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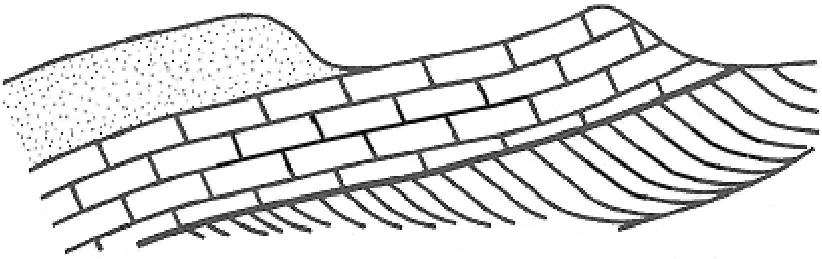

A local group within the GA

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Editorial

First, thanks to Janet Philips and Peter Norgate for their reports on the Mullard Space and Science Laboratory, which I have merged into one - it was clearly a very interesting and enjoyable visit. Space on the trip was severely limited so it is nice to have their memories.

Also field trips to Hebrides tend to be limited to a small number of people as travel and accommodation can be difficult things to arrange. So it is great to have Ian Williamson's excellent summary and photos so that those of you who were unable to attend the talk or have been unable to visit the Inner Hebrides, part of the North Atlantic Igneous Province, brings the many aspects of the lavas and associated sediments together with glimpses of a diverse fauna and flora of the Palaeocene. Enjoy.

Liz Aston

Visit by FGS to the Mullard Space Science laboratory on 28 March 2019

Janet Catchpole and Judith Wilson organized the trip to the Mullard Space Science Laboratories (MSSL) and Stella Willis, one of the administration team, alerted them to the small and busy nature of the laboratories and thus, sadly, there would have to be a limit on the number of visitors for the open evening on 28th March. So a group of about 15 FGS members visited the Laboratories in Holmbury House, near Holmbury St Mary to hear three popular science talks on Mars, Saturn and the Sun.

The Holmbury Iron Age Hill Fort has magnificent views across rural Surrey and Sussex. Nearby, can be seen a grand house with a similar view, perched on the edge of the greensand ridge, overlooking the Weald. This house is the MSSL, part of the department of Space and Climate Change Studies, University College London. It moved to this site in 1967, having outgrown its Central London location and following a generous donation from Mullard Ltd to enable it to acquire this house with its enviable position.

A primary role of MSSL is to design and produce instrumentation for space research vehicles having provided this for about 40 missions with about a dozen still active. In fact, for the last 52 years it has been a major player in Britain's contribution to the exploration of our Solar System.

We entered via the museum, through a Victorian panelled hallway, which was furnished with a Skylark rocket and other early rockets and duplicates of instruments used since space exploration began. The MSSL houses various research scientists and engineers and we were warmly welcomed by Professor Lucie Green, department of Solar Physics, who introduced the speakers to us.

The first talk, about Mars, was given by a postgraduate student, Jacqueline Campbell. We were surprised when she informed us that she had worked for 11 years as an underground train driver, then with the disabled, prior to joining the world of academia. After university she joined MSSL and now studies Mars.

Mars is the second smallest planet and the fourth from the Sun. It presents a hostile environment - there is a thin carbon dioxide atmosphere, which allows intense ultra violet radiation and corpuscular radiation levels to its surface from the Sun. Its proto atmosphere was swept away ~4.2-3.7 billion years ago by solar winds when the planet's internal dynamo cooled and it lost its global magnetic field.

High winds, low temperatures create spectacular dust storms and an early lander vehicle was enveloped in a dust storm and lost shortly after landing. Several landers have been badly battered, their instruments covered with dust and wheels holed by sharp rocks.

There is no tectonic activity on Mars so no moving plates as there are on Earth, but it still has dynamic features, rift valleys and 2 visible shield volcanoes, dark ridges and what looks like an old river system. The highest mountain in the solar system is on Mars, Olympus Mons, an extinct volcano; it is 21 km high from the surface. Liquid water does not exist on the surface of Mars, but it does have polar ice caps and subsurface ice; also large volumes of brackish water are believed to be present.

There have been many space missions to Mars often looking to find signs of life on its surface. The current view is that the conditions on Mars could have supported micro bacterial life forms. Initially lander vehicles and then various heavier rover vehicles have made the journey. We saw various images of Mars taken by these vehicles - by Pathfinder and Sojourner, 1997, the twins: Spirit & Opportunity 2004 (these found the haematite nodules, proving the presence of water at some time). Currently there are eight space vehicles, six in orbit and two on the surface investigating Martian attributes. The Curiosity lander is currently inactive after 15 years roving the planet and the Insight rover landed in November 2018. The Insight lander is designed to investigate the geology of the planet.

Its lack of an atmosphere precluded the use of parachutes to slow down arriving vehicles, either cushioned landing systems or lowering the vehicle from a retro rocket suspended canopy have been used to place objects on its surface, e.g. a 1 tonne lander with a thermoelectric generator was landed using the retro rockets.

Due to the transit time of commands from Earth, these landers employ artificial intelligence (AI) to make routing decisions. A European Space Agency (ESA) rover is planned for 2020 in which MSSL will be heavily involved – it will be given the name Rosalind Franklin after the almost forgotten discoverer of the structure of DNA.

Nuclear power has had to be used since solar panels would be covered with dust. This raised the question of nuclear, biological or chemical contamination by humans. MSSL is obviously taking precautions with clean rooms, special clothing, etc., but this remains a worry for all space exploration. Lucy remarked that Earth receive Martian meteorites and is likely to have received some from Earth.

The second talk was presented by Prof. Geraint Jones about the Cassini – Huygens mission, the lander was launched in 1997 and reached Saturn in 2004. Saturn is the second largest planet best known for its system of 7 rings and counting and less so for its 62 moons.

Cassini orbited Saturn in complex orbits (a mathematical masterpiece reminiscent of a tangle of wool) to encompass many of Saturn's moons and its ring system, the best rings in the Solar System. Although only planned to survive 4 years Cassini lasted for 13 years before being deliberately crashed into Saturn's surface in 2017, recording more useful data as it descended and, according to rumour, a requirement for liquid celebration. Saturn has a year of 29 "Earth years", a 10.5-hour day as "Earth days". It has an ice core covered by thick ice and aurora borealis.

