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A. A. Monaghan and M.A.E. Browne

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British Geological Survey offices

BGS Central Enquiries Desk
Tel 0115 936 3143 Fax 0115 936 3276
email enquiries@bgs.ac.uk

Kingsley Dunham Centre, Keyworth, Nottingham NG12 5GG
Tel 0115 936 3241 Fax 0115 936 3488
email sales@bgs.ac.uk

Murchison House, West Mains Road, Edinburgh EH9 3LA
Tel 0131 667 1000 Fax 0131 668 2683
email scotsales@bgs.ac.uk

Natural History Museum, Cromwell Road, London SW7 5BD
Tel 020 7589 4090 Fax 020 7584 8270
Tel 020 7942 5344/45 email bgslondon@bgs.ac.uk

Columbus House, Greenmeadow Springs, Tongwynlais, Cardiff CF15 7NE
Tel 029 2052 1962 Fax 029 2052 1963

Maclean Building, Crowmarsh Gifford, Wallingford OX10 8BB
Tel 01491 838800 Fax 01491 692345

Geological Survey of Northern Ireland, Colby House, Stranmillis Court, Belfast BT9 5BF
Tel 028 9038 8462 Fax 028 9038 8461
www.bgs.ac.uk/gsni/

Parent Body

Natural Environment Research Council, Polaris House, North Star Avenue, Swindon SN2 1EU
Tel 01793 411500 Fax 01793 411501
www.nerc.ac.uk

Website www.bgs.ac.uk
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Contents

FIGURES

TABLES

Summary

This report describes the location and character of ten Carboniferous-Permian igneous rock samples from the Midland Valley of Scotland and the results of $^{40}Ar/^{39}Ar$ step-heating experiments on nine of the samples to obtain the radiometric age of eruption or emplacement of the rock. The quality of the new radiometric ages are discussed along with their integration with the chronostratigraphy, lithostratigraphy and biostratigraphy of the Midland Valley of Scotland.

1 Introduction and rationale

Nine $^{40}Ar/^{39}Ar$ radiometric dates have been obtained to constrain the age of eruption or emplacement of Permo-Carboniferous igneous rocks from the Midland Valley of Scotland. After BGS sample collection and mineral separations in 2006/7, the $^{40}Ar/^{39}Ar$ analysis was undertaken at the NERC Argon Isotope Facility of the Scottish Universities Environmental Research Centre (SUERC), East Kilbride in 2008/9.

The work follows on from $^{40}Ar/^{39}Ar$ dating reported in Monaghan and Pringle (2004) and U/Pb Thermal Ionisation Mass Spectrometry (TIMS) dating reported in Monaghan and Parrish (2006). The new $^{40}Ar/^{39}Ar$ rock samples were chosen from stratigraphically well-constrained sections with the aims of enhancing integration of Carboniferous chronostratigraphy, biostratigraphy and lithostratigraphy, regional tectono-magmatic correlations and possibly contributing to poorly constrained parts of the global Carboniferous timescale. It was hoped the dates would help to chronologically constrain onset of northern hemisphere Mississippian glaciation. Some samples, such as those collected at Arthur's Seat, were also chosen due to academic interest in volcanic evolution and public understanding of science. Dates from the Kinghorn Volcanic and Clyde Plateau Volcanic formations had the potential to constrain the age of world-class palaeobotanical sites nearby.

More specific scientific questions to be answered included:

- The age of quartz-dolerite dykes of the Central Scotland Tholeiitic Dyke Suite compared to sills of the Midland Valley Sill Complex and the 'Whin Sill' magmatism of Northumberland
- The date of Mauchline Volcanic Formation lavas compared to very early Permian age of intercalated plant floras and the Permo-Carboniferous boundary in Western Europe
- The ages of Arthur's Seat Volcanic Formation lavas and associated vents and intrusions, and links with Garleton Hills Volcanic Formation lavas in East Lothian
- Links between Mississippian volcanic episodes and ages of intercalated limestone stratigraphic marker beds
- Dating of the change in style of Midland Valley volcanism to wholly basic in the late Viséan, links to tectonism and sedimentation styles at this time.

1.1 SAMPLING STRATEGY

Rock sample collection was undertaken in a short timeframe and tight budget, restricting the number and location of samples taken. Sampling focussed on covering suites poorly represented by recent $^{40}Ar/^{39}Ar$ and U-Pb work from lithostratigraphically well-constrained extrusive rocks (lavas), to answer the questions summarised above.

The requirements for sample collection were either that rocks contained fresh feldspar, hornblende or biotite >300 microns (0.3 mm) in size for mineral separations. Extrusive lavas from the Clyde Plateau, Garleton Hills and Arthur's Seat volcanic formations contain feldspar phenocrysts, some with unaltered domains > 300 microns. However, after the late Viséan, large feldspar phenocrysts are rare; basalts are often alkaline with olivine and clinopyroxene phenocrysts. In this case, a groundmass separation technique was used for relatively fresh rocks.

1.2 CHOSEN SAMPLES

Thirty four samples were collected including 7 from BGS borehole core. After photomicrographic screening and discussion with SUERC staff, the samples were ranked based on freshness of sample, phenocryst presence/size and lithostratigraphic position. Ten samples (Figure 1, Table 1) were sent for mineral and groundmass separation at BGS Keyworth.

The samples were the freshest available but were variably altered. Feldspars in several of the samples were not large enough to analyse as separates (phenocrysts <250 microns are not suitable due to recoil loss). However, in this case a groundmass separate step-heating technique could be utilised (after Koppers et al., 2000).

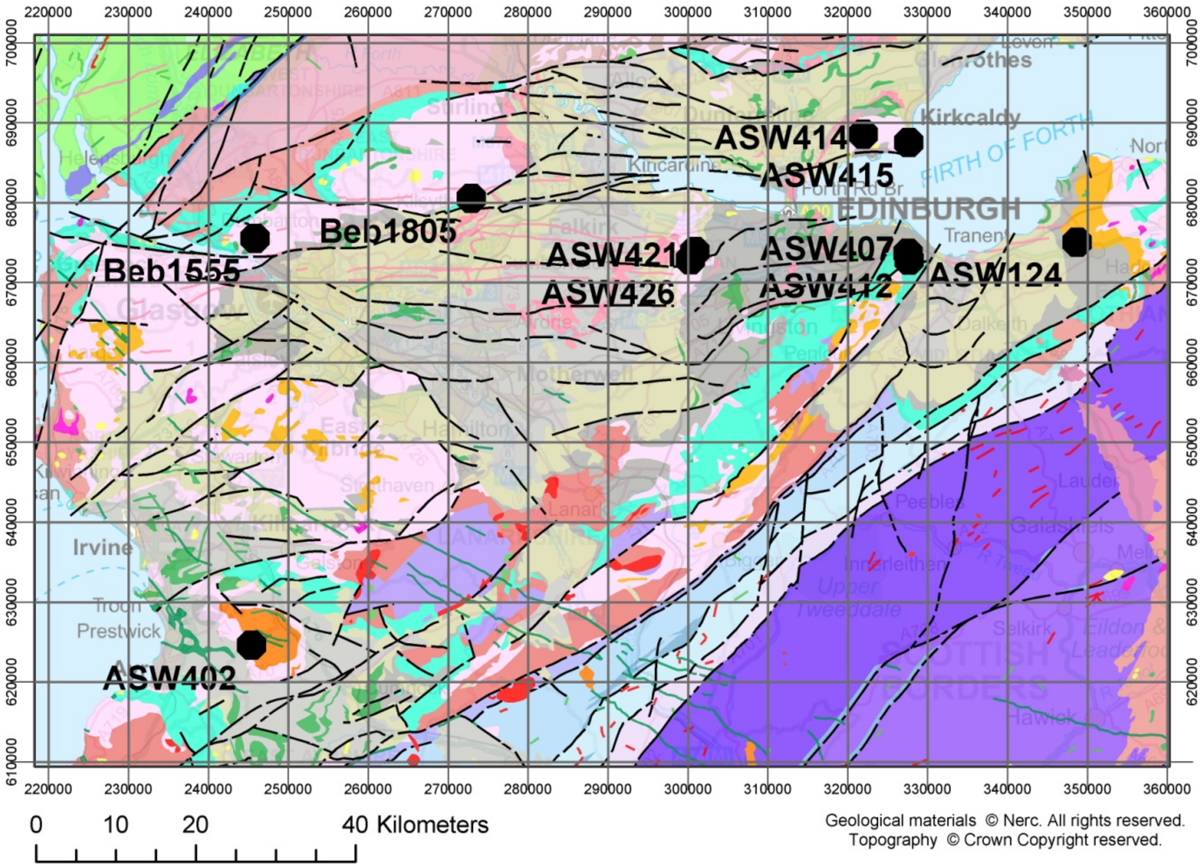

Figure 1 Bedrock geological map of the central part of the Midland Valley of Scotland showing the location of the ten samples chosen for mineral separation and analysis. Geological materials BGS © NERC. OS Topography © Crown Copyright BGS100017897/2010. All Rights Reserved

Sample number	Sample location	Easting	Northing	Thin section number	Stratigraphy
Beb1555	BGS Loch Humphrey Borehole	245820	675550	Beb1555	mid Clyde Plateau Volcanic Formation (CPV)
Beb1805	BGS Tak-Ma-Doon Borehole	272910	680530	Beb1805	base Clyde Plateau Volcanic Formation (CPV)
ASW124	Bangley Quarry	348713	675070	N3665	Garleton Hills Volcanic Formation (GHV)
ASW402	Stairhill	245390	624616	N5363	Mauchline Volcanic Formation (MVL)
ASW407	Lion’s Haunch, Arthur’s Seat	327669	672827	N9246	Arthur's Seat intrusion
ASW412	Lava 3, Arthur’s Seat	327565	673677	N9251	Arthur's Seat Volcanic Formation (ASV)
ASW414	Orrock Quarry	321934	688589	N9256	Kinghorn Volcanic Formation (KNV)
ASW421	Beecraigs climbing wall	300853	673911	N9263	Central Scotland Late Carboniferous Tholeiitic Dyke Swarm (CSTD)
ASW426	Cow Craig, Bathgate Hills	300317	672868	N9268	Bathgate Hills Volcanic Formation (BHV)
ASW415*	Kinghorn-Kirkcaldy coast	327633	687552	N9257	Kinghorn Volcanic Formation (KNV)

Table 1 Summary of sample location and stratigraphy for the ten samples selected for $^{40}Ar/^{39}Ar$ analysis (*ASW 415 was irradiated but not run). Grey shading indicates a groundmass separate was used, white indicates a feldspar separate was used.

2 Dating Methodology

A standard methodology for sample preparation, irradiation, analysis and calculation was followed.

2.1 GROUNDMASS SAMPLE PREPARATION FOR ALTERED BASALTS

1) Clean away any loose surficial material from rock
2) Saw off any altered zones
3) Crush sample in jaw crusher to less than 2000 µm grain size
4) Sieve sample to ≥100 µm (removing fines and dust)
5) Grind sample in disc mill to ≤500 µm
6) Sieve sample to into separate 150 – 300 µm and 300 – 500 µm aliquots
7) Select aliquot for further processing depending on the grain size of the groundmass and phenocrysts, i.e., coarser grain size 300 – 500 µm aliquots
8) Pass a strong hand magnet (wrapped in paper) over the crushed samples to remove metal particles introduced by the crushing process
9) Rinse samples in deionized water (DI)
10) Thoroughly wash samples in DI in an ultrasonic bath for 10 minutes. Repeat until DI remains clear following ultrasonic bath.
11) Dry samples at ≤100 °C
12) Magnetically separate samples (using a Frantz Isodynamic Separator) to remove phenocrysts and alteration products from groundmass
13) Leach samples in 3N HNO_3 for 20 minutes in an ultrasonic bath at 50 °C. Repeat if the acid becomes cloudy (i.e. opaque at 2 cm thickness/depth), until a clear solution is reached.

14) Rinse samples in deionized water (DI)
15) Thoroughly wash samples in DI in an ultrasonic bath for 10 minutes. Repeat until DI remains clear following ultrasonic bath.
16) Dry samples at ≤100 °C
17) Hand-pick under a binocular microscope to remove all remaining phenocrysts and altered grains, to produce a homogeneous groundmass separate.
18) Aim for 200 – 300 mg of separate if possible (dependent on age and K_2O content)

Koppers et al. (2000) suggest repeatedly crushing the sample with a ball mill to remove the softer components of the rock followed by sieving, leaving only the hardest (~5 – 10%) of the rock. This is advisable for heavily altered samples, but is only possible if sufficient sample is available, given that every preparatory step causes attrition of the sample mass.

2.2 SAMPLE PREPARATION FOR PLAGIOCLASE

1) Clean away any loose surficial material
2) Saw off any altered zones
3) Crush sample in jaw crusher to less than 2000 µm grain size
4) Sieve sample to ≥100 µm (removing fines and dust)
5) Grind sample in disc mill to ≤500 µm
6) Sieve sample to into separate 150 – 300 µm and 300 – 500 µm aliquots
7) Select aliquot for further processing depending on the grain size of the groundmass and phenocrysts, i.e., coarser grain size 300 – 500 µm aliquots
8) Pass a strong hand magnet (wrapped in paper) over the crushed samples to remove metal particles introduced by the crushing process
9) Rinse samples in deionized water (DI)
10) Thoroughly wash samples in DI in an ultrasonic bath for 10 minutes. Repeat until DI remains clear following ultrasonic bath.
11) Dry samples at ≤100 °C
12) Magnetically separate samples (using a Frantz Isodynamic Separator) to remove groundmass, phenocrysts and alteration products from feldspar (plagioclase).
13) Leach samples in 3N HNO_3 for 60 minutes in an ultrasonic bath at 50 °C. Repeat if the acid becomes cloudy (i.e. opaque at 2 cm thickness/depth), until a clear solution is reached.
14) Leach plagioclase in 7% HF for 5 minutes.
15) Rinse samples in deionized water (DI)
16) Thoroughly wash samples in DI in an ultrasonic bath for 10 minutes. Repeat until DI remains clear following ultrasonic bath.
17) Dry samples at ≤100 °C
18) Hand-pick under a binocular microscope. Remove all altered grains and those with numerous inclusions. Attempt to produce a homogeneous plagioclase separate.
19) Aim for 200 – 300 mg of separate if possible

2.3 ANALYTICAL PROCEDURES

Purified separates were loaded into copper packets, placed within quartz vials and then loaded into an aluminium can for irradiation. Packets of the international standard FC sanidine (28.02 ± 0.28 Ma, Renne et al., 1998) were interspersed with the Cu sample packets to permit characterization of the irradiation flux to the samples; J values assume ± 0.5 % (1σ) precision. The samples were irradiated in the Petten HFR reactor for 48 hours, in the Cd-lined facility (RODEO). Two international standards, GA-1550 and PP20 (Hb3gr) were irradiated with the samples and yielded 98.0 ± 0.3 Ma (1σ, n=20, accepted age= 98.8 ± 0.5 Ma, Renne et al., 1998) and 1065 ± 6 Ma (1σ, n=13, accepted age= 1072 ± 11 Ma, Turner, 1971) respectively.

Samples were step heated using a resistively-heated double-vacuum furnace over a range of temperatures from 500 – 1600°C, with the total number of steps ranging from *c.* 14 to 70 per experiment. Furnace blanks were stable at less than 2x10^{-15} mol ^{40}Ar, 7 x10^{-18} mol ^{39}Ar, 2x10^{-18} mol ^{38}Ar, 4x10^{-18} mol ^{37}Ar and 4x10^{-18} mol ^{36}Ar. Data were collected on an Argus multi-collector mass spectrometer (Alexandre et al., 2006) or an MAP-215-50. The Argus employs five high-gain, low-noise Faraday cups with 10^{11} (^{40}Ar) and 10^{12} ($^{39-36}$Ar) ohm resistors for simultaneous collection of all five isotopes of argon. The MAP 215-50 employs a single Balzers SEV217 electron multiplier collector. All ratios are blank and mass discrimination corrected.

Errors are cumulative and include contributions from the decay constant, standard and 0.5 % in J value. Errors are reported at the 2σ (95 %) significance level of analytical precision apart from where stated.

2.4 INTERPRETING THE ANALYTICAL RESULTS

The incremental step-heating technique allows one to separate apparent ^{40}Ar/^{39}Ar ages into those released by alteration phases at lower temperatures and those from original igneous phases at higher temperatures. Statistical tests are made for each experiment to test whether the high-temperature steps have yielded a concordant age representing a reliable estimate of the crystallisation age of the sample. The MSWD (means square weighted deviation) is a description of the analytical scatter and should ideally be less than 1.

These samples were run at high resolution - that is there are many incremental heating steps for each result. The number of steps is much greater than in the analysis for Monaghan and Pringle (2004) and the resultant scatter in the numerous steps may be one reason for larger error values in this study. Another reason for the larger error is that more sources of error are included in recent versions of the Isoplot calculation software.

In some instances a ‘plateau-chron’ age result has been used. The ‘plateau-chron’ calculations are iterative calculations derived from the Isoplot software. Plateau-chrons are an attempt to calculate a self-consistent isochron and plateau pair from the data. In normal plateau calculation, all of the age steps are corrected for a trapped component; this trapped component is assumed to be of air composition. However, if it is not air-like, then this can lead to inaccuracies. In a plateau-chron calculation the trapped component composition is determined directly from the regressed data. For example, the plateau-chron method was used where there was evidence of ‘excess argon’. This is where the ^{40}Ar/^{36}Ar ratio is high and non-atmospheric (eg ^{40}Ar/^{36}Ar of air is 295.5, i.e. ^{36}Ar/^{40}Ar <0.0034) due to inclusion of ^{40}Ar as well as ^{36}Ar into minerals at the time of initial crystallisation, at a ratio significantly different than the modern atmosphere.

An isochron age was used where the samples did not yield plateaux using the criteria for plateau assignment (e.g using >60% ^{39}Ar released) or where no plateau could be selected due to a staircase release pattern.

Low apparent ages could result from loss of radiogenic argon during alteration.

3 Detailed assessment of Mississippian palynology in the Midland Valley of Scotland

		BOREHOLE OR SECTION											
	BIO-ZONE	Gass Water Section (Turner, 1994a)	Loch Humphrey Bore (Owens, 1980a)	Barnhill Bore (Owens, 1978a)	Douglas Muir Quarry (Owens, 1976)	Glenarbuck Section (Scott et al. 1984, 1985)	Loch Humphrey Section (Scott et al., 1984, 1985; Bateman and Cleal, 1995)	Lawmuir Bore (Owens 1980b)	Hurlet Bore (Abusham, 2000)	Spilmersford Bore (Neves et al., 1973)		Newburgh B Bore (Armstrong et al., 1985)	
Pendleian	CN												Lower Limestone Formation
Brigantian	VF							X	X	X	[Aberlady Formation]		Lawmuir Formation
Asbian	NM							X	X	X	[Aberlady Formation]		Lawmuir Formation
Holkerian-Asbian	TC				(TS or younger)				(X)	X	[Gullane Formation]		Lawmuir Formation
Holkerian	TS						X						Greenside Volcaniclastic Member (CPV)
Chadian-Arundian	Pu					X	X						Greenside Volcaniclastic Member (CPV)
Chadian-Arundian	Pu		X										Clyde Sandstone Formation
Chadian	Pu									X		X	Ballagan Formation
Courceyan	CM		X	X			(X in CPV)			X		X	Ballagan Formation
(Famennian) -Courceyan	LN-PC	X											Kinnesswood Formation

Table 2 Summary of Mississippian biozone markers present in key boreholes and sections across the Midland Valley of Scotland, see text for discussion. CPV=Clyde Plateau Volcanic Formation, (x) and lighter colouring indicates a problematic result.

