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Depositional system and plant ecosystem responses to long-term low tempo volcanism, the Interbasaltic Formation, Antrim Lava Group

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Abstract

The Antrim Lava Group of northeast Ireland comprises a volcanic sequence dominated by basaltic lava flows. Including subsidiary sedimentary interlayers and some evolved lavas and intrusions, the overall sequence reaches a cumulative thickness of ~800 m. However, the tempo of eruption of the Antrim Lava Group is poorly constrained, but can be evaluated via weathering patterns and environmental reconstructions derived from lava-flow interbeds. In this contribution we present palynology from a newly-identified and well-developed 2 - 2.5 m thick sedimentary sequence (interbed) at Ross's Quarry, Ballycastle, Co. Antrim, that helps elucidate the contemporary development of environments in a setting subject to periodic basaltic volcanism. The interbed is subdivided into geologically distinct subunits of cross-bedded and parallel bedded sandstones and sandy siltstones, all rich in visible organic remains such as rootlets and fragments of wood and bark. A total of 19 samples were collected from the sequence and subsequently analysed for palynological content. The palynomorph data point toward a diversity of inputs ranging from estuaries, chalky soils, dry soils, swamps, lakes, floodplains, sand bars, wet soils, established bogs and fenlands. In contrast to current understanding, the palynological data and their inferred environments collectively reveal the presence of flora that favour a temperate climate rather than the subtropical climate that has previously been inferred from the lateritic interbeds of the Antrim Lava Group. By combining the Ross's Quarry observations with palynological data from other quarry sites and boreholes in Antrim, we provide new insights into the climate, weathering systems and eruptive history of the Antrim Lava Group.

Keywords: Antrim Lava Group, North Atlantic Igneous Province, Ballycastle, Ross's Quarry, Interbasaltic Formation, fen carr, fenland, palaeobotany, palynology, laterite

The predominantly basaltic rocks of the Antrim Lava Group, Northern Ireland, were erupted during the formation of the North Atlantic Igneous Province (NAIP) and covered much of northeast Ireland during the Paleocene (Figure 1). Available chronostratigraphical evidence indicates that the Antrim Lava Group mainly erupted during the Danian and Selandian stages of the Paleocene (63.24–60 Ma, Wilkinson et al., 2017), part of Phase 1 of North Atlantic rifting (Knox & Morton, 1988; Jolley et al., 2021). The Antrim Lava Group is divided into three formations; the oldest and youngest of these, respectively termed the Lower and Upper Basalt formations (Patterson, 1955; Old, 1975), comprise olivine-normative basalt. Positioned stratigraphically between these lavas are the sedimentary and varied extrusive igneous rocks of the Interbasaltic Formation (Cole, 1912; Patterson, 1955; Old, 1975). This formation includes a series of quartz-normative tholeiitic basalts, termed the Causeway Tholeiite Member, present predominantly (if not exclusively) to the north of the Tow Valley Fault, as well as a number of dacitic intrusions and rhyolitic lavas occurring across the lava plateau, e.g. the Tardree Rhyolite (Figure 1). In the long standing but now revised Antrim Lava Group lithostratigraphy (cf. Figure 1 in Simms, 2021) the Interbasaltic Formation included the Port Na Spaniagh Member (containing weathered Lower Basalts, now placed at the top of the LBF by Simms, 2021) and the Ballylagan Member (containing weathered Causeway Tholeiites), respectively identified by their position below and above the Causeway Tholeiite Member (Patterson, 1955) (Figure 1). However, the current absence of identified Causeway Tholeiite Member outcrops south of the Tow Valley Fault, makes it difficult to correlate these other members beyond their type localities.

The Antrim Lava Group forms one part of the British & Irish Paleogene Igneous Province (BIPIP), along with the similar terranes of Skye, Mull and Arran on the west side of Scotland (collectively the Hebridean Igneous Subprovince). However, unlike the lava successions of Mull and Skye NAIP volcanics (Bailey et al., 1924; Anderson & Dunham, 1966), the thick, heterolithic volcanic and sedimentary rocks of the ALG Interbasaltic Formation suggests a significant hiatus or change in the nature of volcanism during emplacement. These rocks have been the focus of much academic and economic interest for well over a century. Prominent amongst this early work is that of Cole et al., (1912), who reviewed the economic resources of the aluminium and iron-rich lateritic horizons that are recorded in the Interbasaltic Formation interval. Workers have variably described the reddened horizons in the Antrim Lava Group as either a 'laterite', 'bole' or 'lithomarge' (Mallet, 1881; Cole et al, 1912; Eyles, 1952; Lyle & Preston, 1993; Simms, 2021), although not always in a consistent way. Where discussed, the presence of these interbeds was taken as indirect evidence of a subtropical climate, since such a climate is widely associated elsewhere with the production of laterites and lateritic soils (e.g., the red clays of East Africa (Muff, 1908); Deccan Traps, India (Ghosh et al., 2006)). The presence of extensive and sometimes thick laterites in the Antrim Lava Group, along with the occurrence of commercially viable bauxites (Cole, 1912), implied formation under extended periods of weathering, which would be required to transform the original basalt lavas and other volcanic products from parent rock to weathered deposits.

Here, we have applied the generic term '**interbed**' throughout the Antrim Lava Group to refer to any lithological unit that was formed or deposited during periods of quiescence between episodes of effusive volcanism, including deep weathering and the onset of soil formation and/or lateritisation. Additionally, we have avoided using the terms 'interbasaltic' or 'intrabasaltic' to describe these strata in the same manner as some previous NAIP studies (e.g., Jolley, 1997; Passey & Jolley, 2009;

Williamson & Bell, 2012) as their use here could cause confusion with the Interbasaltic Formation stratigraphic unit of the Antrim Lava Group.

A number of volcanic and sedimentary rock successions are broadly coeval with the well-developed interbed horizons of the late Lower Basalt Formation and Interbasaltic Formation; specifically intermediate lavas and intrusives (Patterson, 1951; Walker, 1960; Lyle & Thompson, 1983) and acidic volcanic centres such as the Tardree Rhyolite Complex (Old, 1975; Ganerod et al., 2011) and the rhyolitic centre identified by Lonmin borehole NIRE 01/08-0001 (Figure 1) which proved 145.3 m vertical thickness of porphyritic and tuffaceous rhyolite under 17 m of overburden. These varied lithologies occur above, between and below the often columnar jointed lava flows of the Causeway Tholeiite Member (Eyles, 1950; Lyle, 2000) and throughout the Antrim Lava Group. This heterolithic succession suggests formation, either by weathering or sedimentary processes, over an extended time period in varied environments. Examining the record of spatial and temporal environmental change within the uppermost Lower Basalt Formation and the Interbasaltic Formation helps constrain the dominant lava field processes and tempo of eruptive activity. Environmental indicators aid with the identification and interpretation of interbeds, allowing some determination of eruptive hiatuses across the plateau as well as providing a sense of their duration. Identifying the locality and duration of these hiatuses helps to determine if these are local and asynchronous features, or consistent with dominant vent positions and their migration. Timescale information from both weathering patterns and environmental or depositional reconstructions also provide a route to evaluating the overall rate of lava emplacement in the Antrim Lava Group.

As mentioned above, the terms laterite, lateritic, lithomarge, and bole have been widely used to describe interbeds (Eyles, 1952; Patterson & Mitchell, 1955; Old, 1975; Hill et al, 2000; Hill et al, 2001) as well as in the wider NAIP (Bell et al., 1996), although not always consistently. These terms allude to the composition and method of deposition or formation of the strata, which may include both sediment input and in-situ weathering, or a combination thereof. Applied to the Antrim Lava Group, the term 'lithomarge' refers to an advanced stage of weathering in the sequence; basalt –> saprolite –> lithomarge –> laterite –> duricrust (Hill *et al.*, 2001). Early workers were divided as to the nature of formation of the red interbeds of Antrim; some argued that they were lacustrine in origin (Hull, 1874; Mallet, 1881; Cole et al., 1912), noting the presence of plant remains as additional evidence for this (Tate & Holden, 1870). Other workers saw them as advanced palaeosol artefacts, e.g. Muff (1908) compared the red bole interbeds of Antrim with the 'red clay' of East Africa (Kenya), claiming them to be identical at outcrop and very similar in chemistry. However, those 'red clay' soils were forming on sloping land surfaces where they were experiencing "alternate soaking by rain and [drying by] solar evaporation", and since lakes cannot form on a sloping topography some other mechanism is suggested. The point at which the laterite, lithomarge and bole horizons of Antrim were accepted as being indicative of a subtropical weathering process is unclear, but the red interbeds of the Antrim Lava Group have mostly been interpreted as deriving from a subtropical climate (e.g. Mallet, 1881; Cole et al, 1912; Scrivenor, 1937; Eyles, 1952; Evans et al., 1973; Lyle, 1988; Lyle & Preston, 1993; Hill et al., 2000; Simms, 2021).

The interbeds found throughout the Antrim Lava Group are key to understanding the palaeoenvironmental conditions, how those environments were established and impacted by volcanism, and the tempo of volcanic activity, because they can provide information about the duration and relative timing of periods of quiescence. Here, we focus particularly on two interbeds of the Interbasaltic Formation revealed at Ross's Quarry and combine these findings with observations from other interbeds across the Antrim plateau (principally within the Interbasaltic Formation and adjacent strata, e.g. the Port na Spaniagh Member of the Lower Basalt Formation) (Simms, 2021; Figure 1). Within the NAIP, this wide range of lithotypes formed or deposited during an eruptive hiatus is seemingly a unique feature of the Antrim Lava Group. It also provides an opportunity to elucidate the range of environmental variation, the pace of environmental change and the wider impacts of this eruptive hiatus early in the formation of the NAIP.

METHODS

Lithology

Interbed exposures and cored sections of the Interbasaltic Formation were selected for this study from sites across the extent of the Antrim Lava Group. For each exposure or borehole, the lithologies present were recorded in graphic logs, which provided the basis for further sampling. For field sampling of exposures, the surface of the interbeds were cleaned to remove the weathered, uneven outer face. For interbeds of sedimentary origin, a small steel trowel was then used to excavate samples from the main sedimentary subunits. Between samples, all equipment was washed clean using fresh mains tap water to remove soil and sediment and thereby minimise the risk of cross contamination.

Continuous cores from four boreholes penetrating the Interbasaltic Formation were logged for lithology and are included in this study (NIRE 02/08-0001, NIRE 03/08-0001, NIRE 09/08-0001 and NIRE 09/08-0002) (Figure 1). These are part of a total of nineteen boreholes comprising over 8.5 km of core, drilled by Lonmin (NI) Ltd. and deposited with the Geological Survey of Northern Ireland (GSNI). Along with the cores, datasets of portable X-Ray Fluorescence (pXRF) geochemistry and magnetic susceptibility data were also donated to the GSNI and made available to the authors.

Basalt weathering depth and interbed thickness / character

Lonmin NIRE borehole log records were investigated for detailed log information on the presence of vesicles and amygdales as well as noting the depth of weathering measured from flow tops. By examining and processing these data we were able to identify flow crusts and calculate depth of weathering through the flow tops and into the flow cores.

Petrological and palynological examination of interbeds within the NIRE borehole core samples and field exposures was carried out to determine their lithology, depositional environment and catchment ecology.

Palynology Laboratory processing

Samples from outcrop sections and core were selected based on lithology, sampling at 10 cm intervals at outcrop where possible. The lithologies of interest were identified between lava flows, appearing variously as sediments, lignitic material, volcaniclastic tuffs, palaeosols and other interbeds situated between lava flows. These lithologies were sampled before undertaking detailed identification in order to minimise the risk of sampling bias. Both exposure and borehole core samples were prepared using the standard techniques detailed below.

First, rock material was broken down to sub-4 mm size fragments and then demineralized by digestion in HF. Residues were boiled in 40% hydrochloric acid to remove calcium fluorite precipitate. Residues were sieved through a nylon 7 µm mesh and subsequently treated with dilute 40% nitric acid to remove pyrite. Where necessary, samples were subjected to heavy liquid separation using Sodium-Polytungstate ($3Na_2WO_4 \cdot 9WO_3$) at a specific gravity of 2.2 g/cc. The resultant

residues were strewn mounted on glass microscope slides using a permanent epoxy mounting medium and analysed using an Olympus BX53 transmitted light microscope. Counts of > 200 palynomorphs per sample were taken where possible, all specimens within the strew mounts being recorded in depauperate samples.

Because of the complexity of some of the palynofloras recovered from the Interbasaltic Formation, specific taxa were targeted for more detailed analysis using a scanning electron microscope (SEM). Strew mounts were made of the selected residues, suspended in glycerine. Selected palynomorphs were picked out from the residue using an eyelash picking tool and concentrated in a small blob of glycerine. Transmitted light photographs of these specimens were then taken as a record of their identity (Figure 9) and the specimens transferred to SEM stubs following the methods of Halbritter et al. (2020). Scanning Electron Microscopy (SEM) was conducted in the Aberdeen Centre for Electron Microscopy, Analysis and Characterisation (ACEMAC) facility at the University of Aberdeen using a Carl Zeiss GeminiSEM 300 VP equipped with Deben Centaurus CL detector, an Oxford Instruments NanoAnalysis Xmax80 EDS detector and AZtec software suite. Prior to electron microscopy at ACEMAC the stubs were coated with Au-Pd 80/20 in a sputter coater. Imaging was conducted with low accelerating voltages with the secondary electron detector (SE2) and an InLens secondary electron detector for higher magnification images. The acceleration voltage used was 5 kv with a working distance of ~ 6 mm.

Statistical data analysis

Because of the complexity of the data set derived from the principal study sections, an initial statistical analysis was undertaken to determine the overall characteristics of the data. This was followed by a multivariate statistical analysis to identify the main trends in the data and simplify its presentation (Hill and Gauch, 1980). Following data normalisation and reduction to remove rare or singleton taxa, Detrended Correspondence Analysis (DCA) was undertaken (Hill, 1979; Hill and Gauch, 1980). DCA arranges data along two principal axes which represent variables, such as environmental factors. The eigenvalues associated with each axis reflect the extent to which each axis influences the data (Ramette, 2007).

pXRF Analysis

Existing pXRF analysis of all cores held by GSNI, and new analyses of lithologies of interest, were obtained using an Olympus Vanta M Series Delta Premium model with a rhodium anode tube. The pXRF data inherited by GSNI with the core samples were taken by Lonmin staff at set intervals, e.g. 1 m, 2 m, rather than by geological unit or feature. Lithologies of research interest were often missed by this method due to being relatively thin, hence the need to re-analyse certain specific horizons of NIRE borehole core samples by pXRF.

All new analyses were obtained by placing samples within an Olympus Vanta workstation for analysis. Individual readings were taken over a two minute count time. Beam 1 (<40 kV) ran for 60 seconds, then beam 2 (<10kV) ran for another 60 seconds.

Geochemical data generated using a handheld portable X-Ray Fluorescence tool (pXRF) were examined to identify geochemical trends among and between lava flow packages, as well as to help identify interbeds and weathered horizons when core samples could not be viewed in person. In case of the latter, pXRF data already held by GSNI was used.

In order to both calibrate and ascertain reliability, pXRF data values were compared with geochemical results generated by WD-XRF methods on identical samples. This process revealed that while the absolute values generated by pXRF tended to be unreliable (assuming WD-XRF values are more accurate and precise), the trends of element ratios used for identifying weathered horizons and interbeds (e.g. Ba/Sr) were consistently similar to those produced by WD-XRF data.