Much of the talk was devoted to the largest of the moons, Titan, which is the same distance from Saturn as the Moon is from the Earth. It is the second largest moon in the solar system after Ganymede, a moon of Jupiter. Huygens had peeled off to visit this interesting moon. Huygens was an ESA lander which landed on Titan in 2005, it was battery powered so lasted a few hours after landing during which images of Titan's surface were relayed to Earth via Cassini. Valuable data were acquired which included the presence of methane seas. Titan has a dense, thick atmosphere, ~600km (375 miles), mainly nitrogen (97%) and methane (2.5%) The atmosphere is opaque to visible light so little was known about its surface before the Cassini-Huygens mission (2004-18)

The final talk was given by Professor Lucie Green on the Sun, her passion for the subject was clearly evident. She spoke of the gamma-ray, X-ray, UV and visible red light sections of the spectrum, of mass ejections, flares and the Sun's magnetic field - the poles flip at the peak of the solar activity cycle, every 11 years. Her main interest is coronal mass ejection and the mechanisms which power these massive ejections of matter which occur every 70-100 years. In principle these events can wipe out our communication systems and there was great concern that such an event could impact on the 2012 Olympic games. In fact a coronal mass ejection did occur in July 2012 but fortunately it was not in our direction.

This has led to a governmental interest in space weather and a satellite to observe the Sun from a stable point in space; direct observation of these events as they leave the Sun will provide 17-20 hours warning of their arrival. She is involved with Solar Orbiter that is expected to be ready for launch in 2022. This will be carrying instruments built in the former potting sheds at MSL, while the orbiter itself is currently being built at ESA in Stevenage, UK with input from MSSL. Professor Green expressed her delight in being able to see but, sadly, not touch the vehicle. Her enthusiasm for her work was inspiring.

Earlier Professor Green had challenged our perceived knowledge that light energy takes 8 minutes to reach us on Earth by saying that the Sun can be likened to a contained nuclear fusion bomb and photons generated in the thermonuclear reaction, take about 100,000 years to jostle their way from its centre to the surface, before their 8 minute journey to Earth, hence setting out about the time homo sapiens evolved.

Professor Green also mentioned Voyagers 1 and 2, launched in 1977, with their initial exploration of Jupiter and Saturn and making a string of discoveries there, such as active volcanoes on Jupiter's moon Io and intricacies of Saturn's rings, the mission was extended. Voyager 2 went on to explore Uranus and Neptune, and is still the only spacecraft to have visited those outer planets. Having explored the outermost edge of the Sun's domain, the spacecraft are now exploring interstellar space, the Voyager Interstellar Mission (VIM), and are still sending scientific information back about their surroundings.

She also explained that comets' trails always point away from the Sun so the tail will appear behind a comet as it approaches the Sun and ahead as the comet leaves the Sun. This is a visual reminder of the solar wind with invisible particles streaming from the Sun. There is a zone around the Sun where hot gas is held close by the Sun's gravitational pull. An extremely interesting and informative evening enjoyed by all, but with challenging drives there and home.

Peter Norgate and Janet Phillips

Sedimentary systems, life and landscape during formation of Palaeocene lava fields of the Hebridean igneous province

Lecture given to FGS on 21st September 2018 by Dr Ian Williamson

Introduction & Context

A mantle plume upwelling beneath Laurasia and crustal-rifting events in the proto- North Atlantic region during the early Palaeogene resulted in magmatic activity that impacted an area extending from north-east Canada, across Greenland and the British Isles, as far as mainland north-west Europe. Huge volumes of magma were generated, giving rise to what has become known as the North Atlantic Igneous Superprovince (NAISP). The terminology used in this article describes the Scottish sector - the Hebridean Igneous Province (HIP).

One aspect of this volcanism was the formation between c.61-58 Ma of extensive, continental flood-basalt-style lava fields. Portions of two such fields are preserved in the Hebrides – Skye (including Canna-Sanday, Rum and Raasay), and Mull (including associated small islands such as Staffa and Ulva, SE Ardnamurchan, and Morvern) (Figure1). Similar sequences on Eigg and Muck, are possibly related to the early development of the Mull field.

They were emplaced between c. 61-58 Ma; fissure-fed eruptions of basaltic compositions dominate. Thicknesses are >2km with interflow sedimentary sequences. Following their emplacement, the lava fields were intruded sequentially by large volumes of upwelling magma which developed into the so-called Central Intrusive Complexes; these are interpreted as the shallow roots of large composite volcanoes.

It's easy to dismiss these lava fields as little more than monotonous piles of featureless grey basalt, and for many of us of limited geological interest. Presenting case studies from the Hebridean islands of Skye, Canna, Rum and Mull this lecture aimed to show that they are considerably more diverse. The lava fields neither comprise just basalt nor are they simple sequences of laterally continuous, uniform sheet-flows. Rather, each lava field comprises overlapping units termed flow fields, each the product of a single, often protracted, eruption, and with differing 'architectures'. In geochemical terms the lavas are mainly transitional alkali-olivine basalts, but most sequences also include flows of intermediate composition, such as hawaiite, mugearite or trachyte; pyroclastic deposits however are rare. ***[Note: an explanation of the terminology of some of the igneos rocks can be found at the end of this article].***

Sedimentary rocks representing several depositional environments and facies were deposited on the lava fields mainly during periods of relative local or regional quiescence. Today, these form useful stratigraphical markers and environmental indicators. Less life-hostile conditions between eruptions favoured biotic colonization of otherwise barren lava fields, and a limited fossil record is preserved. Research, into volcanic and sedimentary systems and processes and how they interacted at various levels, along with palaeontology, has facilitated a wider consideration of basin evolution, landscape and ecology on these ancient volcanoes.

