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Petrology and geochemistry of the igneous and sedimentary rocks exposed in the Ayr District (Sheet 14W) of the Southern Midland Valley, Scotland

Geology and Landscape Northern Britain

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GEOLOGY AND LANDSCAPE NORTHERN BRITAIN

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Petrology and geochemistry of the igneous and sedimentary rocks exposed in the Ayr District (Sheet 14W) of the Southern Midland Valley, Scotland

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Map

Sheet 14W, 1:99 000 scale, Ayr

Bibliographical reference

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Foreword

This report is the published product of a study by the British Geological Survey (BGS). It describes the petrology of a suite of sedimentary and igneous rocks exposed in the Ayr District and the geochemistry of the Carrick Volcanic Formation (Sheet 14W) of the southern Midland Valley of Scotland. The samples were collected by BGS field geologists R.A. Smith, A. Monaghan and S.L.B. Arkley during the resurvey the Ayr District between 1998 and 2001. This work forms part of the Strathmore Basin and Midland Valley Project, Geology and Landscape Northern Britain Programme.

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Summary

This report describes the petrology of a suite of sedimentary and igneous rocks exposed in the Ayr District (Sheet 14W) of the southern Midland Valley of Scotland.

The lavas from the Carrick Volcanic Formation are calc-alkaline in character and display geochemical characteristics similar to basaltic lavas erupted within either a continental volcanic-arc or within-plate setting with a small number of analyses plotting in the basalt and andesite fields. The lavas can be divided into two suites: (1) a suite of high-Mg basalts and basaltic andesites; and (2) and more “normal” low-Mg lavas. Alteration of the volcanic rocks resulted in the variable remobilisation of the major elements Na_2O, K_2O and CaO, and trace elements Rb and Sr. The major oxides TiO_2, Fe_2O_3 total, MgO and CaO and trace elements Zn, Ni, V, Cr and Sc all show decreasing trends as SiO_2 increases, typical of calc-alkaline magmatic differentiation paths, consistent with the fractionation of olivine and clinopyroxene within the basalts, and hornblende in the more andesitic lithologies. Available whole-rock geochemical data indicates that there is a significant change in composition within the Carrick Volcanic Formation. This change is characterised by marked break in the lithostratigraphical variations of the trace elements Nd, Y, Ce, Zr, Ni, Cr and V contents, and, to a lesser extent, Rb and Hf.

Sandstone compositional data has shown that there are marked differences between the medium- to coarse-grained sandstones of the Ballagan, Kinnesswood and Lawmuir formations and the older Swanshaw and Auchtitench sandstone formations of the Lanark Group. Volcanic rock fragments form the dominant lithic component within the Lanark Group sandstones, with metamorphic rock fragments forming a common component within the Swanshaw Sandstone Formation. There is a marked difference in composition between sandstones from the Duneaton Volcanic and Auchtitench Sandstone formations and those from the underlying Swanshaw

Sandstone Formation. The compositional overlap between Swanshaw Sandstone Formation sandstones from the Lanark, New Cumnock and Ayr districts indicates that they were derived from a similar source. In general, Swanshaw Sandstone Formation sandstones from the New Cumnock and Ayr districts were derived from a transitional, recycled orogenic provenance. The absence of any significant trends on the majority of the sandstone compositional plots suggests that the sediment being supplied to the Lanark Group basins was well 'mixed' and derived from a single source rather than a mixing of detritus from several areas. Consequently, compositional trends recognised within the Swanshaw Sandstone Formation may either reflect a change in the sediment maturity and/or an increase in the volcanic component towards the top of the formation prior to the onset of Lanark Group volcanism. The quartzose sandstones analysed from the Ballagan, Kinnesswood and Lawmuir formations of the Lanark and Ayr districts all fall within the craton interior (continental) and recycled orogenic fields.

1 Introduction

This report describes the petrology of a suite of sedimentary and igneous rocks, including the geochemistry of the Carrick Volcanic Formation, exposed in the Ayr District (Sheet 14W) of the southern Midland Valley of Scotland. A total of 40 thin sections of volcanic and high level intrusive igneous rock were examined during this study. This work forms part of the Strathmore Basin and Midland Valley project. A brief description of each thin section examined during this study is included in Appendix 1.

The igneous rocks were classified using the classification system and nomenclature of Le Maitre (1989) following the recommendations of the International Union of Geological Sciences Subcommission on the Systematics of Igneous Rocks.

2 Lithostratigraphy

2.1 INTRODUCTION

In the course of the revision mapping of the Ayr sheet (14W) selected sedimentary and igneous rock samples were collected for petrological and geochemical analysis by SLB Arkley, A Monaghan and RA Smith. The petrological thin sections were examined by ER Phillips and samples of the Carrick Volcanic Formation were geochemically analysed in the BGS laboratories in Keyworth for major and trace elements. The geochemical results were then plotted in several classification diagrams by ER Phillips.

As an introduction to the report the lithostratigraphy of the area south of Ayr (Figure 1)is given below.

Timescale		Biozones	Group	Formation	Member
Upper Carboniferous	Westphalian	VI	Coal Measures (Scotland)	Lower Coal Measures	
		SS			
	Namurian	FR	Clackmannan Group	Passage Formation	
		KV			Troon Volcanic Member
		SO			
Lower Carboniferous	Viséan	VF	Strathclyde Group	Lawmuir Formation	
		NM			
		TC		Clyde Plateau Volcanic Formation	Greenan Castle Pyroclastic Member
		Pu			
	Tournaisian	CM	Inverclyde Group	Ballagan Formation	

<table>
<tr><td></td><td></td><td>LN-PC</td><td></td><td>Kinnesswood Formation</td><td></td></tr>
<tr><td>Upper Devonian</td><td>Fammenian</td><td></td><td>Stratheden Group</td><td>No formation designated</td><td></td></tr>
<tr><td colspan="2">Lower Devonian</td><td rowspan="5"></td><td rowspan="5">Lanark Group</td><td>Carrick Volcanic Formation</td><td></td></tr>
<tr><td colspan="2" rowspan="4">Siluro-Devonian</td><td rowspan="3">Swanshaw Sandstone Formation</td><td>Crane Dyke Member</td></tr>
<tr><td>Isle Port Conglomerate Member</td></tr>
<tr><td></td></tr>
<tr><td>Greywacke Conglomerate Formation</td><td></td></tr>
</table>

Table 1. Lithostratigraphical nomenclature for the area south of Ayr. Heavy lines represent unconformable relationships in the area.

2.1 LANARK GROUP

These are the oldest rocks referred to in the report and are Siluro-Devonian in age. The group is widespread along the southern part of the Midland Valley and was deposited in the Lanark basin. In the vicinity of Ayr the Lanark Group comprises the Swanshaw Sandstone Formation overlain by the Carrick Volcanic Formation (Figure 1).

2.1.1 Swanshaw Sandstone Formation

The Swanshaw Sandstone Formation (Browne *et al*., 2002) consists predominantly of reddish brown to pinkish buff quartzose and lithic arenites with subordinate mudstones, pebbly sandstones, microconglomerates and conglomerates. South of Ayr the formation forms a substantial part of the Lanark Group (Table 1) and comprises a thick and locally well-exposed sequence (Figure 1) The sandstones are typically medium grained and moderately well sorted. The sandstone beds are mainly planar to cross-bedded and fluviatile in origin, but include the first record of aeolian facies within sedimentary rocks of this age in the Midland Valley (Smith *et al*., 2006).

The Swanshaw Sandstone Formation is essentially a sandstone-dominated fining-upwards siliciclastic succession, deposited in a terrestrial environment. Lithic sandstones form up to approximately 65% of the succession, with lesser amounts of conglomerate (c. 25%) and mudstone (c. 10%). The clasts are considered to have a recycled orogenic provenance (Phillips *et al*. 1998a).

A definitive biostratigraphical age for the formation is lacking. A poor spore assemblage, including *Apiculiretrusispora* and *Synorisporites* sp., recovered from the formation on the Ayrshire coast at [NS 245 133] suggests a Siluro-Devonian age. Radiometric Rb-Sr dating of the overlying volcanic rocks gives an age of c. 410-415 Ma, just above the Silurian-Devonian boundary (Thirlwall, 1988).

The Swanshaw Sandstone Formation overlies the Greywacke Conglomerate Formation (Table 1) south of Straiton in Ayrshire at [NS 390 007], where lithic sandstones include conglomerate lenses in a transitional sequence. Within the Ayr district, the lower part of the formation includes the Chapelton Burn Member (Table 1) characterised by distinctive pale-coloured aeolian sandstones exposed in the gorge of Chapelton Burn [NS 2284 0489] (Figure 1). Within the overlying succession near Mochrum vent [NS 265 100] (Figure 1), lenses of volcaniclastic sandstone are the products of penecontemporaneous volcanic activity. In the upper part of the formation, the Isle Port Conglomerate Member consists mainly of greenish grey clast-supported pebble conglomerates with subordinate matrix-supported conglomerates and interbedded sandstones. The base of the member is exposed in the tributary to Craigencroy Glen [NS 2578 1303] where a sharp-based bed of conglomerate rests on sandstone. The overlying Crane Dyke Member comprises red-brown, purple and greenish grey mudstones including interbedded sheetflood and channel sandstones decreasing in number from its base at NS 2469 1316. In places towards its top, the member contains volcanic pebbles and it is directly overlain by the Carrick Volcanic Formation (Table 1), exposed on the coast at [NS 2449 1382]. Below the Carrick Volcanic Formation south of Ayr [NS 324 160], there are conglomeratic facies which may be laterally equivalent to the Crane Dyke Member.

Fluvial channel, aeolian, floodplain and mudflat facies in the Swanshaw Sandstone Formation, distinguished mainly on the basis of lithology, bedding and sedimentary structures, are combined into genetically or environmentally related associations (Smith *et al*., 2006).

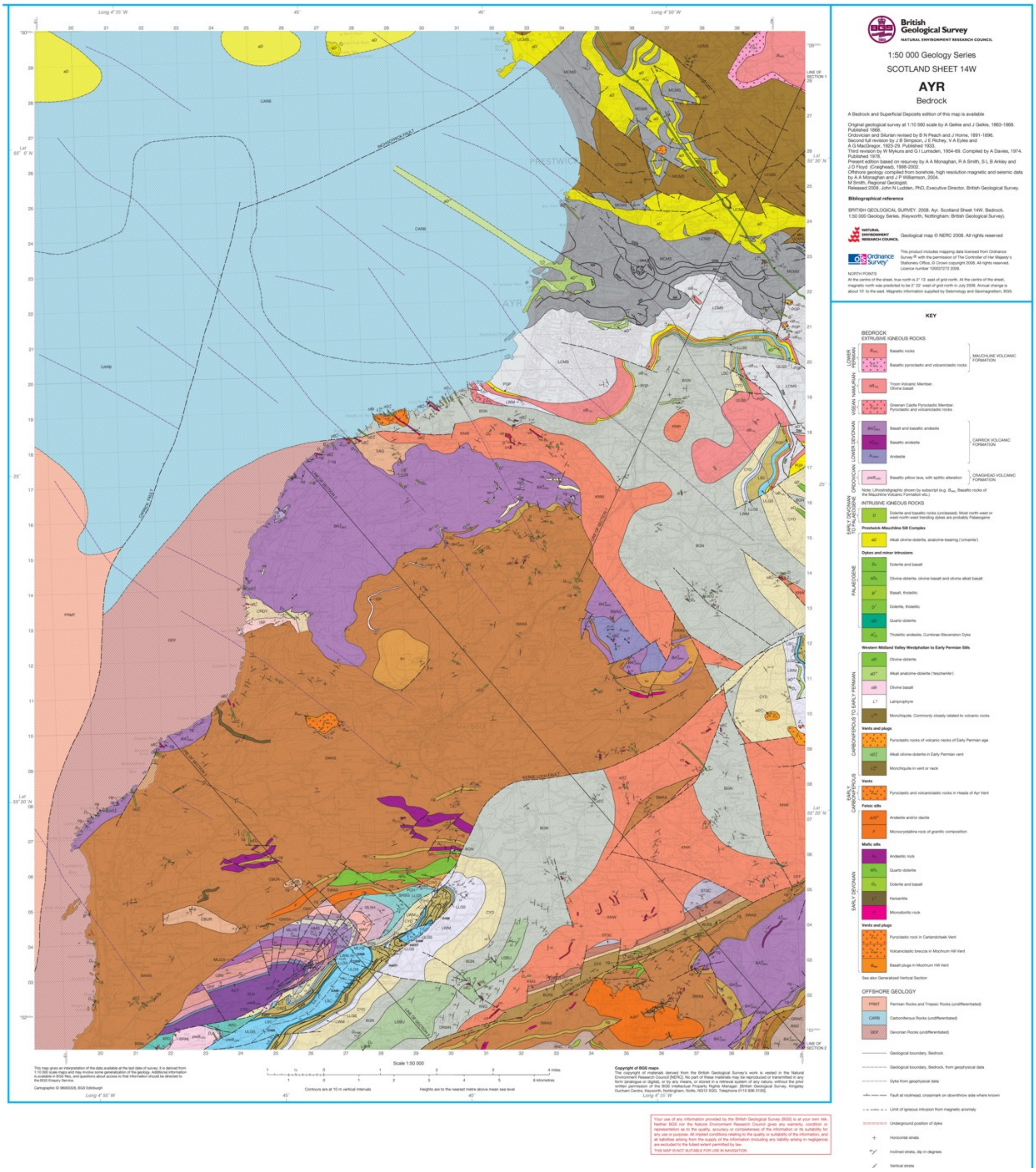

Figure 1. 1:50,000 scale geological map of the Ayr district.

2.1.2 Carrick Volcanic Formation

The Carrick Volcanic Formation in central Ayrshire (Table 1, Figure 1) comprises mainly basaltic andesite lavas and associated sills with subordinate basalts and andesites. The formational name is derived from Brown Carrick Hill, south of Ayr (Browne *et al*., 2002) and the formation is well exposed on the coast near Dunure, Culzean Castle and Maidens and in the Carrick Hills. It was formerly known as the volcanic group of the Lower Old Red Sandstone (Eyles *et al*., 1949). The type section for the Carrick Volcanic Formation is along the foreshore from west of Drumshang [NS 2449 1382] to Bracken Bay, south of Ayr [NS 273 182]. At the base of the formation, west of Drumshang, a basaltic andesite has a sharp, irregular junction above brick-red sandstone (Swanshaw Sandstone Formation) containing volcanic clasts and scattered pebbles of sandstone (Smith *et al*., 2006). The top of the volcanic pile is not seen because it is unconformably overlain by rocks belonging to the Stratheden and Inverclyde groups.

The lavas in central Ayrshire are commonly subject to alteration, being partly hematised, producing purple colouring. The flows have amygdaloidal slaggy tops that range from 3 to 15 m in thickness. Thin sandstone and conglomerate intercalations and sandstone-filled fissures in the lavas have been described several times since Geikie (1897). In contrast, fluidisation of wet sediments during the emplacement of associated hypabyssal intrusions has been recognised more recently on the Ayrshire coast (Kokelaar, 1982) and explains some of the complex relationships between the igneous and sedimentary rocks. These are also described from the geological conservation sites, Port Schuchan to Dunure Castle, Culzean Harbour and Turnberry Lighthouse to Port Murray (Durant, 1999). Olivine-rich basalt is widespread at the base, but there is evidence of earlier volcanic eruptions from the lava pebbles present within the underlying Swanshaw Sandstone Formation. There are no clear eruptive centres or fissures feeding the formation but the Mochrum vent through the Swanshaw Sandstone may be an early indication of the volcanic episode culminating in the eruption of the Carrick Volcanic Formation.

No rhyolitic lavas are known from central Ayrshire (cf. the Pentland Hills Volcanic Formation.), although flow-banded andesites occur south of Dalrymple which may be extrusive. The intercalated volcanic conglomerates and sandstones are mainly derived locally from the volcanic rocks. It is uncertain whether there are any true airfall tuffs in this area. In the Carrick Hills and Dunure areas, there are thin interbeds of fine-grained sandstone, siltstone and sandy mudstone in which several trace fossils have been found (Eyles *et al*., 1949; Walker, 1985) and these have been used to interpret the prevailing environment as an ephemeral shallow lake.

The Carrick Volcanic Formation is part of the Lower Devonian calc-alkaline suite found across the Midland Valley and is correlated with the Duneaton, Biggar and Pentland Hills volcanic formations (Browne *et al*., 2002). The petrogenesis of this suite has been attributed to northwest-dipping, active or recently terminated subduction (Thirlwall, 1982, 1986) or partial melting of a subduction contaminated source (Smith, 1995; Philips *et al*., 1998).

2.2 STRATHEDEN GROUP

The Stratheden Group (Figure 1) comprises white, pink and green sandstones, pebbly sandstones and conglomerates that lie unconformably on an uneven palaeotopography of the Carrick Volcanic Formation to the south of the Heads of Ayr [NS 285 175]. It reaches a maximum thickness of 110 m. Previously described as part of the 'Upper Old Red Sandstone', Fammenian age (Upper Devonian) fish faunas found near the coast at Bracken Bay (*Bothriolepis leptocheira* and *Holoptychius*: Eyles *et al*., 1949; Mykura in Craig, 1991;) allow assignment to the Stratheden Group (Browne *et al*., 2002). The group was not sampled in this study.

2.3 INVERCLYDE GROUP

The Inverclyde Group (Courceyan to earliest Chadian) is interbedded with the underlying strata and the base is taken where strata bearing nodular pedogenic carbonate (calcrete) predominate over the fluvial and aeolian sandstones belonging to the Stratheden Group. In the area south of Ayr the group comprises the Kinnesswood Formation overlain by the Ballagan Formation; the overlying Clyde Sandstone Formation, which is the uppermost formation in the group, is not exposed in this area and probably is overstepped by the Strathclyde Group (Table 1, Figure 1).

2.3.1 Kinnesswood Formation

The Kinnesswood Formation (Figure 1) is the oldest formation in the Inverclyde Group and overlies unconformably the Carrick Volcanic Formation south of Ayr. The formation comprises characteristically medium-grained quartzose sandstones with subordinate red and green argillaceous beds, calcrete lenses and nodular horizons. The white, yellow or purple-red sandstones are commonly in medium bedded, cross-bedded, upward fining units with sharp to erosive pebbly bases. Rare fine-grained conglomerates are interbedded within the formation.

Deposition of the sandstones in braided or meandering river channels was usually followed by overbank deposition of argillaceous beds in which nodules and impersistent beds of pedogenic carbonate developed. These are characteristic of the formation and indicate the development of caliche on relatively long-lasting alluvial plains affected by fluctuating water tables in a semi-arid climate with seasonal rainfall.

The formation is in the order of 150 m thick south of Ayr and was previously considered to be the upper part of the Upper Old Red Sandstone (Eyles *et al*., 1949). The diachronous base overlying the Stratheden Group is not exposed south of Ayr and the junction with the overlying argillaceous Ballagan Formation is faulted out at the coast in Bracken Bay. While the Kinnesswood Formation is considered to be older than the Ballagan Formation, the boundary between the two formations could also be diachronous. The formation is generally unfossiliferous, but palynomorphs assigned to the LN-PC miospore zones at the base of the Tournaisian have been recorded from near the base of the formation near Muirkirk (Smith, 1996).

2.3.2 Ballagan Formation

The Ballagan Formation (Figure 1) comprises a widespread characteristic succession of interbedded grey mudstones, siltstones, sandstones with beds and nodules of micritic dolomites and limestones (cementstones). Indications of evaporite mineral content (such as halite pseudomorphs) are common, which together with the desiccation cracks and impoverished faunas, suggests deposition in a marginal marine or lagoonal environment in a semi-arid climate. The formation extends not only along the length of the Midland Valley but into southern Scotland and Northern England.

The Ballagan Formation, previously termed the Cementstone Group of the Calciferous Sandstone Measures, conformably overlies the Kinnesswood Formation. In the sections south of Ayr and across much of central Scotland, the formation contains palynomorphs assigned to the CM Biozone corresponding to the Tournaisian (locally the formation has been determined to extend into the Early Visean; Williams *et al*., 2005). It is well exposed at the coast south of Ayr from Bracken Bay [NS 277 182] to Greenan Castle [NS 310 195]. In the Ayr district, the characteristic finely laminated mudstone, siltstone sandstone and limestone sedimentary rocks of the Ballagan Formation (Browne *et al*., 1999) are present, reaching up to 442 m in thickness (including the part cut by the vent) in the Heads of Ayr section (Stephenson *et al*., 2002). In the lower part of the formation exposed in Bracken Bay, the succession includes interbedded fine-grained micaceous sandstones, siltstones, mudstones and calcareous mudstones about 120 m thick interrupted by the Heads of Ayr vent. These strata contain a restricted fauna of *Lingula*, *Estheria*, *Modiolus latus*, *Spirobis*, fish remains, *Planolites*-type trace fossils and other indistinct bioturbation. The depositional environment of these beds is interpreted as marginal marine to restricted saline lagoonal, as described for the formation elsewhere (Andrews and Nabi, 1994). The associated sharp-based sandstones may represent distal crevasse splay deposits that were supplied across the floodplain during periodic fluvial flood events. Inland, at the March Burn section [NS 360 080] north of Straiton, pedogenic carbonate nodules developed in a sandstone and red mudstone palaeosol lie within the lower part of the Ballagan Formation (overlying the Kinnesswood Formation) and support the interpretation of a semi-arid environment.

In the section east of Heads of Ayr vent and up to Deils Dyke [NS 310 190] (i.e. between 300 and 380 m above the base of the section of Stephenson *et al*., 2002), the formation is characterised by nodular and thin bedded calcareous dolomite (cementstones) and sandstones are absent. This interval appears to be transitional into the succession to the east of Deils Dyke (380-430 m in the section) which is characterised by thin bedded dark mudstones, siltstones and laminated cementstones. The latter are believed to be primary dolomite deposited in an arid environment. Their prevalence, and the finer-grained nature of the sediments overall, indicates an environment with reduced fluvial energy and subaerial exposure, and more quiescent (probably lagoonal) conditions with fluctuating salinity. Immediately beneath the Greenan Castle Pyroclastic Member [NS 312 195] (see section 2.5.1), at c. 430 m above the base of the coastal section, a few tens of metres of sharp based, cross-bedded, ripple- and parallel-laminated micaceous sandstones are patchily exposed. The relationship with the underlying mudstone-dominated sequence is not clear, but the sandstones are considered to be conformable and represent a return to more active fluvial conditions within the local uppermost part of the Ballagan Formation.

In less extensive sections near the River Doon [NS 323 184], for example, some of the basal beds contain microconglomerates and medium- to coarse-grained quartzose sandstones.

However, there are also considerable facies variations elsewhere in the formation such as the sandstone-dominated strata prevalent to the east within Ayrshire and in the south near Dailly [NS 270 040]. In the Dailly area, the three lithological subdivisions of the Ballagan Formation recognised by Eyles *et al*. (1949) have been further subdivided into the basal Drumwhirn Member, the Lindsayston Burn Member and an upper unit with typical Ballagan Formation facies.

Palynomorph assemblages in the lower part of the Ballagan Formation in Ayrshire are low-diversity terrestrially derived forms interpreted to represent a stressed hinterland flora in arid to semi-arid conditions. The spore assemblages from the upper part of the Ballagan Formation are of two types: **(1)** a *Leiosphaeridia*-dominated assemblage containing scarce terrestrial palynomorphs representing fresh- or brackish water lagoons; and **(2)** a high-diversity assemblage containing *lycopsid* plant spores possibly indicating wetter climatic conditions (Stephenson *et al*., 2002). This palynomorph analysis allows a local two-fold subdivision of the formation (Table 1) but because of lack of exposure inland, these divisions cannot be confidently represented on the maps.

