broken down into a number of formations, each containing subtle differences that reveal the evolution of terrestrial environments in the Silurian (Allen & Williams 1978; Barclay et al. 2015).

The Red Cliff Formation (c. 427 Ma) is the oldest preserved ORS in Wales, and is named after Red Cliff at the southern end of Marloes Sands where it is well exposed. At the Gann Estuary, it is best seen at low tide below the sea wall on the southern side of the estuary (Locality D, Fig. 2). It is dominated by mudstones with calcretes, and is thought to represent deposits of the river channels that fed the delta in the Gray Sandstone Formation (Hillier & Williams 2004). Chemical analysis of small white mica minerals has shown that they originated far to the north, possibly from Scotland, and were transported in rivers during the early Ludlow some 426 Ma to become deposited in southern Pembrokeshire.

The Albion Sands Formation (c. 426 Ma) is well – exposed at the southern end of the seawall (Locality D Fig. 2), and is named after Albion Sands beach where it is best exposed. At the Gann Estuary, it is made up mainly of pale grey coarse-grained pebbly sandstones that were deposited in a high energy, but shallow river channels that frequently dried out because of the seasonal rainfall and climate (Hillier & Williams 2004). The granules and pebbles that make up the sandstones have rounded edges, (Fig. 7b) indicating they have been eroded during transportation, with any sharp edges being knocked off and smoothed as the pebbles jostled with each other, and bounced or rolled along the river bed that transported them. The sand and pebbles were shaped into large dunes in the river channel, and cross – bedding preserved (Fig. 7c) shows us that the river flowed roughly from west to east, ending up at a delta that fed into the sea at Llandeilo (Fig. 6a; Hillier et al. 2011). It was likely that the river valley was bounded by active faults in the Silurian, and gravels were shed off the valley sides into the river at Gateholm and at Lindsway Bay.

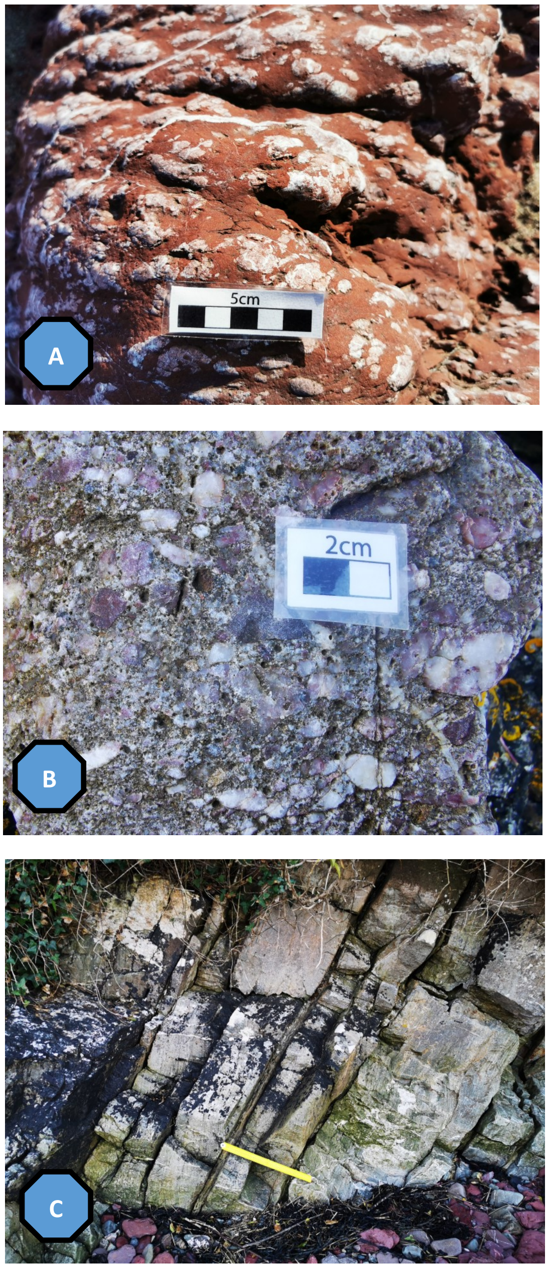

Figure 7. A) White calcrete nodules in ORS mudstone. B). Pebbles in Albion Sands Formation, moulded into dunes preserved in pebbly sandstones and conglomerate (C), scale bar 25 cm.

The Abercyfor Formation (c. 425 Ma) is a thin but significant deposit exposed at the southern end of the sea wall at the Gann Estuary (Locality D, Fig. 2). It is a couple of metres thick, and is made up of red gritty sandstone and thin red mudstones (Fig. 8). This layer can be traced from Gateholm in the west through into Carmarthenshire in the east. It is significant as it records a regional change in the position of land and sea at the time. Prior to its deposition, the land was to the south and west of Pembrokeshire, with the Welsh Basin sea to the north and east (Fig. 6a). Regional faulting pushed up the former Welsh Basin area so that it became subaerial, and the land surface then tilted to the southeast. This meant that rivers that deposited the ORS then flowed from to northwest to the southeast (Fig. 6b). The Abercyfor Formation is believed to have been the first gritty sediments that were shed across this tilted surface (Hillier et al. 2019).