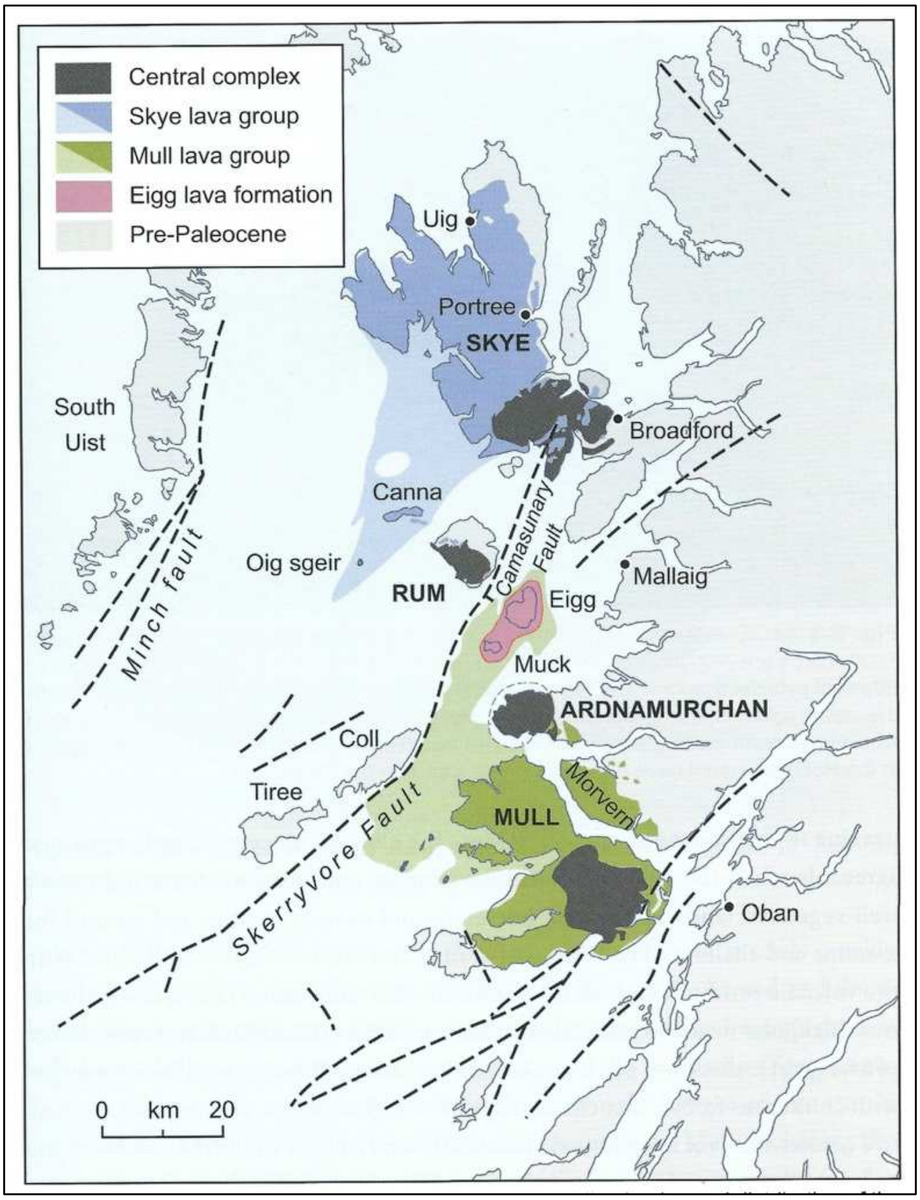

Fig. 1: Outline geological map of the Inner Hebrides showing the location of the lava fields and their relation to the central intrusive complexes Hebridean Igneous Province Lava fields of Skye, Mull & Eigg

Volcanic Systems – Lava Facies Architecture

Previous research efforts were largely aimed at determining the geochemical composition of the lavas in order to determine the origin and evolution of the magmas involved. Today, we have started to take a more holistic facies-based approach - looking also at flow characteristics (volume, viscosity, effusion rate), and integrating field-based studies of distribution and 3-dimensional shape (architecture), stratigraphy and the significance of intercalated sedimentary units and basin dynamics. This considerably improves our modeling of emplacement mechanisms, lava field evolution and palaeo-environments.

The most common lava facies architectures in the Hebridean lava fields are the compound-braided and tabular-classic forms. The former dominates the sequences in both lava fields, producing stacked sets of compound pāhoehoe flows with numerous thin, anastomosing and overlapping ribbon-like flow lobes of limited lateral extent; most have basaltic compositions. These likely built-up in a relatively passive, piecemeal fashion over protracted periods, individual flows being produced by relatively low-volume and low-effusion rate, tube-fed eruptions. The second facies comprise laterally extensive and relatively thick sheet flows and are the products of prolonged, single, major fissure-eruptions with high effusion rates. In today's landscape they are traceable over considerable distances with striking examples particularly in lavas of intermediate composition. Typical examples of these styles are exposed in the cliff sequences of the Storr (Skye) (Figure 2a), Staffa (SW Mull) (Figure 2b) and Ardmeanach (Mull) (Figure 3).

The Staffa Lava Formation, as shown in Figure 3, is characterized by a number of discrete members each comprising columnar-jointed lavas and hyaloclastite deposits; members are separated by sedimentary units; pillow lavas are only locally developed; this association of facies is indicative of subaqueous eruptions and the presence of water bodies (lakes and rivers) in the landscape; another unifying feature in the lavas is columnar jointing, which is associated with static, slowly cooled magma; the upper, irregular part of the two-tier structure, the so-called entablature (seen for example to best effect on Staffa) forms when isotherms are disturbed by the ingress of water along master joint systems from above - this water is commonly thought to be meteoric, but in a 'wet' environment like the Staffa Formation landscape is also likely due to the re-establishment, on top of the flow, of a drainage system and the impounding of streams to form ephemeral lakes behind lava dams. The Mull Plateau Lava Formation consists of interbedded compound braided and tabular classic flows. There are only rare thin and localized 'sedimentary' beds and many interflow horizons are typically characterized by lateritic palaeosols. This association seems to reflect increased rates of eruption and much drier conditions with little or no time for mature drainage systems to develop, though the formation of laterite requires both moisture and a warm-temperate to sub-tropical climate.