In Mississippian (Lower Carboniferous) strata, palynology is the key biostratigraphic marker across the Midland Valley of Scotland and into the Scottish Borders. Some previously published stratigraphical palynology zonations have been contradictory and so a detailed review of the original data is presented here and in Table 2, before applying the palynology to the radiometric dating results.

Palynological zonations are assigned based on the presence of one or two key species in a sample, as a well as a typical grouping of species. As such, any palynological zonation should be considered for example 'TC and younger' as any spore may continue for a considerable time after its first appearance. However sometimes key palynomorphs are missing (as the source plant may have been missing in the palaeohabitat) and in that case the zonation must be evaluated and described carefully.

The oldest known Carboniferous microflora in the Midland Valley of Scotland is from the Gass Water [NS 6670 2159] in Ayrshire. Turner (1994a) and Smith (1996) described an LN–PC biozones flora (of Higgs et al., 1988a,b) near the local base of the Kinnesswood Formation in the basal Inverclyde group. This is the first and currently only record of the existence of an older biozone than CM in the Scottish Lower Carboniferous. The flora consisted of abundant *Apiculiretusispora* spp. with, amongst others, *Verrucosisporites nitidus, Vallatisporites verrucosus* and *Auroraspora macra*. However neither author discusses the precise reasons for this assignment but Higgs et al. (1988b) state that the base of the CM biozone is to be recognised solely on the incoming of *Schopfites claviger*, and this spore is not present in the Gass Water microflora.

The palynology of the Inverclyde and Strathclyde groups, especially the Ballagan, Clyde Sandstone and Lawmuir formations has been well studied, especially during the BGS drilling programme in the Clyde area in the 1980's. The BGS Loch Humphrey Borehole [NS 4582 7555] (NS47NE/1) is a key site in relation to understanding both the biostratigraphic character and the volcano-stratigraphic timeframe of the Mississippian in the western Midland Valley of Scotland. In particular the borehole links the first, well-preserved rich Lower Carboniferous macrofloral localities within the Greenside Volcaniclastic Member (Hall et al., 1998) to the commencement of volcanic activity as represented by the basal Burncrooks Pyroclastic Member of the Clyde Plateau Volcanic Formation.

From beneath the Clyde Plateau Volcanic (base at 180 m depth) and the Clyde Sandstone (base at 245 m depth) formations the Ballagan Formation in the Loch Humphrey Borehole (Fig 10 below) provided 5 samples that yielded miospore populations. These were sufficiently diverse for Owens (1980a) to propose a CM biozone (Tn3c) Courceyan age. The characteristic zonal components, *Schopfites claviger* and *Auroraspora macra* were present in the five samples from 263.00 m, 273.70 m, 325.0 m, 338.10 m and 396.10 m depths (base bore at 423.5 m depth). Owens noted the following additional components in the flora that characterize the CM biozone: *Retusotriletes incohatus*, *Cyclogranisporites palaeophytus*, *Anaplanisporites delicatus*, *Colatisporites decorus*, *C, denticulatus*, *Lophozonotriletes dentatus*, *Discernisporites crenulatus* and *Rugospora minuta*. Most of these are present in the samples at depths of 273.70 m, 325.00 m, and 338.10 m, and absent from the 263 m and 396 m samples. Two higher samples from the Clyde Sandstone Formation at 226.0 m and 239.80 m (*Schopfites claviger* present) lacked one or both zonal indicators of the CM biozone but crucially the higher contained a few specimens of *Lycospora pusilla*, the zonal component for the Pu biozone (basal Chadian), and so can be confidently assigned to the Pu biozone.

The BGS Barnhill Borehole [NS 4269 7571] (NS 47NW/2) located in the same Kilpatrick Hills lava block as the Loch Humphrey bore and only 3 km farther west, also proved Ballagan Formation with CM biozone recognised in two samples at depths of 187.60 m and 260.00 m (Owens, 1978a). These contain most of the miospores named in the previous paragraph, but not *Lycospora pusilla*. Other BGS boreholes at Kipperoch [NS 3727 7742] (NS 37NE/20) 2 km north-west of Dumbarton (Owens 1978b) and Everton [NS 2145 7103] (NS27SW/5) 1.5 km south-east of Inverkip (Owens 1978c) support this general picture for the palynology of the Ballagan Formation in the western Midland Valley, namely that the strata are of Courceyan, CM biozone, age. A little above the top of the formation in the Loch Humphrey Borehole there is evidence for the basal Chadian (Pu biozone) in the overlying Clyde Sandstone Formation. The incoming of *Lycospora pusilla* is the only significant change in the miospore flora at the CM/Pu boundary and palynologists have used its incoming (first appearance) or relative abundance differently in their interpretations of this position. Currently BGS follow the practice of Higgs et al. (1988a,b) of first appearance.

The Douglas Muir Quartz Conglomerate Member at the base of the overlying Lawmuir Formation above the Clyde Plateau Volcanic Formation at Douglas Muir Quarry [NS 5257 7487] is a locality that has furnished good plant macrofossils. It has also provided a microflora (Owens, 1976) that whilst still having one or two CM biozone elements, lacks the two zonal species and has a relative frequency of *Lycospora pusilla* that would justify placing in the Pu biozone

(Chadian) or younger. The presence of *Knoxisporites stephanephorus* could be of some significance, as one of two zonal indicators for the overlying TS biozone (Clayton, 1985), the base of which is possibly the Arundian/Holkerian stage boundary (Higgs et al., 1988b), or even much younger since the species is long ranging after first appearance, i.e. the Lawmuir Formation at this locality is likely to be TS or (much) younger age.

In sections near the top of the Greenside Volcaniclastic Member at Glenarbuck and Loch Humphrey Burn, Scott et al. (1984, 1985) and Bateman and Cleal (1995) described 12 m and 30 m thick plant rich rocks and their microflora, which they believed to be at the base of the Clyde Plateau Volcanic Formation. This stratigraphic position is disproved by the drilling record of the Loch Humphrey Borehole in which further lava flows and pyroclastic rocks belonging to four further members were encountered below the level of the Loch Humphrey plant beds. At Glenarbuck [NS 452 747], Scott et al. (1984, 1985) recognised the presence of *Lycospora pusilla* in the plant-bearing beds and concluded that the strata belonged to the Pu biozone or younger, i.e. Viséan age. However Bateman and Cleal (1995) correlated them with the uppermost part of the Loch Humphrey Burn succession (Pu/TC). The situation at Loch Humphrey Burn [NS467 753] was more complex with CM recognised in their bed 6, Pu in bed 11 and Pu/TC identified in beds 15, 17, 21, 23 and 33. The CM biozone in bed 6 contained both zonal forms. However it is possible that lycopsid trees were growing at a sufficient distance away from this site such that the real zonation is Pu, but the spores were not transported in. Bed 11 is marked by the presence of the zonal form *Lycospora pusilla*. The upper beds contain both *Knoxisporites stephanephorus* and *K. triradiatus*, which currently would suggest that these beds could belong in the TS biozone (this biozone was set up by Clayton, 1985; for history of this and other changes see Owens et al., 2005).

The BGS Lawmuir Borehole [NS 5183 7310] (NS57SW/162) on the north side of Glasgow provides a reference section for strata above the Clyde Plateau Volcanic Formation in the Lawmuir Formation, in particular for the next two younger NM and VF biozones in the western Midland Valley of Scotland. The key components recognised by Owens (1980b) in the NM zone from depths of 75.23 m to 261.10 m are *Raistrickia nigra*, *Murospora parthenopia* and *Triquitrites marginatus*. Other useful indicators are *Crassispora aculeata* and *Rotaspora ergonulii*. However the floras often lack the specific forms and *Schulzospora campyloptera*, one of the two key incomers in the underlying TC biozone is commonly present in samples from both the NM and VF zones whereas the other, *Perotrilites tessallatus* is absent in this borehole.

The key component species in the VF zone from depths of 9.55 m to 68.80 m are *Tripartites vetustus* and *Rotaspora fracta*. Other useful indicators are *Crassispora maculosa* and *Grandispora spinosa* that first appear at or just below the base of the VF zone. The Balmore Marine Band (= Dykebar Limestone), the oldest marine band in the Lawmuir Formation, is at this depth at the base of the biozone.

As Owens did not recognise the TC biozone in the Lawmuir Borehole, the useful indicators for this biozone would have been *Verrucosisporites baccatus*, *Dictyotriletes sagenoformuis* and *Waltzispora planiangulata*, none of which was present. Nor could he have identified the more recently recognised underlying TS zone characterized by the incoming of two species of *Knoxisporites* (*triradiatus* and *stephanephorus*). K *triradiatus* was present at depths of 239.50 m and 261.10 m but the other species occurred in most samples in the borehole. In conclusion, the Lawmuir Formation in this borehole is of NM and VF biozone ages.

In much more recent work on the Ballagan Formation, the CM biozone (Tournaisian Tn3c) assemblages are also present between 200.17m and 53.90m depths in the Blairmulloch Borehole [NS 5605 2820] in Ayrshire (Stephenson, 2003). No specimens of *Lycospora pusilla* were recorded in this interval. The highest sample studied, from 5.75m, yielded a very poorly preserved assemblage consisting almost entirely of *Densosporites* spp., suggesting a possible Viséan or younger age, consistent with the observed Lower Limestone Formation stratigraphy. The findings of the study are very much at variance with those of Abusham (2000) who reported

CM Biozone assemblages from the same prepared slides between depths of 212.0 and 124.65m in the borehole, Pu biozone assemblages between 123.3 and 23.90 m, and TS biozone assemblages from 5.75m. The last zone is plainly erroneous given that the strata belong to Hosie limestones in the Lower Limestone Formation (Clackmannan Group) in the VF biozone.

Abusham (2000) also worked on the Hurlet Borehole [NS 5111 6125] (NS56SW/333) on the south side of Glasgow identifying TC, NM and VF biozones that could also provide a key section for the Lawmuir Formation in the western Midland Valley of Scotland. However only one of the two zonal indicators (*Schulzospora campyloptera*) was present for the TC Biozone and is not therefore reliable as an indicator that the basal Lawmuir Formation is of this age. A reasonable conclusion from the Lawmuir and Hurlet boreholes is that the Lawmuir Formation is contained within just the two biozones, NM and VF, and is therefore Asbian to Brigantian in age.

A recent study in Fife (Owens et al., 2005) of the original sections that Neves et al. (1973) used to set up the Lower Carboniferous miospore zones may contribute to attempts to understanding the timescale for the period. Here the equivalents of the Lawmuir Formation, the Pathhead and upper part of the Sandy Craig and basal part of the Sandy Craig and Pittenweem formations are assigned to the VF and NM biozones (Brigantian and Asbian, respectively) as expected. Interestingly the underlying Anstruther Formation is TC Biozone also as expected but assigned to late Arundian or Holkerian (in the summary) and Holkerian to Early Asbian in the conclusions; rather than early Asbian as previously understood. The Pittenweem Formation contains a number of faunally rich and diverse marine bands associated with the well-described MacGregor Marine Bands (Wilson, 1986). None of these marine beds is present in the Lawmuir Formation in western Glasgow.

In Edinburgh, Neves et al., (1973) recognized the Pu biozone in the lower part of the Arthur's Seat Volcanic Formation (Strathclyde Group). The sample came from the cliff beneath St Anthony's Chapel in the plant-bearing, metre or so thick, volcaniclastic mudstone beneath Lava Three in the local succession. Apart from the zonal form *Lycospora pusilla*, no details of the microflora are provided. The overlying Gullane Formation rocks are not exposed in or near Holyrood Park. It follows that dating either Lava One or Lava Three accurately is important to understanding the Carboniferous timeframe.

Neves et al., (1973) also report detailed work for boreholes and sections in East Lothian including the Garleton Hills and in the Oldhamstocks basin in the Scottish Borders. The Garleton Hills Volcanic Formation is underlain by the Ballagan Formation and overlain by the Gullane and Aberlady formations. The Aberlady Formation contains marine beds that Wilson (1986) assigned to the MacGregor Marine Bands. The key borehole is Spilmersford where Neves et al., (1973, fig. 8) recorded CM and Pu biozones in the Ballagan Formation and TC, NM and VF in the sedimentary rocks above the Garleton Hills Volcanic Formation. The typical CM assemblage was recorded between depths of 801 m and 918.5 m and the Pu between depths of 703 m and 801 m. The authors record that the appearance of *Lycospora* spp (Lycopsid plants) is a significant development in the spore flora and they become a dominant element in younger assemblages.

Neves et al., (1973) record that of 276 species of miospores identified in strata above and below the volcanic formation, only 26 were in common. The TC biozone was recognized from 268.7 m up to 123 m depth (Cove Lower Marine Band) at the base of the Aberlady Formation. Within this unit, the base of the VF biozone was placed at a depth of 56.7 m. Bateman and Scott (1990) and Scott (1990) have reported both macroflora and palynomorphs in the basal member of the Garleton Hills Volcanic Formation at Oxroad Bay, East Lothian.

Crucially in linking biozones to the timescale, Monaghan and Pringle (2004, table 2) and Monaghan and Parrish (2006, table 1) reported $^{40}Ar/^{39}Ar$ and U-Pb radiometric dates from the Garleton Hills Volcanic Formation close to the Tournaisian-Viséan boundary. The $^{40}Ar/^{39}Ar$ dates (on sanidine) were 342.4 ±1.1 and 342.1 ±1.3 Ma from the uppermost Bangley Member. The U-Pb date (on zircon) was 343.4 ±1.0 Ma from a slightly higher horizon (about 50 m) in the

Bangley Member but there are systematic differences between the two methods of dating. Stratigraphically, these results come from not far below the local TC boundary as recognized in the Spilmersford Borehole at the base of the Gullane Formation.

In the Perth and Dundee memoir (Armstrong et al. 1985, p. 56), the BGS Newburgh B Borehole [NO 2320 1852] (NO21NW/7), is recorded as proving the Newburgh Member, the highest of three in the Ballagan Formation in this northern Inverclyde Group outlier. The key detail is that the topmost miospore sample in this shallow bore contained *Lycospora pusilla* and so defines another area where the Ballagan Formation contains the transition from the CM to the Pu biozone.

Owens et al. (2005) have redefined the *Bellispores nitidus – Reticulatisporites carnosus* (NC) biozone as the CN (*Cingulizonates capistratus-Bellispores nitidus*). Owens et al. (2005) place the boundary between the underlying VF biozone and the CN at the level within the Lower Limestone Formation of the St Monans Little Limestone (i.e. Inchinnan) in east Fife and 2nd Abden Limestone (i.e. Hurlet) in the Kirkcaldy area based on their new data. However Turner (1994b) records the incoming of *Cingulizonates capistratus* in the BGS Cults No 1 Borehole [NO 3529 0897] in north Fife at the base of the Pathhead Lower Marine Band up to 85 m lower in the underlying Pathhead Formation.

4 Dating results

Table 3 gives the numerical dating results and Figure 2 summarises the results against known stratigraphy and the internationally accepted timescale.

Sample	Type	Stratigraphy/ Location	Age(total fusion)	±1s	Age (isochron)	±2s	40Ar/ 36Ar(i)	±1s	N	MSWD	Plateau	±2s	%39Ar	N	MSWD	Plateau-chron	±2s	%39Ar	N	MSWD	40Ar/ 36Ar(i)	±1s
ASW 124	plag	GHV, Bangley Quarry	334.3	3.0	334	5	170	40	53	10.1	336	4	87.1	38	1.11	333	6	89.9	41	0.47	443	77
ASW 402	gmass	MVL, Stair	291.3	3.1	292	7	233	41	22	9.3	nrp					289	5	96.3	19	0.41	547	69
ASW 407	plag	ASV,Lion's Haunch	342.2	3.6	343	15	697	560	28	0.56	349	4	62.5	14	1.6	nsr						
ASW 412	gmass	ASV, Lava 3	298.3	3.2	330	17	312	23	16	2.2	334	4	60.6	6	1.5	330	7	69.1	6	0.96	308	12
ASW 414	gmass	KNV, Orrock Quarry	303.8	3.2	303	11	355	44	10	10.4	nrp					319	6					
ASW 421	plag	CSTD dyke, Beecraigs	302.8	2.7	308	10	2195	880	70	0.97	nrp					nsr						
ASW 421	plag	CSTD dyke, Beecraigs	322.2	3.4	323	17	313	50	30	44	nrp					nsr						
ASW 426	gmass	BHV, Cow Craig	332.4	3.5	323	16	719	520	18	0.86	nrp					323	26	89.9	18	0.38	673	230
BEB1555	plag	CPV, Loch Humphrey	312.6	3.3	311	14	316	62	33	32	nrp					nsr						
BEB1555	plag	CPV, Loch Humphrey	308.7	3.2	338	18	269	19	33	56	nrp					nsr						
BEB1800	plag	CPV,Tak-m-Doon	314.4	3.3	319	10	369	68	41	43	nrp					nsr						

Table 3 Summary of dating results. The age that should be used for each sample is shaded in grey. All ages apart from total fusion given with 2 sigma errors, nrp = no resolvable plateau, nsr = no solution resolved, plag=plagioclase, gmass=groundmass see Table 1 for explanation of Lexicon codes e.g. GHV.

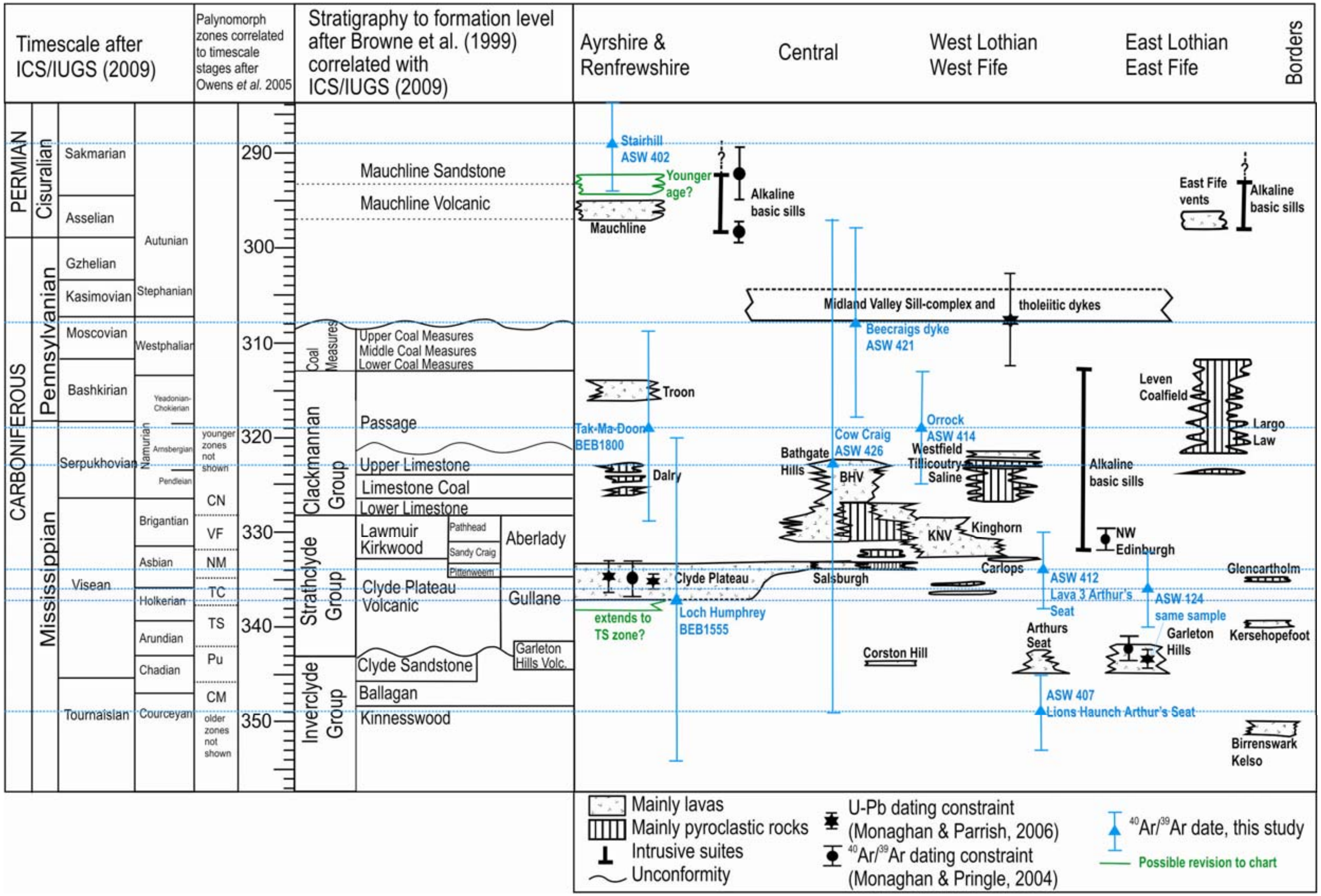

Figure 2 Summary of new radiometric dates placed on existing time-space chart of Midland Valley Carboniferous-Permian volcanism from Monaghan and Parrish (2006). Stratigraphy and palynology zones have been re-mapped to the ICS/IUGS (2009) timescale with substage age definition from Ogg et al. (2008) Note that this timescale is significantly different from the Menning et al. (2000) timescale used in Monaghan and Parrish (2006) and together with the newer Owens et al. (2005) palynomorph zonations, the stratigraphy has been re-mapped to the 2009 timescale.