One key drawback of pXRF analysis for this application is that sodium cannot be detected, and that magnesium values above 3000 ppm are unreliable.

Additionally, pXRF data held by GSNI only had analyses for silicon, magnesium and aluminium in 2 of the 13 boreholes.

pXRF geochemical data usage

The barium (Ba) and strontium (Sr) ratio Ba/Sr is used as a proxy in this study. While soluble, barium has a tendency to adsorb onto clay minerals and so its resulting mobility is reduced in weathering and soil conditions. Strontium has a smaller ionic radius and is highly mobile in the weathering environment. In this regard, the ratio of

Ba to Sr represents a proxy for weathering intensity (Price et al., 1991; Babechuk et al., 2014).

Values for lead and zirconium that were measured on borehole cores were also plotted alongside plant ecology group data as peaks in these datasets may indicate the presence of limited thickness acidic tephra in the core (see Results; Figures 3, 4 and 5).

Magnetic susceptibility data usage

Chen, An & Head (1998) compared Ba/Sr ratios with magnetic susceptibility values of interglacial loess profiles and found remarkable similarities in the plotted trends. In Figures 4 and 5 we have plotted magnetic susceptibility values alongside plant ecology group data and Ba/Sr ratios to provide another proxy for the climate and weathering while the lavas were subaerially exposed. Additionally, peaks in magnetic susceptibility, e.g. visible towards the top of section in Figure 4, may also point toward the presence of thin basaltic ash deposits in the core.

MATERIALS

Analysis of the depositional history of the Interbasaltic Formation north of the Tow Valley Fault was based around three key sections: an operational quarry (Ross's Quarry) 4 km southwest from Ballycastle, and two cored boreholes NIRE 09/08-0001 and NIRE 09/08-0002 (Figure 1). Additional samples were incorporated from previously sampled exposures at Craigahulliar Quarry and the Giant's Causeway / Causeway Coast (Jolley, 1997), as well as from cored boreholes NIRE 02/08-0001 and NIRE 03/08-0001 situated to the south of the fault (Figure 1, Table 1).

Ross's Quarry

Ross's Quarry was visited in October 2020, at which time two interbeds were exposed: interbed 1 and a younger interbed 2, with thicknesses of 1.5 m and 2.5 m, respectively. The lithology of sedimentary interbed 2 is presented in Supplementary Data 1.

The geology exposed at Ross's Quarry in the Craignagat townland consists of basalts and interbeds of the Antrim Lava Group (Figure 2, plate I), but identifying the specific formations and members present in the quarry is difficult. The lower two flows (f1, f2) are laterally extensive, massive, thick (9–10 m), aphyric and lacking significant internal structure aside from jointing. The three upper flows (f3, f4 & f5) are of varying thickness at outcrop, contain phenocrysts of olivine, and are physically quite different; the thickness of f3 varies significantly across the site, pinching out in places, and displays disordered structures, not clearly identified but reminiscent of pillow lavas. Lava flows f4 and f5 show reasonably well-developed columnar jointing and compared to f3 have a more consistent thickness. In Figure 2, plate C shows f3 and f4, plate E shows f4.

Craigahulliar Quarry

The Port na Spaniagh Member of the Lower Basalt Formation and the Causeway Tholeiite Member of the Interbasaltic Formation (Figure 1) crop out at this repurposed quarry (now a landfill site). Here, a deep red silty clay palaeosol with a carbonaceous/lignitic claystone horizon has been attributed to the Port na Spaniagh Member (the Lower Interbasaltic Bed of Patterson, 1955; Figure 1). It is overlain by columnar jointed flows mapped as the Causeway Tholeiite Member, with evidence of the lava ploughing into the underlying palaeosol interbed and filled topographic lows (Wilson, 1965). The oldest of these flows has a well-preserved pahoehoe flow top, itself being overlain by a lignitic sedimentary interbed of uncertain thickness (due to a cover of thick vegetation). This interbed is overlain by a second columnar jointed tholeiitic basalt flow which crops out at the top of the hill within the Craigahulliar landfill site.

Giant's Causeway

The lavas exposed along Causeway Head between Portnaboe and Port Noffler bays have recently been mapped at high resolution by Simms (2021). Starting at sea level, Simms identified five flows of the LBF, the uppermost of which weathered to form the sediments and lateritic palaeosol of the Port na Spaniagh Member prior to the eruption and emplacement of the Causeway Tholeiite Member flows. Two flows of the Causeway Tholeiite Member are exposed above this. The structural relationship between exposures on the foreshore and those in the cliffs of Causeway Head remain debated.

Boreholes

Horizons interpreted as being of the Interbasaltic Formation are visible in core retrieved from the NIRE boreholes in this study. NIRE 09/08-0001 was also inspected, however, core from the lower section of this borehole was not available for inspection.

Composite logs were drafted using existing borehole logs provided by GSNI and supplemented by subsequent logging undertaken during fieldwork in October 2020 and October 2021. They are presented in part in Figures 4, 5, 6 and 7. Figure 8 presents selected core examples highlighting the nature of the lava flows as described within this study.

RESULTS

Palynology

Twenty eight samples from the interbeds 1 and 2 exposed in the Ross's Quarry succession were collected and analysed for their palynofloras (Figure 3). This analysis yielded variably diverse palynofloras with a total of 115 taxa, mostly comprising pollen and spores. These floras were dominated by taxa derived from the families Sphagnaceae, Polypodiaceae, Cupressaceae, Pinaceae, Betulaceae, Juglandaceae and Hamamelidaceae in assemblages of varying composition (Supplementary data 2). Algal palynomorphs were distributed throughout the Ross's Quarry interbeds succession, occurring in all samples. Recovery of palynomorphs was moderate to high, with two intervals (samples 215–217 and 220–221; Figure 3) of lower recovery. The lower of these intervals sampled an erosively-based coarse sandstone unit, the higher depositional energy probably caused winnowing of palynomorphs (Figure 3).

Palynofloras recovered from 52 core pieces from borehole NIRE 09/08-0002 were diverse (105 taxa) and revealed stratigraphical variation. The palynofloral assemblages can be divided into three intervals; the oldest occurs within both the youngest interbed within the Lower Basalt Formation and the lowermost Interbasaltic Formation lithologies, separated from each other by a deeply weathered lava flow; the next youngest assemblage occurs in carbonaceous shales and coals of the middle Interbasaltic Formation, and finally; the third assemblage occurs within mudstones separated by deeply weathered lavas near the top of the Interbasaltic Formation (Figure 4). The oldest floras are of low diversity and frequency, containing pine (*Pityosporites* spp) and swamp cypress (Taxodiaceae; *Inaperturopollenites* *hiatus*) pollen. These taxa are associated with a low frequency, moderately diverse angiosperm pollen flora, bryophyte spores and freshwater algae (Figure 4, Supplementary data 1). Carbonaceous sediments in the middle part of the Interbasaltic Formation yielded a palynoflora with sub-dominant *Cupuliferoidaepollenties, Cupuliferoipollenties* and *Tricolpites* species (Fagaceae). These are associated with common occurrences of other angiosperm pollen including *Nyssapollenites* species (Nyssaceae)*, Retitricolpites* species (Platanaceae), Myricaceae type pollen (*Triporopollenties coryloides*), bryophyte spores and variably abundant freshwater algae. The upper part of the Interbasaltic Formation in borehole NIRE 09/08-0002 is characterised by a palynoflora totally dominated by abundant *Botryococcus braunii* (green algae, Chlorophyceae). Only in the uppermost bed of this unit is a moderately diverse higher plant palynoflora recovered, dominated by *Tricolpites* cf. *hians* (Fagaceae), fern spores (*Laevigatosporites haardtii*) and alder type pollen (*Alnipollenties verus*).

Recovery of palynomorphs from borehole NIRE 09/08-0001 is limited, no cores being available below the uppermost few metres of the Interbasaltic Formation (Figure 5). Samples from this interval yielded palynofloras dominated by fern spores, in particular *Deltoidospora adriennis* and green algae (*Botryococcus braunii*). They also had a low diversity and frequency of angiosperm pollen. A more impoverished palynoflora was also recovered from an interbed within the Upper Basalt Formation, which was dominated by fungal hyphae (Supplementary data 1).

Samples taken from the deeply weathered basalt lavas of the Interbasaltic Formation in boreholes NIRE 02/08-0001 and NIRE 03/08-0001 yielded similar palynofloras, wholly dominated by green algae (Figures 6,7). A few scattered occurrences of pollen and spores were noted, an influx of *Retitricolpites retiformis* (Platanaceae) and *Tricolpites* cf. *hians* (Fagaceae) recovered from the lowermost bed of NIRE 02/08-0001.

A more diverse palynoflora was recovered from two thin beds of carbonaceous shales above the oldest lava flow of the Upper Basalt Formation in borehole NIRE 02/08-0001. These palynofloras are dominated by swamp cypress pollen (*Inaperturopollenites hiatus*), sub-dominant bryophyte and pteridophyte spores (*Stereisporites (Stereisporites) stereioides* and *Deltoidospora adriennis*) and common *Momipites tenuipolus* (Juglandaceae, hickory types). A similar, *M. tenuipolus* rich palynoflora of this type was also recovered from lignites cropping out between the two columnar jointed flows mapped as the Causeway Tholeiite Member at Craigahulliar Quarry (Figures 1; Supplementary data 1)

Additional samples from sedimentary interbeds within the Lower Basalt Formation exposed at Port Noffler to the east of the Giant's Causeway yielded palynofloras dominated by swamp cypress pollen (*Inaperturopollenties hiatus*). These were associated with sub-dominant fern spores (*Laevigatosporites haardtii*) and the angiosperm pollen *Retitricolpites retiformis* (Platanaceae) and *Cupuliferoipollenties* species (Fagaceae).

Age of the Palynofloras

Occurrences of the Normapolles taxon *Complexipollis sp* (Figure 9) are recorded in the lowermost samples from the Interbasaltic Formation in both the lowermost carbonaceous bed of interbed 2 in Ross's Quarry (Figures 2, 3) and within interbeds in the lowermost Interbasaltic Formation and Lower Basalt Formation of borehole NIRE 09/08-0002. This taxon is widely recorded from the Late Cretaceous (e.g., Tschudy, 1980). The scarcity of drilled subsurface, or exposed Danian strata, limits the record of this taxon in NW Europe, (see Krutzsch, 1966). Recent investigation of palynofloras from offshore Norway (Ormen Lange well 6305/8-2; Vieira et al., 2018) by one of the authors has consistently recorded *Complexipollis* sp. in Danian strata. Correlation with dinoflagellate cyst stratigraphy for this well (Vieira et al., 2018), indicates that this taxon occurs within an age range from 64.5 Ma to 63 Ma. This age is in agreement with the Ar-Ar age (63.24+/-0.61 MSWD) derived from Lower Basalt Formation lavas (Ganerød et al., 2009; Wilkinson et al., 2017).

The common to abundant occurrences of *Cupuliferoidaepollenites* and *Cupuliferoipollenites* in the middle beds of the Interbasaltic Formation in NIRE 09/02-0002 (Figures 4,8), and in the upper interbeds of the Lower Basalt Formation at Port Noffler (Supplementary data 1) probably reflect the widespread regional distribution of these taxa. Raised frequencies of these taxa have been recorded in strata of the Vaila and Lamba formations, deposited 61.3 Ma to 59.6 Ma in the Faroe-Shetland and Rockall basins (Jolley et al., 2021).

The lignites exposed between the lower two flows of the Causeway Tholeiite Member at Craigahulliar Quarry (Figure 1) yielded common *Momipites tenuipolus* (Figure 9). An influx of *M. tenuipolus* was also recorded in carbonaceous interbeds between the oldest flows of the Upper Basalt Formation in borehole NIRE 02/08-0001. Similar common occurrences of *Momipites* species and *M. anellus* in particular, have been recorded across the Selandian–Thanetian boundary in the North Sea Basin (Jolley & Morton, 1992) and the Faroe Shetland Basin (Jolley et. al., 2021). A correlative flora with common to abundant *Momipites* species, including *M. tenuipolus* has also been recorded from the Thanet Sands Formation of Kent, southern England (Jolley, 1998). In the NAIP, common occurrences of *M. tenuipolus* have been recorded within the upper Vaila to early Lamba formations of the Faroe

Shetland Basin to the northeast and occurs in the Thanet Sands Formation of south eastern England and is therefore indicative of an age of approximately 59.5 Ma to 59.0 Ma (Jolley et al., 2021) for the oldest units of the Upper Basalt Formation in borehole NIRE 02/08-0001.

Depositional Environments of Interbed 1 (Ross's Quarry)

Exposed between two flows of the Causeway Tholeiite Member, the lower part of this < 2 m thick unit is barren of palynoflora. This may indicate that these oldest sedimentary rocks were derived relatively rapidly from eroded basaltic lava flows or reworked basaltic tephra. However, 20 cm above the base of the unit, lacustrine palynofloras dominated by green algae are recorded. Frequencies of lacustrine palynomorphs decline up-section, reflecting a decline of lacustrine influence (Figure 3). The youngest palynoflora is dominated by bryophyte spores and early to mid-succession angiosperm pollen. The absence, or sparse occurrences of such pollen in the lower 0.5 m of this bed suggests that the sedimentary source may have been reworked tephra (Ebinghaus et al., 2017). The increase of pollen and spore frequency up-section is mirrored in kerogen sorting. Very well-sorted vitrinite characterises the oldest samples. Sorting decreased up-section, reflecting encroachment of vegetation in the lacustrine catchment. Although this is predominantly a reddened interbed of the kind often described as a laterite, the abundance and preservation of structured organic material negates formation by weathering. Instead, the red colour of the bed is probably derived from the source material of which it is composed. Red sandstone and claystone units of this character are common in the NAIP (e.g., Passey & Jolley, 2009), and while some are formed from pedogenic degradation of basaltic lavas (e.g., Williamson et al., 1996), many are derived from transported and degraded basaltic volcaniclastic material (e.g. Jolley et al., 2022).

Depositional Environments of Interbed 2 (Ross's Quarry)

The lowest subunit of interbed 2 is a carbonaceous siltstone passing laterally into lignite deposits including fossilised wood and bark fragments (Figure 2 plate F and F'). Palynofloras from this interval include common algae, spores derived from a bryophyte-dominated wetland community and riparian associations, indicating deposition in a lacustrine palaeoenvironment. Cross stratification of the overlying 1.7 m of interbed 2 indicates that it was laid down by a shallow fluvial channel system (Figure 3). The occurrence of acritarchs, chlorophycean algae, copepod eggs and testate amoebae (*Arcella* spp.) support an interpretation that it was deposited in a fresh- to weakly-brackish water environment. Occurrences of the acritarchs *Micrhystridium* and *Leiofusa* spp. are concordant with deposition in a very low salinity fluvial system with a link to the marine environment. Assemblages of this type have been recorded in tidally influenced fluvial channels in the lava fields of the Faroe Islands Basalt Group (Jolley et al., 2022).