Fig. 2a: Storr Cliffs, NE Skye.

Fig. 2b: Staffa, SW Mull.

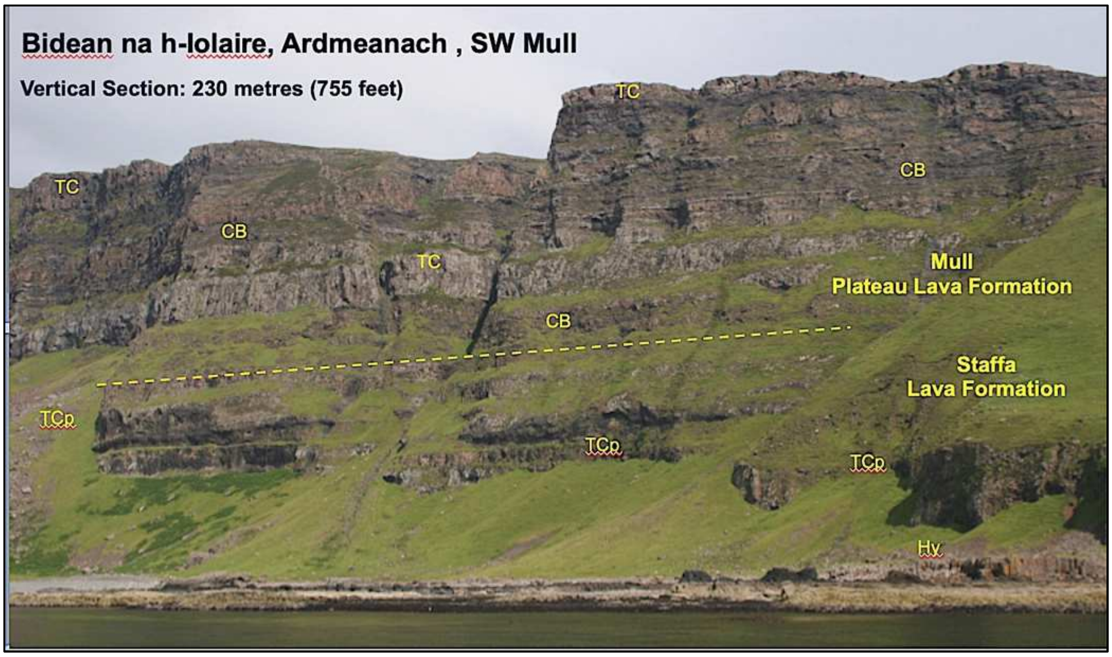

Fig. 3: Ardmeanac SW Mull.

Figure 3 legend:

TC = Tabular Classic facies
CB = Compound Braided facies
Tcp = Tabular columnar-jointed subfacies
Hy = Hyaloclastite facies

The Storr cliffs (Trotternish, Skye), the island of Staffa and Ardmeanach on (Mull) display good examples of lavas with compound-braided and tabular-classic facies architectures.

The third and fourth types are the Ponded Facies and the Hyaloclastite-Pillow Facies Association and are less common than the others. Their formation is dependent upon quite specific conditions. The morphology of developing lava fields is to a large degree, controlled by the distribution of pre-existing lava flows, flow fields and the relative topographical low points and channels created between them. Flows impounded within deeper blind valleys or steep-sided gorges result in a static body of slowly cooling lava – this is the ponded facies. They are the products of voluminous, low viscosity, high effusion rate eruptions and must be rapidly emplaced. The interiors of such flows cool slowly promoting the formation of columnar joints. The most spectacular example in the HIP is the Talisker Lava Formation in SW Skye (Figure 4). This lava infilled a palaeovalley to a depth >120 m. What remains today is a classic example of erosional 'topographic inversion'.

The fourth facies resulted from subaqueous eruptions, likely within fresh-water lakes of moderate depth. Quenching rapidly, magma brecciated explosively into innumerable small, angular, homogenous, glassy (but quickly devitrifying) fragments, accumulating as deposits of hyaloclastite. As eruptions continued lava entered the water body more passively and pillow-lava units were formed. The best examples of this facies in the HIP are the basal lava field sequences north of Portree on Skye and those on the island of Staffa (Figure 2) and the adjacent mainland of Mull (Figure 5).

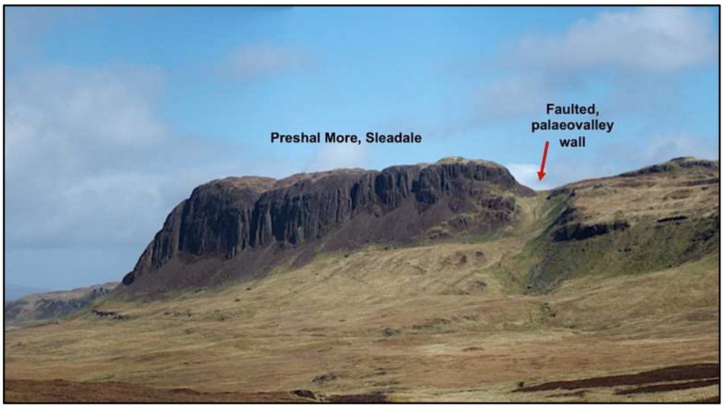

Fig. 4: The hill of Preshal More is one of two outliers of the Talisker Formation, a ponded facies flow. Note the faulted palaeovalley wall.

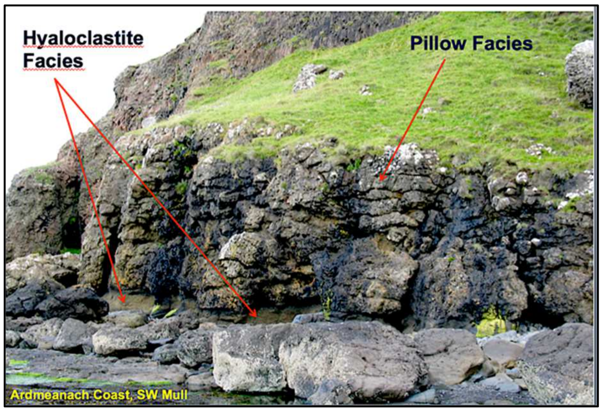

Fig. 5: An example of the hyaloclastite-pillow facies association exposed on the Ardmeanach coast of SW Mull.