Several palynomorphs indicative of brackish or fresh water facies have been identified within the Ballagan Formation in Ayrshire (Stephenson *et al*., 2004).

The ostracod faunas are low-diversity assemblages typically dominated by one or two species of *paraparchitacean*, *cavellinid* or *Acutiangulata*, and confirm the prevailing marginal or quasimarine conditions. Ostracod faunas including *Cavellina coela* and C. *incurvescens* identify the Tournaisian B. gyptopleuroides-Eriella ostracod Biozone at 230-270 m in the Heads of Ayr section (Stephenson *et al*., 2002; Williams *et al*., 2005), and this ties in with the CM Biozone floras from this interval. However, in the upper part of the formation, two age interpretations are possible; the presence of the ostracods *Glyptolichvinella* cf. *spiralis* and *Sulcella* cf. *affiliata* suggest a Visean age, but in the absence of *L. pusilla*, the palynological marker for the basal Visean Pu Biozone, it suggests the CM Biozone Tournaisian age.

2.4 STRATHCLYDE GROUP

The Strathclyde Group (late Chadian to mid Brigantian) is a varied succession of sedimentary and volcanic rocks. The Clyde Plateau Volcanic Formation lies at the base and in the north of the Midland Valley it is overlain by reworked volcaniclastic sediments belonging to the Kirkwood

Formation. In the south-western part of the Midland Valley, including the area south of Ayr, a minor unconformity separates the overlying Lawmuir Formation from the volcanic rocks. The Lawmuir Formation is variable in sedimentary facies but characterised by its carbonaceous content.

2.4.1 Clyde Plateau Volcanic Formation

2.4.1.1 Greenan Castle Pyroclastic Member

This member consists of well bedded and massive, grey-green lithic lapilli-tuff, about 25 m thick, forming the promontory on which Greenan Castle stands [NS 312 196]. The reworked beds contain accretionary lapilli and trough cross-bedding. The material forming the tuff is similar to that at the Heads of Ayr vent and it is therefore considered to be the source of the pyroclasts. No fossils have been obtained from the member but since the age of the underlying Ballagan Formation is Tournaisian and the overlying Lawmuir Formation is assigned to the mid-late Asbian, both the vent and the member are limited to a time in between i.e. probably Lower Visean. This age assignment correlates with the timing of the Clyde Plateau volcanism active to the north within the Midland Valley and the member is considered to be part of the Clyde Plateau Volcanic Formation (Stephenson *et al*., 2002).

2.4.2 Lawmuir Formation

The formation includes variable successions of mudstones, siltstones and sandstones with local palaeosols, coals and limestones. In the coastal exposures south of Ayr [NS 310 190] it comprises thinly laminated mudstones rich in plant debris which pass upwards into medium-grained sandstones also with plant debris (Stephenson *et al*., 2002). These beds lie unconformably above the Greenan Castle Pyroclastic Member and have been assigned to the mid to late Asbian NM Biozone age, in agreement with Neves *et al*. (1973). The strata have therefore been correlated with the Lawmuir Formation.

2.5 CLACKMANNAN GROUP

The Clackmannan Group (Brigantian to Langsettian) has been defined in the Midland Valley (Browne *et al*., 1999) and includes the Lower Limestone, Limestone Coal, Upper Limestone and Passage formations. The whole group is extremely condensed over a palaeohigh around Ayr and south of Ayr the Passage Formation is the only representative of the group at outcrop.

2.5.1 Passage Formation

The Passage Formation (Browne *et al*., 1999) characteristically comprises a dominantly fluvial succession of sandstones, siltstones, and mudstones including seatearths and fireclays. In Ayrshire it included a widespread volcanic lava field represented by the Troon Volcanic Member. In the area south of Ayr, the formation unconformably overlies the Strathclyde and Inverclyde groups. It is overlain by the Lower Coal Measures Group (Scotland).

A section through the condensed succession of the Passage Formation is provided by the shoreline exposures south of Ayr near Longhill Point [NS 315 197]. This consists of the Troon Volcanic Member at its base overlain by a thin succession (< 10 m) of mudstones and brown and blue-green siltstones with clasts, apparently of volcanic rock.

The Troon Volcanic Member is about 50 m thick in this section and comprises bluish grey to black, basaltic lavas and intercalated volcanic mudstones. The basalts are reported to contain microphenocrysts of olivine in a matrix of plagioclase feldspar, augite and iron ore (Eyles *et al*., 1949). In the field most of the exposures are severely decomposed and altered.

2.6 CARBONIFEROUS-PERMIAN AND PALAEOGENE MINOR INTRUSIONS

Monchiquite dykes and minor intrusions exposed near the Heads of Ayr are considered to be Carboniferous-Permian in age. Numerous dykes varying from olivine, alkali olivine and tholeiitic dolerite and basalt in type are exposed trending northwest to north-northwest on the shore south of Ayr. They are considered to be Palaeogene in age and include the prominent olivine dolerite dyke known as the Deils Dyke which cuts through the Ballagan Formation on the foreshore at [NS 307 193]. The Prestwick-Mauchline Sill, also of Palaeogene age, is composed of alkali olivine dolerite and was emplaced prior to the intrusion of the later Palaeogene dyke suite.

3 Petrology

3.1 CARRICK VOLCANIC FORMATION

3.1.1 Plagioclase-olivine-pyroxene-phyric basalts

In thin section these basaltic lavas are, in general, fine- to medium-grained, hypocrystalline, weakly pilotaxitic, macroporphyritic, weakly to highly altered, inequigranular rocks (N2546, N2559, N2560).

Phenocrysts are mainly composed of plagioclase with subordinate bowlingite/iddingsite pseudomorphs after pyroxene as well as mesh-textured pseudomorphs after olivine microphenocrysts (± orthopyroxene). Plagioclase forms anhedral to subhedral, twinned, equant, elongate to lath-shaped crystals (ranging from 0.2 up to 2.8 mm in size) which exhibit minor alteration to carbonate and/or chlorite along fractures. In some rocks (N2546), plagioclase phenocrysts are rounded due to partial resorption. These plagioclase phenocrysts locally possess sieve-textured cores containing rounded inclusions of chloritised glass and rare pseudomorphs after pyroxene and/or olivine. Plagioclase phenocrysts may be variably shape-aligned and define a weakly developed pilotaxitic fabric (N2559, N2560). Pseudomorphs after olivine are typically composed of a rounded to irregular core of cryptocrystalline chloritic material (± carbonate) enclosed within a rim of opaque oxide and/or iddingsite. Olivine crystals were originally rounded, anhedral to occasionally subhedral in shape.

The fine- to medium-grained groundmass is massive and composed of randomly orientated plagioclase laths with minor amounts of a interstitial to intersertal dusty brown, inclusion-rich mesostasis. This feldspathic groundmass also contains pseudomorphs (opaque oxide + chlorite) after intergranular pyroxene (± olivine) as well as granular to needle-like opaque minerals. The remainder of the interstitial to intersertal areas are composed of cryptocrystalline chlorite which is locally partially replaced by carbonate. Traces of interstitial quartz may be present in some rocks.

The more highly altered lithologies (N2546, N2659) comprise an inequigranular assemblage of plagioclase, opaque minerals, chlorite, iddingsite, bowlingite, white mica and quartz.

3.1.2 Rubbly/pepperitic plagioclase-phyric basalt

One thin section (N2561) of a possibly pepperitic, plagioclase microporphyritic basalt was examined from the Carrick Volcanic Formation. The sample is mainly composed of a very fine-grained, inequigranular, amygdaloidal, pilotaxitic, highly altered, microporphyritic basalt. The very fine-grained, originally glassy groundmass to this basalt is variably altered to/replaced by hematitic oxide. A well-developed pilotaxitic to hyalopilitic fabric within the groundmass is defined by shape-aligned needle-like plagioclase laths. Larger plagioclase microphenocrysts (≤ 0.6 mm in length) are variably aligned parallel to this primary igneous foliation. Chloritic pseudomorphs after possible pyroxene microphenocrysts are also present. Irregular vugs or amygdales are composed of finely cryptocrystalline chloritic material.

The basalt occurs as highly irregular fragments within a fine- to very-fine-grained sandstone ‘matrix’. These fragments possess complex to irregular margins, indicative of very little or no sedimentary reworking. The quartzose sandstone matrix to this sample is well sorted, lithic-rich (litharenite) and possesses an open-packed clast-supported texture. A very finely cryptocrystalline quartzose cement is developed within this sandstone. The detrital assemblage is mainly composed of monocrystalline quartz, variably degraded lithic fragments (protolith uncertain) and feldspar. Other detrital components include muscovite, chlorite, opaque, biotite and garnet. Detrital grains are subrounded to rounded in shape with a low sphericity.

It is possible that this rock represents either: **(a)** the rubbly top to a basaltic lava flow into which sediment has infiltrated; or **(b)** a pepperite formed by the interaction of hot lava with wet sediment.

3.1.3 Highly altered basalts

The Carrick Volcanic Formation also includes a suite of highly altered basaltic rocks. In thin section (N2562, N2576, N2577) they are fine- to coarse-grained, massive, aphyric microporphyritic rocks in which the primary mineral assemblage has largely been replaced by inequigranular assemblage of cryptocrystalline chlorite, albitic plagioclase and hematitic oxide.

Chloritic pseudomorphs after anhedral to weakly euhedral after pyroxene and olivine microphenocrysts are common in some rocks (N2562, N2576). Pseudomorphs after olivine are composed of an outer rim of opaque oxide enclosing a chlorite-rich core; the latter may be partially replaced by later carbonate. Both pyroxene and olivine occurred as single isolated phenocrysts as well as in small glomerophyric clusters.

The groundmass is composed of randomly orientated to locally shape-aligned plagioclase laths which are only slightly finer grained than the microphenocrysts. Plagioclase forms twinned and locally weakly zoned crystals that are variably recrystallised to albite and altered to cryptocrystalline chlorite (± carbonate) along fractures. The interstitial to intersertal areas are composed of turbid, brown hematitic material which may represent a hematised mesostasis. Small irregular voids and larger, rounded to irregular amygdales are composed of pale yellow-green chloritic material with trace amounts of quartz and carbonate.

3.1.4 Olivine-plagioclase-phyric basalts

In thin section the olivine-plagioclase-phyric basalts are typically medium- to coarse-grained, inequigranular, hypocrystalline, highly altered, aphyric to microporphyritic rocks which comprises the assemblage plagioclase, chlorite, opaque minerals, carbonate, quartz, bowlingite and iddingsite (N2541, N2543, N2544, N2547).

Phenocrysts within these basaltic rocks are typically only slightly more coarse-grained than the groundmass. They are mainly composed of olivine (± 0.9 mm in size) and occasional slightly larger plagioclase microphenocrysts. Minor to rare pyroxene phenocrysts are present in some rocks. Olivine microphenocrysts are completely pseudomorphed by a cryptocrystalline assemblage of chlorite, bowlingite, opaque minerals and iddingsite, with trace amounts of quartz and carbonate in some rocks. These pseudomorphs consist of an outer rim of opaque oxide enclosing a core of chloritic material. Fractures within the original relict olivine are preserved by thin seams or veinlets of opaque oxide. Olivine originally occurred as single isolated microphenocrysts was well as clusters of several anhedral crystals. Plagioclase phenocrysts are anhedral to subhedral in shape and exhibit minor alteration to chlorite (± albite). These phenocrysts are variably aligned parallel to a pilotaxitic fabric present within the groundmass. Larger plagioclase phenocrysts may possess a dusty-looking sieve-textured core.

The groundmass to these basalts is mainly composed of variably aligned plagioclase laths which define a well-developed pilotaxitic fabric which wraps around the phenocrysts. Plagioclase is fractured and may exhibit minor alteration to chlorite. Interstitial pyroxene and glass have been completely replaced by a pale green chloritic assemblage (± carbonate, opaque oxide). Minor to trace amounts of interstitial to intersertal feldspar and mesostasis are present in some rocks. The mesostasis locally forms a rim upon plagioclase and contains very fine-grained, dusty looking inclusions of opaque minerals. Needle-like and anhedral granular opaque crystals are common within the groundmass of some rocks. Irregular vugs and amygdales, where present (N2543), are texturally zoned and composed of cryptocrystalline to radial fibrous chlorite with an outer rim of cryptocrystalline quartz. In sample N2544 the patchy replacement of the groundmass by carbonate locally overprints the primary igneous texture of the rock.

3.1.5 Plagioclase-pyroxene-phyric basalts and basaltic andesites

The plagioclase-pyroxene-phyric basalts and basaltic andesites are fine- to very fine-grained, massive to pilotaxitic, hypocrystalline, microporphyritic to macroporphyritic, feldspathic rocks which comprise an inequigranular assemblage of plagioclase, clinopyroxene, and opaque minerals as well as minor to trace orthopyroxene and/or olivine (N2540, N2542, N2545, N2563, N2587). Alteration and hydration of these basaltic to andesitic rocks resulted in the replacement of interstitial phases and primary ferromagnesian minerals (pyroxene) by a very fine-grained assemblage of chlorite, carbonate, Fe-oxide, iddingsite, bowlingite and, in some cases, quartz.

Phenocrysts are mainly composed of plagioclase with subordinate pyroxene. In the more highly altered lithologies pyroxene is completely pseudomorphed by chlorite, iddingsite, bowlingite and opaque oxide. Pyroxene originally formed anhedral to subhedral, locally embayed to skeletal crystals. Rare pseudomorphs after originally anhedral to rounded olivine were observed in some of the more basaltic lithologies (N2545). Small Fe-oxide and iddingsite pseudomorphs after possible orthopyroxene have also been observed.

Plagioclase forms anhedral to subhedral, twinned, simply to oscillatory zoned, prismatic to lath-shaped phenocrysts (up to 4.5 mm in length) which may exhibit minor replacement by chlorite and/or carbonate. The larger plagioclase phenocrysts may possess a dusty-looking, sieve-textured core which contains very fine-grained inclusions of opaque minerals and irregular to worm-like chloritised glass. Plagioclase occurs as single isolated phenocrysts and as clusters of several (3 to 4) crystals. In sample N2540 the plagioclase phenocrysts show a range in grain size and grade into the groundmass, defining a weakly developed seriate texture. Minor rounding of plagioclase phenocrysts due to partial resorption was noted in some rocks (N2545). Plagioclase phenocrysts may also exhibit a preferred shape alignment parallel to a variably developed pilotaxitic fabric present within the groundmass to these basalts and basaltic andesites. In the most highly altered lithologies (N2542) primary plagioclase is variably recrystallised to albite.

The groundmass is fine-grained and massive in appearance. It is mainly composed of randomly orientated to aligned, elongate to needle-like plagioclase laths with pseudomorphs (chlorite + opaque oxide) after interstitial, granular pyroxene. The alignment of plagioclase defines a locally well-developed pilotaxitic fabric which was observed wrapping around the phenocrysts and, where present, amygdales. Minor to trace amounts of a dusty mesostasis may be present filling the remaining interstitial and intersertal areas. This mesostasis contains numerous very fine-grained inclusions of opaque minerals/oxide and was observed forming rims upon plagioclase crystals. The groundmass to the basalts and basaltic andesites may also contain trace interstitial quartz. Rounded amygdales are composed of cryptocrystalline chloritic material.

3.1.6 Olivine-pyroxene-phyric basalts

In thin section (N2564, N2565, N2567, N2569) the highly altered, olivine-pyroxene-microporphyritic basalts are fine- to medium-grained, massive, inequigranular, originally glassy, hypocrystalline, basaltic rocks in which the phenocrysts are only slightly coarser grained than the groundmass. Anhedral to subhedral microphenocrysts of olivine and pyroxene have been completely replaced by cryptocrystalline chlorite, bowlingite, iddingsite and carbonate with trace amounts of quartz. The mimetic growth of these alteration products locally preserves the original pyroxene cleavage. The microphenocrysts occur as single crystals as well as small glomerophyric clusters of several crystals. Pseudomorphs after olivine are composed of an outer rim of hematitic oxide which forms an outer rim enclosing a core of chloritic material and/or carbonate. Fe-oxides also preserve original fractures within olivine.

The groundmass of these highly altered basalts is composed of randomly orientated, anhedral to subhedral plagioclase laths with subordinate anhedral to subhedral granular pyroxene (± olivine). Plagioclase forms anhedral, twinned crystals with the larger crystals and occasional microphenocrysts showing a weakly developed zonation. Plagioclase may exhibit minor alteration to chlorite and carbonate. Interstitial to intersertal areas are mainly composed of cryptocrystalline, yellow-green chloritic material which is itself partially replaced by carbonate. Minor to trace amounts of a dusty brown to locally feldspathic mesostasis is patchily developed or preserved within these highly altered basalts. This mesostasis fills the interstitial to intersertal spaces between plagioclase and pyroxene crystals and contains finely disseminated as well as needle-like crystals of opaque oxide. The remaining intergranular areas are composed of cryptocrystalline chloritic material which is interpreted as replacing glass and interstitial ferromagnesian minerals (pyroxene). Chlorite may be partially replaced by small patches of carbonate. Trace amounts of quartz were also noted within these basaltic rocks. In sample N2565, quartz is a relatively common accessory phase and typically occurs interstitial to intersertal to plagioclase and may, therefore, be primary in origin.

Amygdales, where developed within the basalts, are composed of cryptocrystalline, locally radial, fibrous chloritic assemblage which is variably replaced by later carbonate. The mimetic growth of carbonate locally preserves the originally zoned nature of the amygdales.

Sample N2569 is mainly composed of a highly altered, medium-grained, amygdaloidal, weakly microporphyritic to aphyric basalt. This basaltic rock is fractured with the fissures filled by mudstone. The mudstone is itself fractured with these fractures being infilled by fluidised siltstone.

3.1.7 Coarse-grained basalts or microgabbros

A small number of samples of coarse-grained basalt or fine-grained microgabbro (dolerite) from the Carrick Volcanic Formation were also examined. In thin section (N2570, N2573) they are coarse-grained, aphyric, inequigranular, hypocrystalline, massive, weakly altered rocks which are mainly composed of randomly orientated plagioclase laths with intergranular subophitic clinopyroxene.

Plagioclase is fresh forming small (≤ 0.8 mm in length), twinned and zoned, anhedral to subhedral, prismatic to lath shaped crystals. In sample N2573 plagioclase locally exhibits a weak preferred shape alignment defining a poorly developed pilotaxitic fabric. Clinopyroxene is very pale brown in colour and forms irregular to anhedral, intergranular, ophitic to subophitic crystals which range up to 1.0 mm in size.

A turbid brown mesostasis occurs interstitial to both plagioclase and clinopyroxene, and contains needle-like to granular crystals of opaque minerals. Interstitial glass/mesostasis is altered to a cryptocrystalline chloritic assemblage. Similar chloritic material also occurs as thin veinlets and infilling rare vugs or amygdales.

Pseudomorphs after granular anhedral to euhedral olivine and/or orthopyroxene are composed of very finely cryptocrystalline, locally mesh-textured chlorite, bowlingite, opaque oxide and iddingsite. This mainly chloritic assemblage is locally being replaced by later carbonate (trace). Locally these apparently early formed olivine and/or orthopyroxene crystals are overgrown or rimmed by later clinopyroxene. Clinopyroxene is essentially unaffected by this phase alteration.

3.1.8 Intercalated sedimentary rocks

One thin section (N2568) of a laminated siltstone which is intercalated with lavas of the Carrick Volcanic Formation was also examined during this present study. In detail, the finely laminated siltstone contains thin mudstone partings which occur at the top of individual graded laminae. This grading is reflected in a change in grain size from silt to clay and a corresponding change in colour. Individual laminae range from 0.3 to 5.0 mm in thickness. An apparent systematic variation in the thickness of the laminae was also recognised, resulting in discrete packets of slightly more coarse-grained and thicker laminated sediment that exhibit a more pronounced grading and distinct medium- to coarse-siltstone bases to the laminae.

Recognisable detrital grains are composed of variably altered (hematised) biotite, muscovite and opaque minerals. The micas are variably aligned parallel to bedding. The mudstone partings possess a moderately developed bedding-parallel fabric defined by the alignment of clay plasma (cf. plasmic fabrics developed in unconsolidated glacial materials). Minor haematitic staining of the clay-grade component was noted within this siltstone.

3.2 SWANSHAW SANDSTONE FORMATION

3.2.1 Microconglomerates

The microconglomerates are a poorly sorted, lithic-rich, open to moderately packed, clast- to matrix-supported, immature rudaceous rocks which comprise very coarse sand, granule and small pebble-sized clasts within a finer grained sandstone matrix (N2549, N2555, N2566, N2574).

The coarse sand to pebble-sized clasts are up to 20 to 30 mm in size and are subangular, subrounded to rounded in shape with a low sphericity. However, subangular clasts were also recognised in some rocks. Sample N2555 is slightly more coarse-grained with a few of the larger granule to pebble-sized clasts ranging up to c. 1.5 cm in diameter. These large detrital grains are mainly composed of rock fragments. Recognisable lithologies include: tuffaceous and volcanic rocks; very fine-grained sandstone to coarse-grained siltstone; mudstone; siltstone; foliated metasiltstone with aligned white mica flakes; hematised, plagioclase microporphyritic basaltic rock; very fine-grained, recrystallised sandstone/metasandstone; cherty rock locally containing thin quartz veinlets; chalcedonic quartz; quartz microporphyritic rhyolite (porphyry); and fine-grained quartzose litharenite.

In sample N2566, the larger detrital grains are mainly composed of a very fine-grained, massive to finely banded cherty or tuffaceous rock. In contrast to this volcanic lithic-rich microconglomerate, the lithic clasts in samples N2549, N2555 and N2574 are dominated by sedimentary and low-grade metasedimentary rock fragments; including mudstone, siltstone, fine- to medium-grained sandstone (quartzose litharenite), very fine-grained metasandstone (psammite), quartzite, and fine-grained ‘greywacke’ sandstone. All of these rock fragments possess a hematitic-stained clay matrix or hematitic cement and appear to have been derived from the same source area. The very fine-grained sedimentary and other unstable lithic clasts may be embayed, indented or moulded around neighbouring more rigid grains.

The sandstone matrix to the microconglomerates is composed of a fine- to medium-grained, poorly sorted, moderately to very closely packed, clast-supported, immature, quartzose litharenite. Detrital grains within the sandstone matrix are angular, subangular to occasionally subrounded in shape with a low sphericity. They are mainly composed of monocrystalline quartz and variably altered/degraded rock fragments. The latter are composed of a similar range of lithologies to the larger sand- to small pebble-sized clasts. Other recognisable rock types present within the sandstone matrix include: very fine-grained siltstone; very fine-grained volcanic or tuffaceous rock; hematised basalt; very fine-grained phyllitic to slaty metasedimentary rocks; feldspathic microcrystalline igneous rock (felsite); and a fine-grained sandstone/metasandstone with a chloritic matrix.