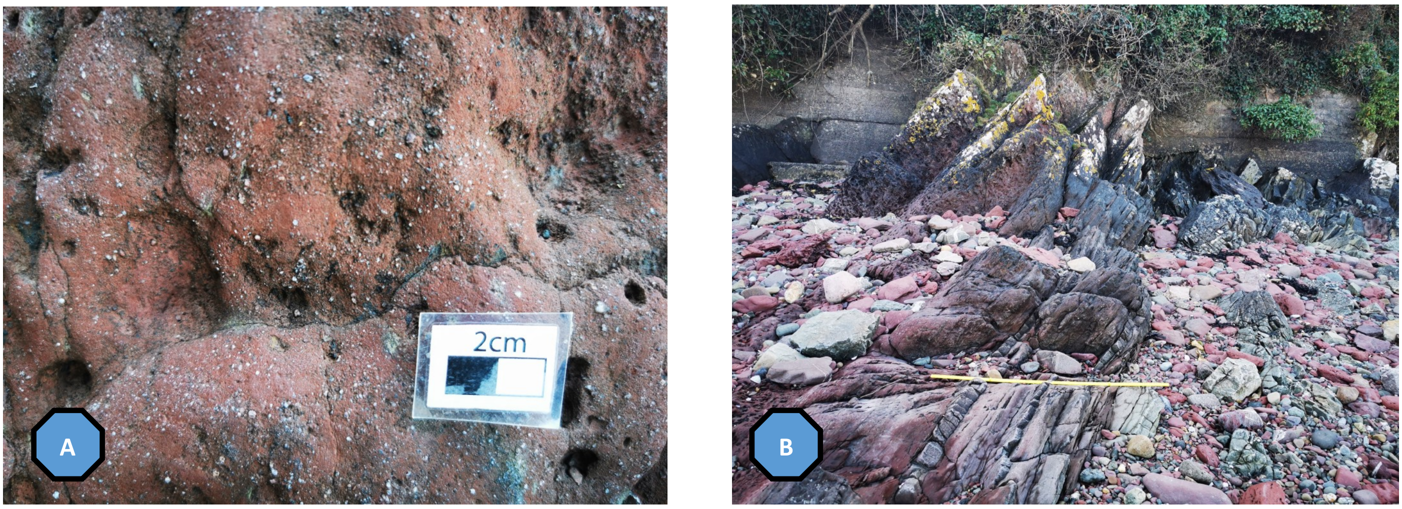

Figure 8. Abercyfor Fprmation at end of sea wall, Locality D (Fig. 2). A). Gritty mud rich sandstones rich in angular white vein quartz fragments and volcanic clast debris that are typical of the Formation across the region. B). Beds of Abercyfor Formation overlying Albion Sands Formation (to right) and underlying Moor Cliffs Formation (to left). Scale bar of 1 m.

The Moor Cliffs Formation (c. 425 to 419 Ma) makes up the majority of the ORS that is well exposed in the low cliffs and wave cut platform on both sides of the estuary (Localities E,F,G and J Fig. 2). It is dominated by mudstones and calcretes. Some of the fossil soils contain structures believed to represent fossil roots (Fig. 9A). Their discovery is an enigma, as their size is deemed too big for the plants fossils that are preserved at the time. Instead, it is believed they represent the rooting structures of the giant fungus like fossil *Prototaxites* that grew up to several metres tall (Hillier et al. 2008). The rivers were shallow, muddy, and frequently dried out (Williams & Hillier 2004; Marriott & Hillier 2014). Evidence for this comes from commonly seen desiccation cracks, structures that develop in muds when they shrink due to water evaporation (Fig 9B). Some of the rivers had a pebbly sand channel fill. Good examples of these with large scale cross – bedding can be seen at Black Rock (Locality G Fig. 2; Fig. 9C). Some of these cross – bedded dune sets were contorted soon after deposition either by very high discharge and sedimentation rates, or possibly by seismic shaking generating “quicksand” within the channels (Fig. 9D).