4.1 ARTHUR'S SEAT VOLCANIC FORMATION AND INTRUSION

4.1.1 ASW 407 Lion's Haunch Vent Intrusion

4.1.1.1 Sample location and rock type

Sample ASW407 comes from the Lion's Haunch Vent, Crow Hill intrusion just to the south-west of the summit of Arthur's Seat (Figure 3). The olivine-pyroxene-plagioclase porphyritic alkali basalt contained good sized feldspars for separation. Numerous inclusions within the plagioclase separate could not be avoided.

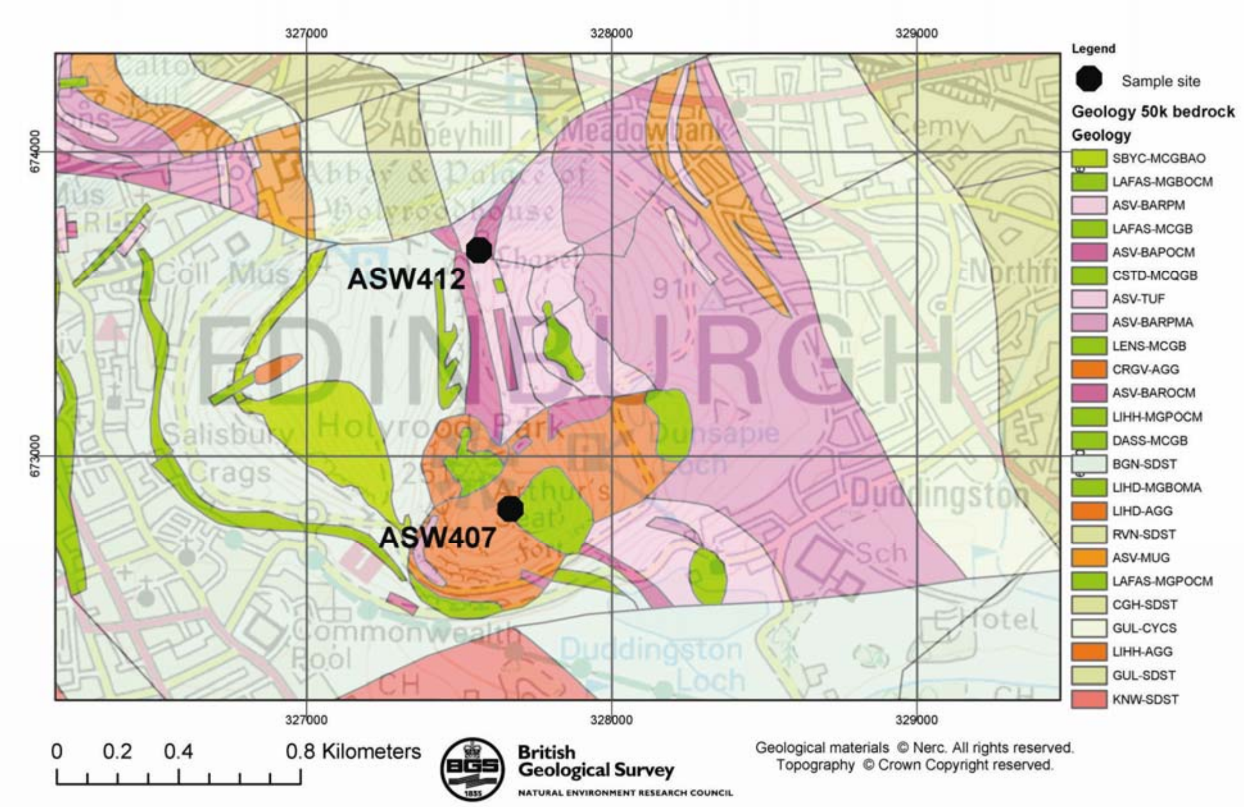

Figure 3 Location of the two chosen samples from Arthur's Seat. Shown with BGS Digmap 1:50,000, see the BGS Lexicon (http://www.bgs.ac.uk/Lexicon/home.cfm) for a description of the codes used in the Legend. Geological materials BGS © NERC. OS Topography © Crown Copyright BGS100017897/2010. All Rights Reserved

4.1.1.2 ASW407 RESULT

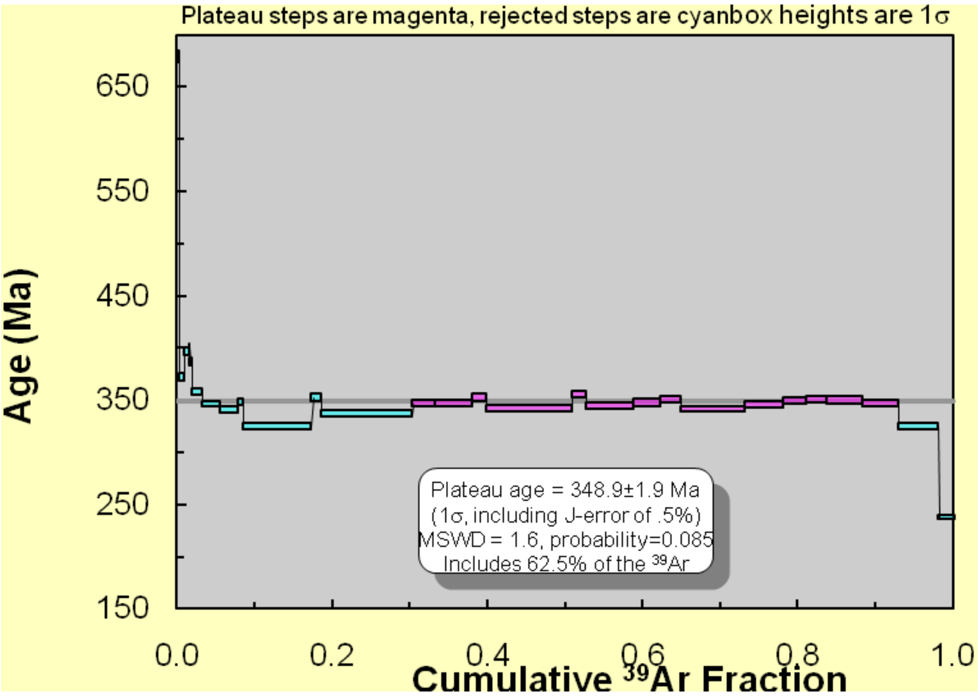

Figure 4 Summary of the $^{40}Ar/^{39}Ar$ step-heating experiment on ASW407.

The plagioclase step-heating experiment gave a reasonable plateau result with 63% of gas used and an age of 349 ± 4 Ma (2 σ error; Figure 4).

4.1.2 ASW412 Lava 3 St Antony's Chapel

4.1.2.1 SAMPLE LOCATION AND ROCK TYPE

The rock sample was taken close to St Antony's Chapel, just above the Upper Ash of the Dry Dam Tuff (See Figure 3 above). The plagioclase phenocrysts in this rock were not big enough for analysis, so a groundmass separate of this olivine-clinopyroxene microporphrytic alkali basalt (Figure 5) was used.

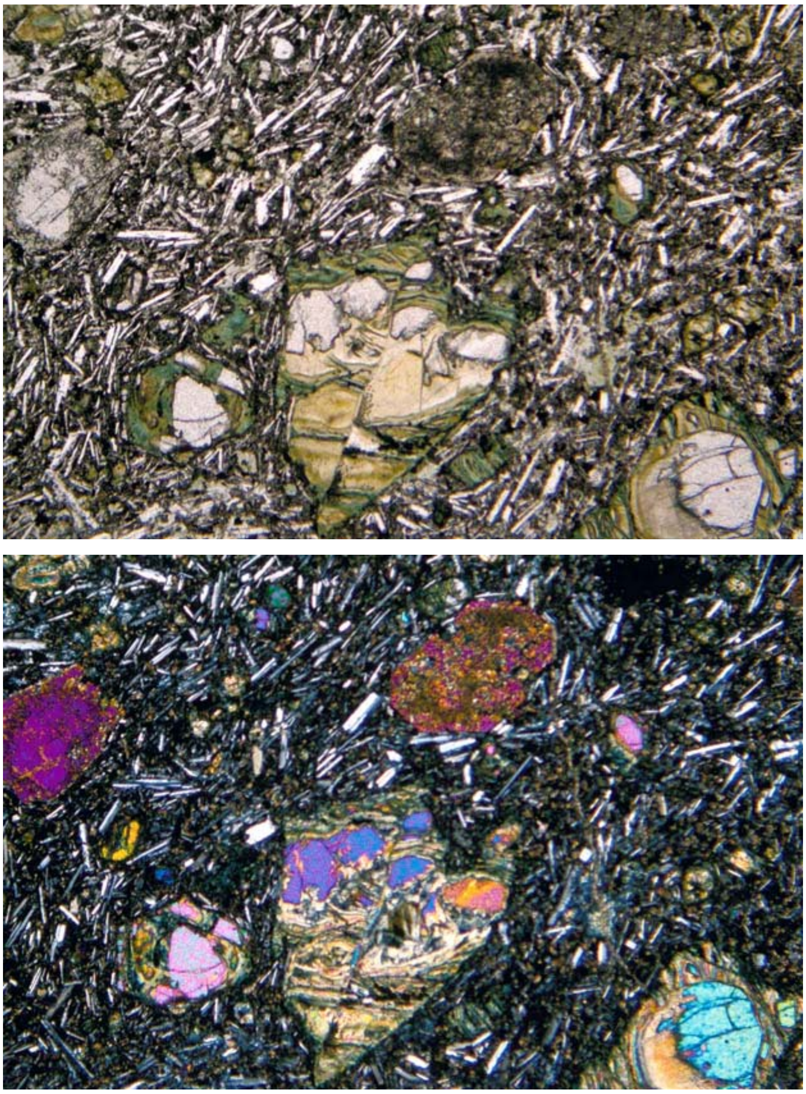

Figure 5 Photomicrograph of Lava 3 St Anthony's Chapel showing serpentinised olivine phenocrysts, pyroxene phenocrysts and small plagioclase phenocrysts in a pilotaxitic groundmass, under plane and cross-polarised light 2.5 times magnification.

4.1.2.2 ASW412 Result

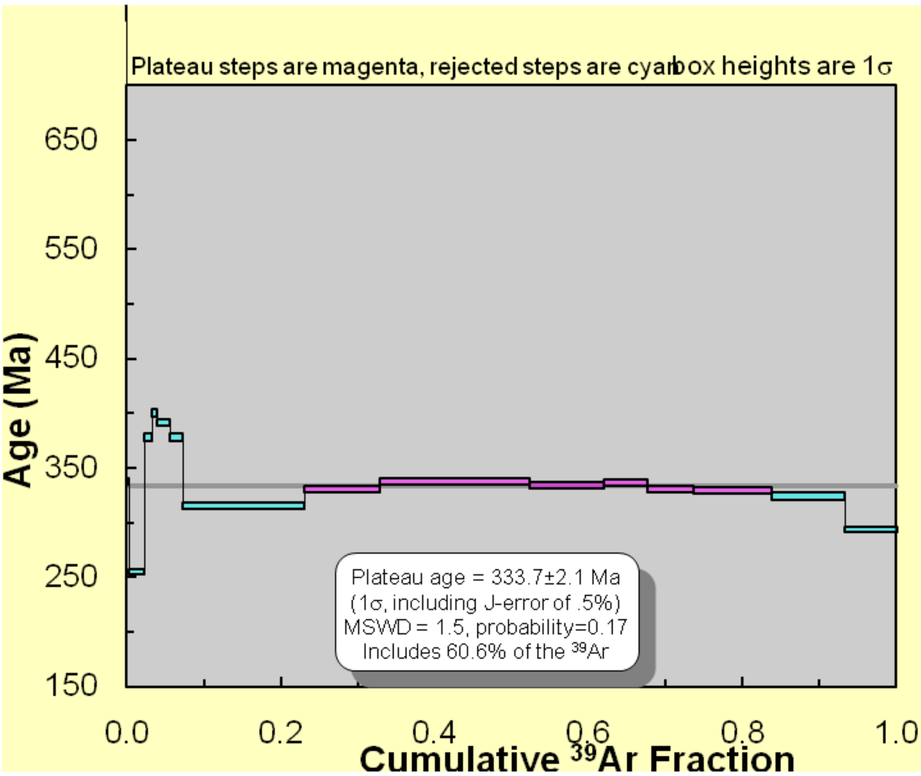

Figure 6 Summary of the $^{40}Ar/^{39}Ar$ step-heating experiment on ASW412.

The plagioclase step-heating experiment gave a reasonable plateau with 61% of the gas used and an age of 334 ± 4 Ma (2 σ error, Figure 6).

4.1.2.3 Fit with stratigraphy and other radiometric dates

Previous K/Ar radiometric dates from Arthur's Seat include HS151 Lava 3 Whinny Hill 302 ± 9 Ma though this sample was altered and the date believed to be too low (De Souza, 1979). De Souza (1979) also dated the Lion's Haunch basalt HS155 320 ± 7 Ma, consistent with a late stage intrusion. Fitch et al., (1970) obtained a minimum age for Lava 1 of 347 ± 5 Ma; other ages from Lava 3 and Dunsapie Hill were considered very poor minimum ages due to sample alteration. De Souza (1979) commented that this Fitch sample was less altered than those in his study and provided the best evidence for a pre-340 Ma age for the Arthur's Seat volcanicity.

The Arthur's Seat Volcanic Formation (Strathclyde Group) in Holyrood Park and on Calton Hill comprises a series of easterly-dipping lava flows thought to have been erupted from four vents (Castle Rock, Lion's Head, Pulpit Rock and the Lion's Haunch). A large number of basaltic intrusions, petrographically similar to the lavas are believed to have been emplaced during or shortly after the main volcanic episode (Clark, 1956; Black, 1966). The dipping lava succession is underlain by Tournaisian age Ballagan Formation (Inverclyde Group) strata and overlain by early Viséan age Gullane Formation (Strathclyde Group) rocks. The Lower Dry Dam Tuff of the Arthur's Seat Volcanic Formation close (< 50 m) to the sample location of, and stratigraphically immediately below Lava 3 has palynomorphs of the lowermost Viséan Pu miospore zone (Neves et al., 1973). The $^{40}Ar/^{39}Ar$ age of 334 ± 4 Ma for Lava 3 is too young for the surrounding biostratigraphic constraints.

The Lion's Haunch Vent is mainly agglomerate-filled and may have been initiated around the time of Lava 5 extrusion, but the Crow Hill intrusion from which sample ASW407 came is believed to be a late stage intrusion (Clark, 1956; Black, 1966). The $^{40}Ar/^{39}Ar$ age of 349 ± 4 Ma on this intrusion seems too old for the surrounding stratigraphic constraints.

The two Arthur's Seat samples analysed here are separated by a fault, but it would be expected that the intrusion ASW407 might be younger, rather than significantly older than the ASW412 Lava 3. The results are puzzling as the samples were reasonably fresh and gave reasonable step-heating plateaux.

4.2 GARLETON HILLS VOLCANIC FORMATION

4.2.1 ASW124 Bangley Quarry

4.2.1.1 SAMPLE LOCATION AND ROCK TYPE

The Early Carboniferous Garleton Hills Volcanic Formation of East Lothian is a *c.* 520 m-thick succession composed of a basal sequence of tuffs and volcaniclastic sedimentary rocks, overlain by basic lavas (McAdam and Tulloch, 1985). Up to 160 m of felsic tuffs and trachytic lavas form the uppermost Bangley Member of the formation (McAdam and Tulloch, 1985), from which the $^{40}Ar/^{39}Ar$ sample was taken (Figure 7). The $^{40}Ar/^{39}Ar$ sample ASW124 from Bangley Quarry is a feldspathic trachyandesite from close to the top of the member. A plagioclase separate was picked, though a pervasive yellow-brown alteration was hard to completely avoid.