Minor to accessory detrital components include polycrystalline quartz, K-feldspar, muscovite/white mica, tourmaline, micrographic intergrowth and opaque minerals. Minor to trace amounts of a very pale green chloritic and/or hematitic rim cements are present within the sandstone matrix. Compaction resulted in the localised plastic deformation and embayment of unstable lithic grains. The very close packing of the clasts within the matrix of some of the microconglomerates has locally resulted in the modification of the shape of more unstable grains and pressure solution of quartz. Sample N2574 also contains a discrete, 2.0 to 3.0 mm-thick layer of fine-grained sandstone which is texturally and compositionally similar to the matrix of the microconglomerate. This microconglomerate also exhibits patchily developed preferential replacement of the sandstone matrix and some lithic clasts by secondary carbonate.

3.2.2 Quartzose lithic-rich sandstones

In thin section these quartzose sandstones are, in general, fine- to coarse-grained, immature, poorly to moderately sorted, closely to very closely packed, heterolithic, clast-supported litharenites (N2552, N2553, N2571, N2572, N2575). Sedimentary structures present within these sandstones include grading, bedding and/or parallel lamination; the latter is locally defined by the intercalation of coarse siltstone and fine-grained sandstone laminae (N2571). An increase in the matrix content within some of the sandstones (N2572) results in a variation in the overall texture of the rock from closely to moderately packed and clast supported to a more open packing with a matrix-supported texture.

Detrital grains are angular, subangular to occasionally subrounded in shape with a low to rare moderate sphericity. Occasional well-rounded grains were noted in some rocks. In samples N2553 and N2575, however, the very close packing of these sandstones and relatively higher degree of compaction has resulted in the modification of the shape of detrital grains. The very close packing and alteration of some of these quartzose sandstone also makes the identification of individual grain boundaries difficult (N2552).

The clast assemblage is mainly composed of variably degraded lithic fragments and monocrystalline quartz. Lithic clasts are typically composed of a very fine-grained to cryptocrystalline, intermediate to felsic tuffaceous and volcanic rock fragments. However, in many of the sandstones the actual composition of the protolith is uncertain due to the intensity of alteration. Recognisable rock fragments are composed of: rhyolite/felsite; mudstone; hematised metabasaltic rock; chert; quartzite; cleaved mudstone; very fine-grained biotite-schist; white mica-rich phyllitic or very fine-grained schistose rock; trachytic rock; chloritic sandstone and siltstone (‘greywacke’); very fine-grained phyllitic or slaty metasedimentary rock; hematised mudstone and siltstone; and very fine-grained micrograntic or rhyolitic rock. Occasional subrounded to rounded, very coarse sand- to small pebble-sized clasts are present within some of the coarser grained sandstones. Other minor to accessory detrital components present within these sandstones include polycrystalline quartz, plagioclase, sericitised rock or feldspar, opaque minerals, tourmaline, titanite/rutile, white mica, garnet, biotite, K-feldspar, chloritic pseudomorphs after a ferromagnesian minerals and possible staurolite.

Localised quartz overgrowths were noted developed upon monocrystalline quartz grains. Compaction resulted in grain boundary etching and pressure solution of quartz, flattening of mudstone/siltstone lithic clasts, as well as minor kinking of detrital micas. Detrital micas within the siltstone layer may be stained by, or altered to hematitic oxide. Trace to minor amounts of a hematitic/clay rim, pore-filling chloritic and quartzose cements are present in some rocks. However, sample N2572 is characterised by a well-developed red-brown hematitic matrix or cement. It is possible that this matrix component may have been partially derived from degraded unstable lithic clasts. Very thin hematitic coatings were also been recognised on detrital grains within this sandstone. A weak shape alignment of detrital grains and traces of a replacive carbonate were noted in sample N2575A. Sample N2553 is distinguished by the presence of a moderately to well-developed, honey brown-stained (hematitic) carbonate cement. Carbonate appears to have replaced the original clay- to silt-grade components within the sandstone as well as unstable lithic clasts. The carbonate initially formed a fine rim or coating on quartzose grains, then appears to have progressively filled and/or replaced the intergranular porosity and matrix.

3.2.3 Lithic-rich sandstones

The lithic-rich sandstones are distinguished from the previously described quartzose litharenites by their lower detrital quartz content. In thin section these lithic-rich sandstones are fine- to coarse-grained, poorly to moderately sorted, massive, matrix-poor, heterolithic litharenites which possess a closely to very closely packed clast-supported texture (N2548, N2551, N2554, N2556, N2557, N2558). A sedimentary lamination present in sample N2554 is denoted by a marked change in grain size resulting alternating fine- and medium-grained sandstone laminae.

Detrital grains are angular, subangular to occasionally subrounded in shape with a low to occasionally moderate sphericity. Occasional subrounded grains are also present with elongate clasts showing a weakly developed preferred shape alignment. Subrounded, low sphericity granule to small pebble-sized clasts may also be present in the coarser grained sandstones. Sample N2551 possess a weak bimodal sorting with a distinct break between medium-sand grade and very coarse sand to granule-sized clasts which give the rock its ‘pebbly’ appearance. The very close packing and alteration (chloritisation) of the more unstable lithic components within some of the sandstones (N2554, N2558) locally makes identification of individual clast boundaries difficult.

The clast assemblage is mainly composed of altered lithic clasts and monocrystalline quartz with subordinate plagioclase. The lithic clasts are typically composed of variably altered or degraded, sedimentary and tuffaceous volcanic rock fragments. Recognisable lithologies including: very fine-grained to cryptocrystalline tuffaceous rock; siltstone or very low-grade metasiltstone; cherty mudstone; hematised fine-grained basalt or metabasaltic rock; very fine-grained quartzite or psammite; very fine-grained hyalopilitic/pilotaxitic andesitic rock; coarse-grained siltstone to very fine-grained sandstone; very fine-grained phyllitic rock; and felsite. In sample N2548 the bulk of the clast assemblage is composed of variably altered (chloritised or hematised), very fine-grained, basaltic to andesitic rock fragments. Although altered these rocks may contain feldspar microphenocrysts and pseudomorphs after hornblende.

Minor to accessory detrital components present within these lithic-rich sandstones include polycrystalline quartz, variably hematised or chloritised biotite, chlorite, muscovite/white mica, felsite, garnet, opaque minerals, carbonate rock, tourmaline, K-feldspar (including microcline), plagioclase, deformed vein quartz or quartz mylonitic rock and chlorite pseudomorphs after ferromagnesian mineral. Sample N2556 also contains irregular, elongate/flattened, colourless Mg-chloritic aggregates or pseudomorphs after rock fragments (?serpentinite). This cryptocrystalline material also contains radiating, very fine-grained, fibrous to spherulitic aggregates of chlorite or clay minerals.

Compaction resulted in localised etching of grain boundaries, pressure solution between adjacent quartz grains, the kinking of detrital micas and localised embayment of lithic grains against neighbouring more rigid clasts. Minor to trace amounts of a clay-grade matrix, chlorite cement, quartz overgrowths and/or a haematitic rim cement are locally developed within some sandstones. The clay-grade matrix forms a minor component within the sandstones and appears to have, at least in part, been derived from degraded lithic clasts. This matrix and/or the chloritic cement may be partially replaced by irregular patches (trace) of haematitic oxide and/or secondary carbonate. In samples N2554 and N2556 this replacive carbonate cement is locally well developed resulting in the modification of the original texture of the sandstone and the development of a moderate to open packed, cement-supported texture. Locally, carbonate replacement may result in the overprinting of the primary clastic texture of these sandstones.

3.3 BALLAGAN FORMATION

3.3.1 Microconglomerates

One sample of a microconglomerate from the Ballagan Formation has been examined. In thin section (N2578) it is a poorly sorted, moderately to open-packed, matrix-supported, calcareous rocks with a medium-grained, slightly feldspathic quartz-arenite matrix. It is characterised by the presence of subrounded, rounded to irregular clasts of limestone and/or carbonate replaced mudstone, sandstone and occasionally siltstone. These carbonate-rich clasts have a moderate to low sphericity. The shape of the clasts has been variably modified during compaction and diagenesis which resulted in pressure solution, localised stylolite development along the inter-clast boundaries and embayment against neighbouring, more rigid, quartzose grains. A number of these calcareous clasts are fractured (compaction related) and partially recrystallised to a fine-grained sparry carbonate mosaic. The calcareous siltstone and sandstone clasts contain very fine-grained relict detrital clasts of quartz, tourmaline, opaque oxide and oxidised biotite.

The matrix to this microconglomerate is composed of a slightly feldspathic quartz-arenite which possesses a well-developed sparry carbonate cement. The sandstone exhibits a moderately packed, clast to locally cement-supported texture. Detrital grains within this sandstone matrix are subangular to subrounded with a low sphericity. However, grain shape has locally been modified during the development of the replacive carbonate cement. The clast assemblage is dominated by monocrystalline quartz with minor feldspar and carbonate-replaced mudstone lithic fragments. Other minor to accessory detrital components include felsite/chert, microcline, polycrystalline quartz, garnet, plagioclase, epidote and opaque minerals.

3.3.2 Calcareous quartz-rich sandstones

The calcareous quartz-rich sandstones are, in general, fine- to medium- to coarse-grained, moderately to well-sorted, mature, quartz-arenites which possess a moderately to open-packed, clast-supported texture (N2580A, N2580, N2581). A sedimentary lamination present in some of the sandstones (N2580) is defined by a variation in grain size and the modal proportions of a carbonate cement. Thin muddy partings may also be present.

The clast assemblage is dominated by monocrystalline quartz. Quartz is unstrained to weakly strained. The shape of the quartz grains has been modified due to localised pressure solution and grain boundary etching associated with the development of a carbonate cement. However, locally the originally subangular to subrounded shape and a moderate to low sphericity of these quartzose clasts are preserved (N2581). In some sandstones (N2580A) pressure solution between quartzose grains was apparently accompanied by the localised development of quartz overgrowths.

Samples N2580 and N2581 also contain very coarse sand-, granule- to occasional small pebble-sized clasts (> 6.0 mm in length) of carbonate-replaced mudstone or recrystallised micritic limestone. In sample N2581 these calcareous mudstone clasts occur within a layer of closely to moderately packed, clast-supported breccia. The shape of mudstone clasts has been modified due to pressure solution and embayment against neighbouring more rigid quartzose grains. Localised stylolite development was noted associated with pressure solution between adjacent calcareous clasts. The calcareous mudstone clasts appear to have originally been rounded to subrounded in shape with a low to occasionally moderate sphericity. Other minor to accessory detrital components include polycrystalline quartz, plagioclase, K-feldspar (including microcline), tourmaline, opaque minerals, garnet, chlorite, cryptocrystalline quartz or chert, rutile and monazite.

These sandstones are characterised by the presence of a well-developed carbonate cement which appears to be replacing the original matrix and/or earlier cement(s). This cement may locally contain anhedral to weakly subhedral rhomb-shaped crystals which may be used to suggest that the cement is or was dolomitic. Traces of a haematitic rim cement, pre-dating the main carbonate cement, was also noted in some rocks.

3.3.3 Calcareous mudstones

One thin section (N2584) of a laminated, calcareous mudstone was examined from the Ballagan Formation. The clay/fine silt-grade fraction within this originally argillaceous rock has been completely replaced by massive very fine-grained, micritic carbonate. Sedimentary structures preserved within this sample include grading, minor soft-sediment deformation and a weak convolute lamination.

Silty layers and bases to normally graded laminae contain fine-grained clasts of monocrystalline quartz. Other minor to accessory detrital components include white mica, carbonate-replaced mudstone rip-up clasts, tourmaline, opaque minerals and plagioclase. Small irregular to dusty looking opaque material may represent carbonaceous plant remains. Small scale erosional surfaces are preserved at the base of these coarse siltstone laminae.

One complete ostracod/bivalve shell has been recognised. This very fine bioclast is filled by clay-grade material. Fractures and an irregular vug/void within the rock are filled by clear, sparry carbonate.

3.4 PALAEOGENE MINOR INTRUSIVE ROCKS

One thin section (N2579) of a olivine-phyric basalt which forms a dyke in Ballagan Formation has also been examined during this study. The original mineralogy of this rock has largely been replaced by a very fine-grained to cryptocrystalline chlorite-dominated assemblage. Alteration has resulted in the variable overprinting of the original igneous texture of the rock. However, microporphyritic and weakly amygdaloidal textures are preserved within this basaltic rock. Originally anhedral to subhedral olivine microphenocrysts and small, rounded intergranular crystals are pseudomorphed by carbonate (± opaque oxide). Plagioclase forms small randomly orientated, twinned and zoned, lath-shaped crystals which exhibit minor replacement by chlorite and carbonate. Interstitial glass and granular-looking pyroxene are replaced by cryptocrystalline chlorite, bowlingite, opaque oxide and carbonate. Trace amounts of interstitial to intersertal quartz and small chloritised flakes of biotite were also noted within this rock.

3.5 GREENAN CASTLE PYROCLASTIC MEMBER

One thin section (N2583) of a weakly laminated, coarse-grained volcaniclastic sandstone was examined from the Greenan Castle Pyroclastic Member. This poorly sorted, moderately to open packed, immature litharenite possesses a very close to open packed texture reflecting a variation in the grain size of this sandstone; the greater density of packing occurring in the finer grained laminae.

Detrital grains are angular, subangular to slightly irregular in shape with a low sphericity. A weakly developed preferred shape-alignment of elongate clasts was also recognised. The detrital assemblage is mainly composed of chloritised basaltic rock fragments. These volcanic lithic clasts range from medium sand- to granule in size and are enclosed within or coated by a thin oxide rim. Other minor to accessory detrital components include plagioclase, monocrystalline quartz, hematised rock fragments and chlorite-carbonate-quartz vein material or highly altered rock.

Traces of chloritic and pore-filling sparry carbonate cements were noted within this sandstone. Compaction resulted in localised pressure solution and embayment of unstable lithic clasts.

3.6 KINNESSWOOD FORMATION

3.6.1 Limestones and calcareous rocks

A small number of thin sections (N2585, N2591) of fractured limestone or fine-grained calcareous rock have been examined from the Kinnesswood Formation. These brecciated, very fine-grained calcareous rocks form irregular, angular to subangular fragments and are mainly composed of dusty looking, cryptocrystalline or micritic carbonate as well as slightly more coarse-grained sparry carbonate. These calcareous rocks may contain angular, subangular to occasionally subrounded monocrystalline quartz grains (fine- to medium-sand grade). The quartz grains may represent relict detrital clasts and/or diagenetic quartz crystals. Rounded to subrounded clasts of micritic carbonate were also recognised within these calcareous rocks.

In sample N2585 the fractured calcareous rock is cemented by fine- to medium-grained sparry carbonate. This sparry carbonate is texturally zoned and forms fine-grained, granular-looking rims upon the calcareous rock fragments, with the remainder of the fractures/vugs being composed of coarser grained, anhedral granular carbonate. In contrast, within sample N2591 the fractures are filled by texturally zoned, cryptocrystalline to very fine-grained (c. 0.2-0.3 mm in size) quartz.

3.6.2 Microconglomerates

One sample of calcareous microconglomerate was examined from the Kinnesswood Formation. In thin section (N2586) it is a very poorly sorted, open packed, very coarse-grained, calcareous pebbly sandstone or microconglomerate which contains granule- to pebble-sized clasts of a very fine-grained to micritic carbonate rock. These clasts are subrounded to slightly irregular in shape with a low to moderate sphericity. However, the shape of these clasts have been modified due to pressure solution during compaction, which also resulted in the embayment of these unstable lithic fragments against neighbouring more rigid quartzose grains. The carbonate rock fragments occur in distinct layers and may be shape-aligned parallel to a weak sedimentary lamination. Other granule to pebble-sized clasts are composed of a very fine-grained possibly tuffaceous rock, strained polycrystalline quartz and hematised cherty rock.

The sandstone matrix to this microconglomerate consists of low to moderate sphericity monocrystalline quartz clasts set in a well developed carbonate cement. The shape of the quartz grains have been modified during the development of the carbonate cement. This led to the etching of the clast grain boundaries. However, the detrital grains appear to have originally been subrounded to rounded in shape. The sandstone has an open-packed and cement-supported texture. This cement appears to have replaced the original matrix component to the sandstone and/or unstable detrital grains.

Other minor to accessory detrital components include polycrystalline quartz, plagioclase, sheared vein quartz or quartz mylonite, K-feldspar, muscovite/white mica and tourmaline. Clasts of deformed vein quartz or quartz mylonite are a common minor detrital component.

3.6.3 Feldspathic quartz-rich sandstones

One thin section (N2589) of a coarse-grained, poorly sorted, open-packed, cement-supported, slightly feldspathic quartz-rich sandstone was examined from the Kinnesswood Formation. This feldspathic quartz-arenite possesses a well developed medium- to coarse-grained sparry carbonate cement. Detrital grains (up to 1.7 mm in size) are angular, subangular to subrounded in shape with a low sphericity. However, the shape of the clasts have been modified due to grain boundary etching during the development of the carbonate cement. The detrital assemblage is mainly composed of monocrystalline quartz with minor K-feldspar (including microcline). Other minor to accessory detrital components include polycrystalline quartz, plagioclase, opaque minerals, garnet, biotite, felsite, tuffaceous volcanic rock, mesoperthite and muscovite.

Compaction resulted in minor fracturing of quartz clasts and localised pressure solution between adjacent quartz and quartz-feldspar grains.

3.6.4 Calcareous sandstones

One thin section (N2590) of a fine- to medium-grained, calcareous sandstone was examined from the Kinnesswood Formation. This poorly sorted, moderately to open packed, clast- to cement-supported, fine- to medium-grained, immature sandstone possesses a well developed carbonate cement. The cement apparently replaced the original matrix and unstable detrital components within this sandstone. Carbonate forms anhedral crystals (± 0.8 mm in size) which include or overgrow detrital grains. Lithic clasts appear to have formed a common minor component within this sandstone. The outlines of these highly altered/replaced rock fragments can still be recognised.

Relict detrital grains are subangular to subrounded in shape with a low to occasionally moderate sphericity. The detrital assemblage was originally composed of monocrystalline quartz with subordinate rock fragments and minor feldspar clasts. The composition of the rock fragments is uncertain due to alteration, however they may have include a very fine-grained tuffaceous rock. Other minor to accessory detrital components include plagioclase, muscovite, K-feldspar, microcline, chloritised biotite, opaque minerals, polycrystalline quartz, chloritised rock or chlorite pseudomorphs after a ferromagnesian minerals.

Compaction resulted in localised pressure solution between adjacent quartz grains. Traces of a chloritic matrix are also present and may have been partially derived from degraded/altered rock fragments. A sedimentary lamination present within this sandstone is preserved by a change in grain size from fine- to medium-grained sand.

3.7 PASSAGE FORMATION

3.7.1 Quartz-rich sandstone

One sample of a fine-grained, quartz-rich sandstone was examined from the Passage Formation. In thin section (N2588) it is a closely packed, relatively mature, massive quartz-arenite sandstone which contains small pockets or patches of a replacive carbonate cement.

Detrital grains are subangular to subrounded in shape with a low sphericity. The shape of the clasts is locally modified by the pressure solution of quartz and localised development of early quartz overgrowths. The clast assemblage is dominated by monocrystalline quartz. Other minor to accessory detrital components include polycrystalline quartz, degraded/altered rock fragments (protolith uncertain), K-feldspar, plagioclase, opaque minerals, white mica, epidote, variably chloritised biotite, chlorite and apatite.

Compaction resulted in the minor kinking of detrital micas. Pressure solution appears to result in the main form of cementation within this sandstone. However, minor amounts of a pore filling, intergranular, cryptocrystalline to very fine-grained radial fibrous feldspathic or clay matrix or cement is also present. This matrix component is variably replaced by red-brown, hematite-stained carbonate. Carbonate includes rhomb-shaped crystals which may be either dolomite or pseudomorphs after dolomite (calcified dolomite).

4 Geochemistry of the Carrick Volcanic Formation

The Silurian to Lower Devonian ('Lower Old Red Sandstone') volcanic succession of the Midland Valley of Scotland is dominated by a sequence of typically calc-alkaline basaltic to andesitic lava flows (Thirlwall, 1981, 1982, 1983; Phillips, 1994; Phillips and Smith, 1995) with subordinate intercalated pyroclastic rocks and thicker volcanic/epiclastic sandstones and conglomerates. In general the Siluro-Devonian lavas exhibit geochemical characteristics comparable to calc-alkaline volcanic rocks erupted in an active continental margin setting. The parental magmas were apparently derived from the partial melting of subduction modified mantle containing a strong 'within-plate' continental component. Thirlwall (1981, 1983) identified the Siluro-Devonian lavas in most of northern Britain as calc-alkaline, and suggested that they were related to a former west-northwest/northwest-dipping subduction zone. Alternatively, Smith (1995) and Phillips *et al*. (1998) have suggested that these volcanic rocks may be derived from partial melting of a subduction-contaminated mantle source in an overall sinistral strike-slip regime; i.e. potentially unrelated to active plate subduction. Radiometric ages for the volcanic rocks and associated intrusions range from 411 to 407 ± 6 Ma (Thirlwall, 1983, 1988).

This section briefly describes the initial results of a whole-rock geochemical study of the Carrick Volcanic Formation. Whole-rock geochemical data obtained for the Ayr district are listed in Table 2.

Sample	SiO_2	Al_2O_3	Fe_2O_3T	MgO	CaO	K2O	Na2O	MnO	TiO2	P2O5	LOI	Total
N2160	56.36	16.78	7.52	5.10	2.15	2.77	4.40	0.05	1.29	0.29	3.00	99.87
N2159	55.92	16.95	8.30	2.55	2.26	4.67	3.96	0.10	1.29	0.29	2.82	99.26
N2162	54.85	16.73	7.75	5.67	7.28	1.04	3.75	0.21	1.24	0.26	1.20	100.16
N2156	58.14	16.13	6.84	4.62	5.66	1.03	3.66	0.10	1.17	0.24	1.78	99.53
N2161	55.12	16.71	7.28	4.82	7.25	1.54	3.64	0.11	1.23	0.27	1.15	99.31
N2158	52.83	16.44	8.68	6.47	7.59	1.04	3.55	0.13	1.19	0.25	1.29	99.62
N2157	53.21	15.96	15.39	1.37	4.10	2.27	4.22	0.08	1.76	0.33	0.97	99.80
N2151	54.47	17.67	7.36	3.66	6.64	2.43	3.84	0.21	1.20	0.29	1.12	99.10
N2164	55.39	16.99	9.01	3.30	4.74	2.26	4.29	0.16	1.89	0.36	1.32	99.86
N2152	51.99	17.37	9.88	5.68	1.66	2.97	4.64	0.06	1.94	0.37	3.11	99.85
N2150	54.46	17.32	6.49	5.26	7.11	1.50	4.29	0.10	1.29	0.28	1.07	99.35
N2149	54.20	17.12	8.07	5.48	3.25	1.66	5.40	0.11	1.28	0.28	2.81	99.82
N2153	59.50	16.38	6.63	2.59	5.49	1.14	4.07	0.11	1.38	0.29	1.93	99.67
N2154	61.01	15.92	6.03	2.93	3.08	2.56	4.19	0.04	1.36	0.29	1.75	99.29
N2155	45.63	17.38	10.24	6.42	6.74	1.15	3.87	0.10	1.18	0.20	6.21	99.36
Sample	**Zn**	**Cu**	**Rb**	**Sr**	**Ba**	**Nb**	**Zr**	**Y**	**Ni**	**Cr**	**La**	**V**
N2160	216	12	61	205	317	10	244	27	65	142	22	142
N2159	102	26	97	151	458	11	249	26	64	129	23	138
N2162	73	39	16	513	508	9	206	26	87	169	20	133
N2156	59	22	10	436	440	8	189	27	92	177	23	123
N2161	70	28	25	522	452	11	202	27	82	154	19	134
N2158	60	37	13	450	388	10	196	24	71	153	20	126
N2157	94	28	61	340	415	12	305	36	10	36	26	181
N2151	59	21	56	782	635	10	277	28	32	39	25	143
N2164	81	31	65	350	419	13	324	38	14	33	28	183
N2152	502	44	69	138	353	13	337	40	15	40	29	208
N2150	71	35	37	481	391	11	208	25	78	165	21	141
N2149	146	23	35	296	397	11	211	25	73	184	31	158
N2153	108	12	40	464	450	14	235	32	3	20	35	153
N2154	130	8	56	255	459	14	230	28	3	20	30	146
N2155	1212	99	11	271	311	10	148	27	45	150	21	178
Sample	**Ce**	**Th**	**Co**	**Sc**	**Pb**	**Nd**	**Sm**	**Hf**				
N2160	50	7	20	20	10	25	3	6				
N2159	45	8	17	17	13	23	5	5				
N2162	38	7	20	20	14	21	4	5				
N2156	42	5	22	22	24	24	4	4				
N2161	43	7	20	20	12	21	3	5				
N2158	37	7	21	21	11	22	5	5				
N2157	59	7	20	20	26	33	5	7				

N2151	58	10	18	18	25	32	4	7				
N2164	58	9	23	23	17	33	7	8				
N2152	61	9	25	25	13	34	6	9				
N2150	40	7	21	21	10	23	3	5				
N2149	54	6	24	24	21	25	4	5				
N2153	63	7	19	19	17	32	5	5				
N2154	56	7	18	18	20	29	5	6				
N2155	37	5	28	28	10	21	6	5				

Table 2. Whole-rock geochemical data obtained for the Carrick Volcanic Formation of the Ayr district.