Sedimentary Systems, Facies & Environments

Sedimentary rocks provide evidence of contemporaneous erosion, transport and the periodical, but localized presence of significant water bodies within what was a volcanically-dominated landscape. They act as useful stratigraphical markers enabling refined modeling of basin dynamics, former landscapes and environments and, because some include fossils, ecosystems. For the most part sedimentation was confined to the open, narrow and meandering channel systems that formed between flows, flow fields and the bordering extra-basinal hinterland, and was seldom established on a basin-wide scale. The Staffa, Canna and Talisker Lava Formations provide excellent examples.

Sediments

Fig. 6: Debris flow conglomerates & breccias exposed at Dun Beag, island of Sanday (off Canna)

Most sedimentary units were water-lain and have what might be broadly termed 'fluvial' characteristics. The coarser-grained lithologies range from unsorted, polymict, boulder conglomerates and breccias to conglomerates and pebbly sandstones with either planar- or trough-cross bedding. Collectively, these associations represent deposition within a continuum of flow regimes ranging from alluvial fan-sourced, high-energy, debris flow and hyperconcentrated flow (Figure 6) to ephemeral flood flow, braided outwash and channelized stream flow (Figure 7).

Interbedded siltstones, mudstones and coals are interpreted as floodplain channel-overbank, waning flow and abandonment facies transitioning to lacustrine and mire facies (Figure 8). Some mudrocks carry palynomorphs with estuarine (or saline) characteristics (Figure 9). Whereas minor, and highly localized lithologies such as calcareous mudstones and limestones are deemed mainly diagenetic, a limestone from the Staffa Lava Formation may have been deposited within a restricted freshwater pool.

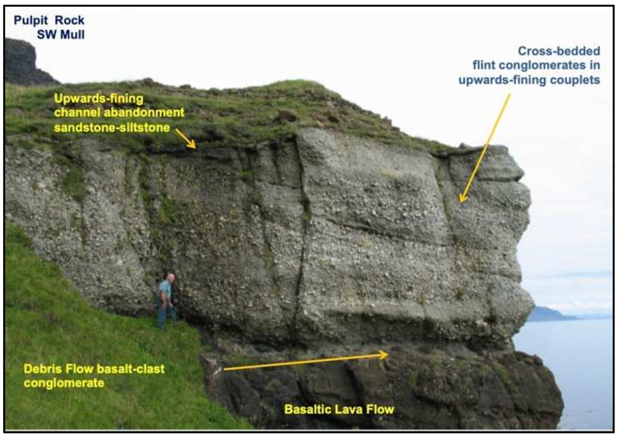

Fig. 7: Fluvial channel flint-clast conglomerates at the Pulpit Rock, west of Carsaig Bay, SW Mull

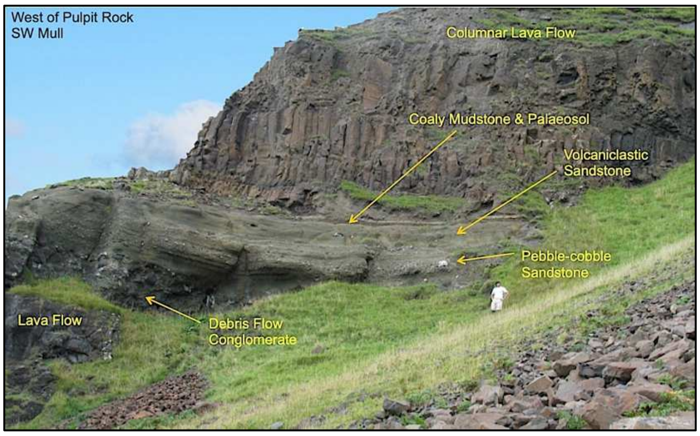

Fig. 8: Waning flow and upwards-fining sequence west of the Pulpit Rock

Fig. 9: Interbedded estuarine coaly mudrocks, peperites and thin pyroclastic flows at Carraig Mhor, east Carsaig Bay, SW Mull

Fig. 10: Reworked hyaloclastite with trough cross-bedding, Ardmeanach, SW Mull

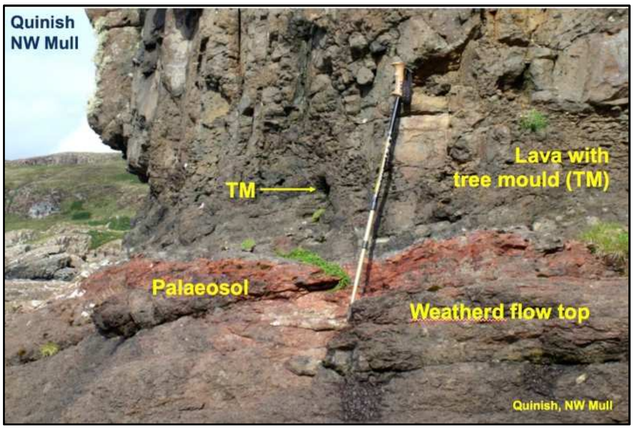

Fig. 11: Weathered lava top with thin lateritic clay palaeosol, Quinish, NW Mull

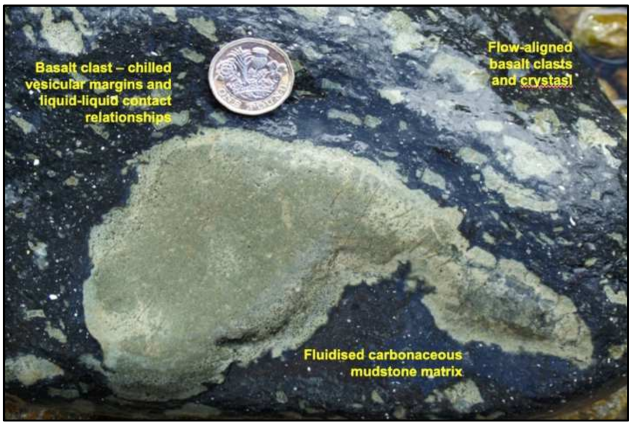

Fig. 12: Liquid-liquid relationships and flow textures in peperite, Carraig Mhor, SW Mull

The only major 'volcaniclastic' sedimentary unit is the thick sequence of reworked hyaloclastite tuffs and tuffaceous sandstones that underlies the famous columnar-jointed lava on Staffa and its equivalents on mainland Mull (Figure10). It exhibits both normal- and reverse-graded-, cross- and surge-bedding, along with large fragments of in-floated carbonized wood; it was likely formed in a shallow lacustrine deltaic environment. Of significance too are thin lithic and crystal tuffs and ashes found within some palaeosols. Good examples are noted from north Skye, Mull and the island of Muck.