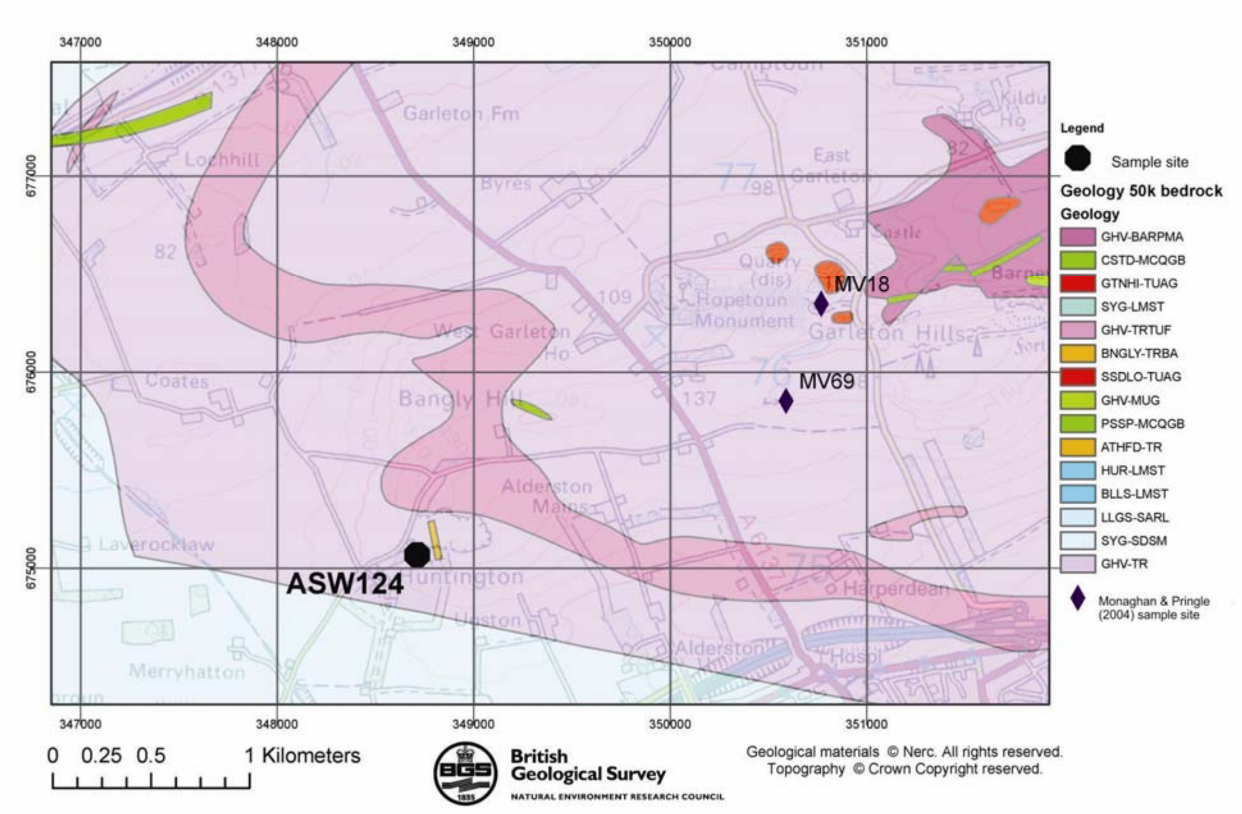

Figure 7 Location of the Garleton Hills sample, along with the location of Monaghan & Pringle (2004) $^{40}Ar/^{39}Ar$ sample sites. Shown with BGS Digmap 1:50,000, see the BGS Lexicon (http://www.bgs.ac.uk/Lexicon/home.cfm) for a description of the codes used in the Legend. Geological materials BGS © NERC. OS Topography © Crown Copyright BGS100017897/2010. All Rights Reserved

4.2.1.2 ASW124 RESULT

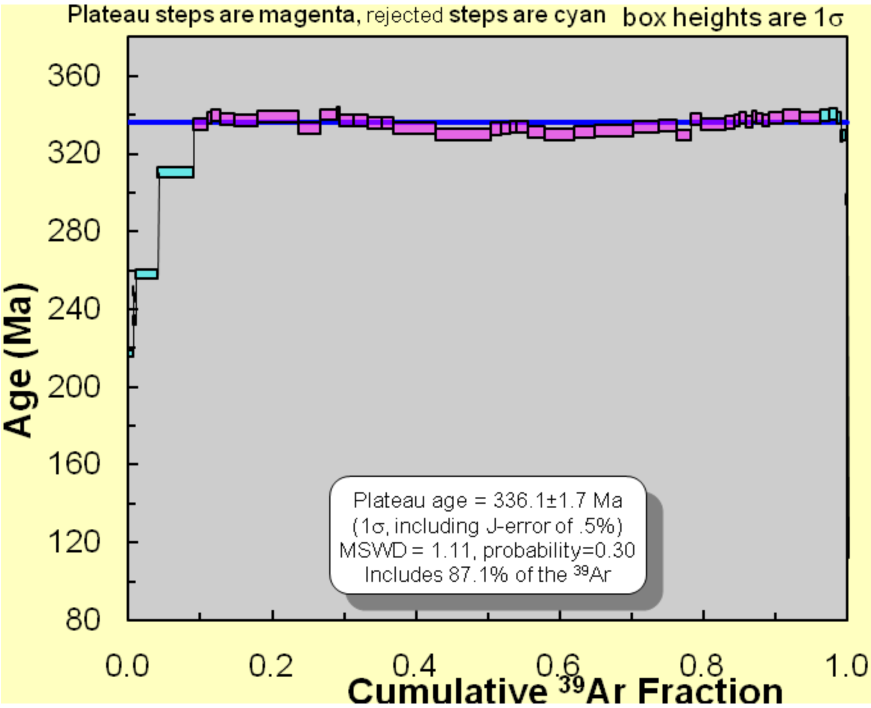

Figure 8 Summary of the $^{40}Ar/^{39}Ar$ step-heating experiment on ASW124.

This plagioclase step-heating experiment produced a good plateau with 87% of the gas used and an age of 336 ± 4 Ma (Figure 8).

4.2.1.3 FIT WITH STRATIGRAPHY AND OTHER RADIOMETRIC DATES

A U-Pb age of 343.4 ± 1.0 Ma exists for this same sample (Monaghan and Parrish 2006). The new 336 ± 4 Ma $^{40}Ar/^{39}Ar$ age is significantly younger and not within 2σ error limits. A known bias exists between the U-Pb and $^{40}Ar/^{39}Ar$ techniques but this is ~0.65 % (e.g. Min et al., 2000; Kuiper et al., 2008) and cannot account for the difference in these two radiometric ages on the same sample.

In addition, two good $^{40}Ar/^{39}Ar$ results from MV18 (342.4 ± 1.1 Ma) and MV69 (342.1 ± 1.3 Ma) were obtained on sanidine separates of the Garleton Hills Volcanic Formation from sites that are approximately 50 m stratigraphically below sample site ASW124 (Monaghan and Pringle, 2004). These $^{40}Ar/^{39}Ar$ results are the same within 2σ error limits as the U-Pb age on ASW124.

Also, palynomorphs and plant remains of the CM to Pu miospore zones (latest Tournaisian, Courceyan to earliest Viséan, Chadian) have been found in the Ballagan Formation that lies beneath the apparently conformable Garleton Hills Volcanic Formation, and from volcaniclastic rocks interbedded within basal strata of the volcanic formation (Bateman and Scott, 1990; Scott, 1990). Strata of the Gullane Formation that contain TC zone (Asbian) miospores (Neves et al. 1973) overlie the Garleton Hills Volcanic Formation. The new 336 ± 4 Ma $^{40}Ar/^{39}Ar$ age would place the rocks in the mid Viséan i.e. mid Gullane Formation and so the new age does not fit well with the known stratigraphy.

In conclusion, whilst ASW124 gave a good step-heating plateau result, the resulting age is significantly younger than the existing radiometric ages or than would be expected from the stratigraphic constraints. It therefore seems possible that the feldspar separate was pervasively altered.

4.3 CLYDE PLATEAU VOLCANIC FORMATION

The Early Carboniferous Clyde Plateau Volcanic Formation crops out in fault-bounded blocks in the western MVS and is up to 1000 m in thickness (Paterson et al., 1990). It is dominated by transitional to mildly alkaline basaltic and hawaiitic lavas with minor trachytic and rhyolitic lavas and intrusions (Smedley, 1986; Stephenson et al., 2003). The samples chosen here came from boreholes that were stratigraphically well constrained, situated in northern fault blocks of the Clyde Plateau Volcanic Formation.

4.3.1 BEB1555 BGS Loch Humphrey Borehole

4.3.1.1 SAMPLE LOCATION AND ROCK TYPE

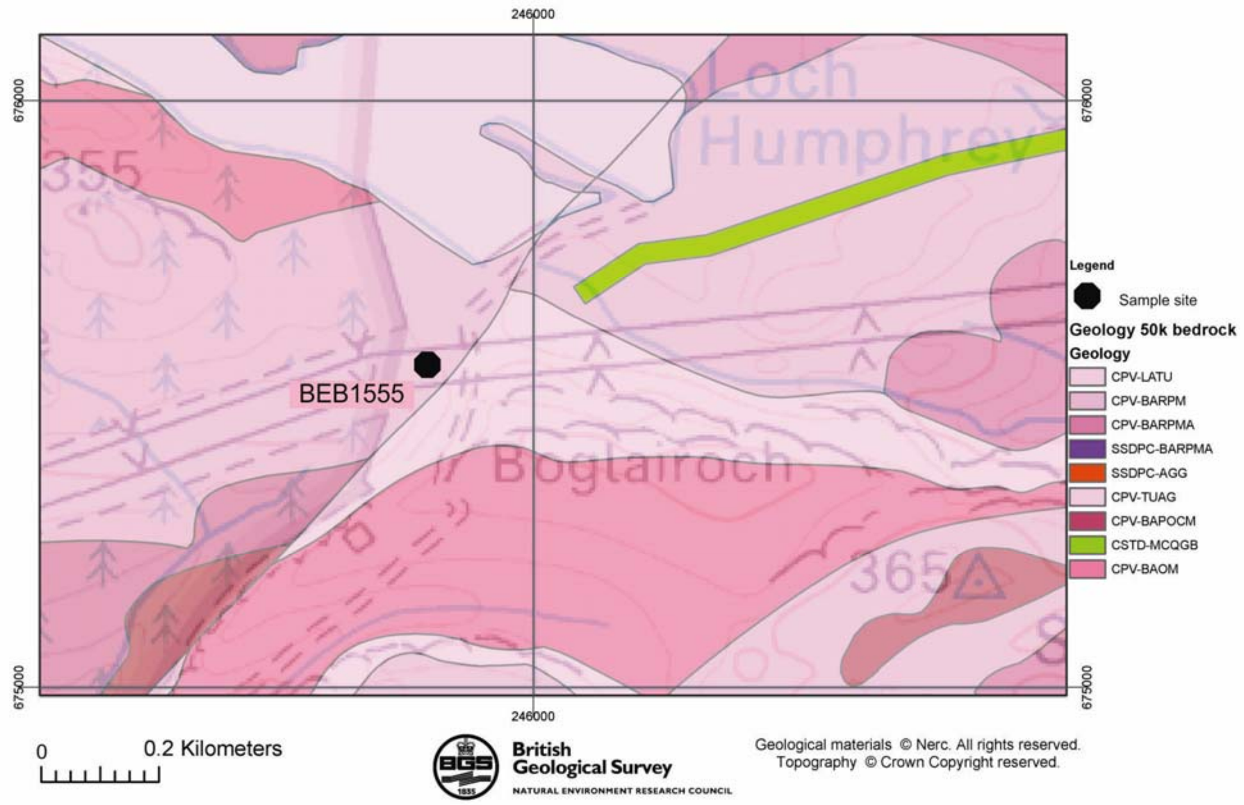

Figure 9 Location of the chosen sample from the BGS Loch Humphrey Borehole. Shown with BGS Digmap 1:50,000, see the BGS Lexicon (http://www.bgs.ac.uk/Lexicon/home.cfm) for a description of the codes used in the Legend. Geological materials BGS © NERC. OS Topography © Crown Copyright BGS100017897/2010. All Rights Reserved

Sample BEB1555 comes from the BGS Loch Humphrey Borehole [NS47NW/1] (Figure 9, 10). The borehole is located within the 'Kilpatrick Block' of the Clyde Plateau Volcanic Formation. It starts in the Greenside Volcaniclastic Member at the top and finishes below the Clyde Sandstone Formation in the Ballagan Formation (with Pu and CM miospores, respectively: after Owens, 1980a; Figure 10). The borehole lies 800 m away from an exposed Greenside Volcaniclastic Member intercalation that contains well preserved plant floras (Hall et al., 1998). The sample BEB1555 came from an olivine-pyroxene-plagioclase macroporphyritic alkali basalt between 22.00 m (core piece BEB 1554) and 22.85 m (core piece BEB 1555; Figures 11, 12) down the borehole just below the bedded ash of the Greenside Volcaniclastic Member (Figure 10). The plagioclase separate was of colourless to white, large and relatively abundant phenocrysts, with some inclusions.

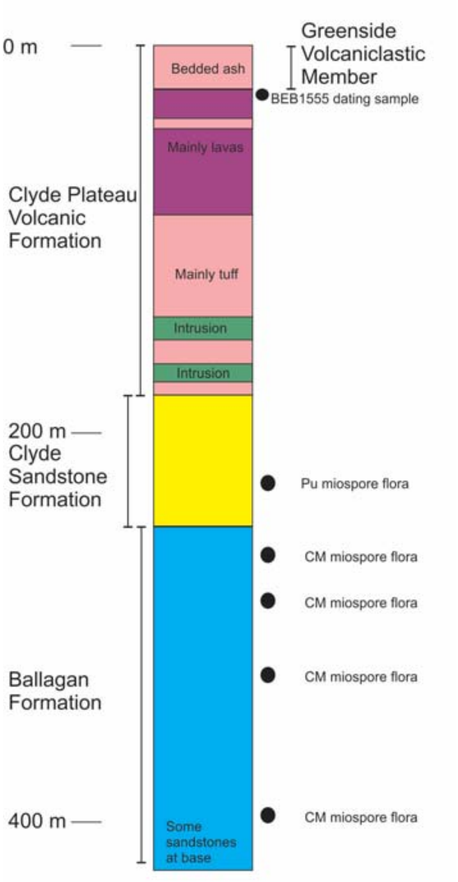

Figure 10 Summary of the interpreted stratigraphy of the BGS Loch Humphrey borehole and the position of argon dating and palynology samples. Depths in metres from the top of the borehole.

Figure 11 Photo of core piece BEB1555 from the BGS Loch Humphrey Borehole, some feldspar phenocrysts can be seen.

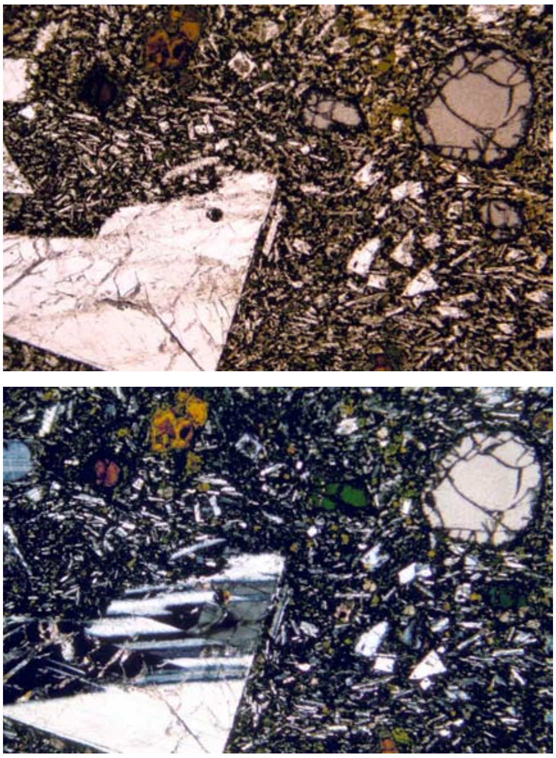

Figure 12 Photomicrograph of BEB 1555 from BGS Loch Humphrey Borehole showing plagioclase and pyroxene phenocrysts under plane and cross-polarised light, 2.5 times magnification.

Electron microprobe analysis on 20 grains of sample BEB1555 showed an average K_20 content of 0.25 weight % with minimal core/rim zonation (see Appendix 1).

4.3.1.2 BEB1555 RESULTS

Two analyses were run on a sample of BEB1555 on two different machines.

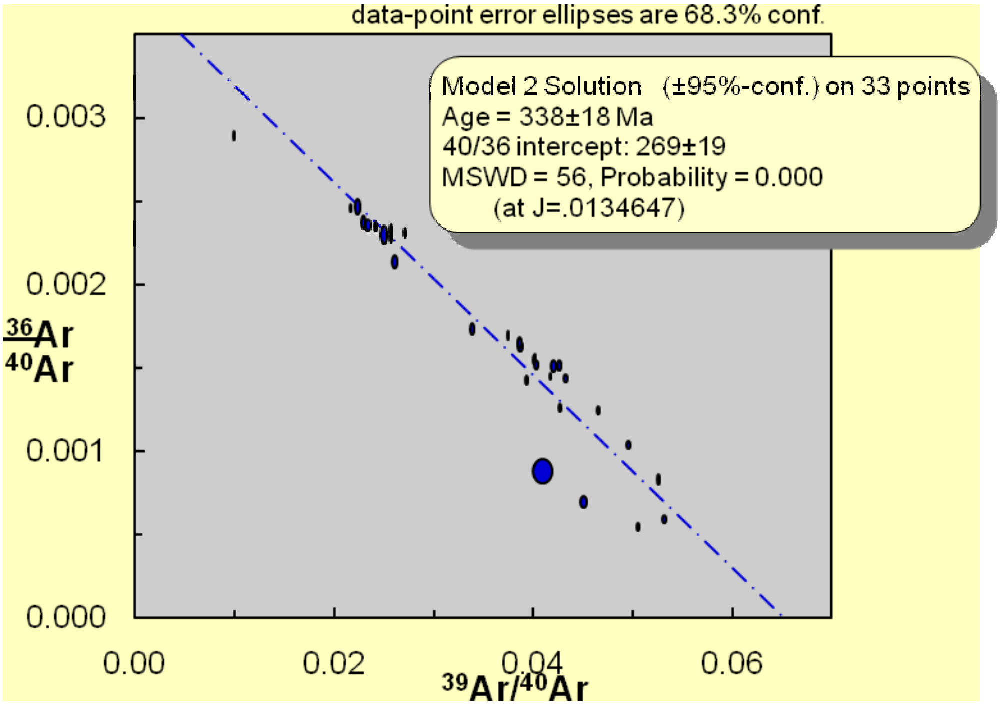

Figure 13 Summary of the ^{40}Ar/^{39}Ar step-heating experiment isochron result on BEB1555.

This plagioclase step-heating experiment did not produce a satisfactory plateau age and thus an isochron age of 338 ± 18 Ma should be used (Figure 13). However, note the large error and MSWD.

The second analysis (Figure 14) differs significantly because the isochron was fitted very differently, within a large error range. With the second analysis there was also no satisfactory plateau and the isochron age of 311 ± 14 Ma was the best obtainable.