4.1 CLASSIFICATION OF THE CARRICK VOLCANIC FORMATION LAVAS

Whole-rock geochemical data obtained for the Carrick Volcanic Formation of the Ayr district have been plotted upon a number of classification diagrams (Figure 2). Data obtained by Phillips (1994) and Phillips and Smith (1995) for the Siluro-Devonian lavas of the Lanark and New Cumnock districts, as well as data published by Thirlwall (1981, 1982, 1983) have also been plotted on these diagrams.

The majority of the lavas are basaltic andesites in composition with SiO_2 contents of between 52 and 57 weight % oxide (Figure. 2c). A small number of the lavas have SiO_2 contents typical of basalts (SiO_2 < 52 wt%, 2 analyses) and andesite (SiO_2 > 57 wt %, 3 analyses). Alteration of the Carrick Volcanic Formation has resulted in the observed range of the Na_2O and, to a lesser extent, K_2O contents of these lavas (see Table 2). The Carrick Volcanic Formation lavas apparently range from basalt and basaltic andesite, through to basaltic trachyandesite and trachyandesite. However, the Nb/Y ratio (see Figure 2a) of the volcanic rocks (Nb/Y ± 0.6) clearly indicates that they are not alkaline, but are in fact calc-alkaline in character.

Due to the potential problems associated with the remobilisation of K_2O and Na_2O during alteration the data were also plotted on the classification diagrams of Winchester and Floyd (1975). These diagrams utilise trace elements (TiO_2, Zr, Nb, Y) which are considered to be essentially immobile during low-grade metamorphism and alteration. On the plot of Zr/TiO_2 ppm versus Nb/Y the bulk of the data plot within the basalt field with a small number of analyses plotting just within the basaltic andesite field (Figure 2a). A greater compositional variation is observed on Figure 2b where the Carrick Volcanic Formation lavas range from basalt to andesite in composition. It is clear from Figure 2 that the Carrick Volcanic Formation has the same compositional range as other Siluro-Devonian volcanic rocks from the New Cumnock, Ochil Hills, Montrose, Pentland Hills, Stonehaven and Sidlaw Hills areas.

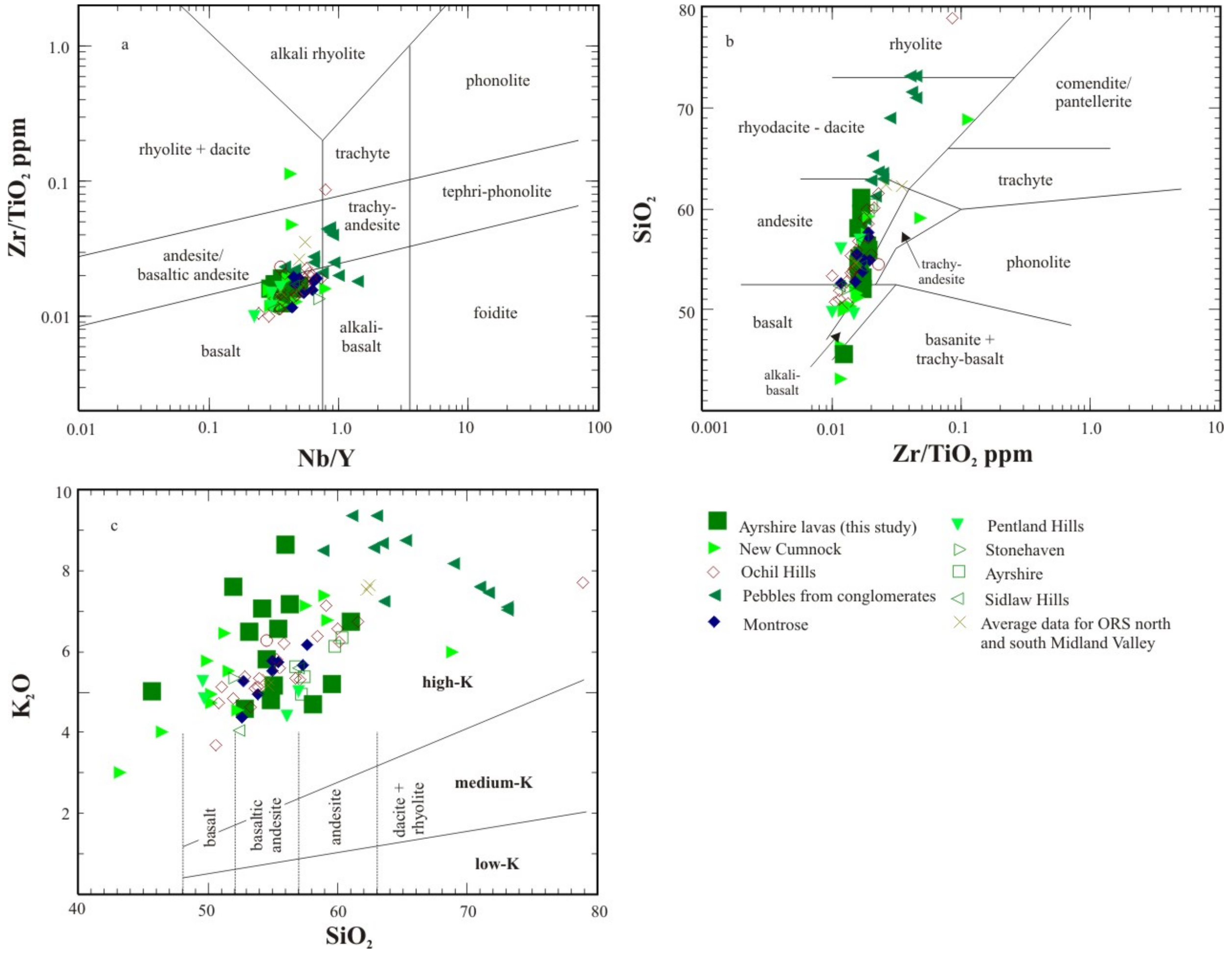

Figure 2. (a) Zr/TiO_2-Nb/Y classification diagram (Winchester and Floyd, 1977); (b) SiO_2-Zr/TiO_2 classification diagram (Winchester and Floyd, 1977); and (c) K_2O-SiO_2 classification diagram (Le Maitre, 1989).

4.2 GEOCHEMICAL VARIATION WITHIN THE CARRICK VOLCANIC FORMATION

4.2.1 Major elements

Major element data obtained for the lavas has been plotted on a series of bivariant (Harker-type) variation diagrams using SiO_2 as a fractionation index (Figures 3 and 4). The Carrick Volcanic Formation lavas range from 45 to 61% SiO_2 and plot within the compositional range of other Siluro-Devonian volcanic rocks from the Midland Valley of Scotland.

The oxides TiO_2, Fe_2O_3 total, MgO and CaO all show decreasing trends as SiO_2 increases, typical of calc-alkaline magmatic differentiation paths (Figures 3a to d). These trends are consistent with the fractionation of olivine and clinopyroxene within the basalts, and hornblende in the more andesitic lithologies. The scatter in the data for CaO (Figure 3d) may, at least in part, be due to the alteration of feldspar and/or introduction of carbonate during hydrothermal alteration. The Carrick Volcanic Formation lavas plot in two discrete groups in terms of their TiO_2 (Figure 3a), MgO (Figure 3c) and CaO (Figure 3d) contents (also see Table 2). The subdivision of the Siluro-Devonian lavas into a suite of high-Mg basalts and basaltic andesites, and more “normal” low-Mg lavas has previously been recognised by Thirlwall (1981) and Phillips (1994). Na_2O, and K_2O (Figures 3e and f) show a wide scatter consistent with the partial remobilisation of these oxides during alteration of plagioclase feldspar.

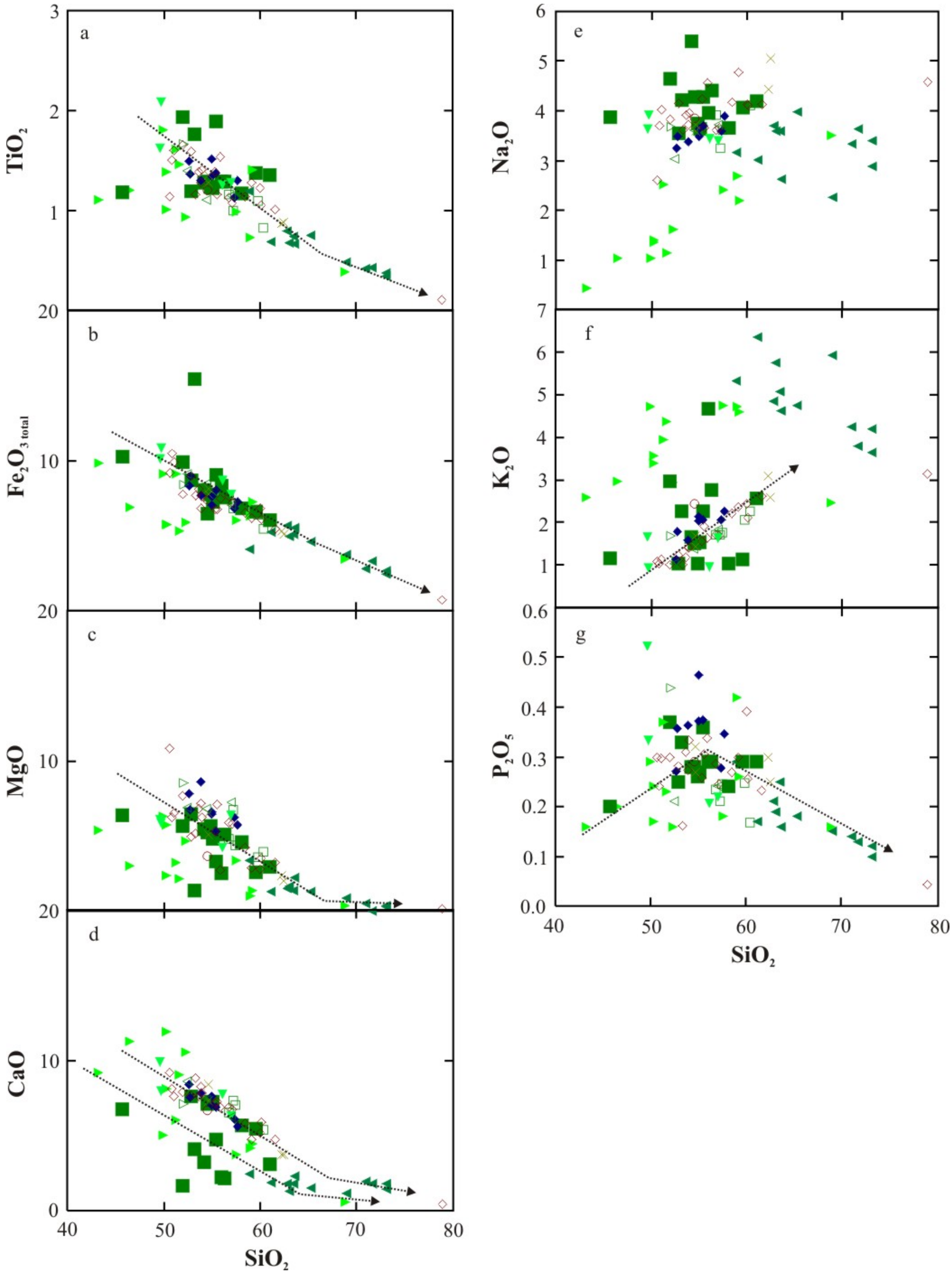

Figure 3. Harker-type variation diagrams showing the variation in a) TiO_2, b) $Fe_2O_{3\ total}$, c) MgO, d) CaO, e) Na_2O, f) K_2O and g) P_2O_5 with respect to SiO_2. For key to symbols see Figure 2.

4.2.2 Trace elements

The variation in trace element data is illustrated in Figure 4. Although there is some scatter in the data the elements Zr, Y and Nb all exhibit, to varying degrees, a positive correlation with respect to SiO2 (Figures 4a, b and d, respectively). This increase in selected immobile trace elements is typical of calc-alkaline magmatic differentiation paths. In contrast, Zn, Ni, V, Cr and Sc (Figures 4e to h) all show a marked decrease (negative correlation) with respect to SiO_2. These elements are partitioned into ferromagnesian minerals, with these trends probably reflecting the fractionation of olivine, pyroxene and/or hornblende. Rb shows a wide scatter on Fig 3c probably reflecting the remobilisation of this element during the alteration of feldspar.

On Figures 4f and 4h the Carrick Volcanic Formation lavas can be subdivided into two groups in terms of their Ni and Cr contents (> 80 ppm high-Ni, < 30 ppm low-Ni,> 100 ppm high-Cr, < 30 ppm low-Cr, cf. Phillips, 1994). In general the high-Cr and Ni lavas also tend to possess high MgO contents and include some of the basaltic andesites. Similar high-Cr lavas were described by Thirlwall (1983) from the Lower Old Red Sandstone volcanic rocks of Fife. In this area, the high Cr-lavas also exhibit higher Ca, Sc and lower Al, Fe, Na and Y for a given SiO_2 content that the low-Cr lithologies (Thirlwall, *op. cit.*). Thirlwall (1981) concluded that these Ni- and Cr-rich lavas are primitive, and represent primary magmas which have undergone less than 25% fractional crystallisation of the ferromagnesian minerals. He suggested that the high-Ni basalts could be parental to the low-Cr, -Ni basalts and basaltic andesites, but fractional crystallisation of the observed phenocryst phases would not provide sufficient silica enrichment to generate high-Cr, -Ni primitive andesites from basaltic parents.

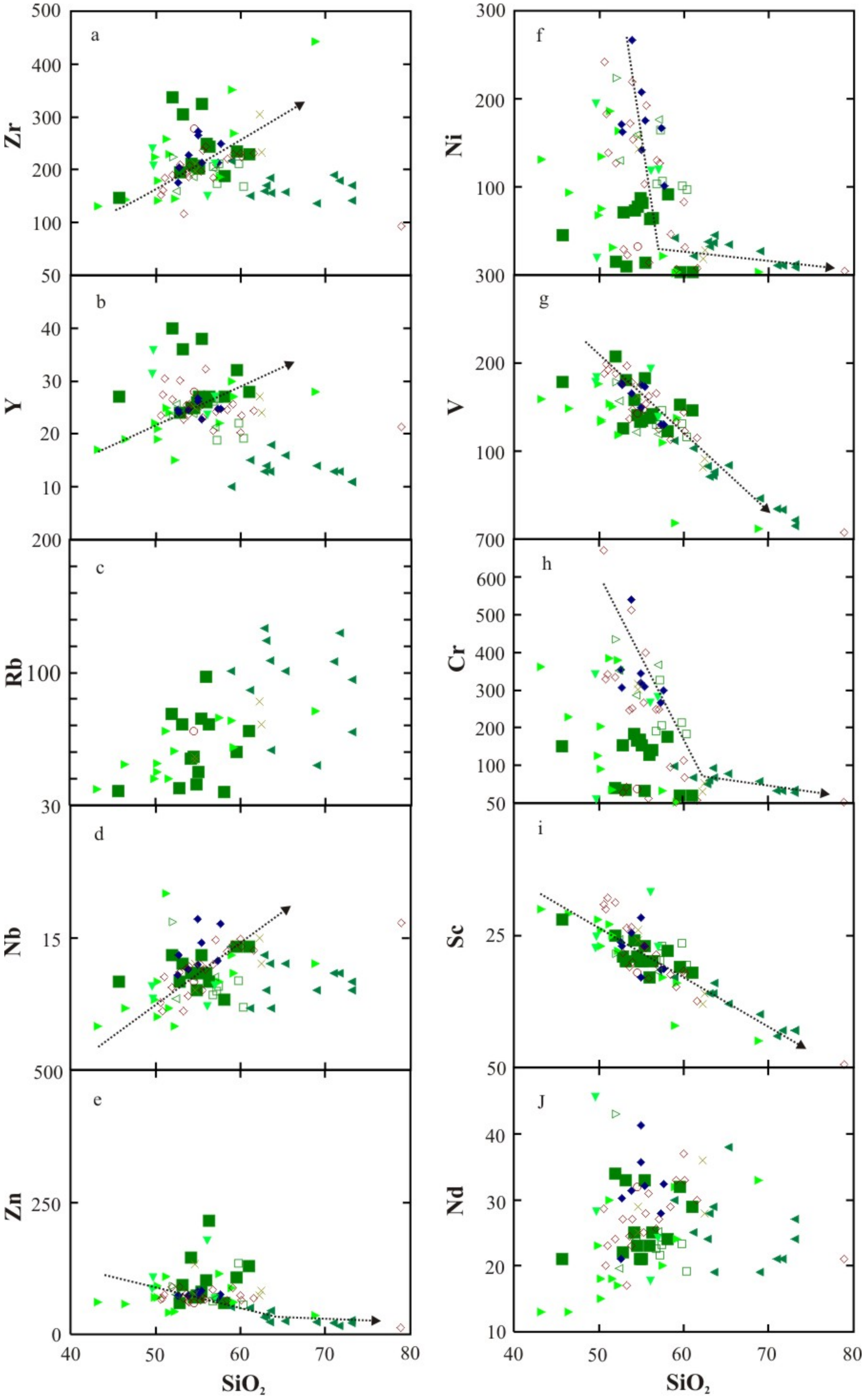

Figure 4. Harker-type variation diagrams showing the variation in a) Zr, b) Y, c) Rb, d) Nb, e) Zn, f) Ni, g) V, h) Cr, i) Sc and j) Nd with respect to SiO_2. For key to symbols see Figure 2.

4.3 LITHOSTRATIGRAPHICAL VARIATIONS IN MAJOR OXIDE AND TRACE ELEMENT CONCENTRATIONS

The samples analysed from the Carrick Volcanic Formation have been placed in their approximate stratigraphical in order based upon their spatial distribution with respect to the base of the formation on the published 1:50 000 geological map of the Ayr district. This approach has been used to highlight any systematic changes in whole-rock composition upward through the volcanic sequence with the data being plotted upon a series of variation diagrams (Figures 5 to 7).

Initial results of this study suggest that there may be a significant break in composition within the Carrick Volcanic Formation denoted by red dashed lines on Figures 5, 6 and 7. This break is most prominent in terms of the variation in Nd, Y, Ce, Zr, Ni, Cr and V contents (Figures 6b and c), and, to a lesser extent, Rb (Figure 6a) and Hf (Figure 6b) contents of the lavas. This compositional break includes the low-Cr and Ni basalts and basaltic andesites identified in section 4.2, which may, therefore, form a discrete lithostratigraphical unit within the Carrick Volcanic Formation. The compositional break within the volcanic strata can also be identified on the ratio plots illustrated in Figures 7a to d.

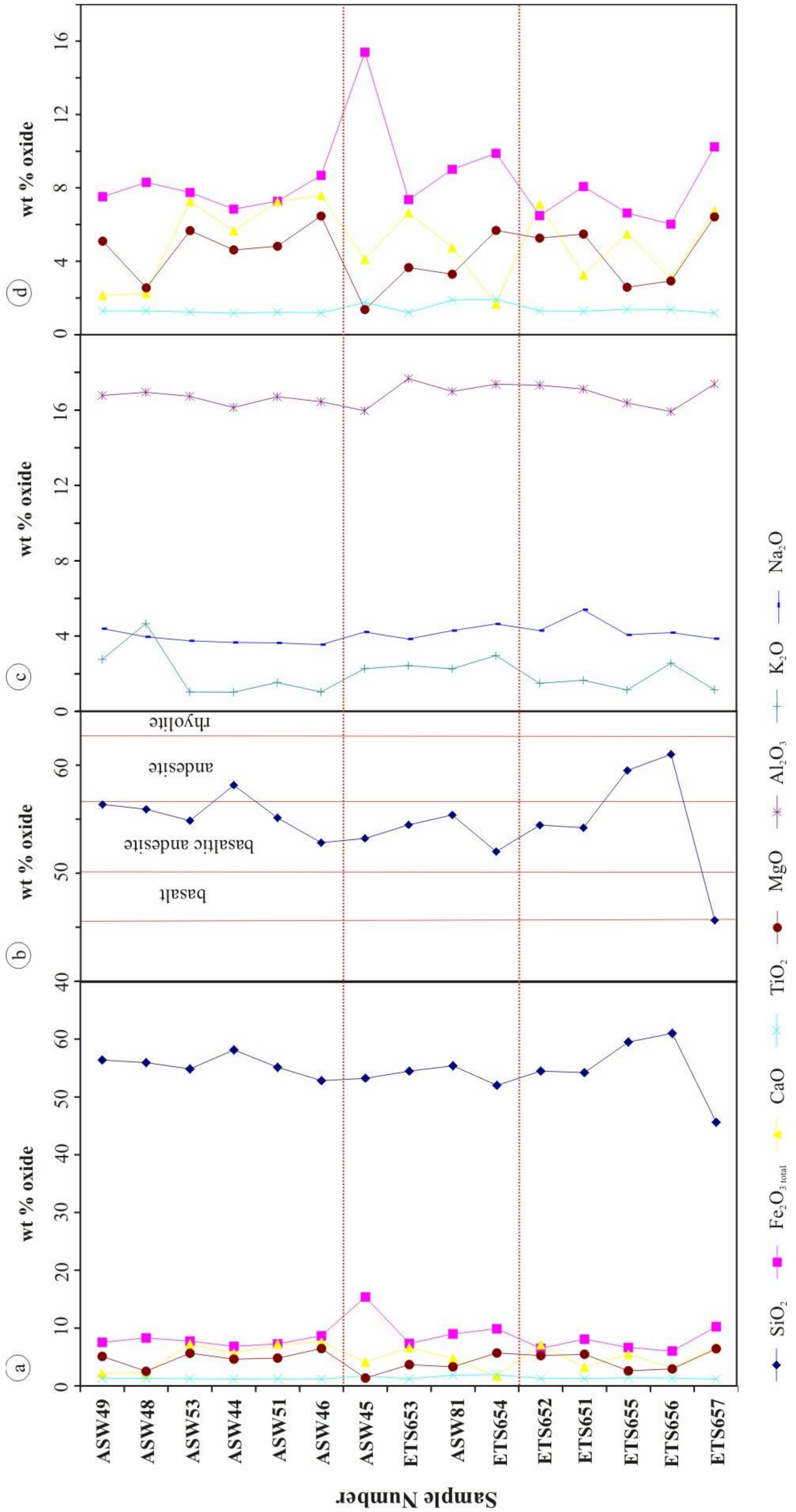

Figure 5. Diagram showing the lithostratigraphical variation in the major oxides a) SiO_2, Fe_2O_{3total}, CaO, TiO_2, MgO, b) Si O_2, c) K_2O, Na_2O, Al_2O_3, d) TiO_2, MgO, CaO.