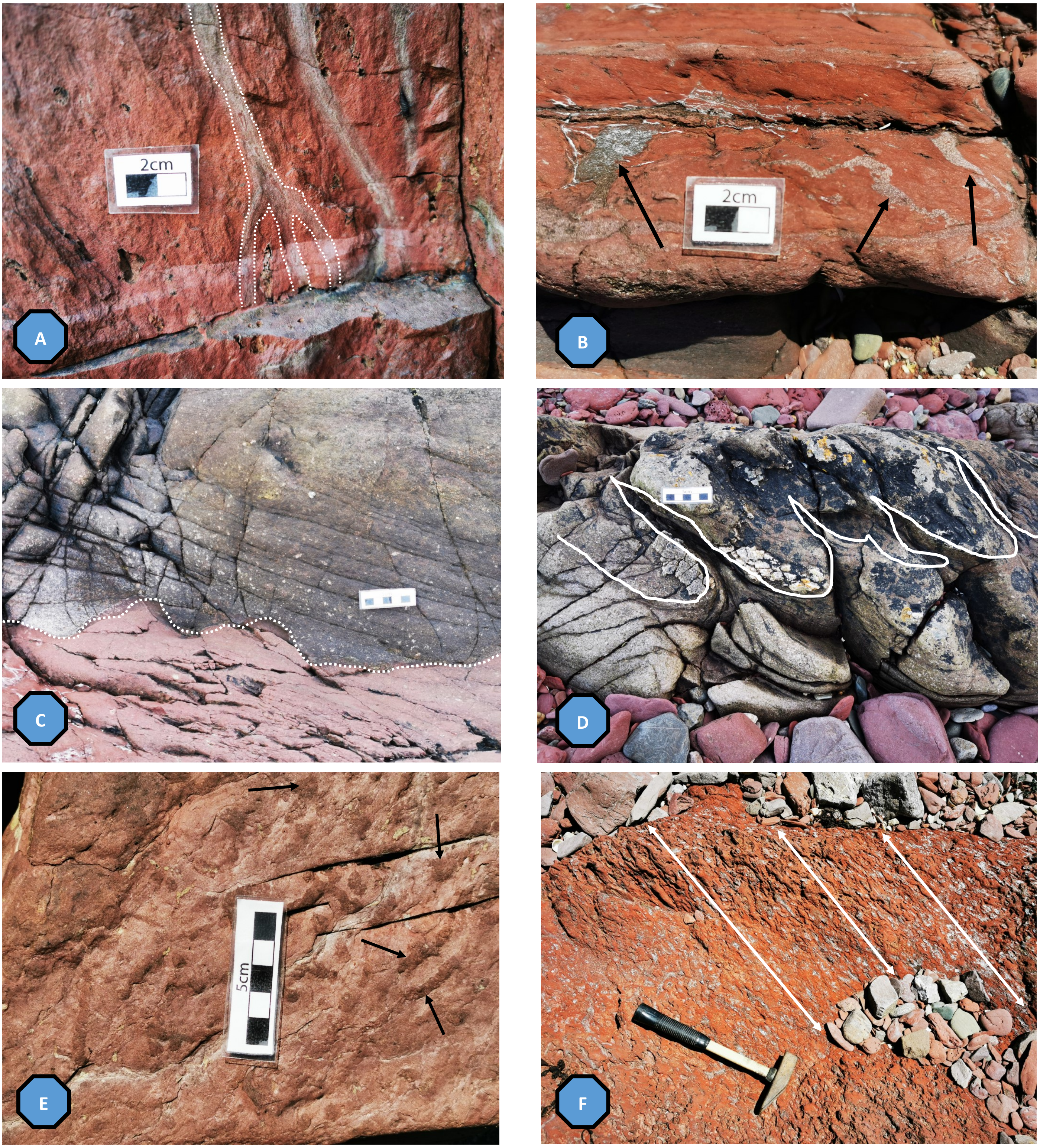

Figure 9. Moor Cliffs Formation. A). Rooting structures exhibiting downward bifurcations. B). Sandstone filled desiccation cracks in cross section (arrowed). C). Pebbly sandstone cross—bedding created by migrating subaqueous sand dunes within a dryland river channel, the base of which is highlighted (scale of 5 cm). D). Sandstone bed with well—developed convolute lamination (highlighted) formed by instability soon after the sand was deposited in the ORS river channel (scale of 5 cm). E). Numerous *Beaconites* burrows (arrowed) in mudstone, with sections cut both across and along the burrow fill. They were most likely produced by small arthropods. F). Cleavage planes (highlighted) developed in mudstone. The pale grey calcrete nodules have been deformed as part of cleavage development, and now are aligned to be sub-parallel to the cleavage orientation.

To the sides of the rivers were shallow lakes or “billabongs” that would have provided temporary refuges for animals during the dry season. The formation contains a range of trace fossils including diverse arthropod trackways and burrows (Fig. 9 E; Morrissey et al. 2012).

As well as the sedimentary rocks present, the Moor Cliffs Formation is a good place to look at aspects of low-grade metamorphism associated with the formation of the Marloes – Lindsway Anticline. When the rocks were buried to depths of a few kms during the Palaeozoic, they were subject to elevated heat and pressure. There were significant stresses operating, and a combination of these as well as large-scale movements along the Ritec, Wenall and Musselwick Faults deformed the once near flat lying sediments into large-scale folds, a bit like rucks in a carpet. It has been estimated that the rocks in southern Pembrokeshire were compressed by over 30% during this process. On a small scale, clay minerals that were present within the rock were rotated, and new clay minerals also grew at right angles to the main stress orientation. This created a parallel fabric within the rock, which today enable it to be split along so called cleavage planes. These appear as closely spaced lines/ surfaces within the rocks at high angles to the bedding planes (Fig. 9F). This is the same process that generated the world famous slates within Cambrian age rocks of North Wales that were split for use as roofing tiles. The deformation and cleavage at the Gann Estuary is both a blessing and a curse. The folding and faulting has enabled a range of geological formations to be exposed today over quite a short geographic distance. The cost of the deformation, and in particular the cleavage is that many small-scale features that might otherwise have been preserved have been lost.