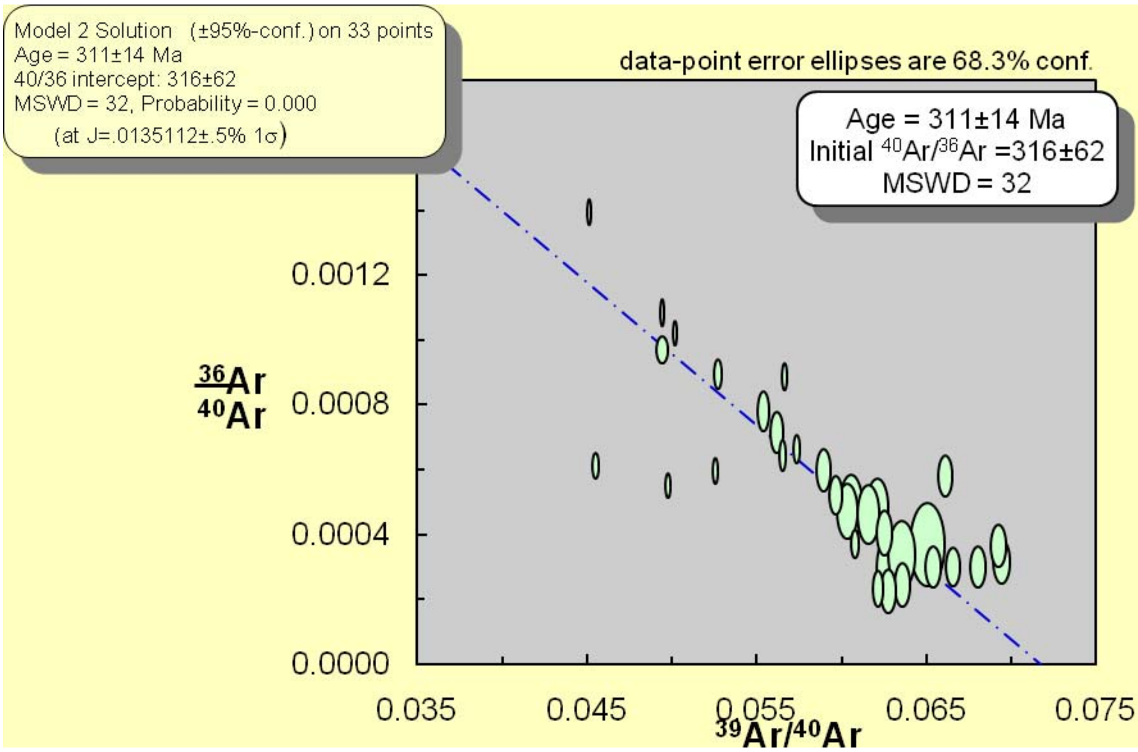

Figure 14 Summary of a second $^{40}Ar/^{39}Ar$ step-heating experiment isochron result on BEB1555

4.3.2 BEB1800 and 1805 BGS Tak-Ma-Doon Borehole

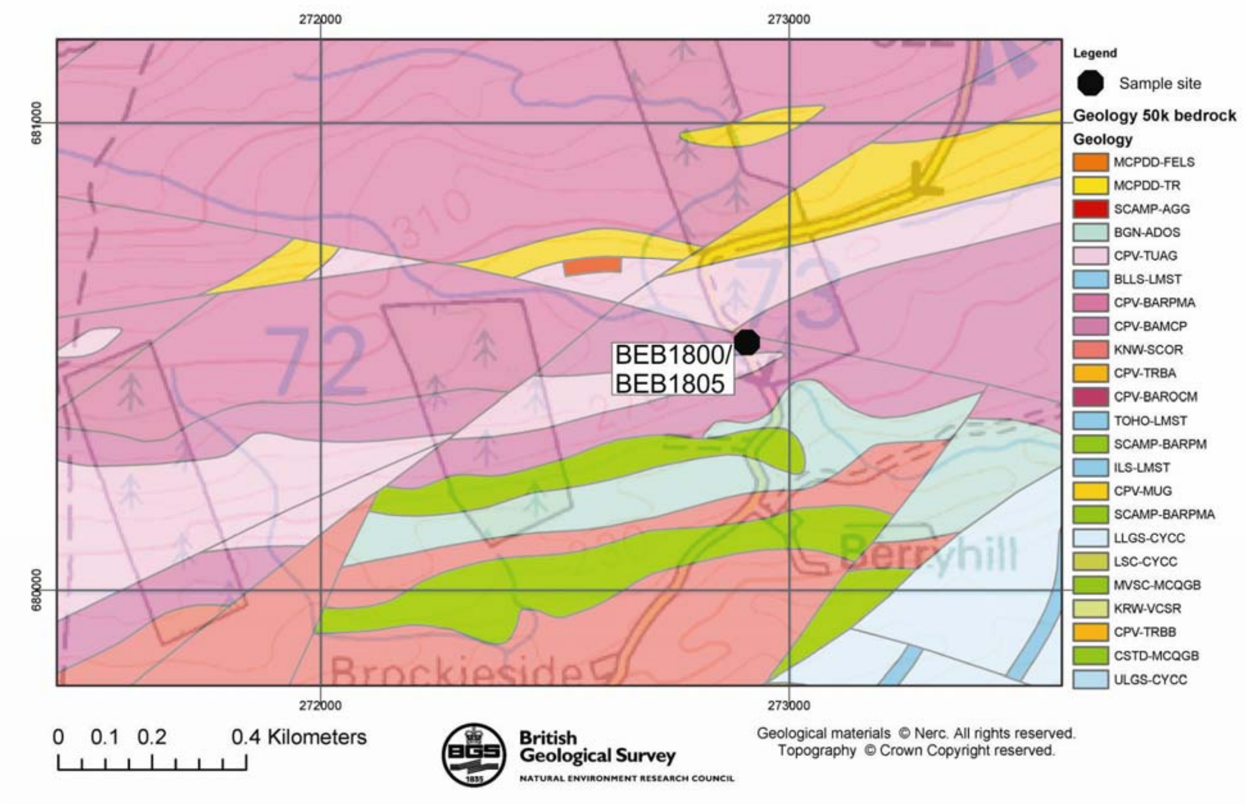

Figure 15 Location of the BGS Tak-Ma-Doon Borehole. Shown with BGS Digmap 1:50,000, see the BGS Lexicon (http://www.bgs.ac.uk/Lexicon/home.cfm) for a description of the codes used in the Legend. Geological materials BGS © NERC. OS Topography © Crown Copyright BGS100017897/2010. All Rights Reserved

The BGS Tak-Ma-Doon Borehole [NS78SW/5], is situated on the southern edge of the Kilsyth block (Figure 15). To obtain enough feldspar separate material from an altered plagioclase-pyroxene microporhyritic alkali basalt, core piece BEB1800 (29.1 m depth) and BEB 1805 (41.3 m depth) were combined. The resulting colourless to white plagioclase crystals were rare. The basalt was from the basal lava flows of the Clyde Plateau Volcanic Formation. Immediately underlying the lava flows are rocks of the Ballagan and Kinnesswood formations.

Electron microprobe analysis on 20 grains of sample BEB1800 showed an average K_20 content of 0.24 weight % with minimal core/rim zonation (see Appendix 1).

4.3.2.1 BEB1800 RESULT

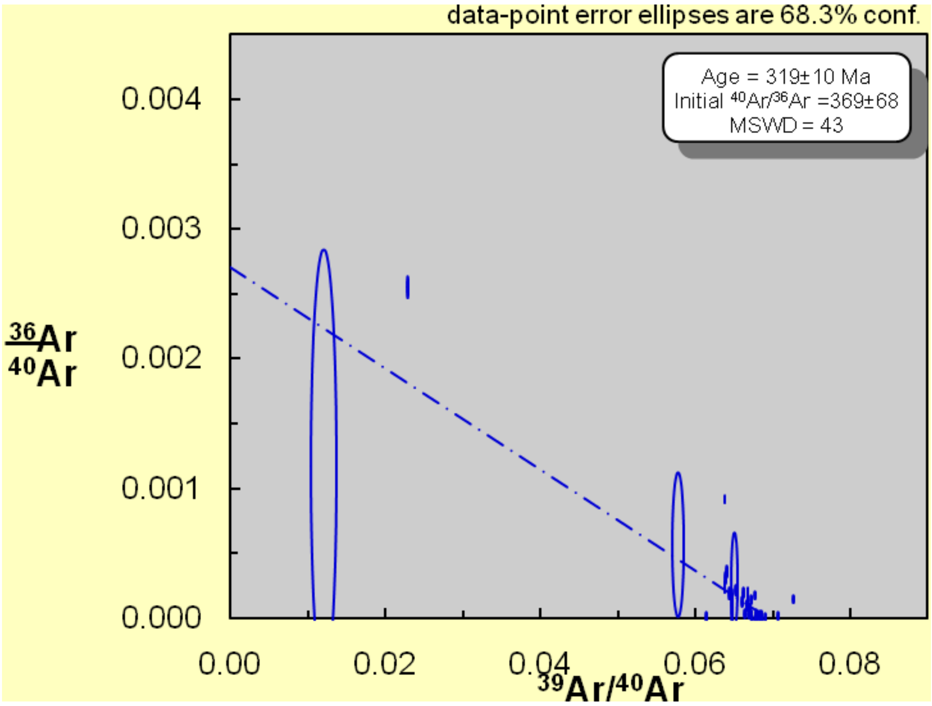

Figure 16 Summary of the ^{40}Ar/^{39}Ar step-heating experiment isochron result on BEB1800

This plagioclase step-heating experiment did not produce a satisfactory plateau age. The isochron age of 319 ± 10 Ma was difficult to fit and has a large error (Figure 16).

4.3.2.2 FIT WITH STRATIGRAPHY AND OTHER RADIOMETRIC DATES

Six ^{40}Ar/^{39}Ar dates on Clyde Plateau Volcanic Formation strata from the southern, Renfrewshire Hills, Beith Hills and Lanarkshire fault blocks gave results ranging from 335 ± 2 Ma to 329.2 ± 1.4 Ma (Monaghan and Pringle, 2004). Two U-Pb ages, also from the southern Renfrewshire Hills and Lanarkshire fault blocks, gave ages of 334.7 ± 1.7 and 335.2 ± 0.8 Ma (Monaghan and Parrish, 2006). The U-Pb and ^{40}Ar/^{39}Ar dates were synthesized (accepting that the two youngest ^{40}Ar/^{39}Ar dates represent minimum ages and that there is a systematic bias of *c.* 1–2.6 Ma between the U-Pb and ^{40}Ar/^{39}Ar techniques) such that the extrusion of the southern Clyde Plateau Volcanic Formation lasted only about 2 Ma at around 335 ± 2 Ma. Correlations have been made between the Renfrewshire Hills Block and the northern fault blocks of the Kilpatrick Hills and Campsie Fells (Stephenson et al., 2003, pg 45) implying that the *c.* 335 ± 2 Ma age is representative of the formation as a whole (Monaghan and Parrish, 2006). However, the difficulties with palynological zonations within and below the CPV (see below) led to the current dating samples from the northern fault blocks being chosen.

The Clyde Plateau Volcanic Formation is known to unconformably overlie Stratheden Group (Upper Devonian) to Inverclyde Group (early Carboniferous) Clyde Sandstone Formation strata. The Clyde Sandstone Formation contains topmost CM to Pu miospore zone floras (latest Tournaisian – Chadian) in the BGS Loch Humphrey Borehole, Kilpatrick Hills (Owens, 1980a following Higgs (1988b) for definition of Pu zone; fig. 1) and is given as Chadian age in Browne et al. (1999). Eight hundred metres to the east of this borehole site at Loch Humphrey Burn, Scott et al. (1984) and Scott (1990) reported miospore zones in the range CM, Pu and TS (latest Tournaisian–Arundian or even Holkerian) within a sedimentary intercalation (Greenside Volcaniclastic Member, BGS, 1993) that is proven by the borehole to be well above the base of the Clyde Plateau Volcanic Formation (Hall et al., 1998). The Glenarbuck section 1 km to the south-west of the borehole in the same volcaniclastic member was assigned to a Pu or younger miospore zonation (Scott et al., 1984). The Loch Humphrey Burn CM zonation from well-preserved palynomorphs (Scott et al., 1984) in the Greenside Volcaniclastic Member is difficult to explain when compared to the younger Pu zonation of the underlying Clyde Sandstone Formation in the nearby borehole. In fact, Bateman and Cleal (1995) considered that the megafloras and lithostratigraphy of this unit were more consistent with the mid-Viséan age of the overlying paleobotanical petrification assemblages. The Kirkwood and Lawmuir formations (Strathclyde Group) and Lower Limestone Formation (Clackmannan Group) diachronously overlie the Clyde Plateau Volcanic Formation and have yielded NM–VF miospore zone determinations (top Asbian–Brigantian; BGS Kirkwood and Lawmuir boreholes, Owens, 1980b).

The 338 ± 18 Ma isochron age for the Loch Humphrey borehole fits with the 335 ± 2 Ma Clyde Plateau Volcanic Formation eruption age suggested by Monaghan and Parrish (2006), is consistent with an underlying CM/Pu zonation in the Clyde Sandstone Formation in the borehole and an overlying TS (but not CM/Pu) zonation in the Greenside Volcaniclastic Member in sections nearby, but note the very large 2σ error. When compared to existing radiometric ages and the stratigraphic constraints, the isochron age of 311 ± 14 Ma for the Clyde Plateau Volcanic Formation in the BGS Loch Humphrey Borehole appears too young, even with the large error limits.

The isochron age of 319 ± 10 Ma for the basal lava flows in the BGS Tak-Ma-Doon Borehole is too young, even given the large error, to fit with the stratigraphic constraints such as the underlying Ballagan Formation.

4.4 BATHGATE HILLS VOLCANIC FORMATION

The Bathgate Hills Volcanic Formation series of bedded tuffs and agglomerates, basaltic and basanitic microporphyritic lavas were erupted between the deposition of the Viséan, West Lothian Oil-Shale Formation and Namurian, Upper Limestone Formation. The thick wedge of lavas and tuffs are intercalated with the sedimentary strata and with marine marker limestones, however they are poorly represented by radiometric ages due to alteration.

4.4.1.1 SAMPLE LOCATION AND ROCK TYPE

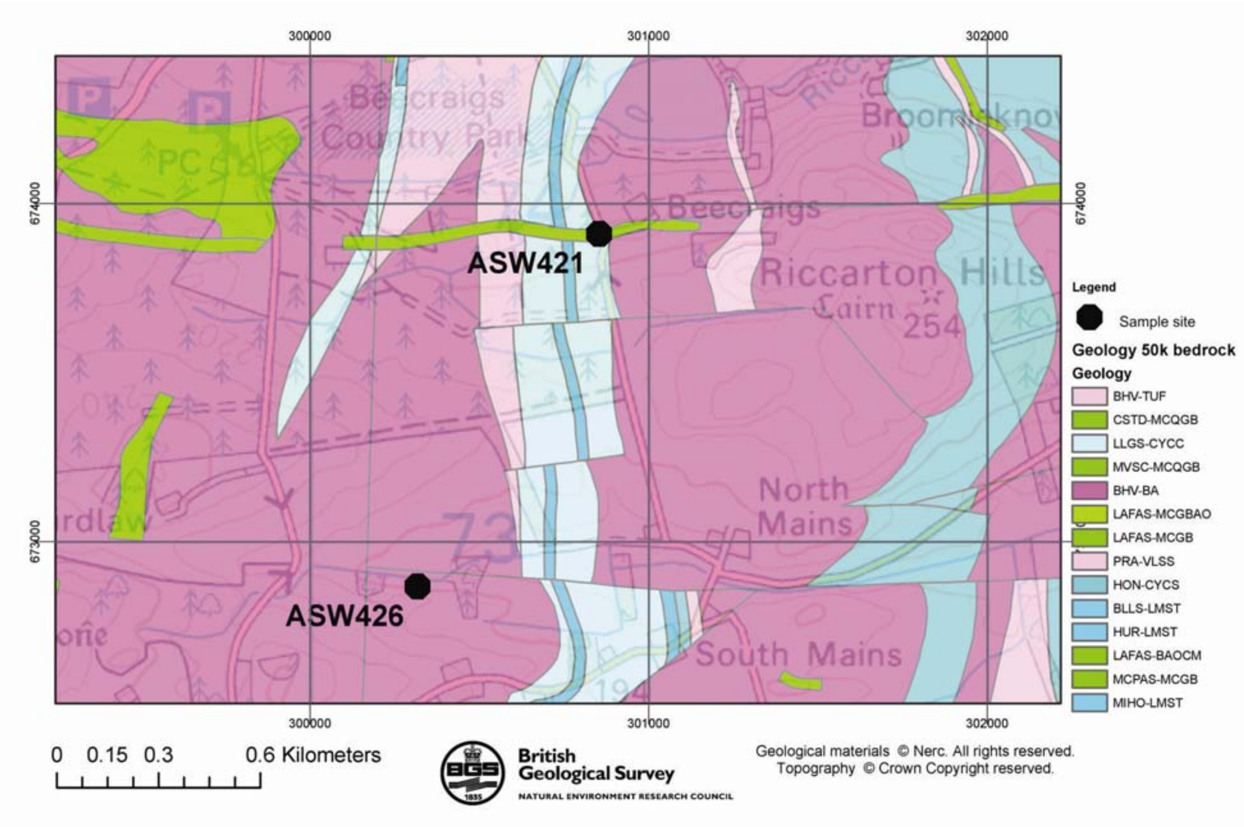

Figure 17 Location of the chosen samples from the Bathgate Hills Volcanic Formation and Beecraigs Dyke. Shown with BGS Digmap 1:50,000, see the BGS Lexicon (http://www.bgs.ac.uk/Lexicon/home.cfm) for a description of the codes used in the Legend. The limestone underlying sample ASW426 is the Blackhall Limestone in the Lower Limestone Formation. Geological materials BGS © NERC. OS Topography © Crown Copyright BGS100017897/2010. All Rights Reserved

Sample ASW426 was the freshest obtained from the lavas of the Bathgate Hills Volcanic Formation. The feldspars were too small to be analysed and so a groundmass separate age was attempted. The sample of olivine-pyroxene microporhyritic alkali basalt came from a lava which sits stratigraphically above the Blackhall Limestone (mid-Lower Limestone Formation) and below the Index Limestone (base of Upper Limestone Formation; Figure 17), therefore constraining the rocks to the top of the Brigantian (c. 326 Ma ICS/IUGS, 2009) and close to the top Viséan boundary.

4.4.1.2 ASW426 RESULT

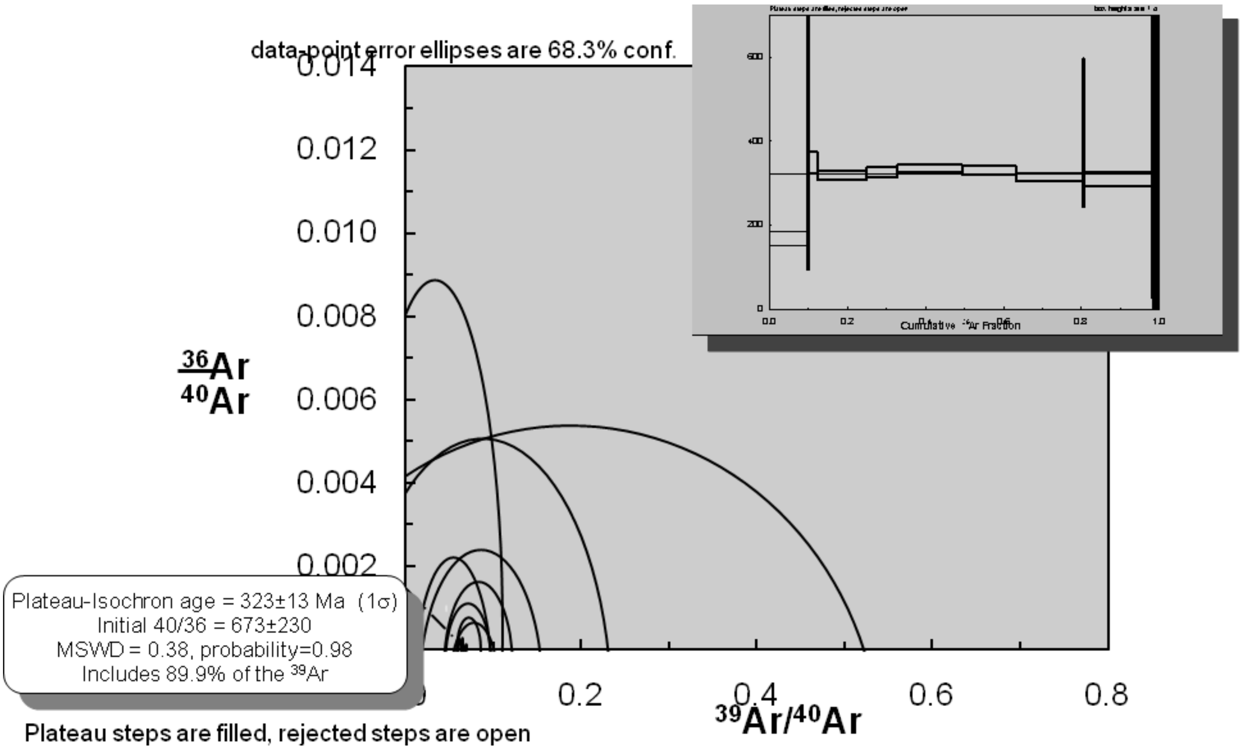

Figure 18 Summary of the $^{40}Ar/^{39}Ar$ step-heating experiment plateau chron result on ASW426

A plateau-chron result of 323 ± 13 (26 at 2σ) Ma gave the best estimate of the age (Figure 18).