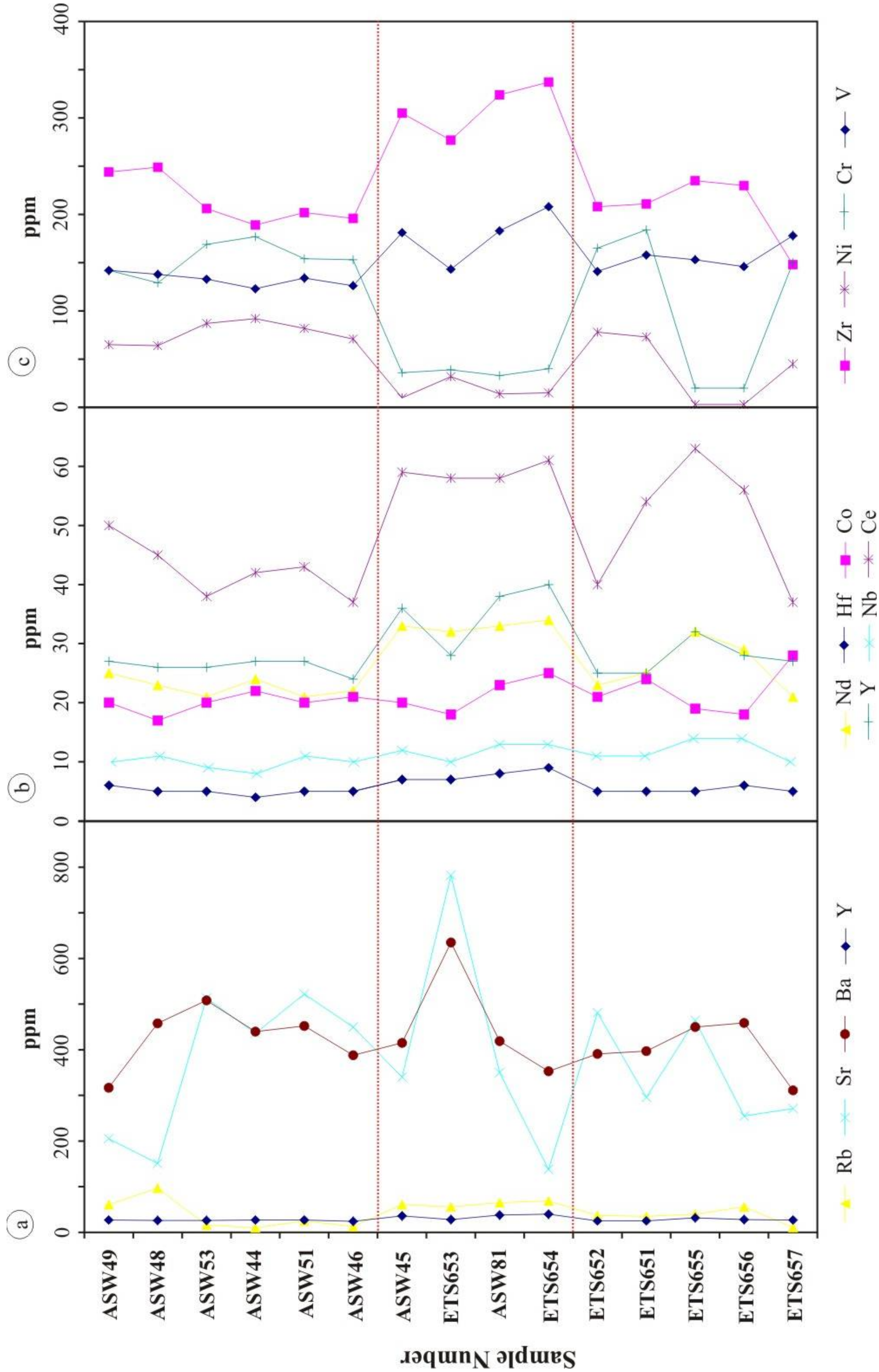

Figure 6. Diagram showing the lithostratigraphical variation in the trace elements a) Rb, Sr, Ba, Y, b) Nd, Hf, Co, Y, Nb, Ce, c) Zr, Ni, Cr and V.

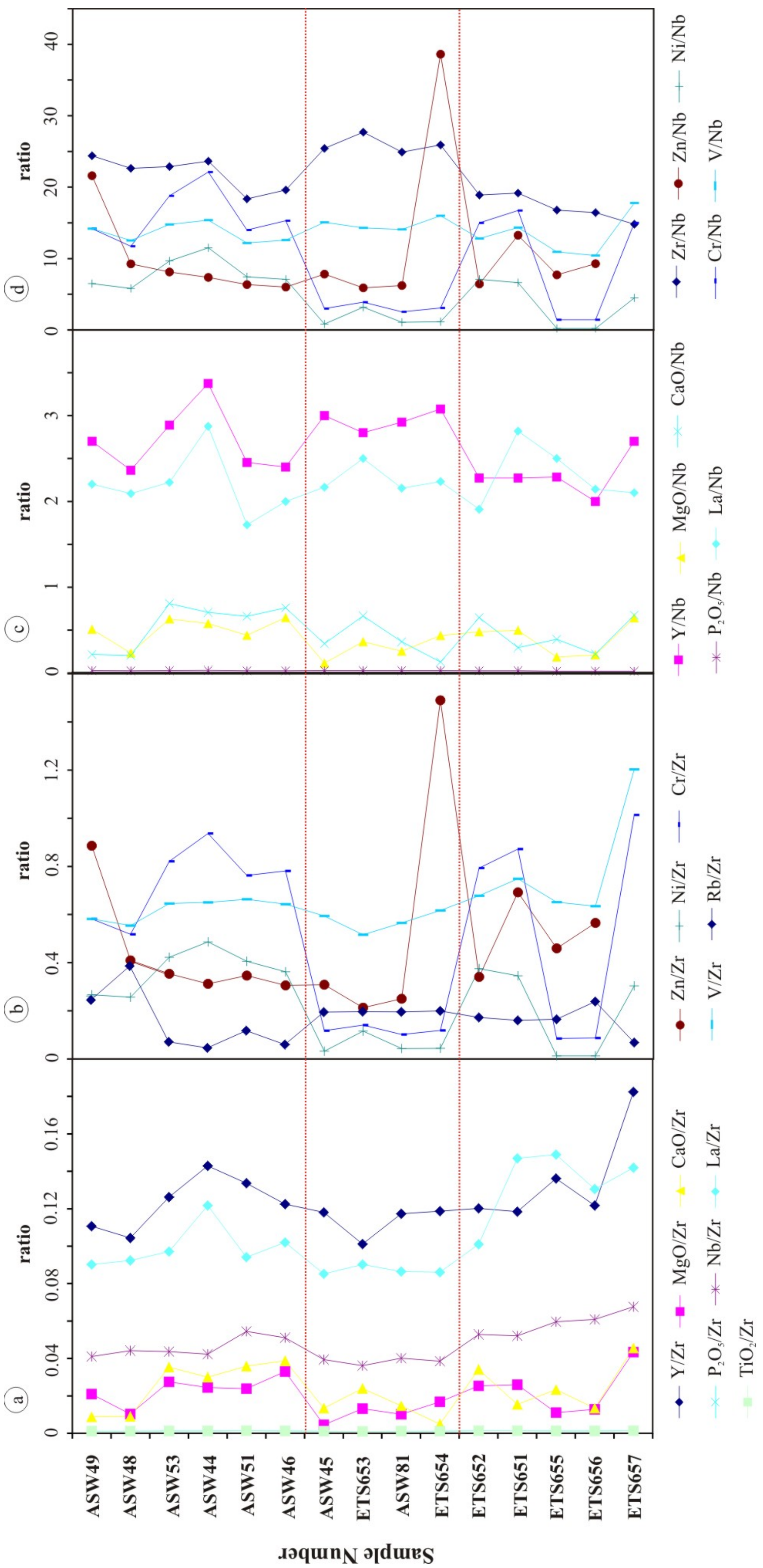

Figure 7. Diagram showing the lithostratigraphical variation in selected trace element ratios.

4.4 TECTONIC SETTING OF THE CARRICK VOLCANIC FORMATION

The trace element characteristics of basalts and andesites have been used by several workers (Pearce and Cann, 1973; Pearce, 1982, 1983; Pearce and Norry, 1979; Shervais, 1982; Meschede, 1986; Mullen, 1983) to discriminate between lavas erupted in different plate tectonic settings. Thirlwall (1981, 1982, 1983) concluded that the Siluro-Devonian lavas have geochemical characteristics typical of calc-alkaline basaltic to andesitic volcanic rocks erupted in a continental volcanic-arc setting. He further suggested that the spatial variation in Sr, Ba, K, P_2O_5, Light Rare Earth Elements (LREE) and the La/Y ratio of these lavas was consistent with a northwest-dipping subduction zone. Recently, Smith (1995) and Phillips *et al*. (1998) have offered an alternative hypothesis, suggesting that the Lower Old Red Sandstone volcanic rocks may potentially be unrelated to active plate subduction. These workers have re-interpreted the whole-rock geochemistry, in the light of the regional geological setting of the Midland Valley terrane during late Silurian to early Devonian times, to suggest that the Siluro-Devonian volcanic rocks may have been derived from the partial melting of a subduction contaminated mantle source in an overall sinistral strike-slip regime.

Data from the Carrick Volcanic Formation of the Ayr district have been plotted on a series of discrimination diagrams and multi-element plots (Figures 8 and 9) in an attempt to establish their tectonic setting. On The Zr-Ti-Sr (Figure 8a) and T-Zr-Y (Figure 8b) plots (after Pearce and Cann, 1973) the data for the Carrick Volcanic Formation plots along with the other Siluro-Devonian lavas within or adjacent to the field of calc-alkaline basalts (i.e. a continental volcanic-arc setting). The linear trend defined by the Carrick Volcanic Formation rocks on the Zr-Ti-Sr ternary diagram (Figure 8a) towards the Sr apex suggests that these lavas have undergone some remobilisation of Sr during hydrothermal alteration.

On the Zr/Y versus Zr diagram (Pearce and Norry, 1979) (Figure 8c) the majority of the data for the various Siluro-Devonian lavas fall within or immediately adjacent to the within-plate basalt field. However, Pearce (1982, 1983) demonstrated that the Zr/Y ratio can be also used as a measure of within-plate enrichment, with continental volcanic-arc basalts possessing Zr/Y ratios of > 3.0. Consequently, both within-plate and active continental margin lavas could, therefore, be derived from similarly enriched sources, the latter only differing in that they contain a subduction component. The basalts and basaltic andesites of the Ayr district have Zr/Y ratios in excess of 5.0. Therefore, a continental volcanic-arc setting to these volcanic rocks can not be ruled out by using the Zr/Y-Zr plot in isolation.

The data were also plotted on the Zr-Nb-Y ternary diagram of Meschede (1986). On this diagram data from the Siluro-Devonian volcanic rocks form a relatively tight cluster (apart from the data for lithic clasts within the conglomerates from the New Cumnock district) which straddles the boundary between within-plate and volcanic-arc fields (Figure 8d). In contrast, on the discrimination diagram based upon the immobile High Field Strength Elements (HFS) Th-Hf-Ta (Wood, 1980) data for the Carrick Volcanic Formation plots well within the field of volcanic-arc basalts (Figure 8e).

A convenient means of comparing analyses of magma types erupted in different plate tectonic settings is by plotting the data as normalised multi-element plots (spidergrams). On Figure 9a selected trace element and major oxide data for the Carrick Volcanic Formation have normalised using an average tholeiitic mid-ocean ridge basalt (MORB) as the normalising factor (Pearce, 1982, 1983). The elements are ordered on these multi-element diagrams according to their petrogenetic properties, with the most mobile elements Sr, K_2O, Rb and Ba having been placed on the left hand end of the plot. Also plotted for comparison are the data obtained for the Siluro-Devonian volcanic rocks exposed in the New Cumnock (Figure 9b), Montrose (Figure 9c) and Pentland Hills (Figure 9c) areas. The basalts and basaltic andesites from the Carrick Volcanic Formation exhibit a pronounced 'humped' pattern typical of within-plate basalts or active continental calc-alkaline basalts in which there is a significant within-plate component. These lavas show enrichment of Sr, K_2O, Rb, Ba and Th relative to TiO_2, Y and Cr. Slight variations in the shape of the left hand part of the patterns (see Figure 9a) are probably due to the remobilisation of Sr, K_2O, Rb and possibly Ba during limited hydrothermal alteration. The elements Nb, Ce, P_2O_5, and Zr are also relatively enriched with respect to average MORB, with Ce forms a slight positive anomaly (Figure 9a). In contrast, TiO_2 and Y are close to unity or slightly depleted with respect to average MORB, with Sc and Cr typically showing marked depletion and plotting below unity (Figure 9a). It is clear from Figures 9b and 9c that the Siluro-Devonian volcanic rocks from the New Cumnock, Montrose and Pentland Hills areas show very similar patterns and degrees of enrichment and depletion.

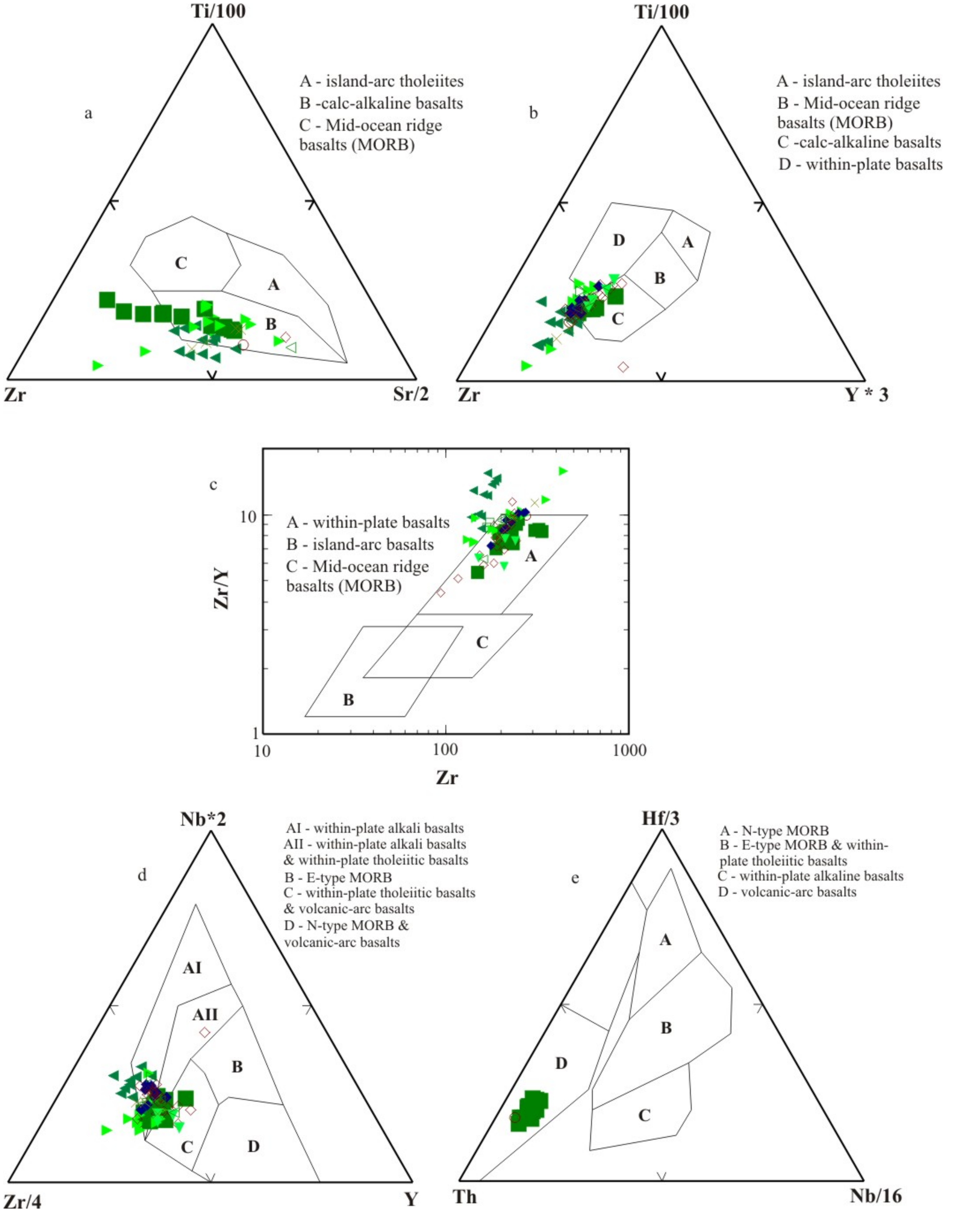

Figure 8. Discrimination diagrams for establishing the tectonic setting of basaltic igneous rocks: (a) Ti/100-Zr-Sr/2 (Pearce and Cann, 1973); (b) Ti/100-Zr-Y*3 (Pearce and Cann, 1973); (c) Zr/Y-Zr (Pearce and Norry, 1979); (d) Nb*2-Zr/4-Y (Meschede, 1986); and (e) Hf/3-Th-Nb/16 (Meschede, 1986). For key to symbols see Figure 2.

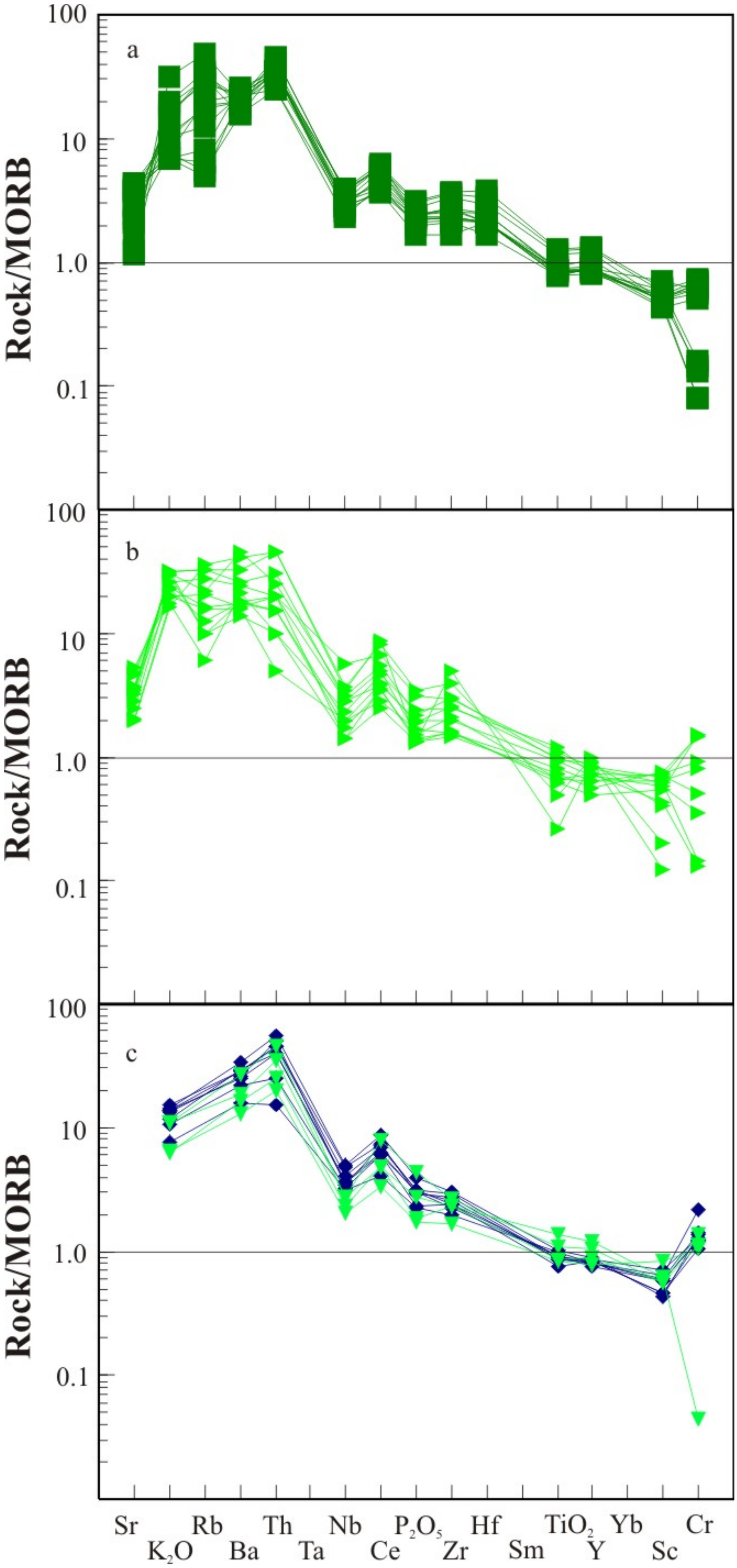

Figure 9. MORB normalised multi-element variation diagrams (spidergrams): (a) Carrick Volcanic Formation, Ayr district; (b) New Cumnock district; and (c) Montrose (triangles) and Pentland Hills (diamonds) districts. For key to symbols see Figure 2.

5 Sandstone petrographic provenance

Previous provenance studies have largely concentrated on Silurian and Lower Devonian sequences of the Midland Valley of Scotland. This work includes the studies of Bluck (1983, 1984) and Syba (1989) on the Silurian Igneous, Quartzite and Greywacke conglomerates of the southern Midland Valley, and Bluck (1983), Haughton *et al*. (1990) and Haughton & Halliday (1991) which concentrated upon the Lower Devonian Dunnottar and Crawton group conglomerates of the northern Midland Valley. Recent work by Phillips and Carroll (1995), Phillips and Smith (1995), Phillips and Aitken (1998), Phillips *et al*. (1998), Phillips and Barron (2000) and Phillips *et al*. (2004) has examined the provenance and compositional variations within the sandstones which dominate both the Silurian and Lower Devonian sedimentary sequences.