The Freshwater East Formation (c. 420 Ma) is exposed on the southern side of the estuary at Locality H, and is recognised by its grey/green colouration within the otherwise red ORS (Fig. 10A). It was deposited in a Silurian estuary that ran from Gateholm, through Dale to Freshwater West and onto Freshwater East where its mouth into the contemporaneous sea lay (Fig 6C; Hillier et al. 2019). At the Gann Estuary, its green mudstones preserve fossil spores called *Chelinospora* (Fig. 10B). These derived from very small vascular land plants that had evolved at the time (such as Rhyniophytes) that were only a few centimetres tall and lacked substantial rooting structures. Vascular plants, the majority of modern terrestrial plants such as ferns and flowering types contain a water conducting system which transfers the water from the root around the plant. This system was one of several significant evolutionary breakthroughs that plants acquired as they colonised the land. Well preserved coalified fossils (e.g. *Cooksonia*) are found in this formation at Freshwater East (Edwards 1979). Also at Freshwater East are both body and trace fossils of fish, and eurypterid “sea scorpions” that were the largest predators at the time. At the Gann Estuary, cross – bedded sandstones in this formation have very thin layers of mudstone preserved at the toes of the dune (Fig. 10C). These were deposited from tidal waters at the time that the dune was active in the estuarine tidal channels.

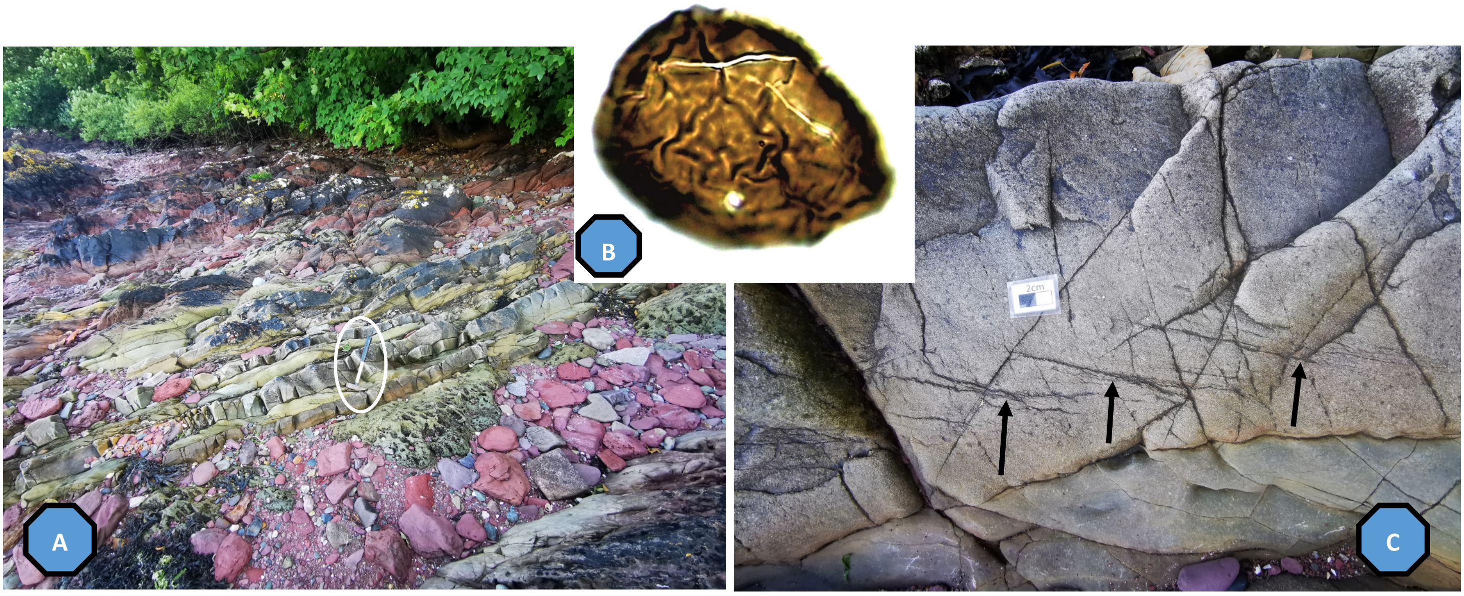

Figure 10. A). Green/grey Freshwater East Formation (hammer for scale). B). *Chelinospora lavidensis* fossil spore from the Freshwater East Formation; it is 43 microns in diameter (0.043 mm). For comparison, human hair is approximately 70 microns wide. Image courtesy of Professor Ken Higgs. C). Cross—bedded sandstone with thin mudstone draped foresets (arrowed).