Overlying this tidally influenced fluvial channel is a unit of darker silty clays with abundant rhizomatous root structures (Figure 3). These originate within and at the top of the silty clay bed, but penetrate down > 30 cm into the underlying cross bedded sandstones. Abundant occurrences of the pteridophyte fern spores *Deltoidospora maxoides* and *D. adriennis* in high dominance, low diversity samples (samples 216–219, Figure 3) from the silty clays indicate that the rhizome structures belong to ferns which likely colonised intra-channel mudbanks.

The 55 cm claystone bed between the top of the silty clays and the overlying basalt lava flow was also penetrated by more infrequent rootlet structures (Figure 3). The palynoflora from this interval is of lower diversity, but the spore/pollen assemblages are again dominated by *D*. *adriennis* and *D*. *maxoides* suggesting that the root structures originated from ferns colonising the emergent surface of the claystone unit. Occurrences of *Arcella* spp. (testate amoebae), *Botryococcus braunii* (green algae), Copepod eggs and *Concentricystes* sp. within this claystone unit indicate that it was deposited in a quiescent freshwater environment. Taken together with only minimal indications of lava – surface water (or wet sediment) interaction at the base of the overlying basalt flow, these data indicate that a low energy channel margin was likely abandoned and colonised by ferns. The fall in base level that this resulted from ensured that the overlying lava flow was able to completely fill and overstep the accommodation space previously occupied by the fluvial system.

Catchment vegetation ecology

Because interbed 2 was deposited within a fluvial channel system, pollen and spores derived from the catchment area are well-preserved. These complex assemblages reflect changes in the plant ecology of the catchment. Because of this complexity, the pollen and spore data was subjected to DCA to express the variability in the data set on two principal axes. This analysis identified nine groups, of which three were based on single outlying taxa (Supplementary data 2). Multi species groups were named according to the known botanical affinities and environmental tolerances of the taxa included in them (Gruas Cavagnetto, 1978; Jolley et al., 2009). The stratigraphical distribution of these DCA groups was plotted against the graphic lithology logs to highlight correspondence between bed units and changes in catchment palaeoecology.

The lowermost sedimentary rocks of interbed 2 (0.2–0.5m, Figure 3) were co-dominated by pollen from the True Swamp (Group D) and Fluvial/Fen Carr (Group F) communities. Dominated by *Inaperturopollenites hiatus* and *Pityosporites* spp. respectively, this co-dominance of True Swamp and Fluvial/Fen Carr groupings is characteristic of fluvial channel facies. Both groups are dominated by pollen from known pollen overproducers (Pinaceae, Cupressaceae), these taxa occurring abundantly in fluvial to shallow marine Paleogene sediments of the NAIP (Simpson., 1961, Jolley, 1997; Jolley et al., 2021). Evidence of increased influence from a Fen Carr association along the riparian margin is presented by increased frequencies of the betulaceous pollen *Alnipollenites verus.* Occurring commonly at the base of the cross-bedded sandstone unit (Figure 3), this Fen Carr association declines in frequency up-section. This decline is correlated to a change in assemblage character from 0.5 m to 0.65 m, where palynofloras are dominated by *Classopollis* sp pollen (Group I). The parent plants of these pollen are included in the family Cheirolepidaceae, plants held to become extinct at the Cretaceous-Paleogene boundary. While there is no conclusive evidence that these pollen were reworked from Upper Cretaceous strata in the catchment area, a reworked Ulster White Limestone source within the catchment area appears likely. It is notable that the common occurrences of *Classopollis* pollen do not correspond to lithofacies changes in the exposure (Figures 2,3), suggesting a catchment control on their occurrence.

Overlying these transported fen carr and fen assemblages, is an abrupt shift at 1.725 m (Figure 3), to spores derived from a Sphagnaceae ombrotrophic bog, dominated by *Stereisporites (Dicyclosporis)* spp. The total dominance of this taxon is indicative of the development of a raised, ombrotrophic bog. Further development of the bog is marked by the replacement of Sphagnaceae spores by abundant bryophyte spores

(*Corrusporis* spp.). These spores wholly dominated the transported in-channel assemblage sampled at 1.05 m, marking the upper limit of a base level fall trend within the catchment (Figure 3). Overlying the ombotrophic bog associations, an abrupt assemblage change was recorded at 1.425 m (Figure 3), reverting to dominance by Fluvial/Fen Carr community (groups F, G). There is no apparent major corresponding change in the sedimentary structures of interbed 2 at this level, but this assemblage change signifies a shift in the catchment from ombrotrophic bog to riparian fen carr. This is associated with an influx of Copepod eggs, occurring with *Micrhystridium fragile*, *M. stellatum* and a dinocyst fragment indicating a weak brackish water penetration into the fluvially dominated channel system.

At 1.025 m (Figure 3) the fen community is abruptly terminated, reflecting the incision of a separate cross-bedded channel (Figure 2). Palynofloras derived from these coarser channel sandstones are of lower diversity and abundance. The palynoflora was initially dominated by an in-channel taphonomic grouping of transported taxa (groups D and E), which is rapidly replaced by mid-successional community taxa (Group C). This largely pteridophyte spore dominated group includes *Deltoiospora adriennis*, a taxon associated with crevasse splay and inter-channel sand bank colonisation.

Occurrences of abundant *D. adriennis* continued to dominate the mid-successional community (Group C) recovered from the overlying rhizomatous silty clays (1.77–1.83 m). Within this unit, assemblage diversity fell and abundant *Deltoidospora maxoides* was recorded. The dual dominance of polypodiaceous and schizaceous ferns in this silty clay unit indicates deposition as an inter-channel emergent sandbank. This emergent sandbank deposit is overlain by claystones with poor palynofloras which are essentially similar to those recovered from the silty clays below. Taken together with the fine grain size and laminar bedding, this unit can be interpreted as being deposited in a low energy channel marginal area, or abandoned channel.

The uppermost 1 cm unit of interbed 2 is significantly different, being marked by an influx of fresh water palynomorphs at 2.3 m, including testate amoebae and *Concentricystes* sp. (Zygnemataceae; Grenfell, 1995). Pollen and spores occur in a low diversity and high dominance assemblage with high frequencies of transported *Pityosporites* spp. (Pinaceae, Group G: Riparian/Channel. Transported Pinaceae pollen and the common occurrence of mixed freshwater-brackish algae indicate deposition of this interval in a fluvially dominated channel. Although rootlets penetrate this bed, there is no evidence for a horizon with rootlets at the top of interbed 2. The non-invasive lower surface of the overlying basalt lava flow indicates that the underlying sediments were probably a dry surface and may have been partly lithified or consolidated. It could be expected that the flooding event at 2.3 m would be overlain by sedimentary rocks deposited during a falling base level, like those seen in the two preceding cycles (Figure 3). The absence of such deposits at the top of interbed 2 could potentially either reflect (a) thermal uplift and landscape rejuvenation associated with eruption of the overlying Upper Basalt Formation lava flows, (b) the lowering of hydrological and hydrogeological water levels due to fracture propagation and expansion associated with thermal uplift, (c) some other mechanism or a combination of all of these.

Depositional Environment, Borehole NIRE 09/08-0002

The majority of the palynofloras recovered from the Interbasaltic Formation of borehole NIRE 09/08-0002 contained algae, indicating that the deposits originated in a succession of freshwater lacustrine environments. The lower unit of the Interbasaltic Formation contained a sparse palynoflora, but with no evidence of degradation of the organic debris. Frequent occurrences of *Pityosporites* spp from 161 to 157 mbgl are associated with a low frequency flora, including early mid successional angiosperm pollen and bryophyte spores. Influxes of *Pityosporites* spp in lacustrine deposits are normally a reflection of wind transport or fluvial input, the pollen being readily transported from an upland or topographically raised source area. The low frequency of other pollen and the numbers of *Stereisporites* species (bryophyte) indicate that the catchment area was only poorly vegetated or barren. Ba/Sr ratio trends derived from pXRF data indicate that the rocks comprising the lower interval of the Interbasaltic Formation in this borehole were moderately weathered. Ratios for interbeds and lavas from both the Lower Basalt Formation and the overlying Upper Basalt Formation flows are typically <3. From the base of the lower interval of the Interbasaltic Formation, Ba/Sr increases to 146.5 (149.5m), remaining at comparable levels until within the oldest part of the upper Interbasaltic Formation unit (Figure 4). This includes the middle section of the Interbasaltic Formation where palynofloras are diverse and abundant.

While the increase in Ba/Sr within the upper part of the Interbasaltic Formation probably reflects increased weathering of the sediment, it does not demonstrate that this weathering happened in-situ. The presence of freshwater algae in this interval suggests deposition in ephemeral lakes or floodplains with little surrounding vegetation. Other examples from the Faroe Islands Basalt Group (Passey & Jolley, 2009; Jolley et al., 2022) are interpreted as accumulations of redeposited volcanic ash and erosion products from adjacent flow fields. In addition, two prominent increases in magnetic susceptibility (Figure 4) could potentially reflect the presence of airfall ash layers (Rosenthal et al., 2018). The most probable interpretation is that this interval represents a complex period of slow vegetation recovery after cessation of Lower Basalt Formation eruptions, and a disturbed floodplain environment in which ashfall may have reset the vegetation communities within the area (Ebinghaus et al. 2015).

Depositional Environment, Borehole 09/08-0001

There is limited data from this borehole, samples only being available from an interbed above the Causeway Tholeiite Member lavas. In this interbed, abundant *Deltoidospora adriennis*, a taxon associated with crevasse splays and channel margins, dominated an early succession flora. Abundant lacustrine and lacustrine marginal palynomorphs indicate that these spores were deposited in ephemeral lakes (Figure 5). In contrast to the extensively weathered lavas and late successional swamp communities identified in the nearby borehole NIRE 09/08-0002, the flora recovered in NIRE 09/08-0001 indicates only a short term eruption hiatus.

Depositional Environment, boreholes NIRE 02/08-0001 and NIRE 03/08-0001

The Interbasaltic Formation penetrated by these two cored boreholes is composed of deeply weathered basalts. Short intervals where green algae are recorded commonly indicates that these weathered flow fields periodically hosted lakes. The low frequency of higher plant pollen is probably partly attributable to extensive oxidation of organic matter during this long period of slow sedimentation and weathering. This does not explain the low frequencies of pollen and spores in samples with common algal preservation. This can be attributed to volcanic disturbance of the catchment vegetation similar to that observed in the Columbia

River Large Igneous Province (Ebinghaus et al., 2017), or alternatively that the interbed sediments were deposited rapidly in ephemeral lakes.

The flora recovered from interbeds in the lowermost Upper Basalt Formation of borehole NIRE 02/08-0001 were sourced from a well-established, transitional swamp, mid successional floral community. This is closely comparable to the *Momipites tenuipolus* dominated palynoflora from the interbed within the Causeway Tholeiite Member at Craigahulliar Quarry, which was deposited in a similar, transitional swamp environment.

DISCUSSION

Exceptional Ecosystem

There are numerous palynofloral records from acid swamps within the NAIP, with communities ranging from lacustrine and riparian to transitional and true swamp (e.g. Jolley, 1997; Schofield & Jolley., 2013). These are characterised by abundant pteridophyte fern spores, often *Laevigatosporites haardtii or Deltoidospora* species derived from primary coloniser ferns (e.g., Figures 3, 5; Jolley et al., 2009). In early to mid seral successional states, swamp palynofloras include juglandacaeous angiosperm pollen (e.g., *Caryapollenties* species, *Momipites* species, *Platycaryapollenites* species), alongside *Cupuliferoipollenites* species (derived from Fagaceae) and Normapolles pollen, probably from herbaceous plants (e.g., Figures 5, 6; Daly & Jolley, 2012). Recorded diversities are high with mid succession communities being well-developed in floodplain swamp community mosaics. Plant macrofossil assemblages of similar composition, dominated by *Glyptostrobus (*pollen taxon *Inaperturopollenites)* and *Cupuliferites* (related to several *Favitricolporites, Tricolpites* and *Cupuliferoipollenties* species) have been recorded from Glenarm

Quarry (grid ref: D304156, Figure 1) in 19th Century fossil collections (Boulter & Kvacek., 1989).

Climax or late seral succession vegetation is mostly preserved as Cupressaceae dominated lowland swamp, often partly as a coastal ecosystem (e.g., Jolley et al., 2009). An alternative to lowland swamp cypress (Cupressaceae, *Taxodium* or *Metasequoia*) late succession communities have been recorded more rarely as upland fern-conifer forest within the basalt lava fields of the Skye Main Lava Series (Jolley, 1997). Macrofloras of comparable composition have been recorded from Ballypalady and Glenarm Quarries (Figure 1) by Gardner (1883-1886), the flora being interpreted as being derived from a mixed mesophytic forest by Boulter & Kvacek (1989) in their review of museum specimens.

In the majority of the records of swamp vegetation communities both within and immediately preceding a period of active volcanism, water draining into the catchment may have been dominantly acidic. Macronutrient availability would have been highly variable in these settings (Jolley et al., 2008), and only sites proximal to contemporary volcanism would have experienced significant eutrophication. While this is true of interbasaltic sedimentary depositional systems, the more limited record of plant ecosystems deposited in environments immediately prior to the onset of volcanism also follows this pattern. Examples from sub-basaltic strata in the NAIP (Mull lava field, Jolley et al., 2008; Faroe Islands Basalt Group, Passey & Jolley, 2009, Faroe Shetland Basin, Schofield & Jolley, 2013; Jolley et al., 2021) show limitation of seral succession by the onset of volcanism but are essentially all swamp-dominated ecosystems.

An exception to these acidic swamp ecosystems was identified from the palynofloras of interbed 2, which point to a significant influence on the pH of groundwater chemistry within the catchment area (Wheeler & Proctor, 2000). The palynoflora of interbed 2 represents the only known published record of a fen ecosystem in the Paleocene of the Northeast Atlantic margin. The common occurrence of *Alnipollenites verus* in sample 205 (at 2.155 m below datum, Figure 3) marks the establishment of an Alder fen carr community within the catchment. In addition to confirming a falling base level during deposition of the lower 1 m of interbed 2, the transition from channel to fen carr and succeeding fen communities identifies the necessity for a higher pH groundwater (Godwin *et al*., 1974; Wheeler & Proctor, 2000).

Although the current land surface of the Ballycastle region is covered by extensive basaltic lavas, the fen ecosystem indicates that this area drained a landscape which was at least in part formed by the Late Cretaceous Ulster White Limestone Group (Figure 1), of which the remaining extent is now almost entirely covered by the Antrim Lava Group.

The subsequent gradation of the oldest identified fen community into sphagnum bog and subsequently a bryophyte dominated raised ombrotrophic bog formed the late successional vegetation during this first period of base level fall. A subsequent rise in base level at the start of the second depositional sequence raised the groundwater table and reset the vegetation ecology. This second depositional cycle occurred during a second period of base level fall and resulted in a second influx of transported upland pollen and dominance by the riparian *Alnipollenties* (Alder) fen carr.

Interbeds, laterites and lithomarges

Our palynological investigations have revealed that all but a few of the red interbeds examined in this study have a significant component of lacustrine influence, showing a floral assemblage of a landscape experiencing a temperate climate not dissimilar to our modern climate. Of the few red interbeds without lacustrine signals in the palynological data, most were barren.

The floral assemblage of Paleocene Antrim varied spatially and temporally for several reasons, with explosive volcanic activity represented by the rocks of the Interbasaltic Formation being of particular importance. Deepening our understanding of interbed palynology will be critical in building up a story of the timing of Antrim Lava Group volcanic activity.