Selected samples of medium- to coarse-grained sandstone from the Lanark Group of the Ayr and Lanark districts as well as samples from the Carboniferous in age Ballagan Formation (Ayr district), Kinnesswood Formation (Lanark and Ayr districts) and Lawmuir Formation (Lanark district) have been analysed as part of an ongoing regional petrographic provenance study. Analysis of the Lanark Group sandstones represents a continuation of the provenance study of Phillips and Smith (1995) and Phillips and Barron (2000) in the New Cumnock and Lanark districts, respectively. A total of 37 thin sections were examined optically using a standard transmitted light petrological microscope. The modal proportion of the matrix (where present), cement and various detrital components within the sandstones were determined using a Swift Automatic Point Counter. These data were added to sandstone compositional data obtained for the Lanark Group from the New Cumnock and Lanark districts (see Phillips and Smith, 1995; Phillips and Barron, 2000; Phillips *et al*., 2004). The 'raw' compositional data are recalculated to 100% and plotted on a series of bivariant and log-ratio diagrams using a commercial spreadsheet package (Microsoft Excel).

Modal compositions of the sandstones (Table 3) were calculated as volumetric proportions of the following categories of detrital grains (Dickinson and Suczek, 1979): stable quartzose grains (Q) including both monocrystalline (Qm) and polycrystalline quartz (Qp); monocrystalline feldspar grains including plagioclase (Pl) and K-feldspar (Ksp); unstable polycrystalline lithic fragments (L) of three main kinds, namely volcanic (Lv), metamorphic (Lm) and sedimentary (Ls) rock fragments. The total lithic component (Lt) of the sandstones was taken as the sum of the unstable lithic fragments (L) plus stable polycrystalline quartz lithic fragments (Qp). The matrix (M) component includes primary cement and matrix, as well as partially degraded, unstable detrital material where the clast shape can no longer be recognised (i.e. a secondary matrix component). Other minor components include muscovite (Mu), biotite (Bio), garnet (Gt), opaque minerals (Op), cement (CC), chlorite (Chl), amphibole (Hb) and granitic lithic clasts (Lg).

Data obtained for the Lanark Group sedimentary sequences exposed in the Lanark, New Cumnock and Ayr districts, and initial data for the overlying Carboniferous sedimentary sequences of the Lanark and Ayr study areas are plotted on a series variation diagrams (Figs. 9 to 13) and are listed in Table 3. Compositional data obtained by Phillips and Smith (1995) and Phillips and Barron (2000) for the Auchtitench Sandstone (including the Wiston Grey Volcaniclastic Sandstone Member), Duneaton Volcanic and Greywacke Conglomerate formations of the Lanark and New Cumnock districts are also plotted on these diagrams for comparison.

sample	district	group	formation	N	Qm	Qp	Pl	Ksp	Ls	Lm	Lv	Lg	L total
S33752	Ayr	Lanark	Swanshaw Sandstone Formation	1038	29.9	10.8	6.5	2.0	4.2	13.7	16.2	0.7	45.6
N2215	Ayr	Lanark	Swanshaw Sandstone Formation	1031	28.6	8.1	7.5	1.6	1.3	5.9	8.9	0.4	24.6
N2216	Ayr	Lanark	Swanshaw Sandstone Formation	1018	20.7	7.5	4.5	2.5	1.1	7.9	11.9	0.4	28.8
N2207	Ayr	Lanark	Swanshaw Sandstone Formation	1029	18.9	8.5	6.2	1.5	0.9	7.9	22.6	0.3	40.2
N2205	Ayr	Lanark	Swanshaw Sandstone Formation	973	13.3	3.4	2.6	0.5	32.9	0.6	28.6	0.0	65.5
N2220	Ayr	Lanark	Swanshaw Sandstone Formation	982	15.4	7.6	0.8	0.0	17.7	5.6	27.1	0.0	58.0
N2207	Ayr	Lanark	Swanshaw Sandstone Formation	990	20.2	6.2	9.6	1.6	1.6	2.7	22.8	0.4	33.7
N2215	Ayr	Lanark	Swanshaw Sandstone Formation	993	27.6	4.5	11.7	1.3	3.1	1.2	10.5	0.0	19.3
N2216	Ayr	Lanark	Swanshaw Sandstone Formation	910	21.5	6.0	10.3	1.8	2.9	1.6	11.5	0.2	22.3
N2227	Ayr	Lanark	Swanshaw Sandstone Formation	971	11.5	2.9	6.4	0.8	0.8	0.6	56.3	0.0	60.8
N2905	Ayr	Lanark	Swanshaw Sandstone Formation	997	28.1	6.7	9.6	0.4	4.1	3.5	11.6	0.1	26.1
N2142	Lanark	Strathclyde	Lawmuir Formation	1008	49.8	16.5	2.1	0.1	3.4	1.3	3.2	0.1	24.4
N2141	Lanark	Strathclyde	Lawmuir Formation	1010	48.3	11.8	4.1	0.2	0.9	0.8	3.3	0.0	16.7
N2127	Lanark	Strathclyde	Lawmuir Formation	1021	39.8	15.9	5.9	1.9	4.6	3.9	5.3	1.2	30.9
N2120	Lanark	Strathclyde	Lawmuir Formation	1006	54.9	13.6	3.6	0.9	2.5	2.5	5.2	0.0	23.8
N2118	Lanark	Strathclyde	Lawmuir Formation	1002	29.4	18.1	3.4	1.4	7.6	8.4	14.2	0.0	48.2
N2129	Lanark	Strathclyde	Lawmuir Formation	997	55.8	15.5	3.6	0.8	3.7	1.9	3.8	0.3	25.2
HFB212	Lanark	Inverclyde	Kinnesswood Formation	994	39.7	10.2	1.8	0.1	0.9	9.7	17.8	0.2	38.7
N2116	Lanark	Inverclyde	Kinnesswood Formation	1005	65.2	8.9	3.9	1.9	1.5	2.2	3.2	0.0	15.8
N2117	Lanark	Inverclyde	Kinnesswood Formation	1001	30.8	30.9	2.4	0.0	9.1	1.9	12.3	0.0	54.1
EY295	Lanark	Inverclyde	Kinnesswood Formation	1006	37.9	9.2	2.7	2.3	3.2	2.6	4.7	0.2	19.9
S96920	Lanark	Inverclyde	Kinnesswood	998	46.3	3.6	1.5	1.1	0.0	0.1	0.0	0.0	3.7

			Formation										
N2590	Ayr	Inverclyde	Kinnesswood Formation	1009	42.6	11.4	5.6	5.2	0.9	1.4	0.9	0.0	14.6
N2589	Ayr	Inverclyde	Kinnesswood Formation	1008	30.7	15.1	2.6	10.4	0.5	1.1	1.2	0.5	18.4
N2586	Ayr	Inverclyde	Kinnesswood Formation	1001	30.8	19.9	1.2	1.5	14.9	0.1	1.3	0.0	36.3
N2055	Ayr	Inverclyde	Kinnesswood Formation	1011	59.4	13.8	3.1	6.2	1.9	2.3	2.2	0.0	20.3
N2580	Ayr	Stratheden	Ballagan Formation	1002	49.4	8.4	1.4	3.2	2.7	0.1	0.5	0.1	11.8
N2578	Ayr	Stratheden	Ballagan Formation	1001	18.2	3.8	0.3	1.1	47.2	0.0	0.5	0.0	51.4
N2057	Ayr	Stratheden	Stratheden Group	1004	43.0	12.8	1.3	2.8	6.7	1.9	3.1	0.0	24.5
sample	**district**	**group**	**formation**	**Gt**	**Bio**	**Mu**	**Op**	**Chl**	**Hb/Px**	**Ep**	**St**	**matrix**	**cement**
S33752	Ayr	Lanark	Swanshaw Sandstone Formation	0.0	2.4	1.2	2.2	0.8	0.0	0.0	0.0	9.4	0.1
N2215	Ayr	Lanark	Swanshaw Sandstone Formation	0.2	0.3	2.9	2.0	0.6	0.0	0.0	0.0	16.1	15.8
N2216	Ayr	Lanark	Swanshaw Sandstone Formation	0.0	0.5	1.2	0.4	0.9	0.0	0.0	0.0	0.5	39.9
N2207	Ayr	Lanark	Swanshaw Sandstone Formation	0.4	0.5	1.1	0.4	1.6	0.0	0.5	0.0	2.5	26.6
N2205	Ayr	Lanark	Swanshaw Sandstone Formation	0.0	0.5	0.5	0.0	0.2	0.0	0.0	0.0	7.3	9.7
N2220	Ayr	Lanark	Swanshaw Sandstone Formation	0.0	0.0	0.6	0.1	0.2	0.0	0.0	0.0	13.9	10.9
N2207	Ayr	Lanark	Swanshaw Sandstone Formation	0.1	0.8	1.6	0.7	1.6	0.0	0.5	0.0	4.3	25.3
N2215	Ayr	Lanark	Swanshaw Sandstone Formation	0.0	0.9	2.9	1.3	0.7	0.0	0.0	0.0	29.2	5.0
N2216	Ayr	Lanark	Swanshaw Sandstone Formation	0.0	0.7	1.9	0.0	0.8	0.0	0.0	0.1	2.3	38.4
N2227	Ayr	Lanark	Swanshaw Sandstone Formation	0.0	0.1	0.8	0.5	0.5	0.0	0.1	0.0	18.2	0.2
N2905	Ayr	Lanark	Swanshaw Sandstone Formation	0.0	1.5	1.6	0.6	1.3	0.1	0.0	0.0	24.8	5.9
N2142	Lanark	Strathclyde	Lawmuir Formation	0.0	0.0	0.5	0.7	0.0	0.0	0.0	0.0	13.9	8.4
N2141	Lanark	Strathclyde	Lawmuir Formation	0.0	0.3	0.5	0.5	0.1	0.1	0.4	0.0	16.5	12.4
N2127	Lanark	Strathclyde	Lawmuir Formation	0.0	0.4	0.2	0.5	0.4	0.0	0.0	0.0	10.1	10.1

N2120	Lanark	Strathclyde	Lawmuir Formation	0.0	0.2	0.1	0.6	0.0	0.0	0.0	0.0	5.8	10.0
N2118	Lanark	Strathclyde	Lawmuir Formation	0.0	0.0	0.6	0.1	0.1	0.0	0.0	0.0	8.8	7.9
N2129	Lanark	Strathclyde	Lawmuir Formation	0.0	0.2	0.4	0.4	0.0	0.0	0.0	0.0	7.7	5.8
HFB212	Lanark	Inverclyde	Kinnesswood Formation	0.0	0.1	0.2	1.0	0.1	0.1	0.0	0.0	18.1	0.0
N2116	Lanark	Inverclyde	Kinnesswood Formation	0.0	0.1	0.3	0.5	0.5	0.0	0.0	0.0	3.4	8.8
N2117	Lanark	Inverclyde	Kinnesswood Formation	0.0	0.0	0.0	0.1	0.0	0.0	0.0	0.0	6.6	5.9
EY295	Lanark	Inverclyde	Kinnesswood Formation	0.0	0.1	0.1	0.4	0.0	0.0	0.0	0.0	4.1	32.5
S96920	Lanark	Inverclyde	Kinnesswood Formation	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	4.2	43.2
N2590	Ayr	Inverclyde	Kinnesswood Formation	0.1	0.7	0.9	0.6	0.3	0.0	0.0	0.0	13.8	15.7
N2589	Ayr	Inverclyde	Kinnesswood Formation	0.1	0.0	0.1	0.2	0.1	0.0	0.0	0.0	2.9	34.6
N2586	Ayr	Inverclyde	Kinnesswood Formation	0.0	0.0	0.1	0.1	0.1	0.0	0.0	0.0	1.2	28.7
N2055	Ayr	Inverclyde	Kinnesswood Formation	0.0	0.2	1.1	0.5	0.6	0.0	0.0	0.0	3.4	5.2
N2580	Ayr	Inverclyde	Ballagan Formation	0.0	0.1	0.1	0.1	0.0	0.0	0.0	0.0	7.1	26.8
N2578	Ayr	Inverclyde	Ballagan Formation	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.9	27.9
N2057	Ayr	Stratheden	Stratheden Group	0.0	0.0	0.3	0.4	0.0	0.0	0.0	0.0	2.3	25.4

Table 3. Modal compositional data for medium- to coarse-grained sandstones from the Swanshaw Sandstone, Kinnesswood and Ballagan Formations, and Stratheden Group of the Ayr and Lanark districts.

5.1 VARIATION IN DETRITAL COMPONENTS

Modal compositional data obtained for sandstones from the Swanshaw Formation of the Ayr and Lanark districts, and the Carboniferous Ballagan, Kinnesswood and Lawmuir formations are plotted on a series of variation diagrams illustrated in Figures 10 to 13. A number of general observations can be made concerning the variation in modal sandstone composition within the Siluro-Devonian (Lanark Group) and Carboniferous sequences:

- There are marked compositional differences between the Ballagan, Kinnesswood and Lawmuir formations and the older Swanshaw and Auchtitench sandstone formations of the Lanark Group (Figures 10a, 10b, 10f, 11 and 12);
- Volcanic rock fragments form the dominant lithic component within the Lanark Group sandstones (Figures 10a and e). However, metamorphic rock fragments are a common component (5 to 20%, Figure 10c) in the Swanshaw Sandstone Formation;
- There is a marked difference in composition between sandstones from the Duneaton Volcanic and Auchtitench Sandstone formations and those examined from the underlying

Swanshaw Sandstone Formation (cf. Phillips and Smith 1995; Phillips and Barron, 2000; Phillips *et al*., 2004);

• Sandstones from the Auchtitench Sandstone Formation show a systematic variation in their volcanic lithic, plagioclase, metamorphic lithic clasts and, to a lesser extent, polycrystalline quartz contents with respect to monocrystalline quartz (Figures 10a to d) (cf. Phillips and Smith, 1995; Phillips and Barron, 2000; Phillips *et al*., 2004);

• Sandstones from the Swanshaw Sandstone Formation show an apparent systematic variation in their polycrystalline quartz and volcanic lithic clasts contents with respect to monocrystalline quartz (Figures 10a and d). However, no comparable variation has been noted in their plagioclase and metamorphic lithic clast components, with the data plotting as clusters on Figures 10c and b;

• Initial data from the Ballagan, Kinnesswood and Lawmuir formations suggest that these Carboniferous sandstones exhibit a systematic variation in their plagioclase, metamorphic lithic and volcanic lithic clast contents with respect to monocrystalline quartz (Figures 10b to d), with these polycrystalline quartz and plagioclase data showing a much higher degree of scatter (Figures 10a and b);

• There are varying degrees of compositional overlap between the sandstones of the Swanshaw Sandstone Formation analysed from the Lanark, New Cumnock and Ayr districts, with these data showing much greater scatter on Figures 10 to 12 than the Duneaton Volcanic and Auchtitench Sandstone formations.

Phillips and Smith (1995) and Phillips and Barron (2000) have already described in detail the systematic variations in sandstone composition within the Duneaton Volcanic and Auchtitench Sandstone formations of the Lanark Group of the Lanark and New Cumnock areas. Consequently, these data will not be re-examined here and are included on Figures 10 to 12 for comparison with the Swanshaw, Ballagan, Kinnesswood and Lawmuir formations.

The systematic variation in polycrystalline quartz and volcanic lithic clast components, with respect to monocrystalline quartz (Figures 14a and d), within the Swanshaw Sandstone Formation may reflect either: **(a)** a change in the maturity leading to an increase in the stable quartzose component of these sandstones; **(b)** or mixing of detritus from two separate source areas, one quartzose and the other volcanic in nature. These systematic variations are most pronounced when the Swanshaw Sandstone Formation compositional data from the Ayr, Lanark and New Cumnock districts are considered together. In detail, these trends are less pronounced. Furthermore there is no obvious systematic variation in the plagioclase and metamorphic clast contents of these sandstones. The compositional overlap between the Swanshaw Sandstone Formation sandstones analysed from the Ayr, Lanark and New Cumnock districts (Figures 10, 11 and 12) suggests that they were derived from a similar source area. The absence of any significant trends on the majority of the plots illustrated in Figures 10 to 12 suggests that the sediment being supplied to the Lanark Group basins was well ‘mixed’ and derived from a single source rather than a mixing of detritus from several areas. Consequently, the trends recognised within the Swanshaw Sandstone Formation may either reflect a change in the sediment maturity and/or an increase in the volcanic clast component towards the top of the formation prior to the onset of volcanism during the accumulation of the Lanark Group.

In detail, slight compositional differences between the Swanshaw Sandstone Formation from the Ayr, New Cumnock and Lanark areas can be recognised, in particular in their plagioclase (Figure 10b) and metamorphic lithic contents (Figure 10c). Swanshaw Sandstone Formation sandstones analysed from the New Cumnock area also show a much wider compositional range on Figure 10. These compositional differences are also seen on the log-ratio plots illustrated in Figures 11 and 12, indicating that they are statistically significant and not a product of closure within the data set. Initial data for the sandstones from the Ayr district suggest that they can be discriminated from the Lanark district sandstones by their overall higher polycrystalline quartz

(Figure 10a) and lower plagioclase contents (Figure 10b), as well as lower Pl/Lt (Figure 11b) and higher Qm/Pl (Figure 12d) ratios.

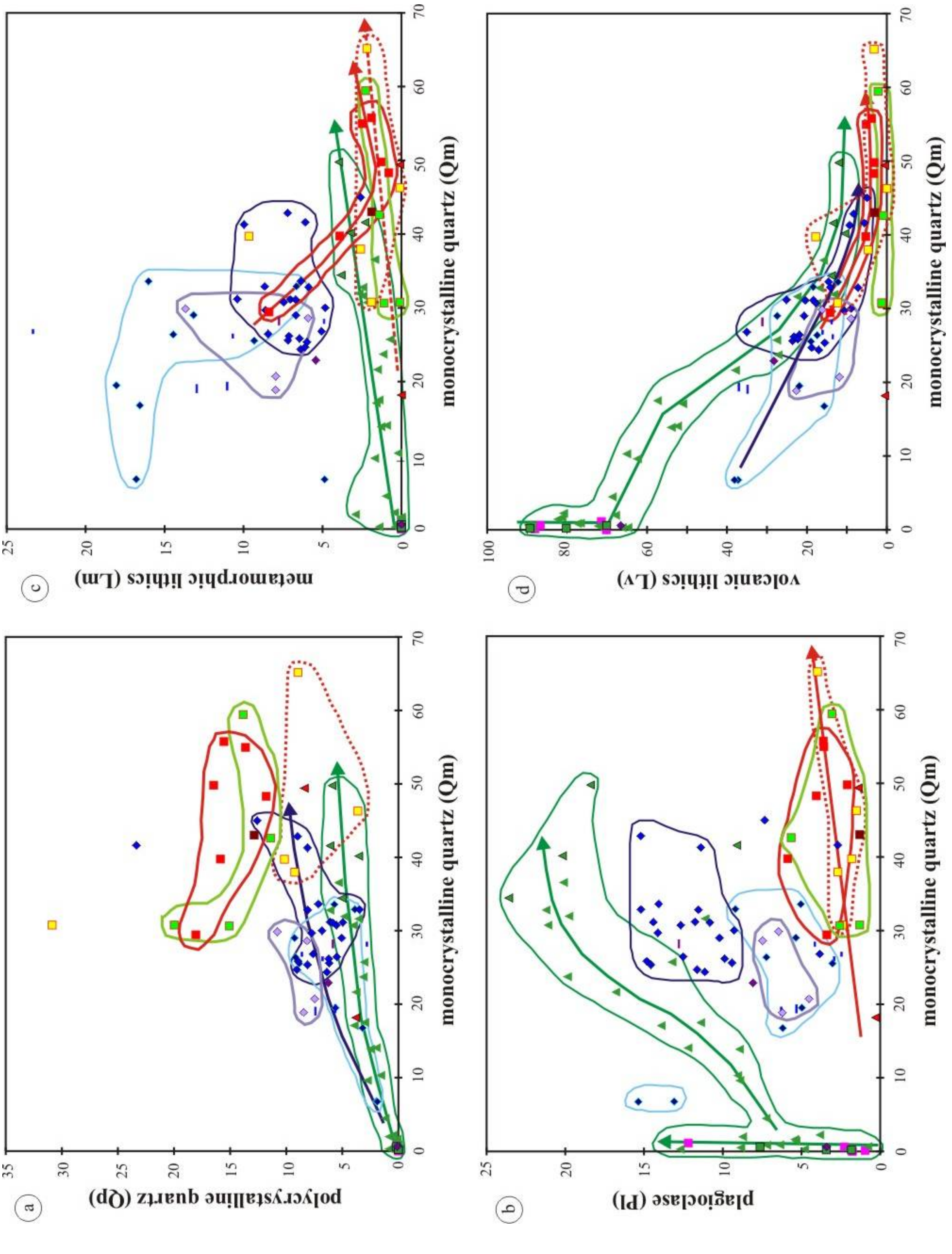

Figure 10. Diagrams showing the variation in modal sandstone composition: (a) polycrystalline quartz-monocrystalline quartz; (b) plagioclase-monocrystalline quartz; (c) metamorphic lithic clasts-monocrystalline quartz; and (d) volcanic lithic clasts-monocrystalline quartz. For key to symbols see Figure 10e to g.

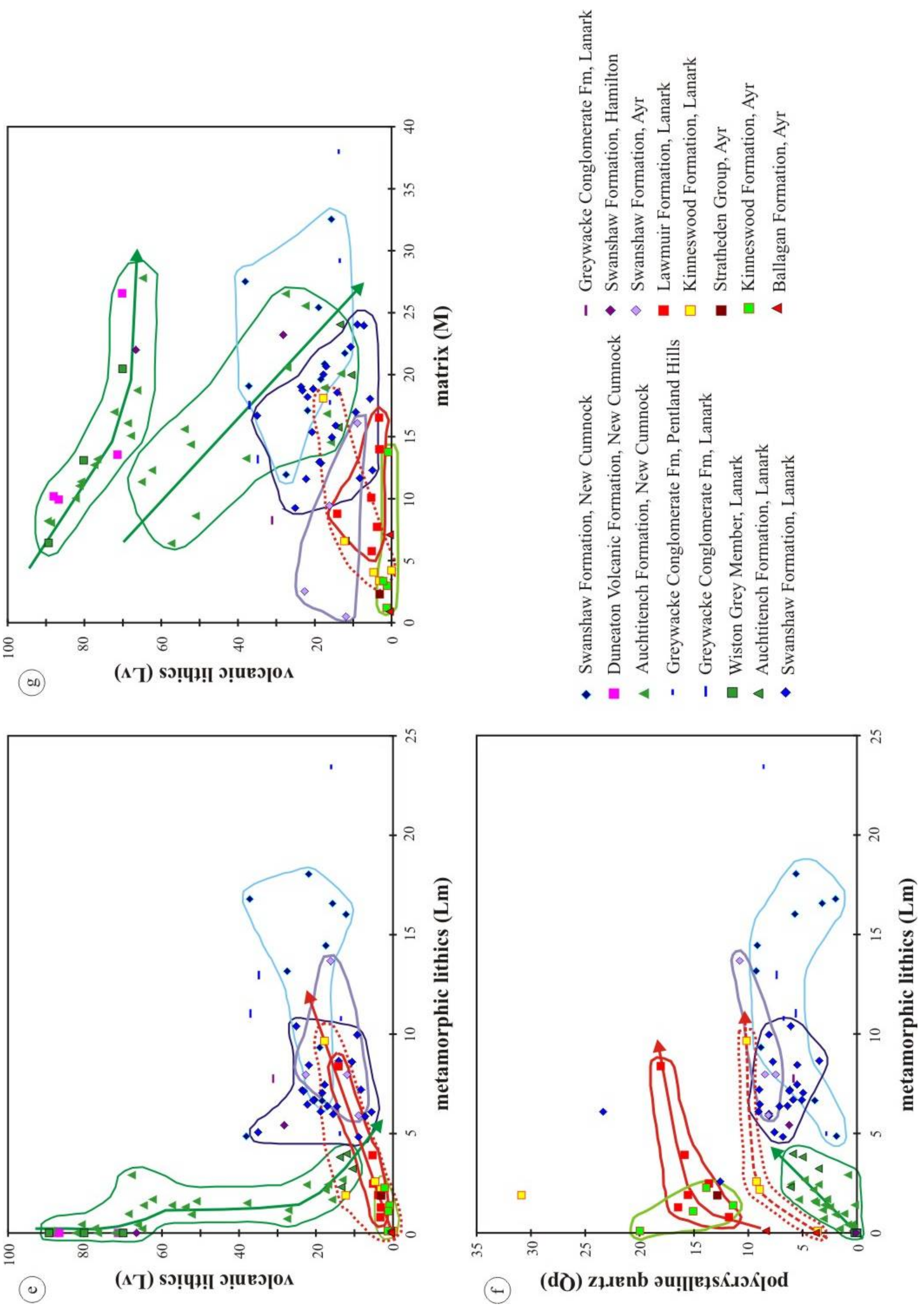

Figure 10 continued. Diagrams showing the variation in modal sandstone composition: (e) volcanic lithic clasts-metamorphic lithic clasts; (f) polycrystalline quartz-metamorphic lithic clasts; and (g) volcanic lithic clasts-matrix. For key to symbols see Figure 10.