The Townsend Tuff Bed is a 4.12 metres thick layer of three volcanic ash falls that were deposited across southern Britain at the end of the Silurian (Allen & Williams 1981). It is exposed at Townsend (Dale) at the mouth of the Gann Estuary (Fig. 11A; Locality I Fig.2). The ash may be thought of as a Silurian Pompeii, as when it lay to rest it preserved evidence of animals that lived at the time, mainly in the form of trackways and burrow openings (Marriott et al. 2009). Of note is the preservation of small ovoid structures believed to be arthropod faecal pellets on the surface of some ash layers (Fig. 11B).

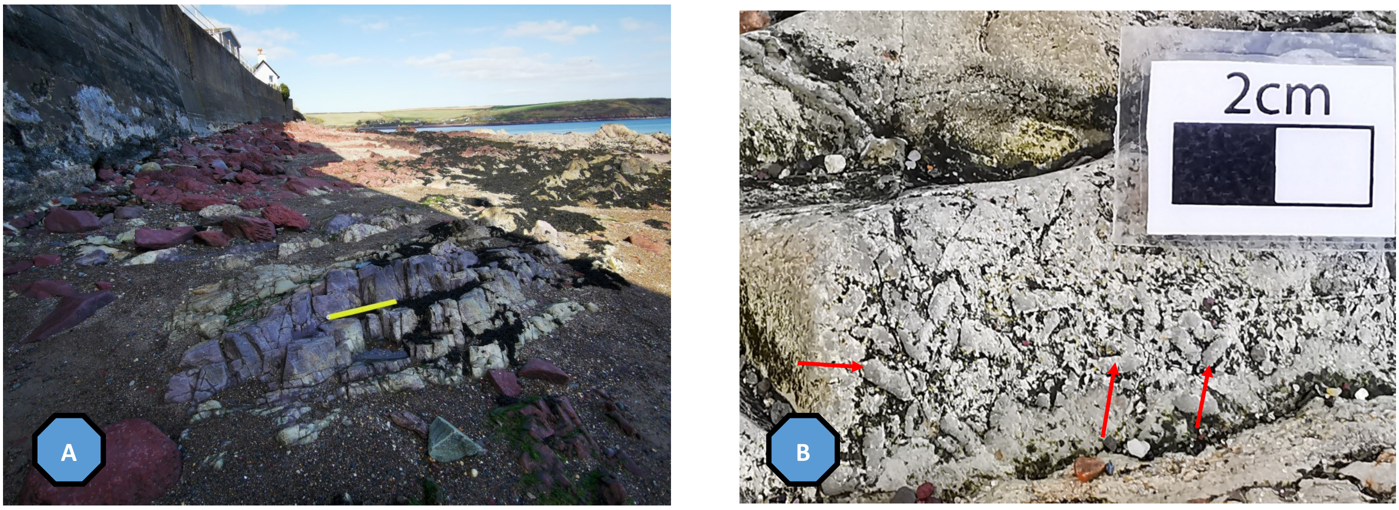

Figure 11. A). Magenta coloured Townsend Tuff Bed exposed below the sea wall at Townsend (scale bar 50 cm). B). Surface of Townsend Tuff Bed with preserved ovoid arthropod faecal pellets (arrowed).

Quaternary Period (2.6 Ma to present day)

Characterised by many climate oscillations between cold glacials (times of large global ice volume), and warmer interglacials (times of reduced global ice volume) the Quaternary Period has been one of significant change in global environments. It is also the period during which much of human evolution took place.

The oldest Quaternary landform in the Dale area is a shore platform which is cut into the Silurian and early Devonian rock succession and is ubiquitous around the coast (Fig 12). It approximates to current sea – level, but is tectonically deformed and so locally can be higher or lower than current sea – level, and is often hidden beneath the modern beach. It is age indeterminate, almost certainly the product of repeated episodes of interglacial high sea – level marine erosion during the Quaternary and possibly during the Neogene. Although there is evidence from Somerset and North Devon of glaciation that must have covered Wales about 620,000 BP and/or 430,000 BP (see for example Andrews et al. 1984; Campbell et al. 1999), locally evidence has been lost to erosion during subsequent events.

Figure 12. A & B). Quaternary shore platform (white stipple) eroded into Silurian Moor Cliffs Formation, Locality J Fig. 2. Ipswichian fossil beach deposits comprising well—rounded pebbles and cobbles directly overlie the seaward dipping shore platform. These deposits in turn are overlain by periglacial head deposits, the base of which is indicated with yellow stipple. Note poorly sorted head deposits, with large blocks of angular ORS clasts. Scale bar of 25cm in A), 5cm in B).