The palynofloral evidence recovered in this study is that all of the palynofloras were derived from mesic vegetation communities. Previous studies including evidence from macrofloras and palynology have attributed the macrofossil record of the Antrim Lava Group to a mixed mesophytic forest (Boulter & Kvacek, 1989) which was stated to be subtropical. Palynofloral assemblages recovered for this study concur that the vegetation was derived from mesic vegetation, including communities which could be attributed to a mixed mesophytic forest. However, other authors (Wang, 1961, Wolfe, 1979, Bondarenko et al., 2020) describe floras of this character as warm temperate.

Palaeoclimate context

Because of the long period of time spanned by Antrim Lava Group activity, the Antrim area was undoubtedly subject to climatic variation during the Paleocene. The Lower Basalt Formation postdates the early Danian Dan-C2 hyperthermal (65.2 Ma, Quellevere et al., 2008), being erupted during a period of relatively stable $\delta^{18}O$ and $\delta^{13}C$ values (Westerhold et al., 2020). Although the time interval spanned by the Antrim record includes the Late Danian Event (62.2 Ma, Westerhold et al., 2011; Bornemann et al., 2021) and the Early Latest Paleocene Event (Bralower et al., 2002), these are short duration potential warming events which would not induce long duration tropical weathering. Our data supports extensive weathering of basaltic lava flows, principally during the period of the Interbasaltic Formation. Evidence that this period of low tempo eruptions and volcanic quiescence experienced two or more phases of long term lava flow weathering is clear in the lithological and biostratigraphical data (Figure 10). Alteration and weathering of lava flows continued during the Interbasaltic Formation and appears to have been contemporary with eruptions (e.g. weathering of the upper Interbasaltic Formation in 09/08-0002 potentially co-occurred with eruption of the Causeway Tholeiite Member, e.g. NIRE 03/08-0001).

There is currently no convincing evidence that Antrim Lava Group volcanic activity was linked to either the Latest Danian Event (Sprong et al., 2013) or the Early Late Paleocene Event (Petrizzo, 2005), both of which occurred within the period of Interbasaltic Formation deposition (Figure 10). Volcanic activity during the Interbasaltic Formation period is broadly coincidental with eruptions in the Inner Hebrides (Figure 10). Eruption of the Upper Basalt Formation has limited absolute age control (Wilkinson et al., 2017), but could be contemporaneous with eruptions of the Skye Main Lava Series. Constrained by isotopic dates for the Isle of Rum western granophyre and the Skye Cuillins Complex pegmatite dyke (Wilkinson et al., 2017; Jolley et al., 2021), the Skye Main Lava Series erupted during volcanic Phase 1 of the British and Irish Paleogene Igneous Province (BIPIP). This late stage Phase

1 effusive volcanism could be linked to the negative carbon excursion of the Early Late Paleocene Event, although a more precise chronostratigraphy is desirable.

Antrim Lava Group thickness and volume

Examination of 19 borehole records with detailed log notes gave a range of lava flow counts per borehole from 5 to 104, with one of these being excluded as only tuffaceous rhyolite was encountered (NIRE 01/08-0001). The remaining borehole records from 18 Lonmin boreholes showed flow counts from 5 to 84 individual lava flows, with an average lava flow thickness of 4.82 m based on 581 discrete flows, the thickest of which was 32.77 m. The distribution of flow thicknesses is presented in Figure 11.

Using a combination of open source satellite data and GSNI geological maps in QGIS we estimate the areal extent of the Antrim Lava Group to be 4,093 km^2. Using geological data from 55 boreholes across the Antrim plateau we found the following average thickness values for the Antrim Lava Group sub-units and as a whole:

Upper Basalt Formation	*158.90 m*
Interbasaltic Formation	*37.01 m*
Lower Basalt Formation	*132.48 m*
Antrim Lava Group	***328.40 m***

The thickness of the Antrim Lava Group varies significantly over the plateau but from the 55 borehole records we have calculated an average thickness of 328.40 m, and note the maximum recorded thickness of 771 m in the Ballymacilroy borehole (Thompson, 1979). If this maximum thickness were taken as being the originally emplaced thickness across the entire lava field, we get an estimated emplaced lava volume of 3,156 km^3. If we instead take the average measured thickness, we would arrive at an emplaced lava volume of 1,344 km^3. Clearly significant erosion has taken place during and subsequent to effusive volcanism, whilst the component of the province that would originally have extended beyond the modern day coastline is unconstrained and would imply estimates based on preserved thickness are likely conservative.

Rates of lava emplacement

Approximating the rates of effusion, eruption or emplacement for a sub-province of the Paleogene NAIP is not straightforward. However, recently active volcanic systems might give us the closest analogous data for rates of effusion of the Antrim Lava Group flood basalts, as well as the wider NAIP and potentially other basaltic LIPs. In the last 1100 years there have been two large basaltic eruption events in Iceland; Eldgjá in 934 and Laki in 1783. These events have been studied and their rates of effusion have been calculated (Eldgjá; Thordarson & Self, 2001) or gleaned from anecdotal evidence (Laki; Thordarson & Self, 2003). These basaltic effusions on Iceland provide relevant examples for interpreting the ALG due to their geographic location within the NAIP and possible connection with the tectonic and mantle processes that gave rise to the lavas of Antrim.

Thordarson & Self (2001) stated that the Eldgjá basaltic flood lava eruption is the largest on Earth in the last millennium. These fissures produced 19.6 km^3 of basalt in 8 distinct phases of activity that spanned 3 to 8 years (in the period 933 to 941 AD). Conversely, Thordarson & Self (2003) calculated that the Laki fissure eruption had effused around 90% of the total volume of basaltic lava within just 5 months (14 km^3), reaching 100% in just 8 months (14.7 km^3). To give context to these events, the 6 month eruption at Holuhraun, Iceland (2014-15) produced just 1.44 km^3.

If we take their calculated rates of magma effusion for these volcanic events (Table 2) and apply it to the possible total volumes for the Antrim Lava Group estimated above, we find that volcanic events on the scale of Eldgjá and Laki would be capable of emplacing the entire Antrim Lava Group within 40 to 1288 years (Table 3).

We know, from a variety of existing research as well as our own findings, that the emplacement of the Antrim Lava Group spanned several million years, perhaps as long as 4.5 million years. Combining this information with the evidence of abundant weathered tops, palaeosols and other well-developed interbeds between flows of the Antrim Lava Group (Hill *et al*., 2000), even our most conservative estimates of effusion rate imply that >99.9% of the geological time locked away in the ~800 m thickness of basalt resides within these palaeosols, boles and interbeds.

Interbeds of the Antrim Lava Group

To date, mostly due to the geochemical and petrological similarities between the lavas of the Lower and Upper Basalt Formations, differentiating these lava formations has mostly focussed upon identifying the presence and relative position of the well-developed 'Interbasaltic Formation' interbeds that signify a break between these two distinct episodes of flood basalt volcanism. Where the interbed is absent or not seen, field identification of the Lower or Upper Basalt Formation is almost impossible.

We have focused primarily on the boles and interbeds of the Interbasaltic Formation, but numerous interbeds are found at various horizons among the basalt flows of the

Lower and Upper Basalt Formations (Figure 12), signifying indeterminate periods of subaerial or subaqueous exposure and weathering throughout the emplacement of the Antrim Lava Group. The regular occurrence of these interbeds among the lava flows of the Antrim Lava Group suggests that relatively long periods of quiescence were common throughout the emplacement of the sub-province.

In this work we have linked the formation of these interbeds to a wet and fertile landscape of swamps, mesic vegetation, rivers and lakes; all of which require time and the absence of significant local volcanism in order to develop. Our results suggest that a chronology based on hiatus duration and weathering horizons holds strong potential to constrain eruptive tempo. At this stage, we provide an initial qualitative analysis; a full quantitative investigation would require additional methodological development and dating that falls outside the scope of our current research.

Focusing on these interbeds is key to unlocking the emplacement timing of the Antrim Lava Group, and this likely applies to different sub-provinces of the NAIP as well as other basaltic LIPs around the globe. Plotting the depth of basalt weathering against flow group thickness (Figure 13) provides a glimpse of the eruptive tempo analysis that may be possible, but quantifying rates of basalt weathering, particularly given uncertainties over contemporary climatic and hydrological/hydrogeological conditions, remains highly challenging. The thickness of weathered horizons among a lava pile is not a robust indicator of time between flows since numerous factors are at work, such as flow composition, flow crust thickness and type, run-off and climate. That said, the plots in Figure 13 give some early indication of the non-linear distribution of effusive episodes and intervening time hidden in these thin horizons pointing towards the need for more detailed future investigations.

The emplacement timing, or volcanic tempo, must also take account of the spatial variability of eruptions, i.e. the presence of the Causeway Tholeiite Member appears to be restricted only to the north of the Tow Valley Fault and suggests that not every episode of volcanicity would have contributed to emplacement across the entire Antrim Plateau, an observation that is also well documented in other parts of the province such as on the Faroe Islands and in the Faroe Shetland Basin (Millett et al., 2017; 2021).

Investigation of NIRE borehole cores has identified certain geochemical flow groups that are absent at other locations. Indeed, analysis of the earliest basalt flows in some NIRE boreholes suggests that first flows at those locations were of the Upper Basalt Formation, likely millions of years after the initial onset of Lower Basalt Formation volcanism elsewhere in the ALG. Combined with the knowledge that calciphile ecologies were providing pollen and spores at the time that sands and silts of the sedimentary interbed at Ross's Quarry were being deposited (interbed 2), it is inferred that some limestone uplands must have persisted after the cessation of Lower Basalt Formation lava emplacement. The present day configuration of the Antrim Lava Group almost entirely covering the limestones of the Ulster White Limestone Formation therefore reflects burial that must have been completed during emplacement of the Interbasaltic and the Upper Basalt Formations.

Increasing our understanding of the basaltic lava fields of the BIPIP and the interbeds contained within has implications beyond academic research. Important hydrocarbon reserves are held within siliciclastic interbeds within the Faroe-Shetland Basin north of the UK with fields such as Cambo and Rosebank looking like they will move towards development (Hardman *et al*. 2018; Duncan *et al*. 2020). Recent studies focused on the sub-surface characterisation of the volcanic sequences in the

Rosebank Field have highlighted the potential for integrating sub-surface borehole data to better understand the volcanic facies, their distribution, correlation, and implications for associated sediment reservoirs (Millett *et al*. 2021). Similar approaches to the sub-surface characterization of the Antrim borehole data for facies analyses may be applied going forward and will help to improve future appraisal of energy resources within the province. In the same way, the potential for Carbon Capture and Storage (CCS) projects within the province (e.g. Andrews, 2023) will benefit from an improved appreciation of how these lava fields develop over time in terms of emplacement, volcanic facies, volcanic tempo and associated alteration which can significantly impact reservoir properties (e.g. Liu *et al.*, 2012; Rosenqvist *et al*., 2023; Rosenqvist *et al*., this volume; Millett *et al*., this volume) and the presence of potential inter-lava sediments.

Integration of focused and detailed palynological studies with high resolution petrological and laboratory geochemical analysis of NIRE borehole core samples and field exposures holds further potential to advance the understanding of flood basalt emplacement mechanisms and timing, the ecology of the local environment and climatic impacts of these eruptions.

CONCLUSIONS

Within this study, a detailed appraisal of interbeds among the lavas of the Antrim Lava Group, focussing on the Interbasaltic Formation, was carried out using a combination of geochemical and palynological analyses. From this study we can draw the following conclusions:

1. New palynological evidence suggests:

i. A warm temperate climate, not subtropical,

ii. An established fen carr was in the catchment area of sediments deposited during the emplacement period of the Causeway Tholeiite Member, and that

iii. Areas of Ulster White Limestone Group persisted coevally with the emplacement of the Causeway Tholeiite Member.

2. Re-evaluation of NIRE borehole core and field outcrop revealed:

i. The presence of a 2.5 m thick sedimentary unit among flows of the Causeway Tholeiite Member at Ross's Quarry, near Ballycastle,

ii. Much of the Interbasaltic Formation is, or was, basaltic lava, and that

iii. In places the Antrim Lava Group has at least 84 discrete lava flows (NIRE 09/08-0002).

3. The presence and distribution of weathering horizons among the Antrim Lava Group is not evenly distributed and suggests that the locations of effusion and eruption moved around over the period of emplacement and that the eruptions were often significantly spaced out over time.

4. Improved knowledge of the internal structure and composition of BIPIP lava fields can aid with understanding energy resources and associated reservoirs in the province, e.g. Rosebank, Cambo as well as the assessment of potential reservoir rocks for CCS.

5. This study highlights the need for high resolution, focussed palynological and geochemical investigation of all Antrim Lava Group boles, laterites and interbeds in

order to more fully constrain the volcanic tempo, ecological diversity, local environment and the wider environmental impacts of the basaltic, intermediate and acidic volcanism of the Antrim Lava Group.

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Figure Captions

Figure 1 (a) Map of the Antrim Lava Group. The inset map shows the location of the ALG, NAIP sub-provinces, and the NAIP outline (Horni et al., 2017) within the wider setting, and (b) lithological sections of the studied boreholes and field locations.

Figure 2 Field photos from Ross's Quarry. OVERVIEW. Aerial view of the quarry and locations of images. A. Interbed 2 detail. B. Interbed 2 setting below subsequent lava flows. C. Interbed 3 between lava flows f3 and f4 (showing weak columnar jointing). C'. Fossilised fallen tree trunk on interbed 3 surrounded by f4 lava flow. D. Fossilised root structures (within interbed 3) between f3 and f4 lava flows. E. Well-developed columnar jointing in flow f4. F. Example of the well-preserved fossilised wood found within interbed 2 (although not found *in situ*). G. Detail of interbed 1. H. Detail of hollow structure located within flow f4, possibly evidence of sediment ploughing or cavity infil where once a tree had been. I. Detail of interbed 1 between flows f1 and f2. J. Section of the northwest wall of the quarry detailing the stratigraphy.

Figure 3 Ross's Quarry location, lithology and palynofloral communities.

Figure 4. Borehole NIRE 09/08-0002 lithology and palynofloral communities.

Figure 5. Borehole NIRE 09/08-0001 lithology and palynofloral communities.

Figure 6. Borehole NIRE 02/08-0001 lithology and palynofloral communities.

Figure 7. Borehole NIRE 03/08-0001 lithology and palynofloral communities.

Figure 8: Figure highlighting typical features of the Antrim lava pile as seen in NIRE borehole core. (**a**) Example of a simple pāhoehoe lava flow from within Lower Basalt Formation of the 02 08 0001 borehole showing typical asymmetrical vesicle distribution and oxidation towards the flow top. (**b**) Example of a compound

pāhoehoe lava flow from within the Lower Basalt Formation of the 02 08 0001. (**c**) Details from the Ballylagan Member of the Inter-basaltic Formation highlighting the presence of rubbly flow margins associated with flow margin autobrecciation. (**d**) Reworked and leached scoriaceous breccia clasts in oxidized matrix. (**e**) Reworked and deeply altered volcaniclastic breccia with scoriaceous clasts likely reworked from underlying rubbly flow top. (**f**) Detail of flow top breccia.