4.4.1.3 FIT WITH STRATIGRAPHY AND OTHER RADIOMETRIC DATES

De Souza (1979) synthesised the two least-altered K-Ar ages from the Bathgate Hills to give a common minimum date of 296 ± 8 Ma.

The result of 323 ± 26 Ma from this study fits approximately with the top Brigantian constraint from surrounding marine limestones, though with a very large error.

4.5 KINGHORN VOLCANIC FORMATION

The Kinghorn Volcanic Formation (Bathgate Group) comprises a series of basaltic lavas and subordinate volcaniclastic rocks lying between and intercalated with the Sandy Craig, Pathhead and Lower Limestone formations.

4.5.1.1 SAMPLE LOCATION AND ROCK TYPE

Sample ASW 414 came from the working Orrock Quarry. The lava flow within the quarry exhibits abundant columnar jointing and a sample of very fine olivine microporphyritic alkali basalt was obtained. The lava flow at Orrock sits in approximately the middle of the Kinghorn Volcanic Formation (Figure 19). Lava flows in this area are intercalated with the Sandy Craig Formation (Figure 19) which contains Asbian age NM zone palynomorphs (Brindley and Spinner, 1989; Owens et al., 2005).

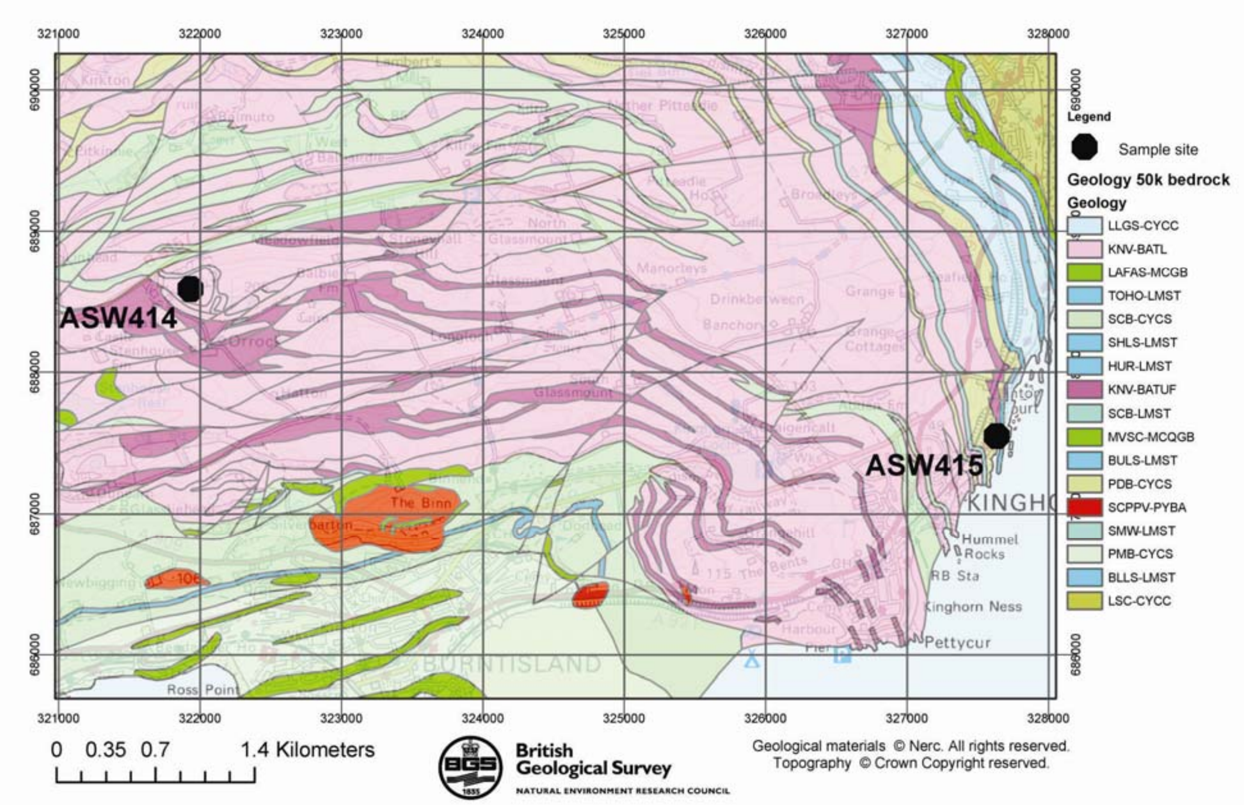

Figure 19 Location of the chosen samples from the Kinghorn Volcanic Formation. Shown with BGS Digmap 1:50,000, see the BGS Lexicon (http://www.bgs.ac.uk/Lexicon/home.cfm) for a description of the codes used in the Legend. Geological materials BGS © NERC. OS Topography © Crown Copyright BGS100017897/2010. All Rights Reserved

Sample ASW415 came from the top of the Kinghorn Volcanic Formation from a coastal exposure just beneath the marker Hurlet Limestone (base Lower Limestone Formation; Figure 19). A feldspar separate was irradiated for this olivine microporphyritic alkali basalt sample but was not analysed.

4.5.1.2 ASW414 Result

A plateau-chron result on a groundmass separate of 319 ± 6 Ma (2σ) Ma, MSWD 0.43 gave the best estimate of the age of ASW414. The plateau-chron result is not available for reproduction.

4.5.1.3 Fit with stratigraphy and other radiometric dates

Previous dates on the Kinghorn Volcanic Formation include a whole rock K-Ar age from Pettycur (MV400) of 309 ± 7 Ma and MV407 of 290 ± 7 Ma (argon loss suspected; De Souza, 1979). A K-Ar whole rock age of 338 ± 4 Ma from a roadside sample between Burntisland and Kinghorn was thought to be a close minimum to the age of extrusion (Fitch et al., 1970).

The 319 ± 6 Ma Namurian age obtained here is significantly too young for the stratigraphic constraint of the overlying Hurlet Limestone and underlying/intercalated Asbian Sandy Craig Formation.

4.6 CENTRAL SCOTLAND LATE CARBONIFEROUS THOLEIITIC DYKE SWARM

The latest Carboniferous Midland Valley Sill-Complex is characterised by intrusive tholeiitic basalts and quartz-dolerites. Sills reaching up to *c.* 200 m in thickness crop out in the eastern MVS and associated ENE- to ESE-trending dykes of the Late Carboniferous Central Scotland Tholeiitic Dyke Swarm up to *c.* 75 m in width are found well beyond the limits of the sill-complex (Smythe et al., 1995; Stephenson et al., 2003).

4.6.1.1 SAMPLE LOCATION AND ROCK TYPE

Figure 20 Example of field collection locality, sample taken where hammer is circled in red, ASW421 Beecraigs Climbing Wall

Sample ASW421 from Beecraigs Climbing Wall (Figure 20) produced a feldspar separate obtained from a regionally extensive, east – west trending quartz-dolerite dyke (Figure 17). The dyke cuts across strata from Viséan to Westphalian age and is near parallel to post-depositional faulting. The dated rock was a relatively coarse-grained microgabbro (Figure 21). The plagioclase separate included some cloudy crystals with inclusions.

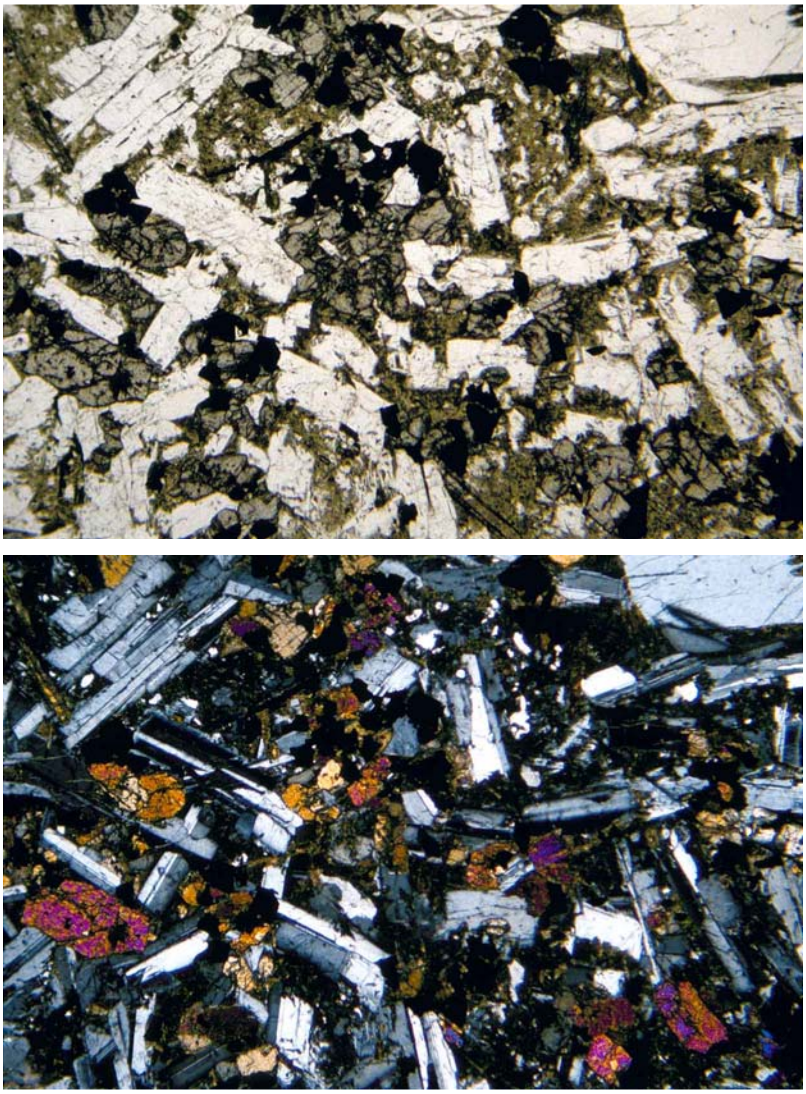

Figure 21 Photomicrographs of ASW421 showing numerous plagioclase, pyroxene and opaque phenocrysts under plane and cross-polarised light, 2.5 times magnification.

4.6.1.2 ASW421 Result

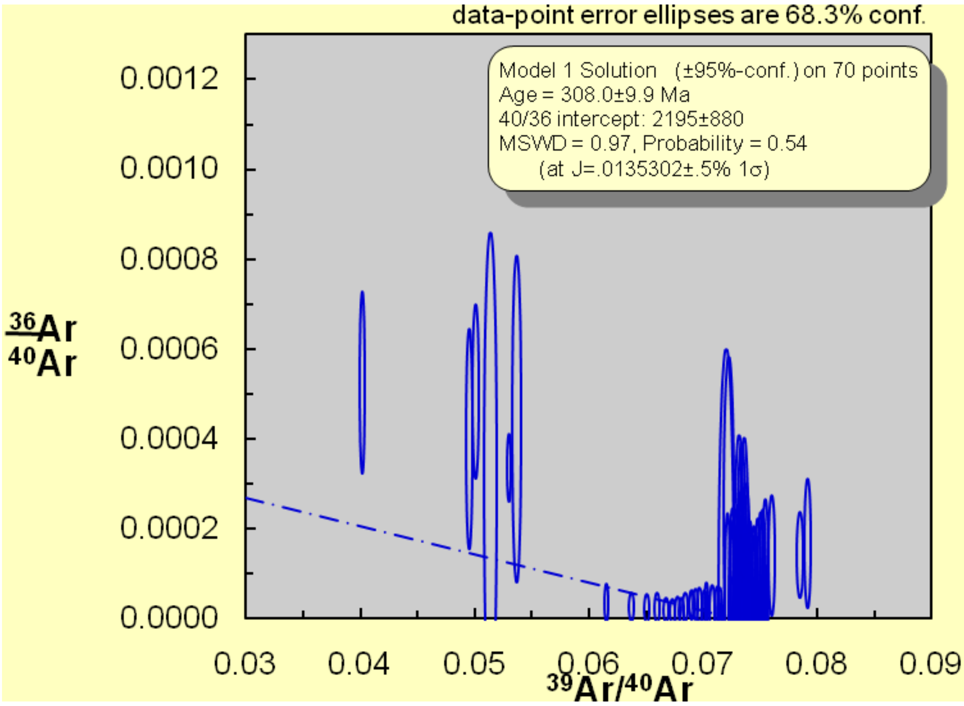

Figure 22 Summary of the $^{40}Ar/^{39}Ar$ step-heating experiment isochron result on ASW421

Two splits were made for this sample and analysed on different machines. The isochrons show similar ages and the release patterns are similar but the total fusion ages are different. This is probably because during one run a split of gas was lost in the extraction line (an unexpectedly large gas release on a heating step had to be discarded rather than damage the machine). Due to the heterogeneity of the sample, this biased the results for a 323 ± 17 Ma isochron result, and this result should not be used. The isochron age of 308 ± 10 Ma (Figure 22) should be used for the age of this sample.

4.6.1.3 Fit with stratigraphy and other radiometric dates

A previous U-Pb date of 307.6 ± 4.8 Ma was obtained from a quartz-dolerite sill 12 km to the east of sample site ASW421 (Monaghan and Parrish, 2006). Previous K-Ar dates on the Midland Valley Sill-complex and associated tholeiitic dykes range from 305 ± 7 Ma to 280 ± 9 Ma (Fitch et al., 1970, De Souza 1974, 1979 recalculated by Wallis, 1989 to Steiger and Jäger, 1977 constants). The isochron age of 308 ± 10 Ma fits with the U-Pb and older K-Ar ages. It is consistent with the intrusive relationship that the Midland Valley Sill-Complex and the Central Scotland Tholeiitic Swarm dykes cut strata up to Westphalian C in age (e.g. BGS, 2004) and is older than sub-volcanic necks considered to be of late Stephanian or Early Permian age that contain blocks of quartz-dolerite (Stephenson et al., 2003). The new $^{40}Ar/^{39}Ar$ and recent U-Pb dates on this dyke swarm are older than the commonly quoted age range of *c.* 295–301 Ma age for the tholeiitic magmatic interlude of both the Midland Valley and Whin sill-complexes (e.g. Stephenson et al., 2003, Upton et al., 2004).

4.7 MAUCHLINE VOLCANIC FORMATION

4.7.1.1 Sample location and rock type

Sample ASW402 was collected from the top part of the Mauchline Volcanic Formation (Figure 23), above the Stairhill plant fauna Site of Special Scientific Interest (SSSI). The feldspars in this reddened olivine microporphyritic alkali basalt lava were too small for analysis, so a groundmass separate age was attempted as the rock was quite fresh. These lavas have been dated as very Early Permian based on the intercalated floral assemblage from Stairhill (Wagner, 1983) and are overlain by the aeolian sandstone of the Mauchline Sandstone Formation.

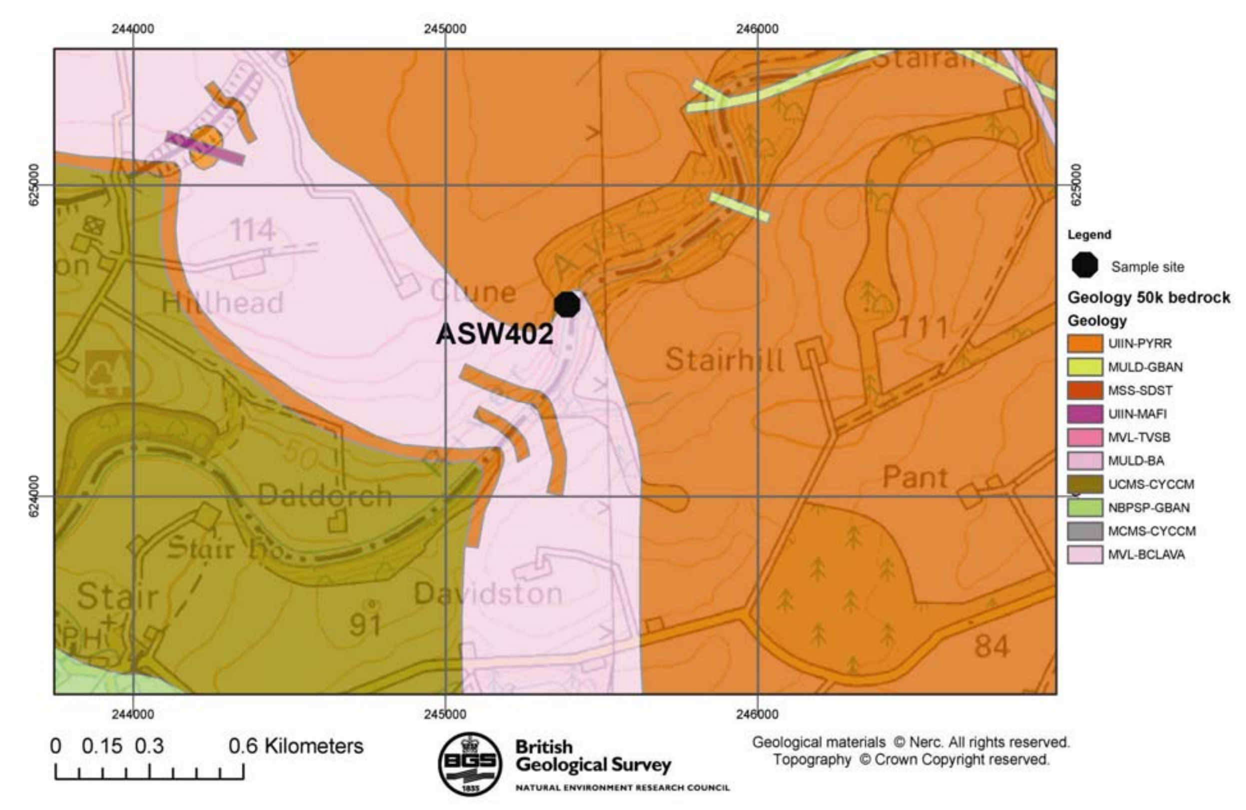

Figure 23 Location of the chosen sample from Stairhill. Shown with BGS Digmap 1:50,000, see the BGS Lexicon (http://www.bgs.ac.uk/Lexicon/home.cfm) for a description of the codes used in the Legend. Geological materials BGS © NERC. OS Topography © Crown Copyright BGS100017897/2010. All Rights Reserved

4.7.1.2 ASW402 RESULT

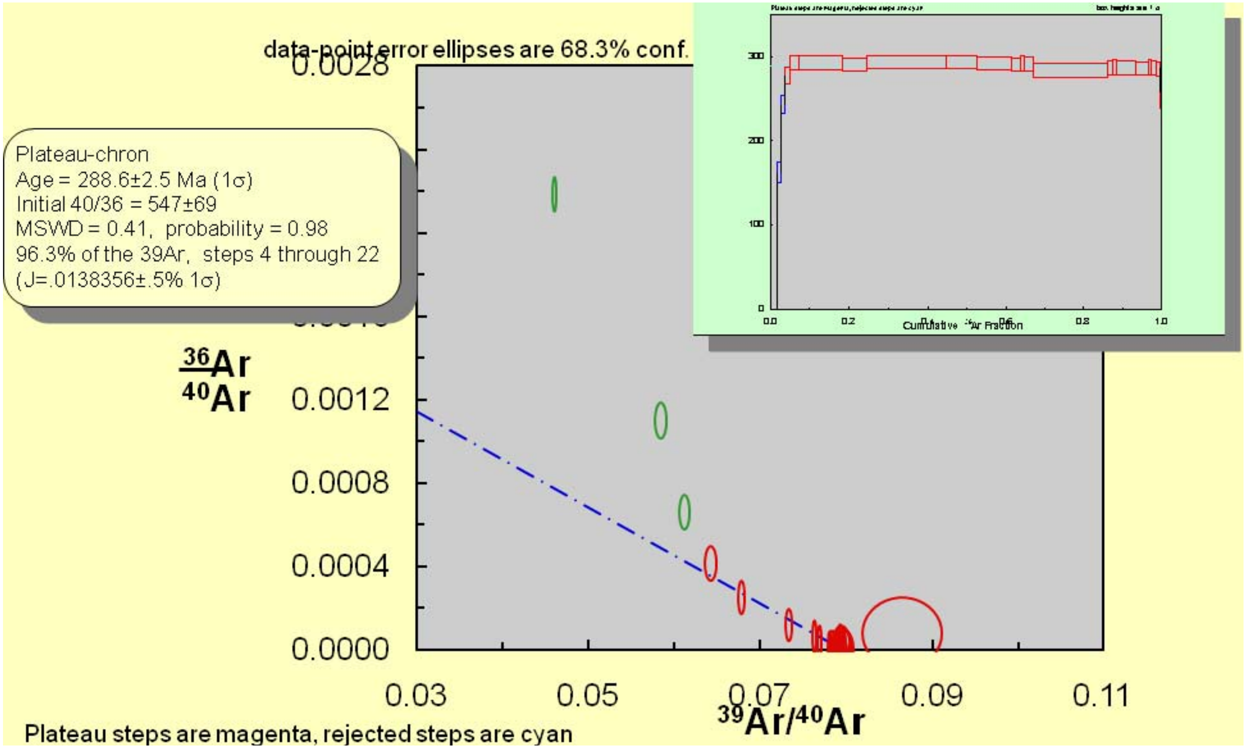

Figure 24 Summary of the $^{40}Ar/^{39}Ar$ step-heating experiment plateau chron result on ASW402

Due to the likelihood of excess argon in this sample, the best estimate of age for this groundmass separate sample ASW402 is from the plateau-chron at 289 ± 5 Ma (Figure 24).