The oldest Quaternary deposit around Dale and the Gann Estuary is a fossil beach that sits on the shore platform at or just above current sea – level. Depending upon the state of erosion or deposition of the modern beach, it is occasionally visible at Marloes Sands but is well exposed in the low coastal cliffs at Musselwick Point. The deposits of this fossil beach contain rounded pebbles and cobbles that sit on the gentle seaward sloping shore platform (Fig. 12). These were smoothed and rounded by the continuous erosion associated with waves and tidal currents in the same way that can be observed on the modern Pickleridge beach. The fossil beach is extensive around the open coast of the Severn Estuary and has been dated to about 122,000 BP (Bowen et al. 1985). This represents the last warm interglacial period (the Ipswichian Interglacial), when climatic conditions would have been as warm if not warmer than today, and sea – level would have been comparable to or higher than today.

Approximately 115,000 BP the climate began to cool marking the start of the Devensian glacial period, which lasted until about 11,700 BP. Although the climate during the Devensian would have been colder than today, the most extensive ice sheet growth did not occur until the Late Devensian, an episode referred to as the Devensian Last Glacial Maximum (26,000 BP to 21,000 BP). Dale was not totally overrun by ice at this time. Analysis of clast lithologies and provenance demonstrate that ice from Central and North Wales was held back by Mynydd Preseli. Only ice from Scotland and the Lake District moving down the Irish Sea reached the Dale Peninsula, pushing a few km inland along its western coastline (Fig. 13). Glacial deposits from this ice, referred to as till, crop out in the Dale village valley, on the plateau surfaces immediately north and south of Dale, to the west of Marloes and around Talbenny (British Geological Survey 1978), but there are no clear exposures. The Irish Sea till is more easily seen along the coast to the north of St Davids (see for example Hiemstra et al. 2005; Hambrey et al. 2001).

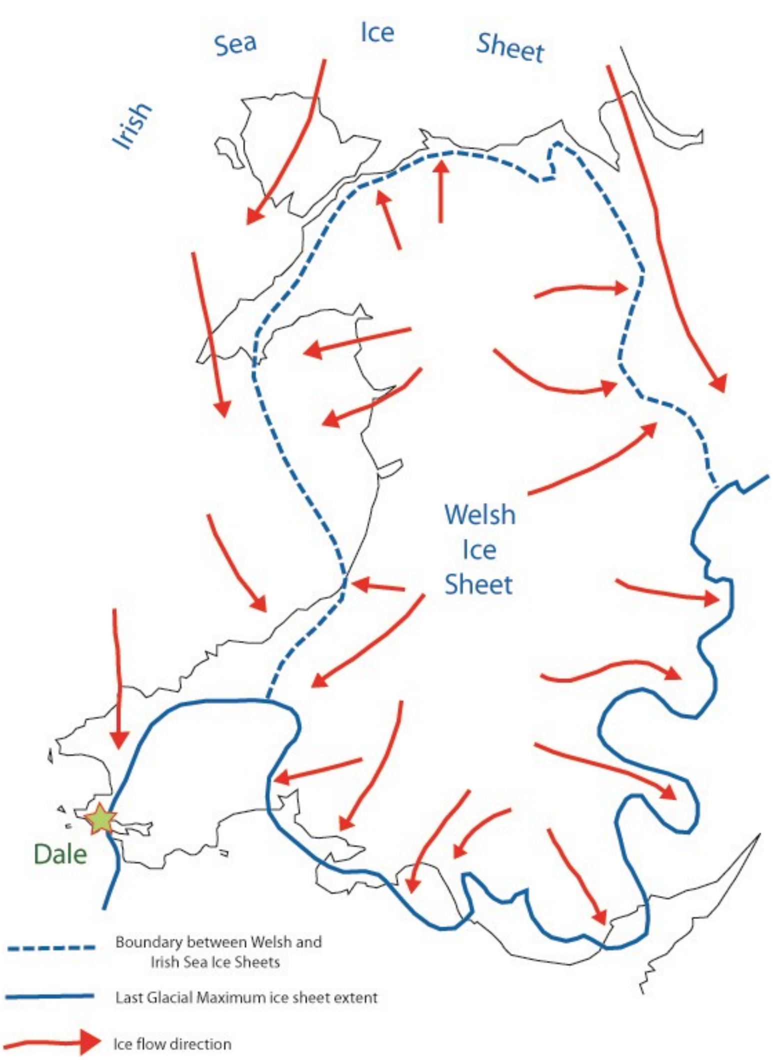

Figure 13. Schematic development of Welsh and Irish Sea Ice Sheets. Note Dale lay close to the edge of the Last Glacial Maximum ice sheet advance, with North Pembrokeshire and the western edge of the Marloes peninsula being overrun by Irish Sea Ice. Based on Campbell & Bowen (1989)

At the time of the Devensian Last Glacial Maximum sea – level would have been about 105 m lower than today due to huge volumes of water being locked up globally on the land as ice. Meltwater draining from the ice front would have cut valleys to this low sea – level, for example the southerly running valley from St Bride's into the Gann Estuary, and the easterly running Dale village valley.