The sandstones from the Ballagan, Kinnesswood and Lawmuir formations are compositionally distinct from the litharenites and quartzose litharenites of the Swanshaw and Auchtitench sandstone formations, i.e. as stated above. The Carboniferous sandstones are discriminated from the immature Siluro-Devonian sandstones by their higher monocrystalline quartz (Figure 10a) and polycrystalline quartz contents (Figure 10f), and lower plagioclase (Figure 10b), metamorphic lithic clast (Figure 10c) contents. This clear discrimination is also achieved on the log-ratio plots, in particular using the Lv/Lt (Figure 11a), Pl/Lt (Figure 11c), Lv/Qm (Figure 12a), Pl/Qm (Figure 12b) and Qm/Pl (Figure 12d) ratios.

The Carboniferous sandstones exhibit a systematic variation in their plagioclase, metamorphic lithic and volcanic lithic clast contents with respect to monocrystalline quartz (Figures 10b to d). The apparent positive correlation observed in the variation in plagioclase and metamorphic lithic clast contents with respect to monocrystalline quartz (Figures 10b and c) suggests that this systematic compositional variation is not simply reflecting an increase in maturity of these quartzose sandstones. A positive correlation is also observed in the variation in volcanic lithic clasts and polycrystalline quartz with respect to their metamorphic lithic clast content (Figures 10e and f), suggesting that there is an increase in all three lithic clast components as the total lithic clast content (Lt) increases. Evidence for potential systematic variations in sandstone compositions within the Ballagan, Kinnesswood and Lawmuir formations can also be seen on the log-ratio plots (Figures 11 and 12) indicating that these variations are statistically valid and not simply an artefact of closure within the data set.

Data for the Ballagan Formation of the Ayr district is limited at present to two samples (see Figures 10 to 12 and Table 3). Consequently, no detailed interpretation of the compositional variation within these sandstones can be made. Initial data for the sandstones from the Lawmuir Formation of the Lanark district and Kinnesswood Formation of Ayr suggests that there is some compositional overlap between these two formations. In particular these sandstones exhibit a similar range in polycrystalline and monocrystalline quartz (Figure 10a) and plagioclase (Figure 10b) contents. However, discrimination between the sandstones from these two formation can be achieved using the log-ratio plots, in particular the Kinnesswood Formation of the Ayr district possesses a markedly lower Lv/Lt and Lv/Qm ratios (Figures 11a and 12a, respectively). On these log ratio plots the Lawmuir Formation displays a more obvious compositional overlap with the sandstones of the Kinnesswood Formation of the Lanark district.

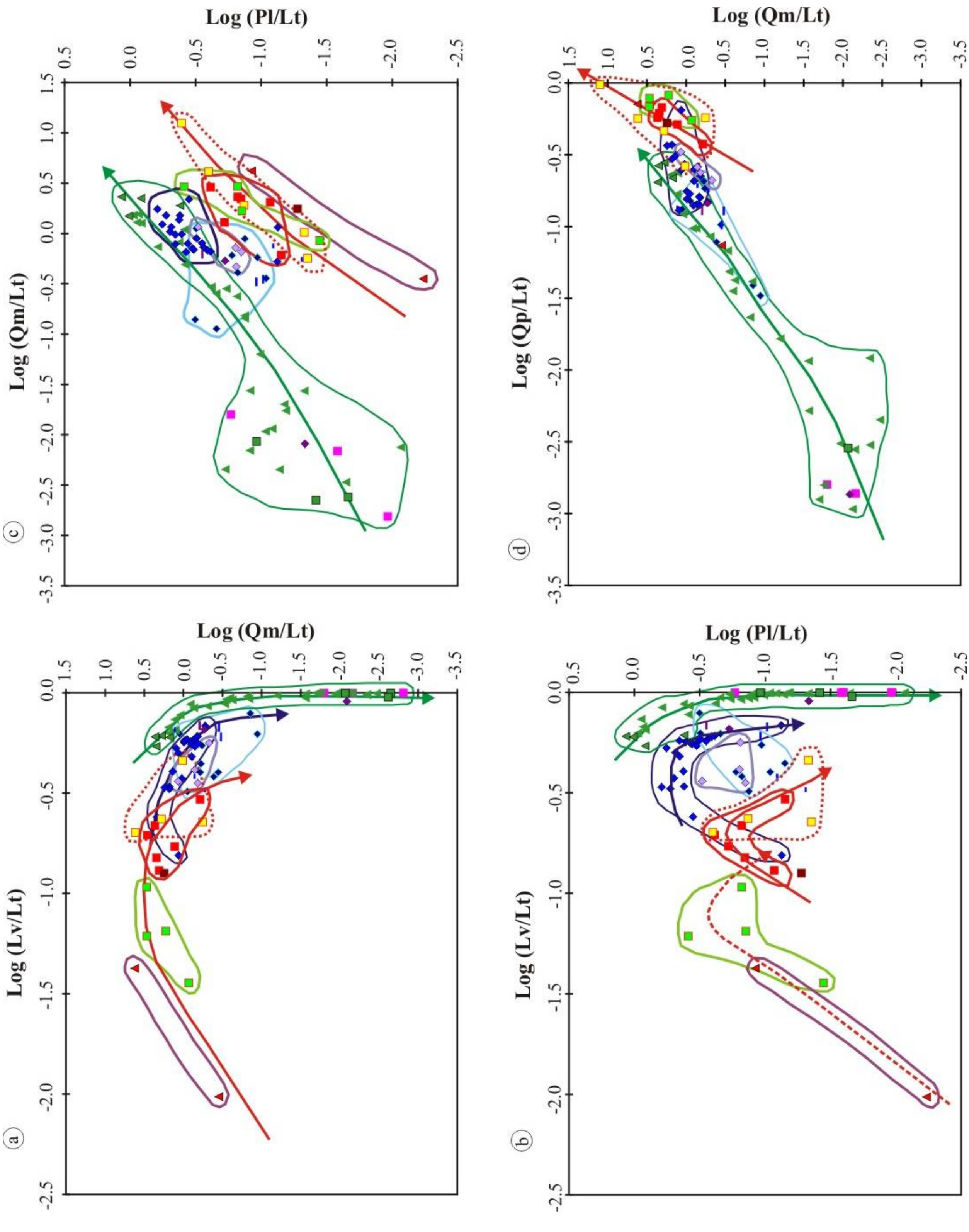

Figure 11. Log-ratio plots showing the variation in modal sandstone composition: (a) Log(Lv/Lt)-Log(Qm/Lt); (b) Log(Lv/Lt)-Log(Pl/Lt); (c) Log(Qm/Lt)-Log(Pl/Lt); and (d) Log(Qp/Lt)-Log(Qm/Lt). For key to symbols see Figure 10.

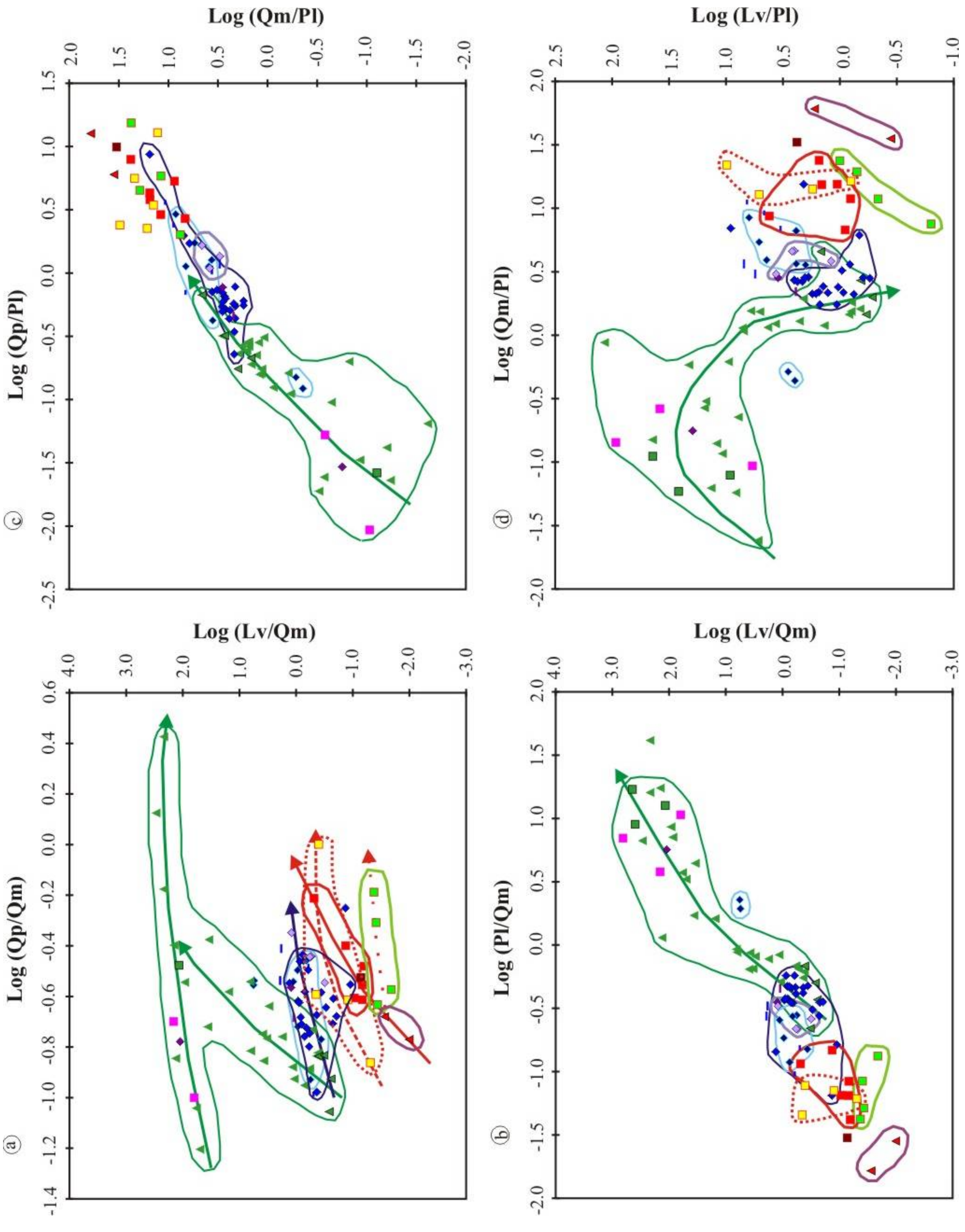

Figure 12. Log-ratio plots showing the variation in modal sandstone composition: (a) Log(Qp/Qm)-Log(Lv/Qm); (b) Log(Pl/Qm)-Log(Lv/Qm); (c) Log(Qp/Pl)-Log(Qm/Pl); and (d) Log(Qm/Pl)-Log(Lv/Pl). For key to symbols see Figure 10.

5.2 PROVENANCE AND TECTONIC SETTING

Compositional data obtained for the Swanshaw Sandstone, Ballagan, Kinnesswood and Lawmuir formations have been plotted on quartz-feldspar-lithic (Figure 13a) and monocrystalline quartz-feldspar-total lithic (Figure 13b) ternary diagrams (after Dickinson & Suczek 1979) to determine their provenance and tectonic setting. Data obtained by Phillips and Smith (1995) and Phillips and Barron (2000) for the Auchtitench Sandstone, Duneaton Volcanic and Greywacke Conglomerate formations, and the Wiston Grey Volcaniclastic Sandstone Member are also plotted on these diagrams for comparison.

In general, sandstones from the Swanshaw Sandstone Formation of the New Cumnock and Ayr districts plot within the transitional, recycled orogenic fields on Figure 13. In contrast, data from Swanshaw Sandstone Formation sandstones of the Lanark district, although they plot within the recycled orogenic field on Fig. 13a, fall within the mixed to volcanic-related provenance reflecting their slightly higher modal plagioclase contents. All of these sandstones possess a relatively high proportion of metamorphic and metamorphic/sedimentary lithic components (see Figures 10c, d and f) which includes low-grade metasedimentary rock fragments as well as clasts of higher grade schistose to phyllitic rocks. The metamorphic component also includes detrital garnet. It is possible that the Swanshaw Sandstone Formation from these three study areas were being supplied by two separate sources: **(1)** a recycled orogenic dominated by quartzose/metamorphic rocks; and **(2)** a volcanic source. However, there is no evidence of the sandstones having been derived from two discrete source areas (e.g. two groups of data for each formation) or any obvious mixing trends on Figures 10 to 12. As stated above, the most likely origin of the minor trends in sandstone composition within the Swanshaw Sandstone Formation is either an increase in sediment maturity, and/or a systematic increase in the volcanic component near the top of the formation prior to the onset of Lanark Group volcanism. The clustering of the data from the Swanshaw Sandstone Formation suggests that the sediment was well ‘mixed’ prior to being supplied to the Lanark basin. These sandstones are, therefore, interpreted as having largely been derived from a recycled orogenic provenance which included quartzose/metamorphic and volcanic rocks.

The quartzose sandstones analysed from the Carboniferous Ballagan, Kinnesswood and Lawmuir formations of the Lanark and Ayr districts plot within the craton interior (continental) and recycled orogenic fields on Fig. 13. On Figure 13b the data define an apparent linear trend ranging from craton interior, through quartzose recycled orogenic into transitional orogenic. This apparent variation in provenance reflects a change in total lithic content of these sandstones. The lithic component within these Carboniferous sandstones is mainly composed of polycrystalline quartz with subordinate to minor acidic tuffaceous volcanic rocks/felsite, chert and sedimentary intraclasts.

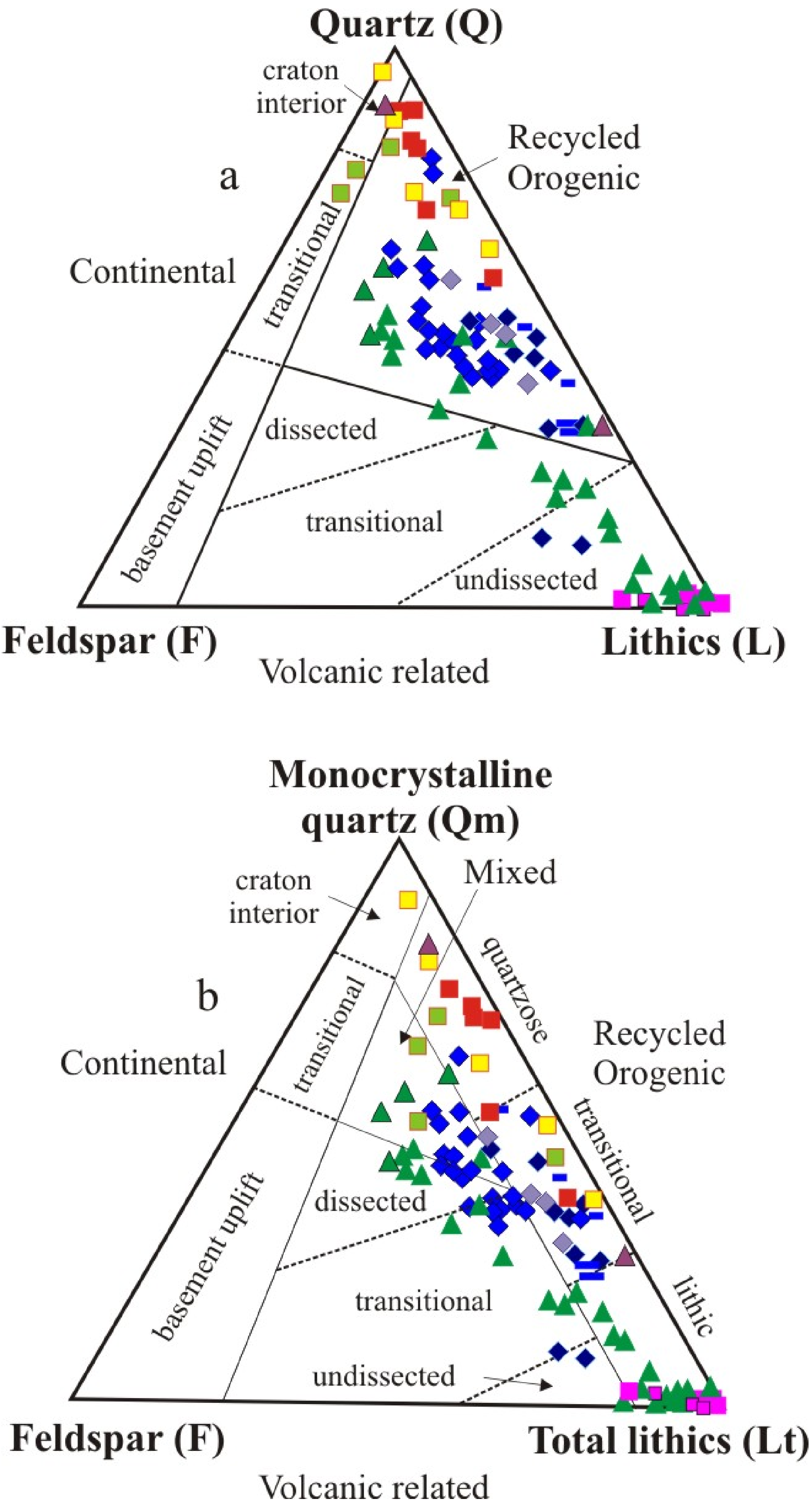

Figure 13. Ternary diagrams (after Dickinson and Suczek, 1979) for determining sedimentary provenance from sandstone compositional data. (a) Quartz-Feldspar-Lithic clasts. (b) Monocrystalline quartz-Feldspar-Total lithic clasts. For key see Figure 10.

5.3 DISCUSSION

The results of this petrographic provenance study clearly indicate that the sandstones from the Swanshaw Sandstone Formation (Lanark Group) exposed in the Lanark, New Cumnock and Ayr districts are compositionally similar and were derived from a recycled (transitional) orogenic source. Andesitic to dacitic volcanic rock fragments form the dominant lithic clast component within these sandstone dominated sequences, however, quartzose and metamorphic rock fragments are also common components. Available compositional data suggests that the sediment being supplied to the basin(s) during the deposition of the Swanshaw Sandstone Formation was well 'mixed' and derived from a single source. The systematic variation in unstable volcanic lithic clasts, with respect to monocrystalline quartz, within the Swanshaw Sandstone Formation may simply reflect an increase in volcanic input prior to the onset of volcanism during the deposition of the Lanark Group (cf. Phillips and Smith, 1995; Phillips and Barron, 2000, Phillips *et al*., 2004). However, in thin section no clear distinction can be made between the older volcanic component and the younger, penecontemporaneous Lanark Group volcanic rocks. Minor differences in sandstone composition between the Swanshaw Sandstone Formation of the Ayr, New Cumnock and Lanark districts probably reflects their deposition within a number of small strike-slip sub-basins, as proposed by Smith (1995) (also see Phillips *et al*., 1998). This evidence supports the conclusion of Phillips and Barron (2000) that these sub-basins, which initially developed during deposition of the older Silurian sedimentary sequence, continued to influence sediment dispersal during the deposition of at least the lower part of the Lanark Group.

The major change in sandstone composition within the Lanark Group coincides with the onset of Siluro-Devonian calc-alkaline volcanism (see Phillips and Smith, 1995; Phillips and Barron, 2000; Phillips *et al*., 2004). This volcanic episode was followed by the deposition of the Auchtitench Sandstone Formation which was largely derived from an undissected to dissected volcanic province. No obvious compositional differences have been recognised between the Auchtitench Sandstone Formation exposed in the New Cumnock and Lanark areas (Phillips and Barron, 2000; Phillips *et al*., 2004). This compositional evidence suggests that Siluro-Devonian basin architecture had changed from a series of relatively small sub-basins, to a single basin in which local controls on sediment composition and dispersal had been overwhelmed. The development of this single basin probably represents the formation of the northeast-southwest-trending Lanark basin referred to by Bluck (1983, 1984; and references therein). The Siluro-Devonian calc-alkaline within-plate volcanism, represented in the Ayr district by the Carrick Volcanic Formation, may therefore be interpreted as marking a major phase of extension. This led to the breakdown/abandonment of the pre-existing sub-basin architecture and the formation of the single Lanark Group sedimentary basin.

Compositional data from the Carboniferous sandstones, as expected, clearly demonstrates that they are compositionally distinct from the older Lanark Group sedimentary rocks. The available data suggests that the sandstones from the Ballagan, Kinnesswood and Lawmuir formations of the Lanark and Ayr districts were derived from a cratonic (continental) interior to quartzose recycled orogenic provenance. This apparent variation in provenance reflects a change in total lithic clast content of the sandstones. This typically minor component consists of polycrystalline quartz with subordinate to minor acidic tuffaceous volcanic rocks/felsite, chert and sedimentary intraclasts. Initial results of this petrographic provenance study also indicate that there are compositional differences between the Kinnesswood Formation of the Ayr district and the Lawmuir and Kinnesswood formations of the Lanark area. These potential regional compositional variations within the Kinnesswood and, possibly, Lawmuir formations may simply be a product of the small size of the data set at present, or be reflecting local changes in sandstone provenance within the Carboniferous sedimentary sequence.