4.7.1.3 FIT WITH STRATIGRAPHY AND OTHER RADIOMETRIC DATES

Previous K-Ar radiometric dates on the Mauchline Volcanic Formation are from De Souza (1979; recalculated by Wallis, 1989) and include a good result from Stair at 281 ± 8 Ma and a whole rock result from a basalt at Howford Bridge, 278 ± 8 Ma.

Previous $^{40}Ar/^{39}Ar$ dates on alkaline sills in Ayrshire range from 295.2 ± 1.3 to 298.3 ± 1.3 Ma (Monaghan and Pringle, 2004) .These alkaline intrusions cross cut late Silesian Coal Measures but none cuts the Early Permian Mauchline Sandstone Formation (Mykura, 1967; Cameron and Stephenson, 1985; Stephenson et al., 2003). The intrusions have been petrologically linked to the extrusive Mauchline Volcanic Formation that underlies the Mauchline Sandstone Formation (Mykura et al., 1967; Cameron and Stephenson, 1985).

The new $^{40}Ar/^{39}Ar$ result of 289 ± 5 Ma overlaps within error the existing K-Ar ages on the lavas and just overlaps the younger of the alkaline intrusion $^{40}Ar/^{39}Ar$ ages. The new result is significantly younger than the global Permo-Carboniferous boundary of 299 ± 1 Ma and places the Mauchline Volcanic Formation in the Sakmarian of the early Permian (Fig 2). The new $^{40}Ar/^{39}Ar$ result is perhaps a little younger than one would expect from results on the 'very early Permian' plant faunas and the associated alkaline intrusions.

5 Conclusions and future work

The results from Arthur's Seat and the Garleton Hills (ASW407, ASW412 and ASW 124) gave reasonable step-heating plateaux but the resultant ages do not fit well with the surrounding stratigraphy or existing $^{40}Ar/^{39}Ar$ and U-Pb radiometric dates. These results are difficult to explain and it is recommended that these dates should not be used unless further information comes to light regarding stratigraphic or geological constraints that places them in context.

The plateau-chron and isochron results from Tak-Ma-Doon borehole and Orrock Quarry (BEB1800, ASW414) had sizeable analytical errors and do not fit with the known stratigraphical constraints, or with other radiometric ages. It is recommended that these dates should not be used further.

The plateau-chron and isochron results from Stairhill, Beecraigs Dyke, Loch Humphrey borehole and Cow Craig (ASW 402, ASW421, BEB 1555, ASW426 respectively) gave ages that fit with the stratigraphic constraints but the latter three results have large errors (≥ 10 Ma).

The three most important outcomes from this study are therefore:

1. Confirmation of the age of the quartz-dolerite tholeiitic sill and dyke suite in the Midland Valley of Scotland as around 308 Ma in the late Westphalian, based on a 307.6 ± 4.8 Ma U-Pb age (Monaghan and Parrish 2006) on a sill and an isochron $^{40}Ar/^{39}Ar$ age of 308 ± 10 Ma on a dyke from this study. This is significantly older than Ar/Ar and U-Pb ages on the Whin Sill of Northumberland and supports a varying tectonic and magmatic style across Northern Britain in the latest Carboniferous – early Permian as discussed in Monaghan and Parrish (2006)
2. An early Permian age for the Mauchline Volcanic Formation lavas which overlaps with the radiometric age of associated alkaline intrusions. This forms a basis for a maximum age of the overlying aeolian Permian sedimentary rocks (Mauchline Sandstone Formation) and which may have implications for the ages of similar Permian basins across Southern Scotland (e.g. Thornhill, Lochmaben).
3. A mid Viséan age for the Clyde Plateau Volcanic Formation in the BGS Loch Humphrey Borehole in agreement with plant megafloras (Bateman and Cleal, 1995) and TS/Pu palynomorph zonations, but not the CM palynomorph zonation (Scott et al., 1984).

Future dating work should focus on obtaining the freshest possible samples from poorly represented, well-constrained volcanic units e.g Bathgate Group (Bathgate Hills, Kinghorn), the northern outcrop of the Clyde Plateau Volcanic Formation and Arthur's Seat Volcanic Formation.

Appendix 1

Field photographs of some of sample sites are available on the BGS Imagebase and the remainder are kept on the BGS shared network drives. Thin section and core photos on BGS Imagebase are numbers P660685-P660720 and P665081-P665088

Microprobe results on the composition of feldspars from BEB1555 and BEB1800 are shown below, all the minerals analysed were plagioclase. These were analysed using a Cameca SX50 at 15kV, 20nA with a 1 micron beam diameter. Values are rounded to one decimal place. Ave=average, stdev=standard deviation

Sample	Analysis			SiO2	Al2O3	CaO	MnO	FeO	Na2O	K2O	Total			Si	Al	Ca	Mn	Fe	Na	K	Total		An	Ab	Or
BEB1555/1554	average	n=40		53.2	28.9	12.8	0.0	0.5	4.1	0.3	99.8			2.4	1.6	0.6	0.0	0.0	0.4	0.0	5.0		62.1	36.5	1.5
	stdev			1.5	1.0	1.2	0.0	0.1	0.6	0.1	0.3			0.1	0.1	0.1	0.0	0.0	0.1	0.0	0.0		5.7	5.4	0.4
BEB1800/1805	average	n=40		51.5	30.1	14.1	0.0	0.5	3.4	0.2	99.8			2.4	1.6	0.7	0.0	0.0	0.3	0.0	5.0		68.6	29.9	1.4
	stdev			0.8	0.5	0.6	0.0	0.1	0.3	0.0	0.4			0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0		2.9	2.6	0.3
BEB1555/1554	core (ave)	n=20		53.3	28.9	12.7	0.0	0.5	4.2	0.3	99.8			2.4	1.5	0.6	0.0	0.0	0.4	0.0	5.0		61.9	36.6	1.5
BEB1555/1554	rim (ave)	n=20		53.2	29.0	12.8	0.0	0.5	4.1	0.2	99.8			2.4	1.6	0.6	0.0	0.0	0.4	0.0	5.0		62.2	36.3	1.4
BEB1800/1805	core (ave)	n=20		51.2	30.2	14.3	0.0	0.5	3.3	0.2	99.7			2.3	1.6	0.7	0.0	0.0	0.3	0.0	5.0		69.5	29.1	1.4
BEB1800/1805	rim (ave)	n=20		51.7	30.0	13.8	0.0	0.6	3.5	0.3	99.8			2.4	1.6	0.7	0.0	0.0	0.3	0.0	5.0		67.8	30.7	1.5
DATA																									
BEB1555/1554	core1		#1	52.9	29.2	13.1	0.0	0.6	3.9	0.3	100.0		#1	2.4	1.6	0.6	0.0	0.0	0.3	0.0	5.0		64.0	34.5	1.5
BEB1555/1554	core2		#3	50.7	30.5	14.9	0.0	0.5	3.0	0.2	99.8		#3	2.3	1.6	0.7	0.0	0.0	0.3	0.0	5.0		72.3	26.8	0.9
BEB1555/1554	core3		#5	52.4	29.3	13.4	0.0	0.5	3.9	0.2	99.8		#5	2.4	1.6	0.7	0.0	0.0	0.3	0.0	5.0		64.6	34.1	1.3
BEB1555/1554	core4		#7	55.3	27.8	11.2	0.0	0.6	4.9	0.3	100.1		#7	2.5	1.5	0.5	0.0	0.0	0.4	0.0	5.0		54.6	43.5	1.9
BEB1555/1554	core5		#9	52.8	29.4	13.3	0.0	0.5	3.9	0.2	100.2		#9	2.4	1.6	0.6	0.0	0.0	0.3	0.0	5.0		64.4	34.4	1.2
BEB1555/1554	core6		#11	52.3	29.5	13.5	0.0	0.5	3.8	0.2	99.8		#11	2.4	1.6	0.7	0.0	0.0	0.3	0.0	5.0		65.4	33.4	1.2
BEB1555/1554	core7		#13	55.1	27.9	11.3	0.0	0.4	5.0	0.3	100.0		#13	2.5	1.5	0.6	0.0	0.0	0.4	0.0	5.0		54.7	43.4	1.9
BEB1555/1554	core8		#15	55.2	28.1	11.3	0.0	0.4	4.9	0.3	100.3		#15	2.5	1.5	0.5	0.0	0.0	0.4	0.0	5.0		55.3	42.9	1.8
BEB1555/1554	core9		#17	51.9	29.7	13.9	0.0	0.5	3.7	0.2	100.0		#17	2.4	1.6	0.7	0.0	0.0	0.3	0.0	5.0		66.9	32.0	1.2
BEB1555/1554	core10		#19	53.7	28.3	12.3	0.0	0.5	4.4	0.3	99.5		#19	2.4	1.5	0.6	0.0	0.0	0.4	0.0	5.0		59.6	38.9	1.6
BEB1555/1554	core11		#21	53.2	28.8	12.5	0.0	0.6	4.0	0.2	99.4		#21	2.4	1.6	0.6	0.0	0.0	0.4	0.0	5.0		62.2	36.3	1.4

BEB1555/1554	core12		#23	50.6	30.8	15.0	0.0	0.5	3.0	0.1	100.0		#23	2.3	1.7	0.7	0.0	0.0	0.3	0.0	5.0		73.1	26.1	0.8
BEB1555/1554	core13		#25	53.1	28.8	12.9	0.0	0.6	4.1	0.2	99.6		#25	2.4	1.5	0.6	0.0	0.0	0.4	0.0	5.0		62.6	36.0	1.4
BEB1555/1554	core14		#27	54.9	27.9	11.7	0.0	0.4	4.9	0.3	100.0		#27	2.5	1.5	0.6	0.0	0.0	0.4	0.0	5.0		56.0	42.2	1.8
BEB1555/1554	core15		#29	55.3	27.3	10.8	0.0	0.8	5.0	0.3	99.6		#29	2.5	1.5	0.5	0.0	0.0	0.4	0.0	5.0		53.2	44.8	2.0
BEB1555/1554	core16		#31	54.5	27.7	11.7	0.0	0.6	4.8	0.3	99.5		#31	2.5	1.5	0.6	0.0	0.0	0.4	0.0	5.0		56.5	41.7	1.8
BEB1555/1554	core17		#33	54.1	28.3	12.0	0.0	0.5	4.4	0.3	99.6		#33	2.5	1.5	0.6	0.0	0.0	0.4	0.0	5.0		59.0	39.0	2.0
BEB1555/1554	core18		#35	53.7	28.5	12.2	0.0	0.5	4.4	0.3	99.6		#35	2.4	1.5	0.6	0.0	0.0	0.4	0.0	5.0		59.6	38.8	1.6
BEB1555/1554	core19		#37	53.7	28.6	12.2	0.0	0.5	4.4	0.3	99.7		#37	2.4	1.5	0.6	0.0	0.0	0.4	0.0	5.0		59.8	38.6	1.6
BEB1555/1554	core20		#39	50.1	30.9	15.2	0.0	0.4	2.8	0.2	99.6		#39	2.3	1.7	0.7	0.0	0.0	0.3	0.0	5.0		74.1	24.9	1.0
BEB1555/1554	rim1		#2	52.5	29.5	13.1	0.0	0.5	3.8	0.2	99.6		#2	2.4	1.6	0.6	0.0	0.0	0.3	0.0	5.0		64.4	34.3	1.3
BEB1555/1554	rim2		#4	51.8	29.5	13.9	0.0	0.5	3.5	0.2	99.3		#4	2.4	1.6	0.7	0.0	0.0	0.3	0.0	5.0		68.2	30.8	1.0
BEB1555/1554	rim3		#6	50.3	30.8	14.9	0.0	0.5	3.1	0.2	99.6		#6	2.3	1.7	0.7	0.0	0.0	0.3	0.0	5.0		72.1	26.9	1.0
BEB1555/1554	rim4		#8	54.1	28.5	12.5	0.0	0.6	4.3	0.3	100.2		#8	2.4	1.5	0.6	0.0	0.0	0.4	0.0	5.0		60.4	38.1	1.5
BEB1555/1554	rim5		#10	51.7	30.2	13.9	0.0	0.5	3.6	0.2	100.1		#10	2.4	1.6	0.7	0.0	0.0	0.3	0.0	5.0		67.6	31.4	1.0
BEB1555/1554	rim6		#12	52.7	29.5	13.4	0.0	0.6	3.9	0.2	100.3		#12	2.4	1.6	0.7	0.0	0.0	0.3	0.0	5.0		64.8	34.0	1.2
BEB1555/1554	rim7		#14	56.7	27.1	10.2	0.0	0.4	5.5	0.4	100.3		#14	2.5	1.4	0.5	0.0	0.0	0.5	0.0	5.0		49.3	48.4	2.2
BEB1555/1554	rim8		#16	54.7	28.5	11.8	0.0	0.4	4.6	0.3	100.4		#16	2.5	1.5	0.6	0.0	0.0	0.4	0.0	5.0		57.8	40.6	1.6
BEB1555/1554	rim9		#18	52.4	29.7	13.6	0.0	0.5	3.8	0.2	100.1		#18	2.4	1.6	0.7	0.0	0.0	0.3	0.0	5.0		65.6	33.1	1.3
BEB1555/1554	rim10		#20	52.7	29.1	13.1	0.0	1.1	3.9	0.2	100.1		#20	2.4	1.6	0.6	0.0	0.0	0.3	0.0	5.0		63.9	34.7	1.4
BEB1555/1554	rim11		#22	53.4	28.5	12.6	0.0	0.5	4.2	0.3	99.5		#22	2.4	1.5	0.6	0.0	0.0	0.4	0.0	5.0		61.3	36.9	1.8
BEB1555/1554	rim12		#24	52.8	29.3	13.0	0.0	0.5	4.0	0.2	99.8		#24	2.4	1.6	0.6	0.0	0.0	0.4	0.0	5.0		63.4	35.3	1.3
BEB1555/1554	rim13		#26	53.0	29.1	12.7	0.0	0.5	4.1	0.2	99.7		#26	2.4	1.6	0.6	0.0	0.0	0.4	0.0	5.0		62.0	36.7	1.3
BEB1555/1554	rim14		#28	53.3	28.8	12.8	0.0	0.5	4.2	0.3	99.9		#28	2.4	1.5	0.6	0.0	0.0	0.4	0.0	5.0		62.1	36.4	1.5
BEB1555/1554	rim15		#30	54.2	28.1	11.7	0.0	0.5	4.6	0.3	99.5		#30	2.5	1.5	0.6	0.0	0.0	0.4	0.0	5.0		57.3	41.1	1.6
BEB1555/1554	rim16		#32	55.4	27.4	11.1	0.0	0.5	5.0	0.4	99.8		#32	2.5	1.5	0.5	0.0	0.0	0.4	0.0	5.0		54.1	43.8	2.1
BEB1555/1554	rim17		#34	53.7	28.3	12.3	0.0	0.5	4.4	0.3	99.5		#34	2.4	1.5	0.6	0.0	0.0	0.4	0.0	5.0		59.8	38.5	1.7
BEB1555/1554	rim18		#36	53.5	28.2	12.3	0.0	0.5	4.4	0.3	99.1		#36	2.4	1.5	0.6	0.0	0.0	0.4	0.0	5.0		59.9	38.4	1.7
BEB1555/1554	rim19		#38	53.6	28.8	12.6	0.0	0.5	4.4	0.2	100.0		#38	2.4	1.5	0.6	0.0	0.0	0.4	0.0	5.0		60.7	38.0	1.3
BEB1555/1554	rim20		#40	51.3	30.3	14.3	0.0	0.5	3.3	0.2	99.9		#40	2.3	1.6	0.7	0.0	0.0	0.3	0.0	5.0		69.6	29.4	1.0
BEB1800/1805	core 1		#1	51.8	29.6	13.9	0.0	0.5	3.4	0.3	99.5		#1	2.4	1.6	0.7	0.0	0.0	0.3	0.0	5.0		68.0	30.5	1.5
BEB1800/1805	core 2		#3	50.6	30.6	14.8	0.0	0.5	3.1	0.2	99.8		#3	2.3	1.7	0.7	0.0	0.0	0.3	0.0	5.0		71.8	26.9	1.3
BEB1800/1805	core 3		#5	51.2	30.2	14.4	0.0	0.5	3.2	0.3	99.8		#5	2.3	1.6	0.7	0.0	0.0	0.3	0.0	5.0		70.1	28.4	1.5
BEB1800/1805	core 4		#7	51.0	30.7	14.5	0.0	0.4	3.2	0.2	100.0		#7	2.3	1.7	0.7	0.0	0.0	0.3	0.0	5.0		70.6	28.1	1.3
BEB1800/1805	core 5		#9	51.7	30.2	14.0	0.0	0.5	3.4	0.3	100.1		#9	2.4	1.6	0.7	0.0	0.0	0.3	0.0	5.0		68.4	30.1	1.5
BEB1800/1805	core 6		#11	51.9	29.9	14.0	0.0	0.4	3.6	0.3	100.0		#11	2.4	1.6	0.7	0.0	0.0	0.3	0.0	5.0		67.4	31.1	1.5