Palaeosols

Thin, reddish to purplish-brown, lateritic claystones are a common feature of most lava sequences (Figure 11). They developed originally as soils during protracted periods of relative quiescence under conditions of intense chemical weathering in a warm, temperate and seasonally wet climate. Their formation was crucial for the (re)establishment of complex ecosystems on the lava fields (see below).

Interaction Between Volcanic & Sedimentary Processes

Although significant sedimentation took place mainly during periods of prolonged volcanic quiescence, there is also evidence of interaction as lavas rode over, shallowly-intruded, remobilized or mixed with unconsolidated sediments.

An unusual rock known as 'peperite' is formed when highly fluidic basaltic magma infiltrates unlithified, water-saturated sediment and disintegrates into fragments with chilled, ragged-, feathery- and cauliform-margins before mingling with the sedimentary host. Clast-matrix relationships are typical of liquid-liquid contacts. A particularly fine example is seen at Carraig Mhor, in SW Mull (Figure 12). Indirect interaction includes situations where loosely consolidated or water-logged sediments are shaken to a thixotropic state by volcanically-induced seismic activity with consequent mixing, loading and remobilization (Figure 13). Loading, shearing and slump folding may also be induced as massive flows override in weakly lithified beds (Figure 14).

Fig. 13: Remobilized sandstone & limestone penetrating as 'fingers' into base of overlying flow.

Fig. 14: Load structures & incipient homogenization of bedding, Camas Thairbearnais, Canna.

Life On The Lava Fields

The interlava sedimentary rocks of the HIP host a sparse but diverse fossil record. This comprises both palynological and plant macro-fossil remains and a rare assemblage of invertebrates; collectively these enable us to reconstruct likely environments and communities. The lava fields must have been violent and life-challenging places, but they were seldom, if ever, completely barren and devoid of life. At any one time, but more especially during their early formation, they likely comprised a complex mosaic of volcanically active and recently active zones hostile to life, and areas at various stages of cooling and ecological recovery. The comparatively unaffected forested hinterlands bordering the lava fields formed the principal sources of colonizing plants and animals, but also important to this process were areas that had been surrounded, but not submerged beneath lava. These latter island refugia worlds have the wonderfully evocative Hawaiian name, kīpuka (Figure 15).

Palaeontology

The most important fossil sites are those at Ardtun in SW Mull and the Allt Mor in west-central Skye. These have yielded leaf-macro and palynological assemblages which include a wide range of fossil vascular plants from several coniferous evergreen and broadleaved deciduous tree families such as metasequoia, redwood, fir, spruce, pine, yew, oak, willow, alder, plane, beech, birch, hazel and ginkgo (Figure 16). These 'temperate' species are accompanied by a host of 'lower' plants such as ferns of various type, horsetails, mosses and liverworts and also more exotic and 'thermophilic' plants such as palms, cashews, walnuts, hickory and maidenhairs, together with club mosses, tree ferns and associated vines and lianas. This palaeoflora has international significance as it is crucial to a wider understanding of plant migration and the floristic evolution of Europe.

But fossils are not only found within sedimentary rocks! On Mull and Canna, there are good examples where trees engulfed by advancing flows have left traces in the form of moulds and casts within solidified lava. The most spectacular example is that of MacCulloch's Tree on Mull (Figure 17). This spectacular and unique fossil 'conifer' measures c. 12m x 1.5m and, though clearly totally submerged in NW of the island, where a small stand of trees was overwhelmed by lava. Several moulds and casts have been preserved (Figure 18). The prostrate specimens have a preferred orientation suggesting flow was to the WSW, broadly perpendicular to the trend of the eruptive fissures.

Fig. 15: An active fissure-fed lava field surrounding a kīpuka, Hawaii

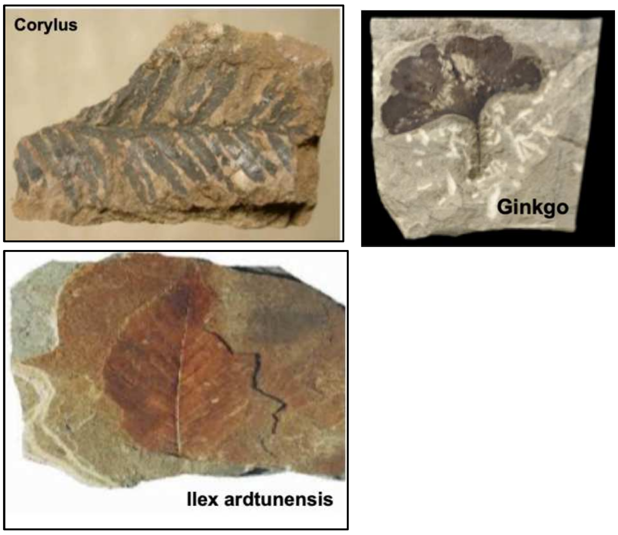

Fig. 16: Examples of leaf macrofossils from the Ardtun Leaf Beds, Staffa Lava Fm'n, SW Mull

Fig. 17: MacCulloch's Tree, Ardmeanach, SW Mull, discovered c.1811-1815. Preserved in lava, almost unique.

Fig. 18: Cast of a prostrate tree trunk, Quinish, NW mull.