Figure 9: Palynomorphs from the Antrim Lava Group. *Complexipollis* sp. 1) sample LAT005, Clinty Quarry, K39/1; 2) 09/08-0002 161m U41/2; 3) 09/08-0002, 167.85m Q41; 4) Ross's 207, M35; 5) *Nudopollis terminalis* 09/08-02, 132.5m, T34/2. *Trudopollis hammenii*, 6) 09/08-0002 109m, C39/4, 7)SEM photograph, Ross's. *Complexipollis* sp. 8-10) Ross's, 10 showing high magnification of the colpate aperture in 9. 10, 11) *Tricolpites* cf *hians*, 09/08-0002, 131m, 11, showing high magnification view of Platanaceae type reticulum. *Arcella* sp. testate amoeba from Ross's 222, X42/2. 12) *Cupaneidites* sp (Loranthaceae), 09/08-0001, 254.25m, R48/1*. Caryapollenites circulus*, 09/08-0002 109m, Q27. 13*) Alnipollenites verus,* Ross's 205, U21. 14) *Ericipites ericius* 09/08-0002, 112m, Q31/1. 14)*Tricolpites hians*, 09/08-0002 109m, L33/1. 15) *Cupuliferoidaepollenites liblarensis* 09/08-0002, 109m, V43/4. 15) Acanthomorph acritarch, SEM photograph, 09/08-0002, 133m. 16) *Classopollis* spp., characteristic cluster, Ross's 206, G31/1, 17) *Classopollis* spp., Ross's 208, J41/3. 18) *Classopollis* spp., SEM photograph showing single sulcus. Note the thick, ornamented wall, Ross's. *Pentacolporites* sp Ross's 212, L39/3. 25) *Concentricystes* sp. 09/08-0002, 109m, N46. 26) *Concentricystes* sp., 09/08-0002, 110m, R32/3. 27)*Micrhystridium stellatum*, Ross's 206, W46/4. 28, 29) *Corrusporis* sp. Ross's 209, G43/4. Ballycastle 208, F31/1. 30) *Stereisporites* (*Dicyclosporis*) sp. Ross's 208, M23/4. 31) *Stereisporites* (*Dicyclosporis*) sp. Ross's 210, N18. 32)

Stereisporites (*Distannulisporis*) sp. Ross's 0.15, N17. 33) *Echinosporis cycloides* Ross's 207, L23. 34) *Botryococcus braunii*, Ross's 206, M47/4.

Figure 10. Antrim stratigraphic table showing interpretations from palynological and geochemical findings.

Figure 11. Antrim Lava Group flow thickness histogram summarising the distribution of lava flow thicknesses encountered in all NIRE boreholes.

Figure 12. Antrim Lava Group boles and interbeds. A. Craig's Quarry. B. Blackmountain Quarry. C. Clinty Quarry. D. Clinty Quarry E. Corky Quarry. F. Roveran Valley Head, Causeway Coast. G. Croaghan Quarry. H. Cam Quarry. I. Craighall Quarry. J. Craighall Quarry. K. Knocklaughrim Quarry. L. Interbed 1 at Ross's Quarry, Ballycastle.

Figure 13. Cartoon of Antrim Lava Group eruptive tempo estimate based on weathering depth and interbed characteristics. Horizontal scale is an approximate time estimate based on weathering depths, interbed and palaeosol development and lava superposition, with flat areas of the plot indicating periods of quiescence between lava flows. The width of lava flow 'spikes' are equal and for graphical purposes only. Vertical scale represents lava flow thickness. Interbasaltic is in quotes due to the evident presence of basalt lava flows during this time period.

Supplementary Data Appendix 1: Lithological Descriptions

Ross's Quarry

The base of the 2.4 m thick sedimentary unit is at 69 mAOD, comprising several horizons from top to bottom, presented here:

A6. Grey carbonaceous mudstone: 25 to 70 cm thick silver grey brittle, slightly hard clay with fine black carbonaceous material throughout. Rootlets throughout.

A5. Brown carbonaceous mudstone: 0 to 20 cm thick brown grey silty sandy clay with fine black carbonaceous material throughout. Sometimes absent, leaving A6 sitting on A4. Brittle, slightly hard clay. Darker brown horizon at top of unit. Thin but variable thickness carbonaceous horizon on top of unit.

A4. Cross-bedded silty sandstone: 1.3 m thick cream to pale tan cross-bedded silty very fine to medium sand with silt horizons. Bedding has well-developed fining-upwards cycles, sometimes with coarse sands at the base, with cross-cutting decreasing and beds become more horizontal up the unit. Clasts of organic material throughout in cycles. Rootlets present, increasing to upper contact. Top 15 cm more brown in colour. Thin but variable thickness carbonaceous horizon on top of unit. A3. Mudstone/Sandstone with organic material: 0 to 15 cm thick cream clayey very fine to medium sand with black carbonaceous clasts up to 0.5 cm. In some outcrops this was seen as a well-lithified lignite up to 20 cm thick with no visible silt or sand content.

A3. Lignite / lignitic silty sandstone: Laterally variable subunit with end members of 0 to 20 cm thick horizon of well-compacted lignite in some places and silty sandstone with organic debris elsewhere.

A2. Mudstone: 10 cm thick green grey mudstone (weathered basalt?). Slightly friable, semi-competent.

A1. Weathered basalt: 10 cm thick silver grey green, conchoidal fracture weathered and altered basalt flow top. Relict basalt textures visible in hand specimen. Moderately competent.

Table Captions

Table 1. List of key localities and Irish Grid references.

Table 2. Rates of effusion for Icelandic flood basalt eruptions at Laki (1783 AD) and Eldgjá (952 AD) based on measured volumes and duration from anecdotal evidence. Superscripts a and b refer to the associated 'Rate of effusion' and 'Time taken' columns in Table 3.

Table 3. Emplacement duration for the Antrim Lava Group based on hypothetically continuous eruptions at rates of effusion calculated in Table 2, showing that the extant ALG lavas could have been emplaced in under 1,300 years if emplacement had been uninterrupted. Superscripts a and b cross-reference to Table 2.

Locality	**Easting**	**Northing**
Giant's Causeway	292903	444476
Craigahulliar Quarry	287110	438954
Ross's Quarry	308097	438438
NIRE 09/08-0001	294362	434582
NIRE 09/08-0002	290853	434532
NIRE 02/08-0001	316129	412540
NIRE 03/08-0001	326391	406143
NIRE 01/08-0001	306212	417691

Table 1

	Volume erupted	Time taken	Time taken	Rate of effusion
	measured km³	*Months*	*Years*	*calculated km³/year*
Laki (90% volume)[a]	14.0	5	0.42	33.60
Laki (100% volume)[b]	14.7	8	0.67	22.05
Eldgjá (short duration)[a]	19.6	36	3	6.53
Eldgjá (long duration)[b]	19.6	96	8	2.45

Table 2

	Areal extent	Thickness	Volume	Rate of effusion[a]	Rate of effusion[b]	Time taken[a]	Time taken[b]
	measured km^2	*estimated m*	*estimated km^3*	*est. km^3/ year*	*est. km^3/ year*	*Years (est.)*	*Years (est.)*
Antrim Lava Group *cf.* Laki	4093.05	328.40	1344	33.60	22.05	**40**	61
		771.00	3156			94	143
Antrim Lava Group *cf.* Eldgjá	4093.05	328.40	1344	6.53	2.45	206	549
		771.00	3156			483	**1288**

Table 3

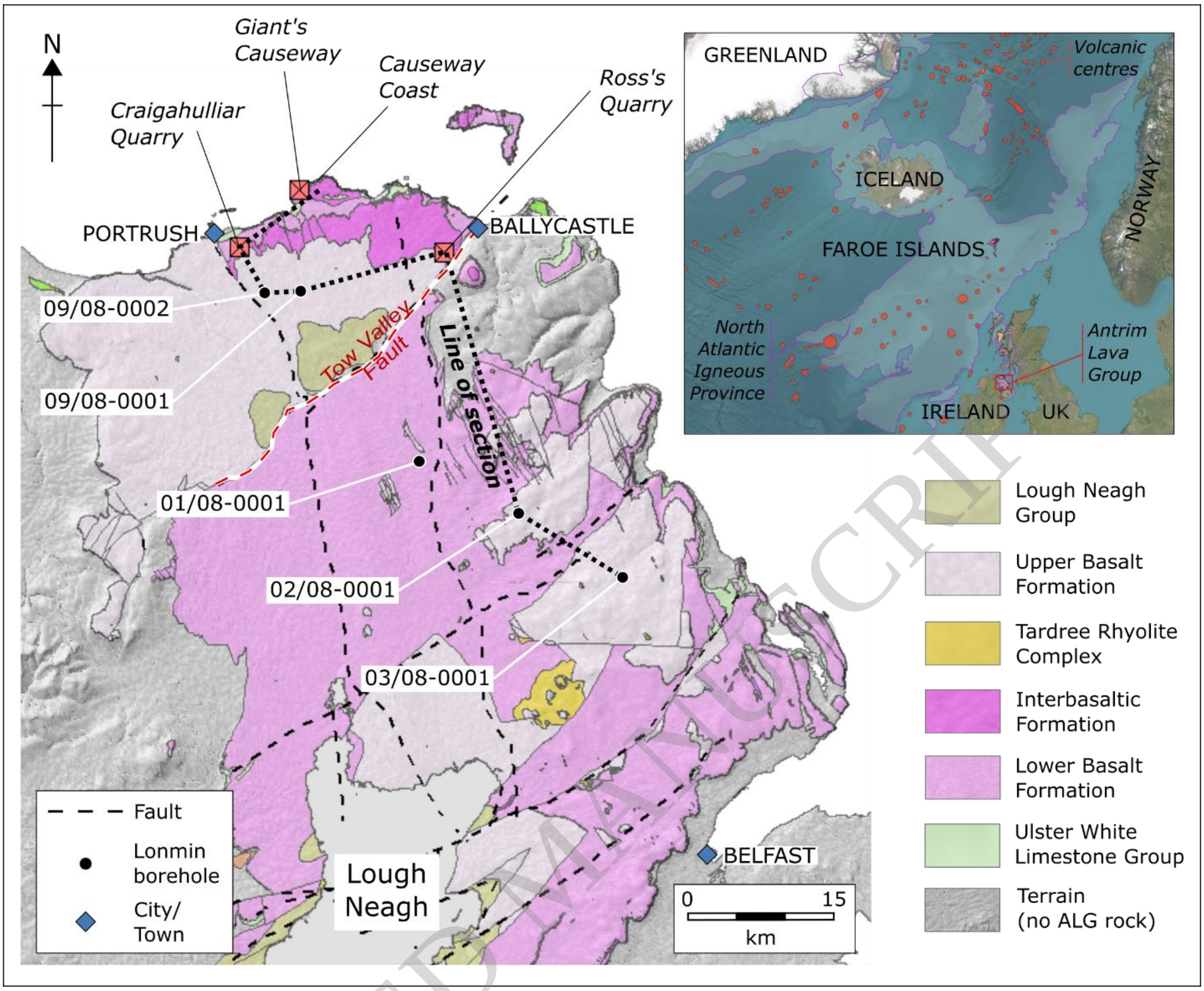

N
Giant's Causeway
Causeway Coast
Ross's Quarry
Craigahulliar Quarry
PORTRUSH
BALLYCASTLE
09/08-0002
09/08-0001
Tow Valley Fault
Line of section
01/08-0001
02/08-0001
03/08-0001
Fault
Lonmin borehole
City/ Town
Lough Neagh
BELFAST
0
15
km
GREENLAND
Volcanic centres
ICELAND
NORWAY
FAROE ISLANDS
North Atlantic Igneous Province
Antrim Lava Group
IRELAND
UK
Lough Neagh Group
Upper Basalt Formation
Tardree Rhyolite Complex
Interbasaltic Formation
Lower Basalt Formation
Ulster White Limestone Group
Terrain (no ALG rock)

Figure 1

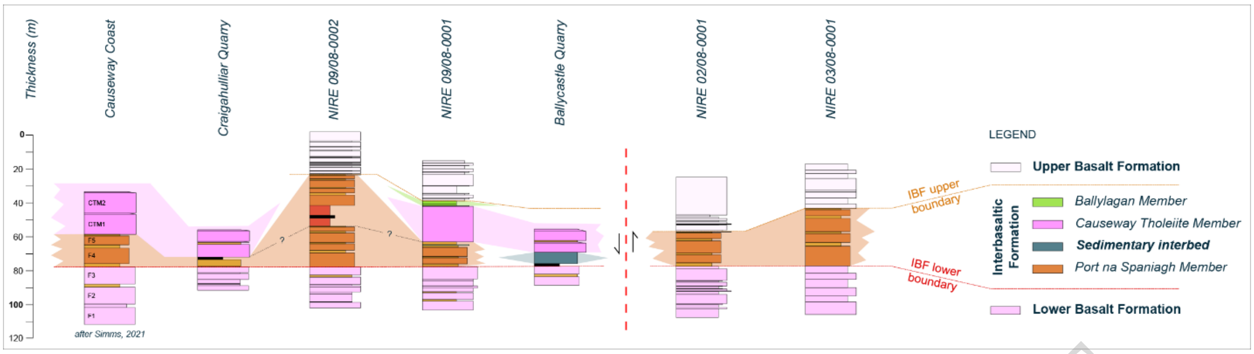


Figure 1(Continued)

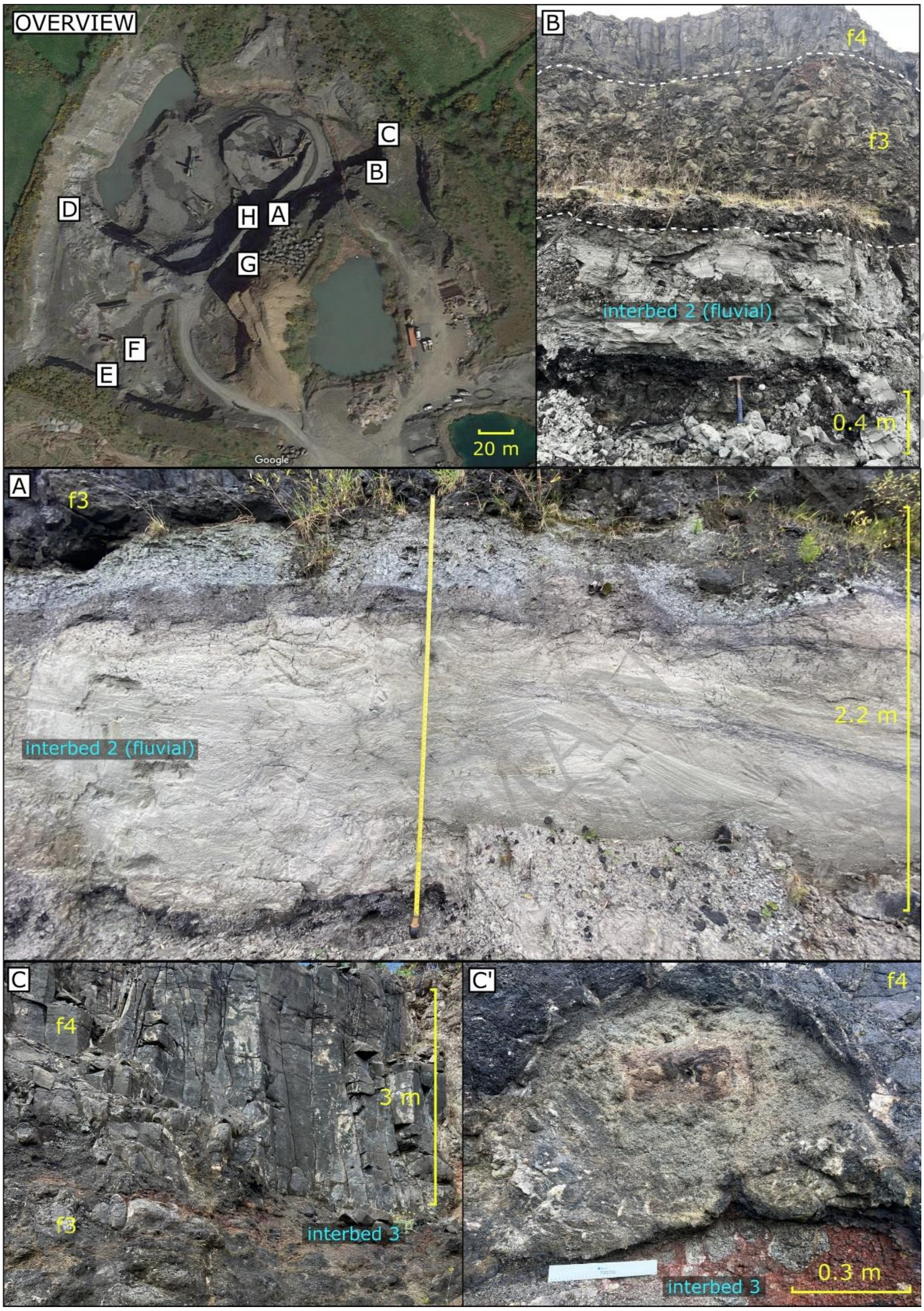

OVERVIEW
C
B
D
H
A
G
F
E
20 m
Google
B
f4
f3
interbed 2 (fluvial)
0.4 m
A
f3
interbed 2 (fluvial)
2.2 m
C
f4
3 m
f3
interbed 3
C'
f4
interbed 3
0.3 m