BEB1800/1805	core 7		#13	51.3	30.4	14.2	0.0	0.6	3.4	0.2	100.2		#13	2.3	1.6	0.7	0.0	0.0	0.3	0.0	5.0		69.0	29.6	1.4
BEB1800/1805	core 8		#15	50.9	30.3	14.4	0.0	0.5	3.2	0.2	99.6		#15	2.3	1.6	0.7	0.0	0.0	0.3	0.0	5.0		70.3	28.3	1.4
BEB1800/1805	core 9		#17	51.7	29.6	13.8	0.0	0.5	3.4	0.3	99.2		#17	2.4	1.6	0.7	0.0	0.0	0.3	0.0	5.0		68.3	30.1	1.6
BEB1800/1805	core 10		#19	50.4	30.6	15.1	0.0	0.5	3.0	0.2	99.8		#19	2.3	1.7	0.7	0.0	0.0	0.3	0.0	5.0		72.5	26.4	1.1
BEB1800/1805	core 11		#21	51.2	30.2	14.3	0.0	0.5	3.2	0.3	99.8		#21	2.3	1.6	0.7	0.0	0.0	0.3	0.0	5.0		69.9	28.6	1.5
BEB1800/1805	core 12		#23	51.1	30.0	14.2	0.0	0.7	3.4	0.2	99.6		#23	2.3	1.6	0.7	0.0	0.0	0.3	0.0	5.0		69.3	29.7	1.0
BEB1800/1805	core 13		#25	50.9	30.4	14.6	0.0	0.5	3.1	0.2	99.7		#25	2.3	1.6	0.7	0.0	0.0	0.3	0.0	5.0		71.0	27.7	1.3
BEB1800/1805	core 14		#27	50.6	30.0	14.4	0.0	0.5	3.3	0.2	99.0		#27	2.3	1.6	0.7	0.0	0.0	0.3	0.0	5.0		70.0	28.9	1.2
BEB1800/1805	core 15		#29	50.9	30.3	14.2	0.0	0.5	3.3	0.2	99.4		#29	2.3	1.6	0.7	0.0	0.0	0.3	0.0	5.0		69.7	29.0	1.4
BEB1800/1805	core 16		#31	51.7	30.0	13.9	0.0	0.4	3.5	0.2	99.8		#31	2.4	1.6	0.7	0.0	0.0	0.3	0.0	5.0		67.8	30.8	1.4
BEB1800/1805	core 17		#33	51.4	29.8	13.9	0.0	0.6	3.5	0.3	99.4		#33	2.4	1.6	0.7	0.0	0.0	0.3	0.0	5.0		67.8	30.8	1.5
BEB1800/1805	core 18		#35	52.4	29.9	13.6	0.0	0.4	3.7	0.3	100.3		#35	2.4	1.6	0.7	0.0	0.0	0.3	0.0	5.0		65.9	32.4	1.7
BEB1800/1805	core 19		#37	50.8	30.4	14.7	0.0	0.5	3.1	0.2	99.6		#37	2.3	1.6	0.7	0.0	0.0	0.3	0.0	5.0		71.8	27.2	1.1
BEB1800/1805	core 20		#39	50.9	30.2	14.5	0.0	0.5	3.2	0.2	99.6		#39	2.3	1.6	0.7	0.0	0.0	0.3	0.0	5.0		70.6	28.4	1.0
BEB1800/1805	rim1		#2	52.5	29.2	13.3	0.0	0.5	3.8	0.3	99.6		#2	2.4	1.6	0.6	0.0	0.0	0.3	0.0	5.0		64.9	33.4	1.7
BEB1800/1805	rim2		#4	50.6	30.6	14.5	0.0	0.4	3.2	0.2	99.5		#4	2.3	1.7	0.7	0.0	0.0	0.3	0.0	5.0		70.5	28.3	1.2
BEB1800/1805	rim3		#6	51.1	30.2	14.4	0.0	0.6	3.1	0.2	99.8		#6	2.3	1.6	0.7	0.0	0.0	0.3	0.0	5.0		70.7	27.8	1.5
BEB1800/1805	rim4		#8	51.1	30.9	14.4	0.0	0.5	3.2	0.2	100.4		#8	2.3	1.7	0.7	0.0	0.0	0.3	0.0	5.0		70.2	28.4	1.4
BEB1800/1805	rim5		#10	51.9	30.7	14.2	0.0	0.5	3.4	0.3	100.8		#10	2.3	1.6	0.7	0.0	0.0	0.3	0.0	5.0		68.8	29.8	1.4
BEB1800/1805	rim6		#12	52.1	30.1	13.8	0.0	0.5	3.7	0.2	100.4		#12	2.4	1.6	0.7	0.0	0.0	0.3	0.0	5.0		66.8	32.0	1.2
BEB1800/1805	rim7		#14	51.6	30.2	14.1	0.0	0.4	3.4	0.2	99.9		#14	2.4	1.6	0.7	0.0	0.0	0.3	0.0	5.0		68.9	29.8	1.3
BEB1800/1805	rim8		#16	54.9	28.1	11.4	0.0	0.5	4.7	0.4	100.1		#16	2.5	1.5	0.6	0.0	0.0	0.4	0.0	5.0		55.8	41.5	2.6
BEB1800/1805	rim9		#18	51.3	30.3	14.3	0.0	0.5	3.3	0.2	100.0		#18	2.3	1.6	0.7	0.0	0.0	0.3	0.0	5.0		69.8	28.9	1.3
BEB1800/1805	rim10		#20	53.1	28.5	12.8	0.0	0.6	4.1	0.4	99.4		#20	2.4	1.5	0.6	0.0	0.0	0.4	0.0	5.0		62.2	35.8	2.0
BEB1800/1805	rim11		#22	50.8	30.3	14.4	0.0	0.5	3.1	0.2	99.4		#22	2.3	1.6	0.7	0.0	0.0	0.3	0.0	5.0		70.8	27.9	1.3
BEB1800/1805	rim12		#24	51.2	30.2	14.4	0.0	0.6	3.3	0.2	99.8		#24	2.3	1.6	0.7	0.0	0.0	0.3	0.0	5.0		69.9	29.0	1.1
BEB1800/1805	rim13		#26	50.7	29.9	13.2	0.0	1.3	3.1	0.3	98.6		#26	2.3	1.6	0.7	0.0	0.1	0.3	0.0	5.0		69.0	29.4	1.6
BEB1800/1805	rim14		#28	51.6	29.8	13.7	0.0	0.5	3.5	0.2	99.3		#28	2.4	1.6	0.7	0.0	0.0	0.3	0.0	5.0		67.4	31.3	1.3
BEB1800/1805	rim15		#30	51.7	29.8	13.9	0.0	0.4	3.5	0.2	99.6		#30	2.4	1.6	0.7	0.0	0.0	0.3	0.0	5.0		67.6	30.9	1.5
BEB1800/1805	rim16		#32	51.7	30.2	13.8	0.0	0.5	3.5	0.3	100.0		#32	2.4	1.6	0.7	0.0	0.0	0.3	0.0	5.0		67.7	30.8	1.5
BEB1800/1805	rim17		#34	52.0	29.7	13.6	0.0	0.6	3.6	0.3	99.7		#34	2.4	1.6	0.7	0.0	0.0	0.3	0.0	5.0		66.3	32.2	1.5
BEB1800/1805	rim18		#36	51.8	29.9	14.0	0.0	0.4	3.4	0.3	99.9		#36	2.4	1.6	0.7	0.0	0.0	0.3	0.0	5.0		68.2	30.3	1.5
BEB1800/1805	rim19		#38	51.1	30.5	14.6	0.0	0.5	3.2	0.3	100.2		#38	2.3	1.6	0.7	0.0	0.0	0.3	0.0	5.0		70.5	27.9	1.6
BEB1800/1805	rim20		#40	51.0	30.2	14.2	0.0	0.5	3.3	0.2	99.4		#40	2.3	1.6	0.7	0.0	0.0	0.3	0.0	5.0		69.4	29.3	1.4

Microprobe results on feldspars from BEB 1800/1805 and BEB 1555.

References

British Geological Survey holds most of the references listed below, and copies may be obtained via the library service subject to copyright legislation (contact libuser@bgs.ac.uk for details). The library catalogue is available at: http://geolib.bgs.ac.uk.

ABUSHAM E.A. 2000 A palynology and palynofacies investigation of the Lower Carboniferous of the Midland Valley of Scotland. Unpublished PhD thesis, University of Sheffield

ALEXANDRE, P, HAMILTON D, AND BARFOD D. 2006**.** The ARGUS multicollection noble gas mass spectrometer. *Geochimica et Cosmochimica Acta*, **70,** Page A8, Abstracts of the 16th annual V. M. Goldschmidt conference.

ARMSTRONG, M, PATERSON, I B, AND BROWNE, M A E. 1985. Geology of the Perth and Dundee district. *Memoir of the British Geological Survey,* Sheets 48W, 48E and 49 (Scotland).

BATEMAN, R M, AND SCOTT, A C. 1990. A reappraisal of the Dinantian floras at Oxroad Bay, East Lothian, Scotland; Volcanicity, palaeoenvironments and palaeoecology. *Transactions of the Royal Society of Edinburgh: Earth Sciences*, **81**, 161-194.

BATEMAN, R M, AND CLEAL, C J. 1995. Loch Humphrey Burn. 155-164 in *Palaeozoic Palaeobotany of Great Britain*. Geological Conservation Review Series, No. 9. Cleal, C J, and Thomas, B A (editors). (London: Chapman and Hall for Joint Nature Conservation Committee.)

BRITISH GEOLOGICAL SURVEY 1993. Sheet 30E Glasgow solid edition 1:50,000 series (Scotland). (Keyworth, Nottingham: British Geological Survey).
BRITISH GEOLOGICAL SURVEY. 2004. Sheet 32E Edinburgh, solid edition 1:50, 000 series (Scotland) (Keyworth, Nottingham: British Geological Survey).

BLACK, G P. 1966. *Arthur's Seat. A History of Edinburgh's Volcano*. (Edinburgh: Oliver and Boyd.)

BRINDLEY, S, AND SPINNER, E. 1989. Palynological assemblages from Lower Carboniferous deposits, Burntisland district, Fife, Scotland. *Proceedings of the Yorkshire Geological Society*, **47**, 215-231.

BROWNE, M A E, DEAN, M T, HALL, I H S, MCADAM, A D, MONRO, S K AND CHISHOLM, J I. 1999. A lithostratigraphical framework for the Carboniferous rocks of the Midland Valley of Scotland. *British Geological Survey Research Report*, RR/99/07.

CAMERON, I B, AND STEPHENSON, D. 1985. *British regional geology: the Midland Valley of Scotland*. (3rd edition). HMSO, London for the British Geological Survey.

CLARK, R H. 1956. A petrological study of the Arthur's Seat volcano. *Philosophical Transactions of the Royal Society of Edinburgh*, **63**, 37-70.

CLAYTON, K. 1985. Dinantian miospores and inter-continental correlation. *Compte Rendu 10th International Congress on Carboniferous Stratigraphy and Geology* (Madrid, 1983), Vol. 4, 9–23.

DE SOUZA, H A F. 1974. Potassium-argon ages of Carboniferous igneous rocks from East Lothian and the south of Scotland. Unpublished MSc thesis, University of Leeds.

DE SOUZA, H A F. 1979. The geochronology of Scottish Carboniferous volcanism. Unpublished PhD thesis, University of Edinburgh.

FITCH, F J, MILLER, J A, AND WILLIAMS, S C. 1970. Isotopic ages of British Carboniferous rocks. *Compte Rendu 6e Congrès International de Stratigraphie et de Géologie du Carbonifère, Sheffield, 1967*, Vol. 2, 771-790.

HALL, I H S, BROWNE, M A E AND FORSYTH, I H. 1998. Geology of the Glasgow district. *Memoir of the British Geological Survey,* Sheet 30E (Scotland).

Higgs, K T, Clayton, G and Keegan, J B. 1988a. Stratigraphic and Systematic Palynology of the Tournaisian Rocks of Ireland. Geological Survey of Ireland, Special Paper 7; 1-93.

HIGGS K T, MCPHILMENY B, KEEGAN J B AND CLAYTON G. 1988b. New data on palynological boundaries within the Irish Dinantian. *Review of Palaeobotany and Palynology*, **56**, 61-68.

ICS/IUGS International Stratigraphic Chart. 2009. http://www.stratigraphy.org/upload/ISChart2009.pdf

KOPPERS, A P, STAUDIGEL H AND WIJBRANS J R. 2000. Dating crystalline groundmass separates of altered Cretaceous seamount basalts by the 40Ar/39Ar incremental heating technique. *Chemical Geology*, Vol. 166, 139-158.

KUIPER, K F, DEINO, A, HILGEN F J, KRIJGSMAN, W, RENNE, P R, AND WIJBRANS, J R. 2008. Synchronizing rock clocks of earth history. *Science,* **320**, 500–504.

MCADAM, A, AND TULLOCH, W. 1985*. Geology of the Haddington District.* Memoir of the British Geological Survey*, Sheet 33W and part of Sheet 41 (Scotland).*

MENNING, M., WEYER, D., DROZDZEWSKI, G., VAN AMEROM, H. W. J. AND WENDT, I. 2000. A Carboniferous timescale 2000: Discussion and use of geological parameters as time indicators from central and western Europe. *Geologisches Jahrbuch*, **A156**, 3-44

MIN, K, MUNDIL, R, RENNE, P, AND LUDWIG, K. 2000. A test for systematic errors through comparison with U-Pb analysis of a 1.1 Ga rhyolite. *Geochemica et Cosmochimica Acta*, **64**, 73-98.

MONAGHAN, A A, AND PRINGLE, M S. 2004 ^{40}Ar/^{39}Ar Geochronology of Carboniferous-Permian Volcanism in the Midland Valley, Scotland.. In Wilson M., Neumann E-R., Davies G.R. et al. (eds) *Permo-Carboniferous Magmatism & Rifting in Europe*. Geological Society, London, Special Publications, **223**, 219-242.

MONAGHAN A A, AND PARRISH, R R. 2006. Geochronology of Carboniferous–Permian volcanism in the Midland Valley of Scotland: implications for regional tectono-magmatic evolution and the numerical timescale. *Journal of the Geological Society of London*, **163**, 15-28

MYKURA, W, CALVER, M A, AND WILSON, R B. 1967. The Upper Carboniferous rocks of south-west Ayrshire. *Bulletin of the Geological Survey of Great Britain*, **26**, 23-98.

NEVES, R, GUEINN, K J, CLAYTON, G, IOANNIDES, N S, NEVILLE, R S W, AND KRUSZEWSKA, K. 1973. Palynological correlations within the Lower Carboniferous of Scotland and northern England. *Transactions of the Royal Society of Edinburgh*, **69**, 23-70.

OGG, J G, OGG G, AND GRADSTEIN F M. 2008. The Concise Geologic Time Scale. Cambridge University Press. ISBN 13:9780521898492

Owens, B. 1976. Palynological report on Lower Carboniferous samples from Doughnot Hill, Muirhouse Quarry, Fynloch Hill, Douglas Muir Quarry and Auchineden Hill. PDL/76/201

Owens, B. 1978a. Palynological report on samples from the IGS Barnhill Borehole. *Report of the British Geological Survey* PDL/78/74

Owens, B. 1978b. Palynological report on samples from the IGS Kipperoch Borehole. *Report of the British Geological Survey* PDL/78/59

Owens, B. 1978c. Palynological report on samples from the IGS Everton Borehole. *Report of the British Geological Survey* PDL/78/61

OWENS, B. 1980a. Palynological report on Dinantian samples from the I.G.S. Loch Humphrey Borehole. *Report of the British Geological Survey,* PDL/80/207.

OWENS, B. 1980b. Palynological report on Dinantian samples from the I.G.S. Lawmuir Borehole. *Report of the British Geological Survey*, PDL/80/216.

OWENS, B, MCLEAN, D, SIMPSON, K R M, SHELL, P M J, AND ROBINSON, R. 2005. Reappraisal of the Mississipian palynostratigraphy of the East Fife coast, Scotland, United Kingdom. *Palynology*, **29**, 23-47.

PATERSON, I B, HALL, I H S, AND STEPHENSON, D. 1990. Geology of the Greenock district. *Memoir of the British Geological Survey,* Sheet 30W and part of Sheet 29E (Scotland).

RENNE, P R, SWISHER, C C, DEINO, A L, KARNER, D B, OWENS, T L, AND DEPAOLO, D J. 1998. Intercalibration of standards, absolute ages and uncertainties in ^{40}Ar-^{39}Ar dating. *Chemical Geology*, **145**, 117-152

RILEY, N J. 1993. Dinantian (Lower Carboniferous) biostratigraphy and chronostratigraphy in the British Isles. *Journal of the Geological Society, London*, **150**, 427-446.

SCOTT, A C. 1990. Preservation, evolution, and extinction of plants in Lower Carboniferous volcanic sequences in Scotland. In; Lockley, M. G. and Rice, A. (eds) *Volcanism and fossil biotas.* Geological Society of America Special Paper, **244**, 25-38.

SCOTT, A C, GALTIER, J, AND CLAYTON, G. 1984. Distribution of anatomically preserved floras in the Lower Carboniferous in Western Europe. *Transactions of the Royal Society of Edinburgh: Earth Sciences*, **75**, 311-340.

SCOTT, A.C., GALTIER, J AND CLAYTON, G 1985. A new late Tournaisian (Lower Carboniferous) flora from the Kilpatrick Hills, Scotland *Review of Palaeobotany and Palynology,* **44**, 81-99.

SMEDLEY, P L. 1986. Petrochemistry of Dinantian volcanism in northern Britain. Unpublished PhD thesis, University of Edinburgh.

SMITH, R. A. 1996. Geology of the Gass Water Area. BGS Technical Report WA/96/22. British Geological Survey, Edinburgh.

SMYTHE, D K, RUSSELL, M J, AND SKUCE, A G. 1995. Intra-continental rifting inferred from the major late Carboniferous quartz-dolerite dyke swarm of NW Europe. *Scottish Journal of Geology*, Vol. 31, 151-162.

STEIGER, R H, AND JÄGER, E. 1977. Subcommission on geochronology: convention on the use of decay constants in geo- and cosmochronology. *Earth and Planetary Science Letters*, **36**, 359-362.

STEPHENSON, D, LOUGHLIN, S C, MILLWARD, D, WATERS, C N, AND WILLIAMSON, I T. 2003. *Carboniferous and Permian Igneous Rocks of Great Britain North of the Variscan Front*. Geological Conservation Review Series Number 27, Joint Nature Conservation Committee, Peterborough.

TURNER, G. 1971 ^{40}Ar/^{39}Ar dating; the optimization of irradiation parameters. Earth and Planetary Science Letters, 10, 227-234

TURNER, N. 1994a. Palynology of Devonian and Carboniferous Rocks of the Cumnock and Doon Valley District, Strathclyde. *British Geological Survey Technical Report* WH/94/294R.

TURNER, N. 1994b. Palynology of the Cults Farm Boreholes Nos. 1-3, East Fife, Scotland. *British Geological Survey Technical Report* WH/94/242.

UPTON, B G J, STEPHENSON, D, SMEDLEY, P M, WALLIS, S M, AND FITTON J G. 2004. Carboniferous and Permian magmatism in Scotland. In Wilson M., Neumann E-R., Davies G.R. et al. (eds) Permo-Carboniferous Magmatism and Rifting in Europe. *Geological Society, London, Special Publications*, **223**, 195-217.

WAGNER, R H. 1983. A Lower Rotliegend flora from Ayrshire. *Scottish Journal of Geology*, **19**, 135-155

WALLIS, S M. 1989. Petrology and geochemistry of Upper Carboniferous-Lower Permian volcanic rocks in Scotland. Unpublished PhD thesis, University of Edinburgh.

WILSON, R B. 1986. A study of the marine faunas of central Scotland. *Transactions of the Royal Society of Edinburgh, Earth Sciences*, **80**: 91-126.