Beyond the ice sheet limit a periglacial environment would have prevailed, characterised by extreme cold, periodic aridity, permafrost and frost shattering of exposed bedrock (French 2007). The surface 1 or 2 metres of the permafrost would have thawed during the summer, the resulting disturbance to and saturation of sediment enabling the process of solifluction, the mobilising of wet sediment under gravity, which around Dale generated flows downslope to the valley bottoms or onto the coastal shore platforms. The resulting deposits, called head deposits, are characterised by angular clasts generally of local lithologies exhibiting a downslope geometry and fabric and set in a fine matrix of varying sand–silt–clay proportions (Figures 12 and 14).

Head deposits are ubiquitous around the coast. At the back of Westdale Bay they exhibit clear alignment with valley side slopes, and there are also extensive exposures around the entrance to the Gann Estuary where locally head can be seen overlying the Ipswichian fossil beach. The downslope movement of the head also deformed the surface layer of underlying bedrock, with downslope creep and rotation of shattered rock being observed. The head deposits would have extended well into the centre of the present day Gann Estuary. The Dale outcrops are complex as in addition to local head there are also diamicts, a non – genetic term for a poorly sorted boulder to gravel sediment set in a sand-silt-clay matrix. Within the Dale context the diamicts could have originated as glacigenic deposits (till) subsequently reworked by solifluction.

Meltwater from the ice would have carried sediment away from the ice front particularly at the time when deglaciation commenced. Evidence for this can be seen around the Gann Estuary with deposits of fluvio-glacial sands and gravels overlying the head and diamict. At Mullock Bridge, extensive workings of this sand and gravel took place during the last century with much of the aggregate used to construct the runways of Dale airfield. These workings exploited a kame delta sequence on the western side of the Gann Estuary, formed as large volumes of sand and gravel were transported southward through the valley by meltwater rivers (John 1972, George 1982).

Figure 14. A). Periglacial head deposits overlying ORS Moor Cliffs Formation bedrock, Locality I Fig. 2. Note overturned beds of ORS deformed by downslope creep of head sheet highlighted in yellow; scale bar 0.5 m. B). Spoil of fluvio-glacial sand and gravel exposed in path close to Telephone Exchange. C). Cryoturbation phenomena developed in fluvioglacial sands, gravel and head deposits Locality F, Fig. 2.

These fed into a lake that was contained within the lower reaches of the valley which was probably ice dammed to the south. The gravel pit workings have now been landscaped with no in situ exposure of the former delta visible, although spoil of the sand and gravel that it contained is visible in paths close to the Telephone Exchange (Fig. 14B).

Quaternary exposures around Dale are all capped by a brown/buff silty loam which has the characteristics of loess, a wind – blown silt, locally containing thin beds and lenses of well sorted fine sand, coversand. Loess and coversand are aeolian sediments, deflated from the meltwater sediments deposited around the front of the ice sheet. A particularly good exposure of loess is found at the back of Marloes Sands, elsewhere the silty nature of the loess has been diluted by mixing with other sediments through cryoturbation, colluviation and later soil formation (Fig. 15).