Figure 2

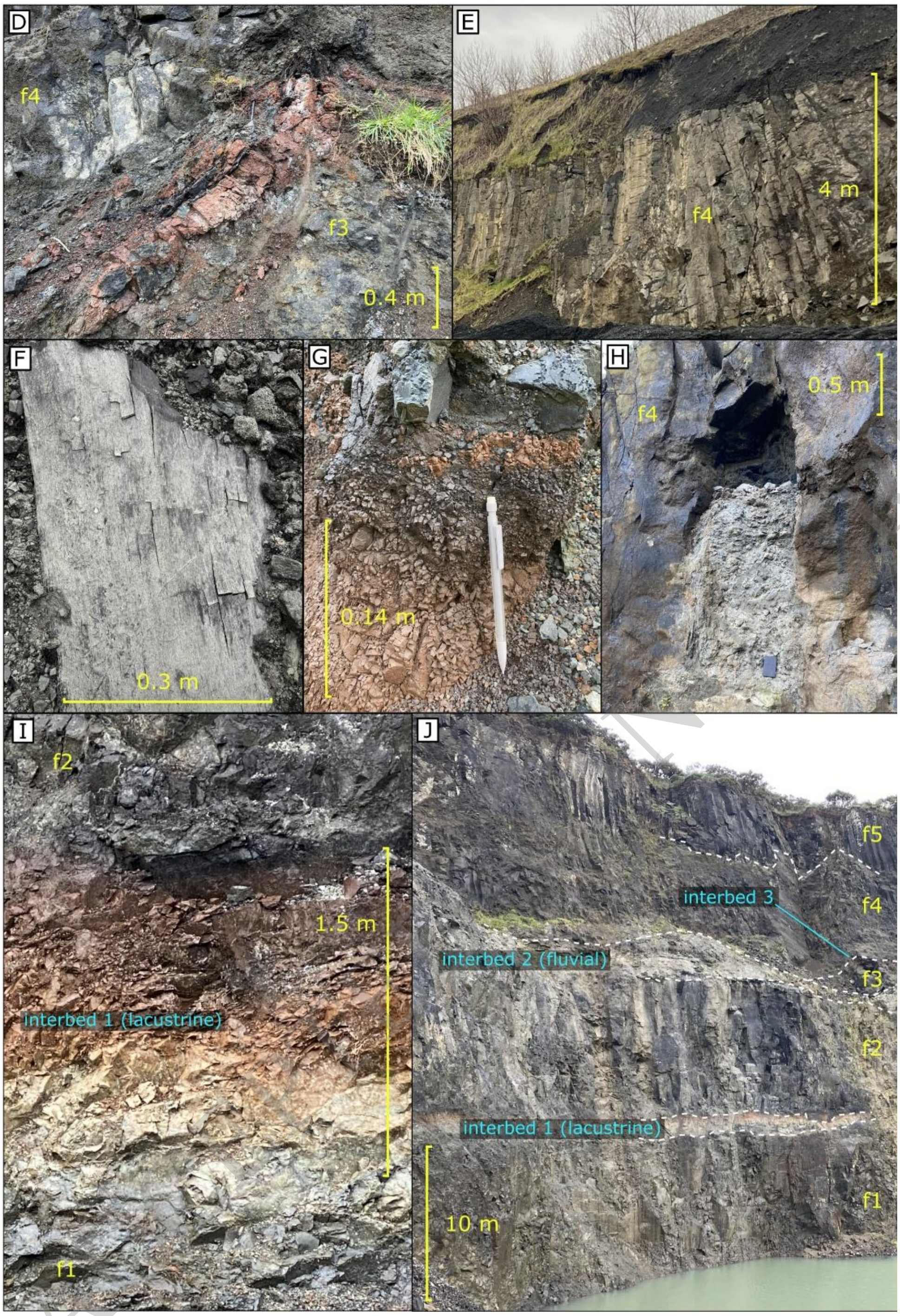
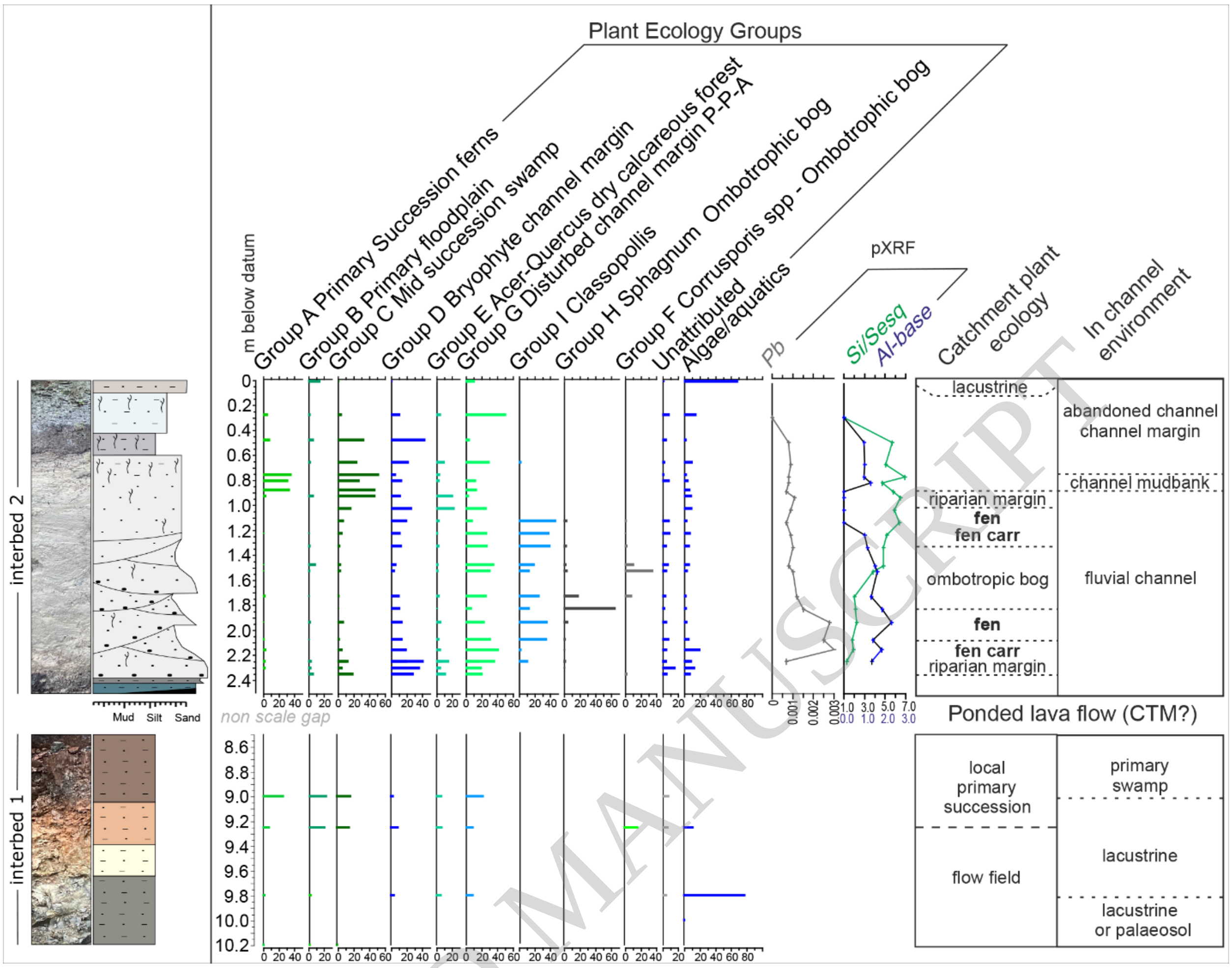


Figure 2(Continued)



Plant Ecology Groups
Group A Primary Succession ferns
Group B Primary floodplain
Group C Mid succession swamp
Group D Bryophyte channel margin
Group E Acer-Quercus dry calcareous forest
Group G Disturbed channel margin P-P-A
Group I Classopollis
Group H Sphagnum Ombotrophic bog
Group F Corrusporis spp - Ombotrophic bog
Unattributed
Algae/aquatics
pXRF
Pb
Si/Sesq
Al-base
Catchment plant ecology
In channel environment
m below datum
interbed 2
interbed 1
Mud
Silt
Sand
non scale gap
lacustrine
abandoned channel
channel margin
channel mudbank
riparian margin
fen
fen carr
ombotropic bog
fluvial channel
fen
fen carr
riparian margin
Ponded lava flow (CTM?)
local primary succession
primary swamp
flow field
lacustrine
lacustrine or palaeosol