Whereas the palaeobotanical record for the HIP is well established, associated animal life has received very little attention. The only reported finds are a sparse, but varied invertebrate assemblage of insects and molluscs recovered from the Ardtun Leaf Beds in the 1930s and 1940s, and more recently comminuted fragments of crustaceans (ostracods) and fish bones found in a limestone west of Carsaig Bay. The Ardtun assemblage has both aquatic and terrestrial elements comprising riffle beetles, river limpets, bladder snails, dragon- and caddis flies, ground-, bark- and jewel beetles, crane- and march flies, cicadas, crickets and weevils. This eclectic collection hints at the complexity of the environmental conditions, processes and ecosystems present on and adjacent to the lava fields.

Palaeogeography – Landscapes & Ecosystems

Today, we know a lot about the physical volcanic and sedimentary (abiotic) systems & processes that governed development of the lava fields, but also, we have a greater understanding of environmental conditions, and the life-styles and habitats of the plants and animals that inhabited them. This allows palaeogeographic reconstruction with meaningful speculation as to the nature of former landscapes and ecosystems.

Landscapes

The lava fields of the HIP were formed over a period of 3 Ma or so, with landscapes evolving as a series of transient mosaics in response to the interplay of coeval volcanic, tectonic, sedimentary, and biotic processes. For most of this period, fissure-fed effusive volcanism was the norm, topography was subdued and dominated by low-elevation, low-gradient flow fields at various stages of development and cooling (Figures 19 & 20). Despite the high levels of magma production, no major volcanic edifices built-up as continued basin subsidence constantly provided accommodation space. Eruptions were widespread and frequent enough, creating rugged, barren, life challenging landscapes that inhibited the development of most soils as well as ecological succession. However, there were times, and most especially during the early stages of field development, when the eruptions were neither continuous nor likely to have been lava-field-wide phenomena. Prolonged inter-eruption interludes favoured weathering, erosion and sedimentation, and importantly, the return of life.

The Canna and Staffa Lava Formations (Skye and Mull lava fields respectively) show clear evidence of the presence of standing water and the development of contemporaneous drainage systems. Sedimentary members chart the formation of alluvial fans, braided outwash plains, incised fluvial channels, floodplain lakes and abandonment mires, these collectively hosted a wide range of habitats and ecological niches - early successional fern-dominated lava plains with refugia (kīpuka), hinterland mixed and conifer forests, riparian woodland, scrub, and freshwater streams and lakes (see also below).

Later, sequences on both lava fields lack this degree of complexity, with interlava sediments rarer and mainly restricted to thin, scattered and unconnected beds of locally derived siltstone and mudstone and palaeosols. This low diversity reflects both a marked increase in the tempo of eruptions which left little time for the establishment of local drainage systems, and possibly climatic variation. An exception to this is the youngest known unit of the Skye lava field, the Talisker Lava Formation. Sometime after the main phase of flood volcanism, and following a period of uplift with concomitant faulting and erosion, this chemically distinct lava (an olivine tholeiite) was emplaced unconformably upon earlier formations as a valley-fill (or intracanyon), ponded facies flow (see previously) (Figure 21). Its abnormal thickness (originally in excess of 120 m), architecture and the presence of an underlying complex of locally-derived debris flow, palaeotalus and fluvial conglomerates suggests rapid emplacement in a deeply incised, steep-sided valley or canyon on the flanks of an emerging shield volcano in the region of today's Cuillin Hills.

Ecosystems

During the mid-Palaeocene Scotland was situated further north than today and lay within a biome known as Polar Broad-leaved Deciduous Forest – a unique suite of high-Arctic temperate ecosystems that has no modern equivalent. Despite the high latitudes (there was no polar icecap), this comprised a typical mix of deciduous conifers and broadleaved angiosperms suggesting a temperate, warm (mesothermal) to humid, equable and largely frost-free climate that favoured a long growing season. However, an annual shut down of growth during a period of winter darkness, and the intrinsic environmental stress brought about by volcanism and shifting patterns of sedimentation, severely limited biodiversity and habitat variation. Life only returned to the lava fields when conditions were suitable.

Plant and animal communities varied across the lava fields responding through time to varying degrees of disturbance (both flooding and volcanic), topography and drainage, and were likely further compromised by the atmospheric conditions (lower temperatures, humidity and precipitation) imposed by the widespread volcanism. Populations in refugia surrounded by active volcanism or recently-formed and barren fields would have faced many challenges, such as water and food availability, and a lack of habitat interconnectivity. Most interlava intervals were short and other than the palynological record of incipient palaeosols, little is known about their biodiversity. As with present-day recently active lava fields ephemeral, early successional habitats colonized by pioneer plant species such as ferns, aerial plankton (small spiders, flies etc.) and low populations of scavenging animals preying on these would have dominated.

Fig. 19: A landscape typical of active fissure-fed lava fields, with surrounding upland, Iceland


Fig. 20: The recently (active fissure-fed lava field of Laki, Iceland

Fig. 21: An example of mature valley with incision similar to that which hosted the Talisker Lava Formation

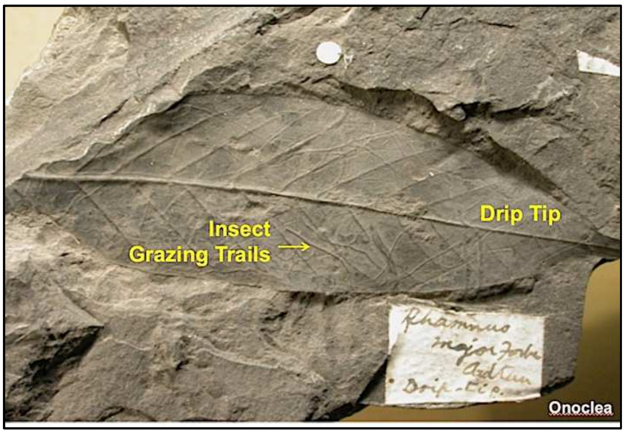

Fig. 22: Evidence of insect herbivory (trails) rainy conditions (leaf drip tip) in the Ardtun Leaf Beds

Sites such as Ardtun (Mull) and Allt Mor (Skye) are key to understanding vegetation community composition and dynamics on the lava fields during prolonged periods of quiescence. Most common were the angiosperm-dominated and mixed angiosperm-conifer forests, comprising climax community conifers and understoreys of angiosperm trees and shrubs; disturbed riparian and floodplain, marginal lacustrine and low-density open swamp communities are also recorded. The Ardtun fauna represents an allochthonous collection of both terrestrial and aquatic invertebrate species. Their habitat preferences, life styles and requirements were likely very similar to those of modern representatives and help paint an even more vivid picture of life on the lava fields (Figure 23). For example, species that live in water for some or all of their life-cycles provide clues as to variations in oxygenation levels, stream flow rates and substrate conditions, annual growth rings on molluscs provide crude estimates as to the minimum duration of the inter-lava interval and the variety of terrestrial insects hints at the complexity of life in the trees and on forest floors. There is even some trace evidence of insect herbivory, with leaf imprints grazing or mining trails of insect larvae (Figure 22).