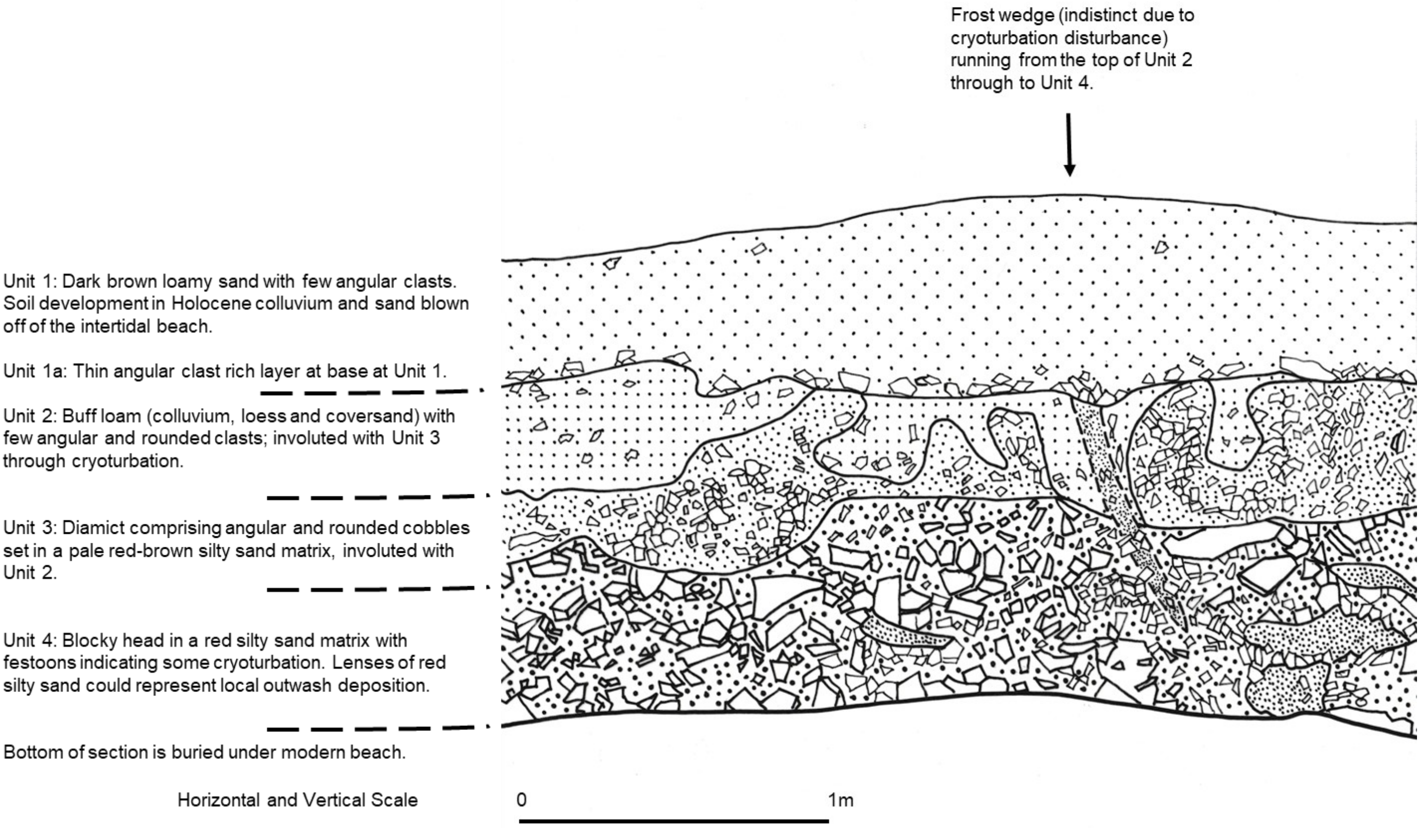

Figure 15. Simplified schematic sketch of the drift sequence to the south east of the Gann Estuary between Localities B and F.

The drift cliff exhibits a range of diamicts, head, fluvial, colluvial and aeolian deposits (loess and coversand), but individual bed and structure clarity (e.g.frost wedges) have been diluted by cryoturbation. Along the full drift section from The Gann to Musselwick there is considerable variation in the total thickness of drift (<0.5 m to 5m), sedimentary characteristics and geometry of the beds and the degree of cryoturbation. Not all of the units and structures in the schematic are present in all of the drift cliff exposures. Overall the drift below the dark brown Holocene bed represents a Late Devensian periglacial environment with Last Glacial Maximum ice very near, if not briefly overrunning the area, depositing till and outwash sands and gravels which were subsequently mixed with head, colluvium and aeolian deposits by cryoturbation.

A characteristic of the periglacial environment is permafrost, permanently frozen ground to depth with a one or two metres thick active layer at the top which thaws in summer and refreezes in winter. The active layer is so called because freeze–thaw stresses distort (cryoturbation) the sediment layers to varying intensities ranging from very simple and shallow festoons through to involutions which can mix and semi invert sediment beds (Figs 14C, 15). Additionally, as the winter temperature of the frozen ground approaches -20 ^{o}C thermal contraction can crack frozen sediment to depth, the cracks filling with fine sediment to form frost wedges. Both of these periglacial structures are visible in the exposures around the Gann Estuary, involutions mixing head, fluvio-glacial sands and gravels and the loess.

The Devensian ended about 11,700 BP when rapid warming marked the start of the current interglacial in which we live, the Holocene. Sea – level rise and transgression, which started during Devensian deglaciation, pushed sediment landwards resulting in the modern day coastline, beaches, sand dunes, and in the Gann Estuary the mudflats, saltmarshes and alluvial floodplain above Mullock Bridge. This landward movement resulted in erosion of the pre-existing Quaternary deposits, forming the present day cliffs hosted on both sides of the valley. The Holocene also enabled temperate soil development with accompanying ecological succession and patterns.

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Further reading

There is no stand – alone text that covers the geology of the Gann Estuary. Readers are referred to the recent accessible texts published by Dr Gareth George that detail aspects of the geology and sedimentology of the area:

George, G.T. 2014. Aspects of the Sedimentology of South Wales. Geoserv Publishing.

George, G.T. 2015. The Geology of South Wales. A Field Guide (Second Edition). Geoserv Publishing.

The British Geological Survey hosts a free app download **iGeology** that contains a digital archive of all the geological maps of the United Kingdom. A hard copy of the geological map covering the Gann estuary and surrounding area is available for purchase from the British Geological Survey:

British Geological Survey. 1978. Milford. England and Wales New Series Sheet 226 & 227. Drift 1:50 000 British Geological Survey, Keyworth, Nottingham.

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