Figure 3

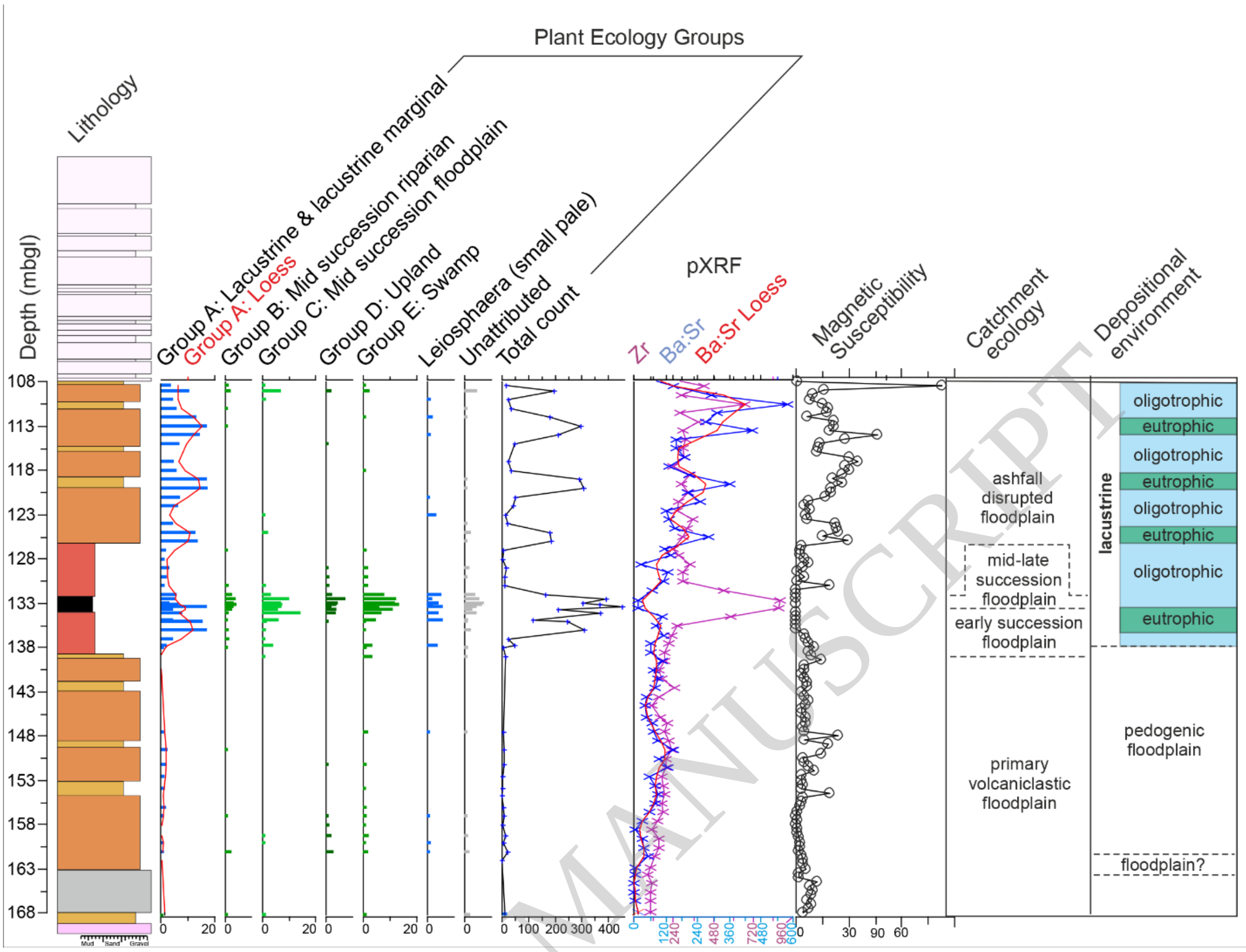
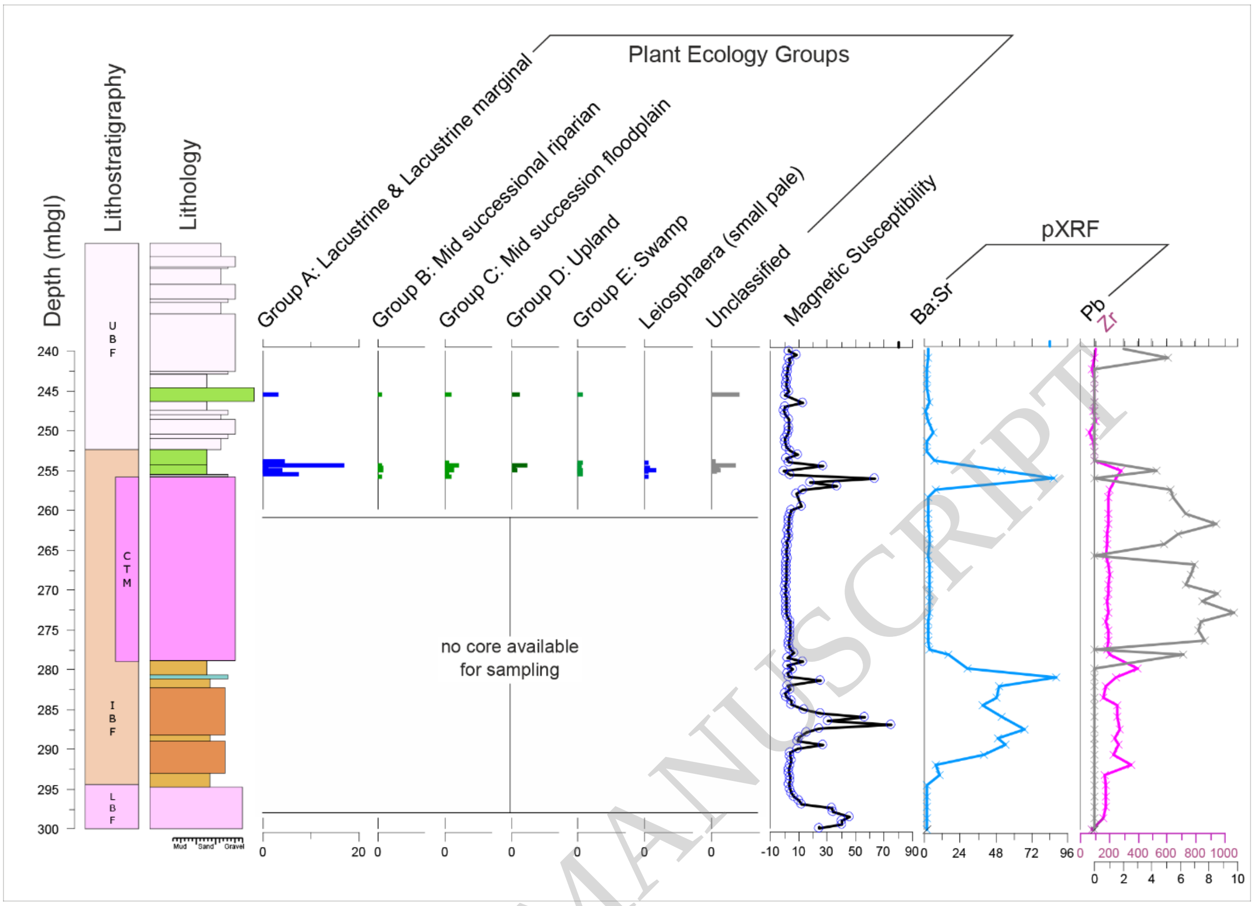
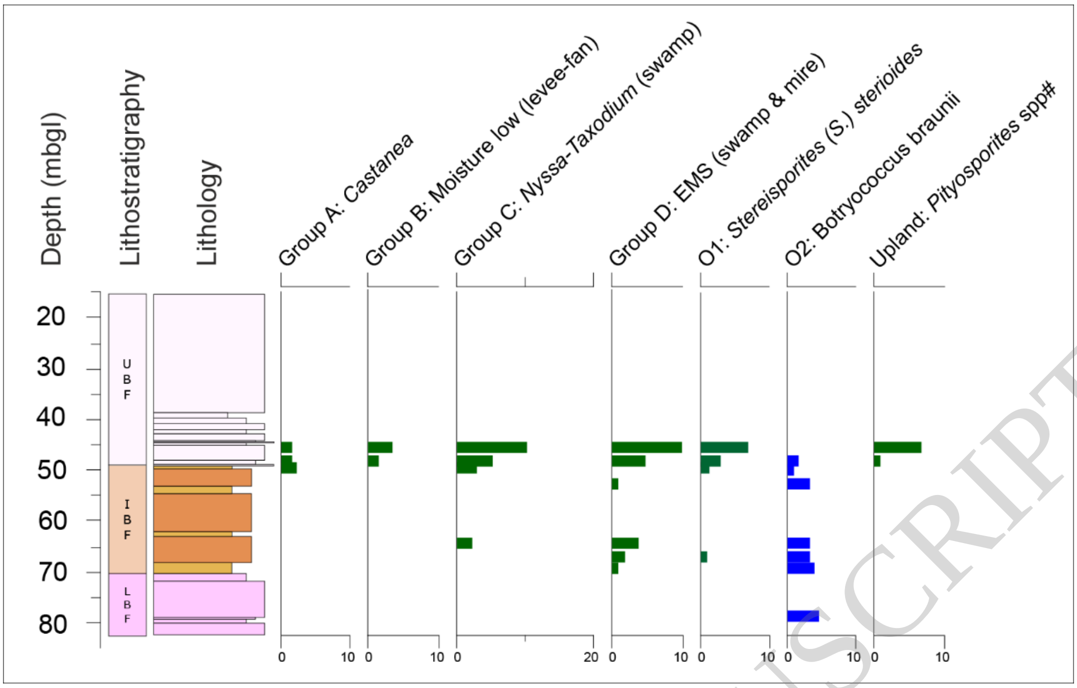

Plant Ecology Groups
Lithology
Depth (mbgl)
Group A: Lacustrine & lacustrine marginal
Group A: Loess
Group B: Mid succession riparian
Group C: Mid succession floodplain
Group D: Upland
Group E: Swamp
Leiosphaera (small pale)
Unatributed
Total count
pXRF
Zr
Ba:Sr
Ba:Sr Loess
Magnetic Susceptibility
Catchment ecology
Depositional environment
ashfall disrupted floodplain
mid-late succession floodplain
early succession floodplain
primary volcaniclastic floodplain
lacustrine
oligotrophic
eutrophic
pedogenic floodplain
floodplain?
Mud
Sand
Gravel

Figure 4



Plant Ecology Groups
pXRF
Depth (mbgl)
Lithostratigraphy
Lithology
Group A: Lacustrine & Lacustrine marginal
Group B: Mid successional riparian
Group C: Mid succession floodplain
Group D: Upland
Group E: Swamp
Leiosphaera (small pale)
Unclassified
Magnetic Susceptibility
Ba:Sr
Pb
Zr
UBF
CTM
IBF
LBF
Mud
Sand
Gravel
no core available for sampling

Figure 5



Depth (mbgl)
Lithostratigraphy
Lithology
Group A: Castanea
Group B: Moisture low (levee-fan)
Group C: Nyssa-Taxodium (swamp)
Group D: EMS (swamp & mire)
O1: Stereisporites (S.) sterioides
O2: Botryococcus braunii
Upland: Pityosporites spp#
20
30
40
50
60
70
80
U B F
I B F
L B F
0
10
20

Figure 6

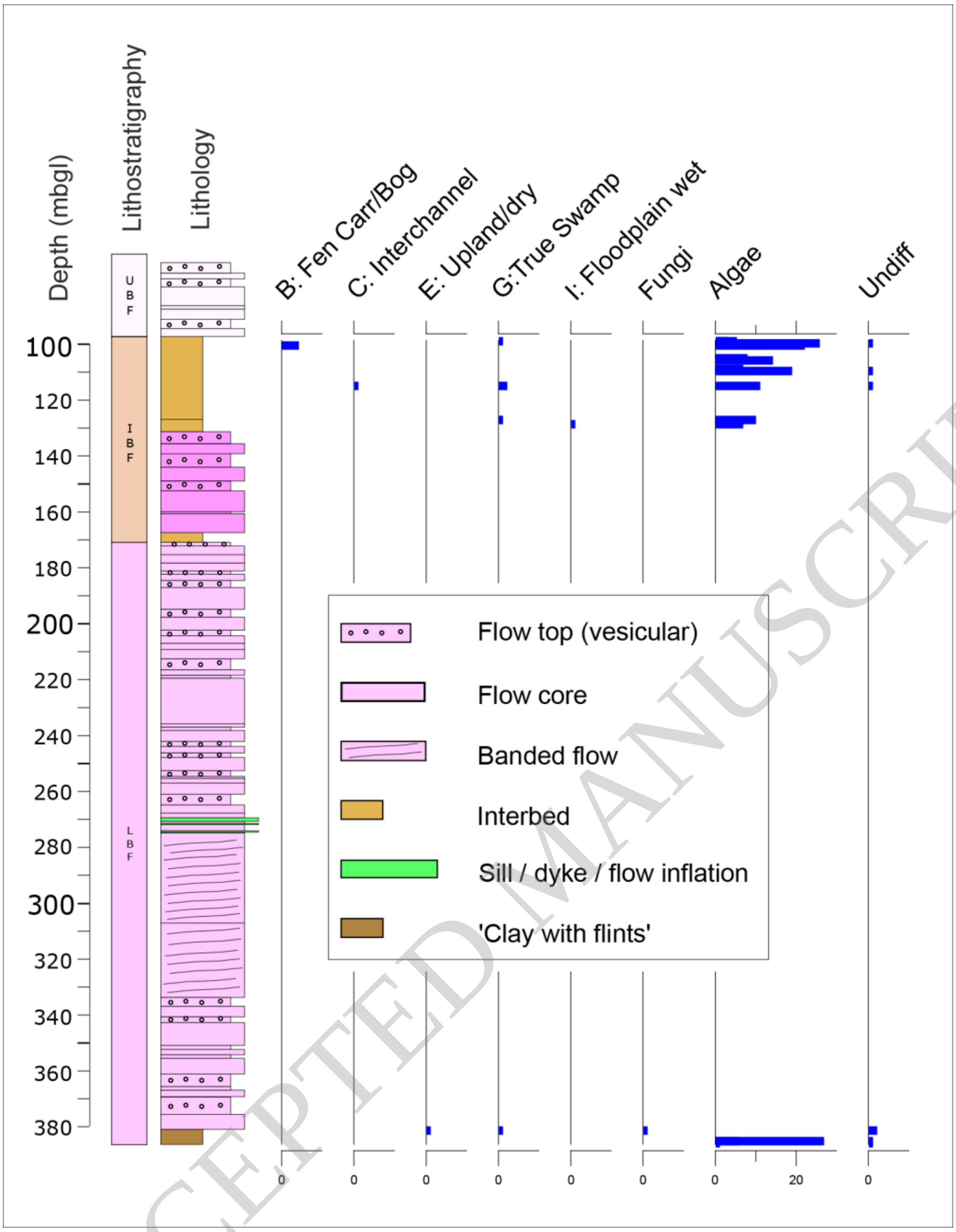

Depth (mbgl)
Lithostratigraphy
Lithology
B: Fen Carr/Bog
C: Interchannel
E: Upland/dry
G:True Swamp
I: Floodplain wet
Fungi
Algae
Undiff
UBF
IBF
LBF
100
120
140
160
180
200
220
240
260
280
300
320
340
360
380
Flow top (vesicular)
Flow core
Banded flow
Interbed
Sill / dyke / flow inflation
'Clay with flints'
0
20

Figure 7

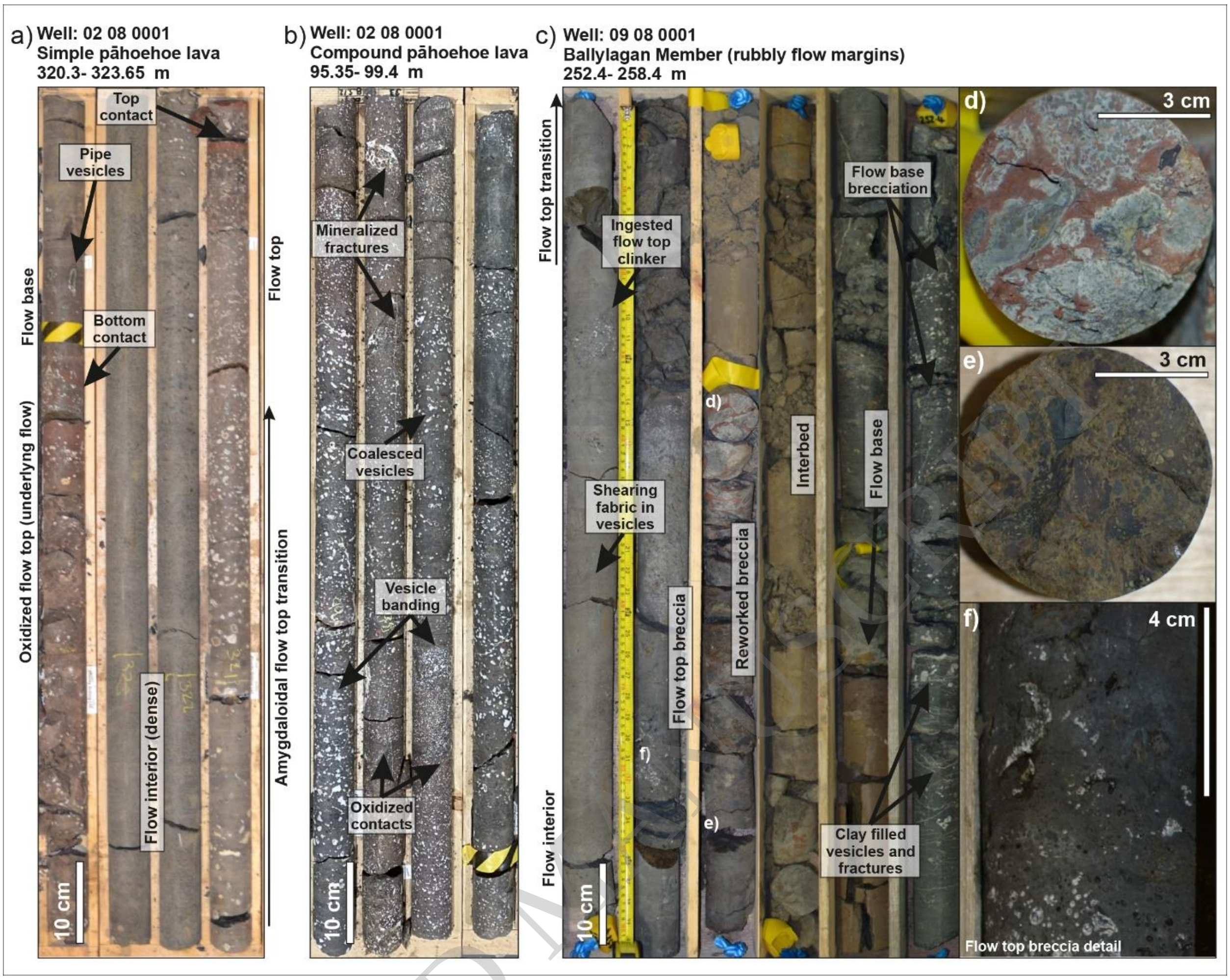

a) Well: 02 08 0001
Simple pāhoehoe lava
320.3- 323.65 m
Top contact
Pipe vesicles
Bottom contact
Flow base
Oxidized flow top (underlyng flow)
Flow interior (dense)
Flow top
Amygdaloidal flow top transition
10 cm
b) Well: 02 08 0001
Compound pāhoehoe lava
95.35- 99.4 m
Mineralized fractures
Coalesced vesicles
Vesicle banding
Oxidized contacts
10 cm
c) Well: 09 08 0001
Ballylagan Member (rubbly flow margins)
252.4- 258.4 m
Flow top transition
Ingested flow top clinker
Shearing fabric in vesicles
Flow interior
Flow top breccia
Reworked breccia
Interbed
Flow base
Flow base brecciation
Clay filled vesicles and fractures
10 cm
d)
3 cm
e)
3 cm
f)
4 cm
Flow top breccia detail