Despite the fragmentary fossil record we may begin to consider wider ecological questions involving topics such as inter-species relationships, niches, guilds, 'missing' elements and likely energy flow (food) webs and to fill-in the missing pieces and construct 'phantom ecosystems' (Figure 24). The most obvious 'missing' elements for example, are carnivorous or herbivorous vertebrates, as to date, only a few fragmentary fish bones have been found recovered.

Whilst rodents such as Neoplagiaulax and Chriacus (Figure 25) most likely dominated any mammalian fauna, there may also have been early bat species and some ground-dwelling herbivores. There were almost certainly populations of reptiles, including lizards, snakes and land tortoises. Where habitat connectivity and potential migration pathways were established with lakes, ponds and marginal riverine environments extraneous to the lava fields, the fossil record from elsewhere within the biome suggests that the HIP fauna likely also included frogs, salamanders, turtles, freshwater (caiman-like) alligators and crustaceans such as crayfish and amphipods, and any number of soft-bodied animals.

Fig. 23: Examples of present-day representatives of the Ardtun Leaf Beds fauna

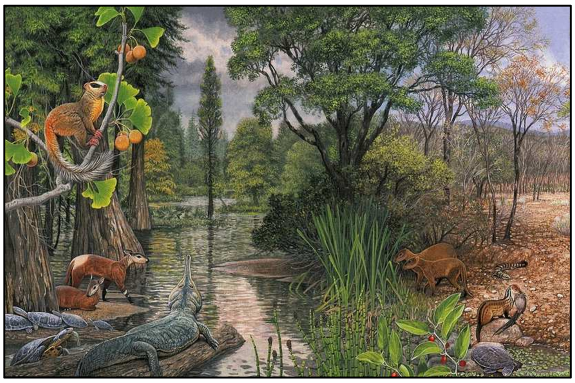

Fig. 24: Artists impression reconstructing a composite Palaeocene forest ecosystem

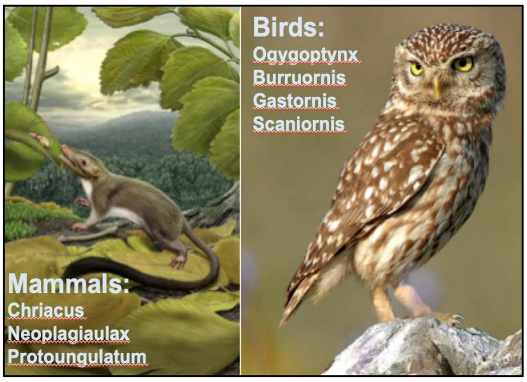

Fig. 25: Examples of mammalian and bird fauna likely to have been present on the lava fields

Another obvious missing group are the birds. The Palaeocene marks the beginning of a spectacular evolutionary divergence of bird groups, but as the fossil record from Europe is fragmentary, little is known about them. Most specimens come from aquatic (marine to estuary) or semi-aquatic species, and so are not readily comparable to the terrestrial setting of the HIP. If habitat and niche requirements were met, then there may however have been small populations of ground-dwelling ratites, perhaps including the large rhea-like Gastornis. There were some early owl-like forms such as Berruornis (Figure 25) but small arboreal birds are conspicuously absent from the fossil record. Perching birds or passerines had not yet evolved, and so these Palaeocene worlds may well have been bereft of bird song and more dominated by the sounds of episodic volcanic rumblings, and the chirping of cicadas and crickets.

Summary & Conclusions

In writing this follow-up article to my lecture I hope that I may have just about convinced you that the lava fields of the Hebridean Igneous Province are considerably richer in 'Geodiversity' and more interesting than you might previously have thought. They are an excellent inter-discipline case-study demonstrating the often-intimate relationships that existed between coeval volcanic, sedimentary, and biotic systems and processes during the evolution of a long extinct volcanic field.

Ian Williamson

- p.3: Hawaiite is an olivine basalt with a composition between alkali basalt and mugearite.
- p.3: Mugearite is a type of basalt, comprising oligoclase feldspar, olivine, apatite, and opaque oxides.
- p.3: Trachyte is a volcanic rock comprising alkali feldspar, minor plagioclase. Quartz or nepheline may be present. Biotite, clinopyroxene, olivine can be accessory minerals.
- p.4: Hyaloclastite is a volcaniclastic deposit or breccia comprising quenched glass clasts of of lava flow surfaces during submarine or sub-glacial extrusion.
- p.5: Pillow lavas have pillow-shaped structures attributed to extrusion under water.
- p.4:Entablature is where columnar jointing is 'less-than-perfect'.
- p.10 Tholeiite is a subalkaline basalt (low Na) rather than a calc-akaline basalt.

Remaining FGS Monthly Meetings - 2019

Date	Speaker	Title of lecture
12th July	John Williams Member FGS	*Building stones of Guildford* **Note: a Field Trip Meeting**
August	No meeting	
20th September **Note: 3rd Friday**	Dr Kevin Pretorius Consultant	*Exploration of Pluto*
11th October	Dr Simon Drake & Dr Andy Beard	*Meteorite impact in Skye*
8th November	Dr Colin Knipe Consultant	*The Black Country: Powerhouse of the Industrial Revolution*
17th November	**FGS Lunch at Frensham Pond Hotel**	
13th December	Dr Andy Gale Portsmouth University	*The Cretaceous world – living in a greenhouse*