Figure 8

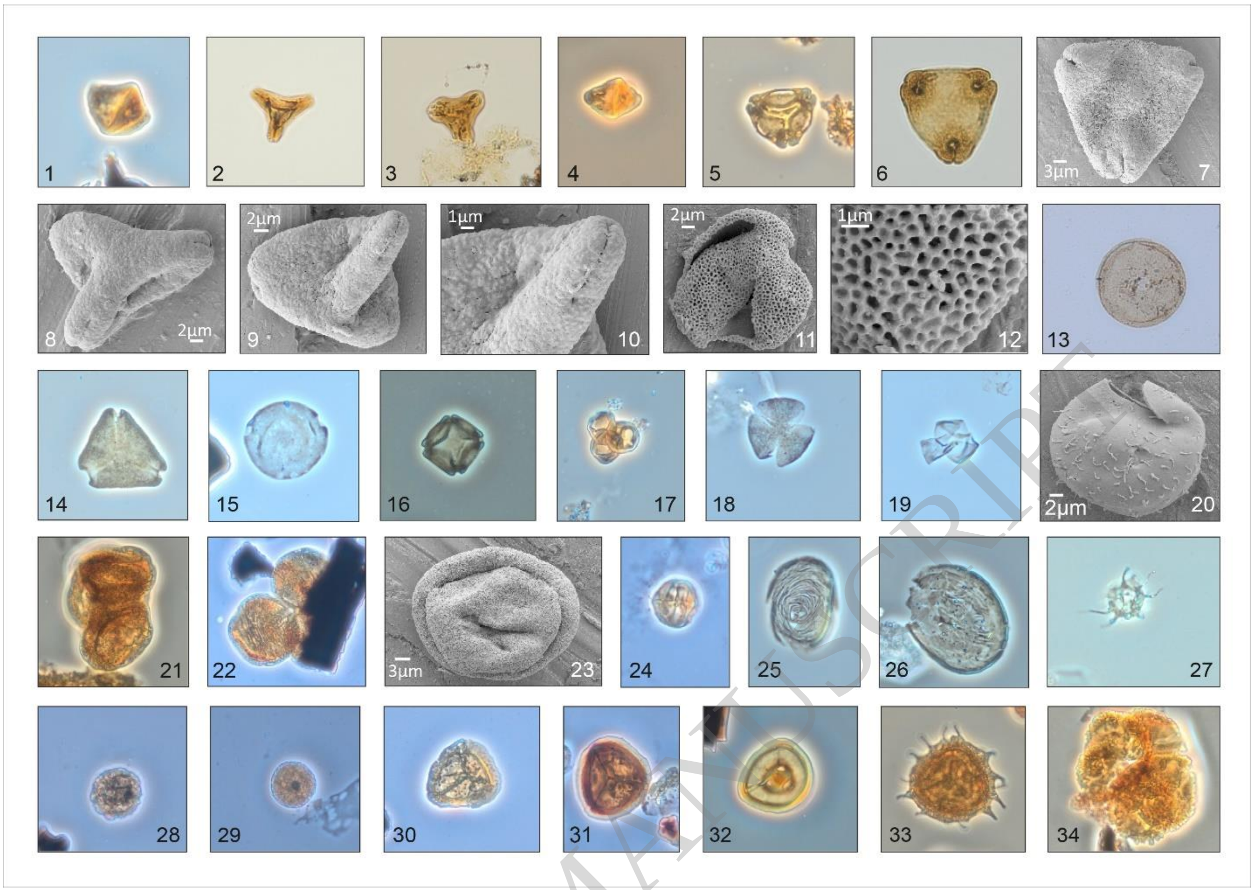
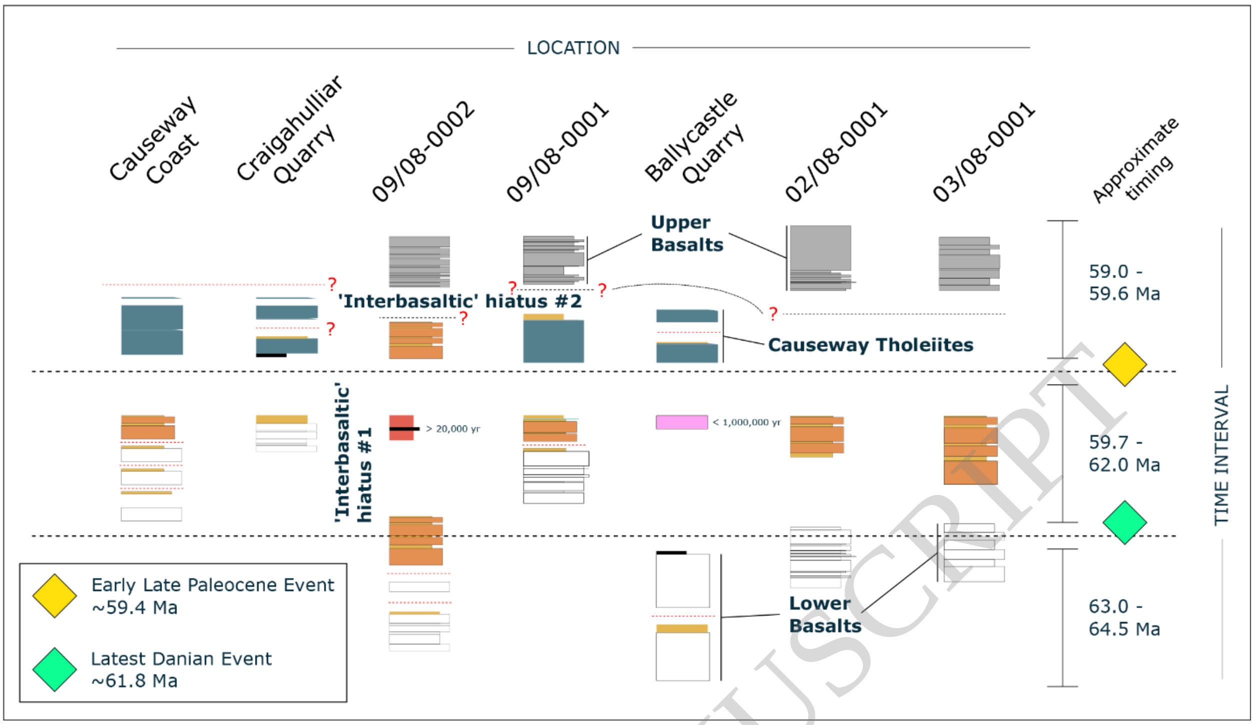

1
2
3
4
5
6
3μm
7
8
2μm
2μm
9
1μm
10
2μm
11
1μm
12
13
14
15
16
17
18
19
2μm
20
21
22
3μm
23
24
25
26
27
28
29
30
31
32
33
34

Figure 9



LOCATION
Causeway Coast
Craigahulliar Quarry
09/08-0002
09/08-0001
Ballycastle Quarry
02/08-0001
03/08-0001
Approximate timing
Upper Basalts
'Interbasaltic' hiatus #2
Causeway Tholeiites
'Interbasaltic' hiatus #1
> 20,000 yr
< 1,000,000 yr
Lower Basalts
59.0 - 59.6 Ma
59.7 - 62.0 Ma
63.0 - 64.5 Ma
TIME INTERVAL
Early Late Paleocene Event ~59.4 Ma
Latest Danian Event ~61.8 Ma

Figure 10

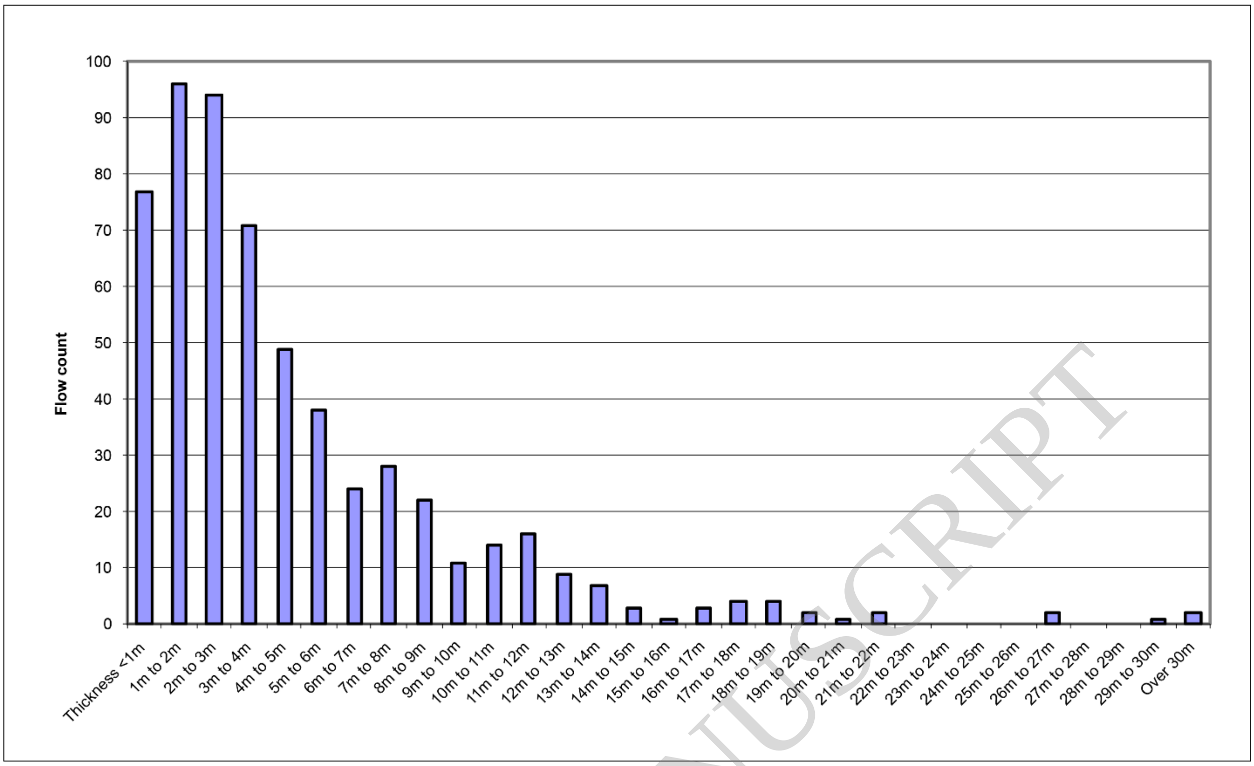

Flow count
100
90
80
70
60
50
40
30
20
10
0
Thickness <1m
1m to 2m
2m to 3m
3m to 4m
4m to 5m
5m to 6m
6m to 7m
7m to 8m
8m to 9m
9m to 10m
10m to 11m
11m to 12m
12m to 13m
13m to 14m
14m to 15m
15m to 16m
16m to 17m
17m to 18m
18m to 19m
19m to 20m
20m to 21m
21m to 22m
22m to 23m
23m to 24m
24m to 25m
25m to 26m
26m to 27m
27m to 28m
28m to 29m
29m to 30m
Over 30m

Figure 11

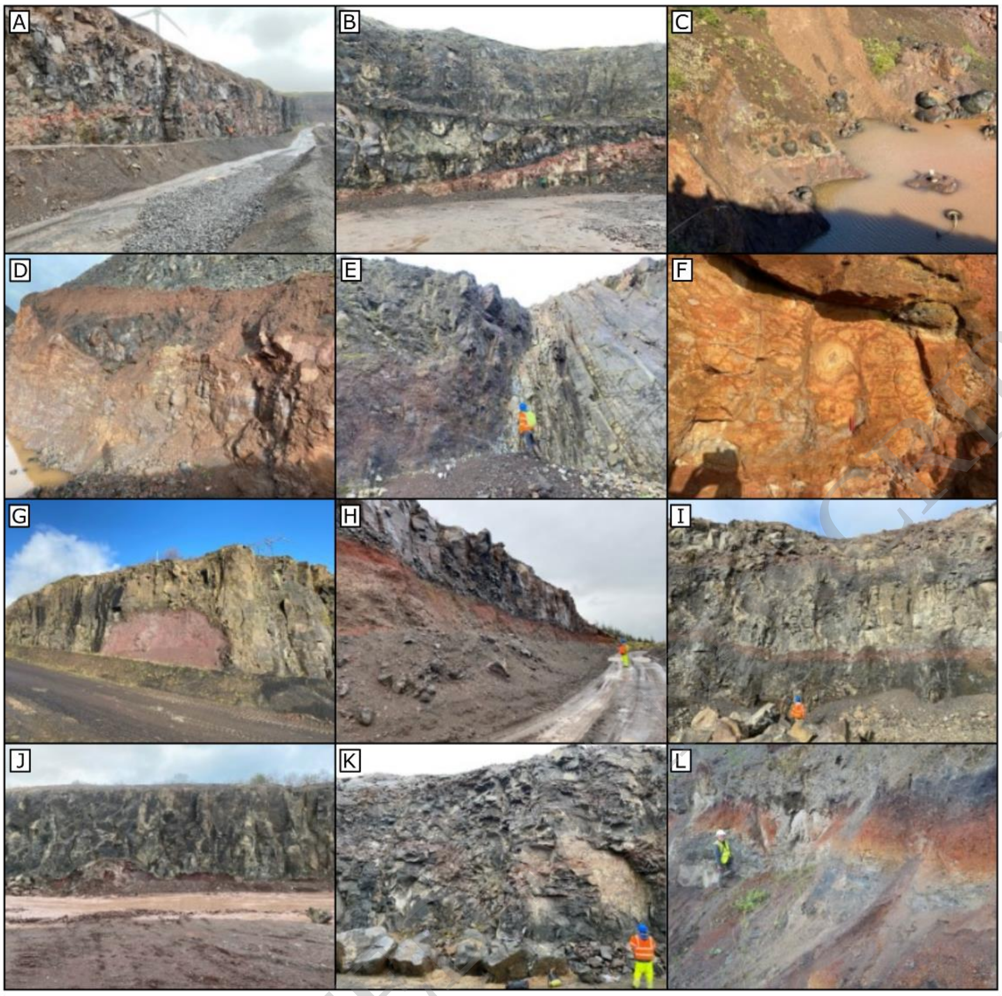


Figure 12


72 discrete flows
Tholeiitic Flood Basalts
30 m
Flow thickness
1 m
Lower Basalt Formation
'interbasaltic'
Upper Basalt Formation
Volcanic ash
onset
Weathering depth / interbed thickness
end
NIRE 09/08-0001
84 discrete flows
Tholeiitic Flood Basalts
30 m
Flow thickness
1 m
base of lavas not proven
Lower Basalt Formation
'interbasaltic'
Upper Basalt Formation
Volcanic ash
onset
Weathering depth / interbed thickness
end
NIRE 09/08-0002
64 discrete flows
Tholeiitic Flood Basalts
30 m
Flow thickness
1 m
Lower Basalt Formation
'interbasaltic'
Upper Basalt Formation
Volcanic ash
onset
Weathering depth / interbed thickness
end
NIRE 02/08-0001
67 discrete flows
Tholeiitic Flood Basalts
30 m
Flow thickness
1 m
Lower Basalt Formation
'interbasaltic'
Upper Basalt Formation
Volcanic ash
onset
Weathering depth / interbed thickness
end
NIRE 03/08-0001

Figure 13