6 Conclusions

A number of conclusions can be made regarding the geochemistry and tectonic setting of the Carrick Volcanic Formation and the provenance of the Siluro-Devonian sandstones of the Ayr district:

1. The lavas from the Carrick Volcanic Formation are calc-alkaline in character with the majority of the analysed rocks being basaltic andesite in composition, with a small number of analyses plotting in the basalt and andesite fields.
2. Alteration of the Carrick Volcanic Formation has resulted in the variable remobilisation of Na_2O, K_2O, CaO, Rb and Sr.
3. The major oxides TiO_2, Fe_2O_3 total, MgO and CaO and trace elements Zn, Ni, V, Cr and Sc all show decreasing trends as SiO_2 increases, typical of calc-alkaline magmatic differentiation paths, consistent with the fractionation of olivine and clinopyroxene within the basalts, and hornblende in the more andesitic lithologies.
4. The Carrick Volcanic Formation can be divided into two suites: **(1)** a suite of high-Mg basalts and basaltic andesites; and **(2)** and more 'normal' low-Mg lavas.
5. Trace element data obtained for the Carrick Volcanic Formation lavas can be used to subdivided these basaltic rocks into two groups in terms of their Ni and Cr content (> 80 ppm high-Ni, < 30 ppm low-Ni,> 100 ppm high-Cr, < 30 ppm low-Cr).
6. The available whole-rock geochemical data indicates that there is a significant change in composition within the Carrick Volcanic Formation. This change is characterised by marked break in the lithostratigraphical variations of the trace elements Nd, Y, Ce, Zr, Ni, Cr and V contents, and, to a lesser extent, Rb and Hf.
7. The Carrick Volcanic Formation rocks possess geochemical characteristics similar to calc-alkaline basaltic lavas erupted within either a continental volcanic-arc or within-plate setting.
8. There are marked compositional differences between the Carboniferous medium- to coarse-grained sandstones of the Ballagan, Kinnesswood and Lawmuir formations and the older Swanshaw and Auchtitench sandstone formations of the Siluro-Devonian Lanark Group.
9. Volcanic rock fragments form the dominant lithic clast component within the Lanark Group sandstones. However, metamorphic rock fragments are a common component in the Swanshaw Sandstone Formation.
10. There is a marked difference in composition between sandstones from the Duneaton Volcanic and Auchtitench Sandstone formations and those examined from the underlying Swanshaw Sandstone Formation.
11. Sandstones from the Auchtitench Sandstone Formation show a systematic variation in their volcanic lithic, plagioclase, metamorphic lithic clasts and, to a lesser extent, polycrystalline quartz contents with respect to monocrystalline quartz.
12. Sandstones from the Swanshaw Sandstone Formation show an apparent systematic variation in their polycrystalline quartz and volcanic lithic clasts, contents with respect to monocrystalline quartz. This systematic variation may reflect either: **(a)** a change in the maturity leading to an increase in the stable quartzose component of these sandstones; or **(b)** mixing of detritus from two separate source areas, one quartzose and the other volcanic in nature.
13. Initial data obtained for the Ballagan, Kinnesswood and Lawmuir formations suggest that these Carboniferous sandstones exhibit a systematic variation in their plagioclase,

metamorphic lithic and volcanic lithic clast contents with respect to monocrystalline quartz. The more mature Carboniferous sandstones are discriminated from the immature Siluro-Devonian sandstones by their higher monocrystalline quartz and polycrystalline quartz contents, and lower plagioclase, metamorphic lithic clast contents.

14. There are varying degrees of compositional overlap between the sandstones of the Swanshaw Sandstone Formation analysed from the Lanark, New Cumnock and Ayr districts suggesting that they were derived from a similar source.

15. The absence of any significant trends on the majority of the sandstone compositional plots suggests that the sediment being supplied to the Lanark Group basins was well 'mixed' and derived from a single source rather than a mixing of detritus from several areas. Consequently, the trends recognised within the Swanshaw Sandstone Formation may either reflect a change in the sediment maturity and/or an increase in the volcanic component towards the top of the formation prior to the onset of Lanark Group volcanism.

16. In general, compositional data for the sandstones from the Swanshaw Sandstone Formation of the New Cumnock and Ayr districts indicate that they have a transitional, recycled orogenic provenance.

17. The quartzose sandstones analysed from the Ballagan, Kinnesswood and Lawmuir formations of the Lanark and Ayr districts all fall within the craton interior (continental) and recycled orogenic fields.

Appendix 1 Thin section descriptions

Collectors Number: SRK28. **Registered Number:** N2560. **Location:** [NS 3312 1724] 450 m south of Doonside. **Rock Type:** Plagioclase-olivine-pyroxene macroporphyritic basalt. **Formation:** Carrick Volcanic Formation. **Symbol:** plopmaB^{B}.

Description: This thin section is of a inequigranular, weakly to moderately altered, hypocrystalline, weakly pilotaxitic, macroporphyritic basalt. The phenocrysts are mainly composed of plagioclase with subordinate bowlingite/iddingsite pseudomorphs after pyroxene. Also present are mesh-textured chlorite, bowlingite and carbonate pseudomorphs after olivine (± orthopyroxene) microphenocrysts. Olivine crystals were originally rounded, anhedral to subhedral in shape with the chloritic pseudomorphs being enclosed within a rim of opaque oxide. Plagioclase forms anhedral to subhedral, twinned, elongate to lath-shaped crystals which exhibit minor alteration to carbonate. These plagioclase phenocrysts locally possess sieve-textured cores containing rounded inclusions of chloritised glass and rare pseudomorphs after pyroxene/olivine. Plagioclase is variably shape-aligned and defines a weakly developed pilotaxitic fabric.

The fine- to medium-grained groundmass is feldspathic and composed of randomly orientated plagioclase laths with minor amounts of a interstitial to intersertal dusty mesostasis. The groundmass also contains pseudomorphs after granular pyroxene as well as granular to needle-like opaque minerals. The remainder of the interstitial areas are composed of cryptocrystalline chlorite which is locally partially replaced by carbonate.

Collectors Number: SRK31. **Registered Number:** N2561. **Location:** [NS 3342 1704] 200 m northeast of Carrick Lodge. **Rock Type:** Plagioclase microporphyritic basalt and fine-grained quartzose litharenite. **Formation:** Carrick Volcanic Formation **Symbol:** plmiB.

Description: This thin section is mainly composed of a very fine-grained, inequigranular, amygdaloidal, pilotaxitic, highly altered, microporphyritic basaltic rock. The basalt possesses a dusty grey appearance in plane polarised light due to the presence of finely disseminated opaque minerals within the groundmass (hematisation). The very fine-grained, originally glassy groundmass is variably altered to/replaced by hematitic oxide. A well-developed pilotaxitic to hyalopilitic fabric within the groundmass is defined by shape-aligned needle-like plagioclase laths. Larger plagioclase microphenocrysts (≤ 0.6 mm in length) are also variably aligned parallel to this foliation. Chloritic pseudomorphs after possible pyroxene microphenocrysts are also present. Irregular vugs or amygdales are composed of finely cryptocrystalline chloritic material. The basalt occurs as highly irregular fragments which possess complex to irregular clast margins; indicative of very little or no sedimentary reworking.

The remainder of the thin section is composed of a fine- to very fine-grained, open packed, well-sorted, quartzose, lithic-rich sandstone (litharenite) which possesses a very finely cryptocrystalline quartzose cement. The detrital assemblage within this sandstone is mainly composed of monocrystalline quartz, variably degraded lithic fragments (protolith uncertain) and feldspar. Other detrital components include muscovite, chlorite, opaque, biotite and garnet. Detrital grains are subrounded to rounded in shape with a low sphericity.

This rock may represent either: the rubbly top to a basaltic lava flow into which sediment has infiltrated; or pepperitic intrusion of basaltic magma into unlithified sand.

Collectors Number: SRK33. **Registered Number:** N2562. **Location:** [NS 3348 1677] 250 m east-south-east of Carrick Lodge. **Rock Type:** Highly altered microporphyritic basaltic rock. **Formation:** Carrick Volcanic Formation. **Symbol:** miB.

Description: This thin section is of a fine-grained, inequigranular, massive, amygdaloidal, microporphyritic basalt in which the primary mineral assemblage has largely been replaced by yellow-green cryptocrystalline chlorite, albitic plagioclase and hematitic oxide. Small, anhedral to weakly euhedral pseudomorphs after pyroxene and olivine microphenocrysts are common. These phenocrysts occur as single isolated crystals as well as in small glomerophyric clusters. The groundmass is composed of randomly orientated to locally shape-aligned plagioclase laths which are only slightly finer grained than the microphenocrysts. The original plagioclase is variably altered to albite and cryptocrystalline chlorite. The interstitial to intersertal areas are composed of turbid brown hematitic material which may in part represent a hematised mesostasis. Small irregular voids and larger rounded to irregular amygdales are composed of pale yellow-green chloritic material with trace amounts of quartz. This cryptocrystalline material is locally arranged in small radial fibrous rosettes.

Collectors Number: SRK34. **Registered Number:** N2563. **Location:** [NS 3304 1683] 100 m north of Maryland. **Rock Type:** Highly altered, pilotaxitic, feldspathic, plagioclase-pyroxene microporphyritic basalt or basaltic andesite. **Formation:** Carrick Volcanic Formation. **Symbol:** flplpmaB^{B}/B^{A} or maB^{B}/B^{A}.

Description: This thin section is of a fine-grained, inequigranular, pilotaxitic, hypocrystalline, amygdaloidal, plagioclase-pyroxene microporphyritic feldspathic basalt or basaltic andesite. Alteration and hydration of the rock resulted in the replacement of interstitial phases and the primary ferromagnesian minerals (pyroxene) by a cryptocrystalline chlorite-dominated assemblage. The phenocrysts are mainly composed of plagioclase with subordinate pyroxene. The latter is completely pseudomorphed by chlorite, iddingsite, bowlingite and opaque oxide. Plagioclase forms anhedral to subhedral, twinned, weakly zoned, prismatic to lath-shaped crystals which exhibit minor replacement by chlorite. The larger plagioclase phenocrysts may possess a dusty looking core due to very fine-grained inclusions of opaque minerals and possible chloritised glass.

The groundmass is composed of aligned, elongate to needle-like plagioclase laths with chlorite + opaque oxide pseudomorphs after interstitial granular pyroxene. Trace amounts of a dusty mesostasis were noted filling interstitial areas and forming rims upon plagioclase crystals. Rounded amygdales are composed of cryptocrystalline chloritic material. The pilotaxitic fabric present within the groundmass locally wraps around these amygdales.

Collectors Number: SRK35. **Registered Number:** N2564. **Location:** [NS 3264 1625] 50 m north-north-east of Halfway Bridge. **Rock Type:** Highly altered, olivine/pyroxene microporphyritic basaltic rock (comparable to N2562). **Formation:** Carrick Volcanic Formation. **Symbol:** omiB.

Description: This thin section is of a fine- to medium-grained, inequigranular, originally glassy, hypocrystalline, massive, weakly porphyritic basaltic rock in which the phenocrysts are only slightly coarser grained than the groundmass. The bulk of the rock is composed of randomly orientated, anhedral to subhedral plagioclase laths with carbonate (± chlorite) pseudomorphs after anhedral to subhedral olivine and/or pyroxene. A dusty brown mesostasis is patchily developed or preserved and contains needle-like crystals of opaque minerals as well as disseminated opaque minerals. The mesostasis fills the interstitial to intersertal spaces between plagioclase and pyroxene crystals. The remaining intergranular areas are composed of cryptocrystalline chloritic material which is interpreted as replacing glass and interstitial ferromagnesian minerals. Small patches of secondary carbonate were noted replacing chlorite. Trace amounts of quartz were also noted within this basaltic rock.

Collectors Number: SRK36. **Registered Number:** N2565. **Location:** [NS 3327 1654] 150 m north-west of Blairston Mains. **Rock Type:** Highly altered, olivine-microporphyritic basaltic rock (comparable to N2564). **Formation:** Carrick Volcanic Formation. **Symbol:** omiB.

Description: This thin section is of a fine- to medium-grained, inequigranular, highly altered, hypocrystalline, massive, weakly microporphyritic basaltic rock in which the phenocrysts are only slightly coarser grained than the groundmass. The primary ferromagnesian minerals (pyroxene and/or olivine) are completely pseudomorphed by hematitic oxide which forms an outer rim enclosing a core of cryptocrystalline chlorite, bowlingite, iddingsite and/or carbonate. Fe-oxides also preserve original fractures within these ferromagnesian minerals.

The bulk of the rock is composed of randomly orientated plagioclase laths. Plagioclase forms anhedral, twinned crystals with the larger crystals to microphenocrysts showing a weak zonation. Feldspar exhibits minor alteration to chlorite and carbonate. Interstitial to intersertal areas are mainly composed of cryptocrystalline, yellow-green chloritic material which is itself partially replaced by carbonate. Minor to trace amounts of a dusty feldspathic mesostasis and quartz were also noted within this basaltic rock. Quartz is a relatively common accessory phase and typically occurs interstitial to intersertal to plagioclase and may, therefore, be primary in origin. Needle-like crystals of opaque minerals are common within the groundmass.

Collectors Number: SRK37. **Registered Number: N2566.** Location: [NS 3355 1613] 350 m south-south-east of Blairston Mains. **Rock Type:** Microconglomerate. **Formation:** Swanshaw Sandstone Formation. **Symbol:** not applicable.

Description: This thin section is of a poorly sorted, lithic-rich, immature, moderately packed, matrix-supported, immature microconglomerate in which very coarse sand, granule and small pebble sized clasts are set within a finer grained sandstone matrix. The larger clasts are up to 20 to 30 mm in size and are subangular, subrounded to rounded in shape with a low sphericity. These larger detrital grains are composed of a very fine-grained, massive to finely banded cherty or tuffaceous rock. These rock fragments may locally contain thin cryptocrystalline quartz veinlets. Other lithologies include: very fine-grained sandstone to coarse-grained siltstone; foliated metasiltstone with aligned white mica flakes; quartz microporphyritic rhyolite (porphyry); and fine-grained quartzose litharenite. The very fine-grained sandstone to siltstone lithic clasts are locally embayed or indented against neighbouring more rigid grains. These sedimentary rock fragments also possess a hematitic or dark clay cement/matrix.

The sandstone matrix to this microconglomerate is composed of a medium-grained, moderately to closely packed, immature, quartzose litharenite. Detrital grains within the sandstone matrix are angular, subangular to occasionally subrounded in shape with a low sphericity. They are mainly composed of monocrystalline quartz and rock fragments. The latter are composed of a similar range of lithologies to the larger sand to small pebble-sized clasts within this microconglomerate. Other recognisable rock types present within the sandstone matrix include a feldspathic microcrystalline igneous rock and a fine sandstone with a chloritic matrix. Minor to accessory detrital components include polycrystalline quartz, muscovite/white mica and opaque minerals.

Minor to trace amounts of a very pale green chloritic cement are present within the sandstone matrix. Compaction resulted in the localised plastic deformation and embayment of unstable lithic grains.

Collectors Number: SRK39. **Registered Number:** N2567. **Location:** [NS 3356 1626] 250 m south-east of Blairston Mains. **Rock Type:** Highly altered, olivine/pyroxene microporphyritic basaltic rock. **Formation:** Carrick Volcanic Formation. **Symbol:** pomiB.

Description: This thin section is of a fine-grained, inequigranular, hypocrystalline, massive, microporphyritic basaltic rock in which the primary mineral assemblage has been largely replaced by a very fine-grained assemblage of chlorite, bowlingite and carbonate. Anhedral to subhedral microphenocrysts of pyroxene and/or olivine have been completely replaced by chlorite, bowlingite and carbonate with trace amounts of quartz. The mimetic growth of these alteration products locally preserves the original pyroxene cleavage. The microphenocrysts occur as single crystals as well as small glomerophyric clusters of several crystals. The groundmass of this basaltic rocks appears to have originally been composed of granular pyroxene with small randomly orientated plagioclase laths. These primary minerals are replaced by a turbid brown secondary assemblage. The rocks also contains rounded pockets of a turbid brown mesostasis.

Collectors Number: SRK41a. **Registered Number:** N2568. **Location:** [NS 3335 1620] 250 m south of Blairston Mains. **Rock Type:** Laminated siltstone intercalated with lavas of the Carrick Volcanic Formation. **Formation:** Carrick Volcanic Formation. **Symbol:** not applicable.

Description: This thin section is of a finely laminated siltstone with thin mudstone partings at the top of individual graded laminae. The grading is reflected in a change in grain size from silt to clay and a corresponding change in colour. Individual laminae range from 0.3 to 5.0 mm in thickness. There is an apparent systematic variation in thickness resulting in discrete intervals of slightly coarser grained and thicker laminated sediment. These intervals of slightly coarser grained sedimentation exhibit a more pronounced grading and distinct medium- to coarse-siltstone bases to the laminae. Recognisable detrital grains are composed of variably altered (hematised) biotite, muscovite and opaque minerals. The micas are variably aligned parallel to bedding. The mudstone partings possess a moderately developed bedding-parallel fabric defined by the alignment of clay plasma. Minor hematitic staining of the clay-grade component was noted within this siltstone.

Collectors Number: SRK41b. **Registered Number:** N2569. **Location:** [NS 3335 1620] 250 m south of Blairston Mains. **Rock Type:** Fragmented/brecciated, highly altered, olivine-pyroxene microporphyritic basaltic rock with a fracture filled by mudstone and siltstone. **Formation:** Carrick Volcanic Formation. **Symbol:** opmiB.

Description: This thin section is mainly composed of a highly altered, medium-grained, massive, hypocrystalline, amygdaloidal, weakly microporphyritic to aphyric basaltic rock in which the microphenocrysts are only slightly coarser grained than the groundmass. This basaltic rock is mainly composed of randomly orientated and variably altered plagioclase laths with pseudomorphs after olivine and/or pyroxene. These pseudomorphs are composed of an outer rim of opaque oxide enclosing a core of cryptocrystalline chlorite/bowlingite and carbonate. The original ferromagnesian mineral ranged from anhedral to subhedral in shape. Due to the alteration it is, in general, difficult to distinguish between the pseudomorphs after olivine and pyroxene.

Amygdales are composed of cryptocrystalline locally radial-fibrous chloritic material which is variably replaced by later carbonate. The mimetic growth of carbonate locally preserves the originally zoned nature of the amygdales. A dusty to turbid brown mesostasis containing finely disseminated opaque minerals occurs as an interstitial to intersertal phase within the groundmass. The groundmass is mainly composed of plagioclase with pseudomorphs after intergranular pyroxene and olivine. Plagioclase forms anhedral, twinned crystals which exhibit minor replacement by very fine-grained chlorite.

The basalt is fractured/brecciated with the fracture being filled by mudstone and subordinate siltstone; these lithologies are similar to N2568. The mudstone is also fractured with these fractures being infilled by fluidised siltstone.

Collectors Number: SRK42. **Registered Number:** N2570. **Location:** [NS 3320 1609] 400 m south-south-west of Blairston Mains. **Rock Type:** Altered, coarse-grained basalt or fine-grained microgabbro (dolerite). **Formation:** Carrick Volcanic Formation. **Symbol:** B or D.

Description: This thin section is of a weakly altered, aphyric, inequigranular, hypocrystalline, massive, coarse-grained basalt or fine-grained microgabbro (dolerite). The bulk of the rock is composed of randomly orientated plagioclase laths with intergranular subophitic clinopyroxene. Plagioclase is fresh forming small (≤ 0.8 mm in length), twinned and zoned, anhedral to subhedral, prismatic to lath shaped crystals. Clinopyroxene is very pale brown in colour and forms irregular to anhedral, intergranular, ophitic to subophitic crystals which range up to 1.0 mm in size. A turbid brown mesostasis occurs interstitial to both plagioclase and clinopyroxene, and contains needle-like to granular crystals of opaque minerals. Interstitial glass/mesostasis is altered to a cryptocrystalline chloritic assemblage. Similar chloritic material also occurs as thin veinlets and infilling rare vugs or amygdales. Pseudomorphs after olivine and/or pyroxene (possibly orthopyroxene) are composed of very finely cryptocrystalline chlorite and bowlingite. Olivine originally formed granular-looking anhedral crystals which, in some cases, appear to have been overgrown/rimmed by clinopyroxene. Clinopyroxene is essentially unaffected by the alteration.

Collectors Number: SRK43. **Registered Number:** N2571. **Location:** [NS 3354 1610] 400 m south-south-east of Blairston Mains. **Rock Type:** Laminated, medium- to coarse-grained quartzose sandstone (litharenite). **Formation:** Swanshaw Sandstone Formation. **Symbol:** not applicable.

Description: This thin section is of an immature, closely to very closely packed, clast-supported, graded, medium- to coarse-grained, quartzose, lithic-rich sandstone (litharenite). Bedding or lamination within the sample is defined by coarse siltstone and fine sandstone laminae, with the bulk of the thin section being dominated by a graded, medium- to coarse-grained sandstone. Detrital grains are angular to subangular in shape with a low sphericity. The clast assemblage is mainly composed of variably degraded lithic fragments and monocrystalline quartz. Lithic clasts are mainly composed of very fine-grained to cryptocrystalline tuffaceous lithologies and apparently related intermediate to felsic volcanic rock fragments. The alteration and degradation of these rock fragments makes identification of their original rock types problematic.

Occasional subrounded to rounded, very coarse sand- to small pebble-sized clasts are present at the base of the graded sandstone layer. Recognisable lithologies include felsite, mudstone, hematised metabasaltic rock, chert, quartzite and cleaved mudstone. Other minor to accessory detrital components include polycrystalline quartz, plagioclase, sericitised rock or feldspar, opaque minerals, tourmaline, titanite/rutile, white mica, garnet, biotite and K-feldspar. Localised quartz overgrowths were noted developed upon monocrystalline quartz grains. Grain boundary etching and pressure solution of quartz have also been recorded. Detrital micas within the siltstone layer are stained by, or altered to Fe-oxide. Minor kinking of detrital micas was also noted. The sandstone layers possess very little obvious matrix, however, traces of a hematitic/clay rim cement are present.

Collectors Number: SRK44. **Registered Number:** N2572. **Location:** [NS 3358 1608] 400 m south-south-east of Blairston Mains. **Rock Type:** Laminated, quartz-rich litharenite with a hematitic cement. **Formation:** Swanshaw Sandstone Formation. **Symbol:** not applicable.

Description: This thin section is of a fine-grained, poorly sorted, immature, quartzose lithic-rich sandstone (litharenite) which possesses a hematitic/clay cement or matrix. The texture of this sandstone varies from closely to moderately packed and clast-supported to locally open-packed and matrix-supported. Detrital grains are angular, subangular to subrounded in shape with a low to rarely moderate sphericity. Occasional rounded grains were also noted. The clast assemblage is mainly composed of monocrystalline quartz and variably hematised and degraded rock fragments.

The lithic clasts appear to have been mainly composed of a very fine-grained to cryptocrystalline tuffaceous or volcanic rock. However, the composition of the protolith is uncertain due to the intensity of later alteration. Recognisable rock fragments are composed of very fine-grained phyllitic or slaty metasedimentary rock, hematised mudstone, hematised siltstone and very fine-grained microgranitic or rhyolitic rock. Other minor to accessory detrital components include polycrystalline quartz, plagioclase, white mica, sericitised rock or feldspar, opaque minerals, hematised rock, K-feldspar, tourmaline, biotite and possible staurolite. A red brown hematitic matrix or cement is a distinctive feature of this sandstone. Very thin hematitic coatings have also been recognised on detrital grains. It is possible that part of the matrix may have been derived from degraded unstable lithic clasts.

Collectors Number: SRK47. **Registered Number:** N2573. **Location:** [NS 3237 1633] 300 m east-north-east of Halfway Bridge. **Rock Type:** Highly altered, coarse-grained basaltic rock. **Formation:** Carrick Volcanic Formation. **Symbol:** B.

Description: This thin section is of a coarse-grained, inequigranular, hypocrystalline, massive to weakly pilotaxitic, essentially aphyric, highly altered basaltic rock. The bulk of the rock is composed of anhedral, prismatic to lath-shaped, albitised plagioclase laths. Plagioclase locally exhibits a weakly developed preferred shape alignment defining a poorly developed pilotaxitic fabric. The primary ferromagnesian minerals (pyroxene, olivine) formed anhedral to euhedral crystals which are completely replaced by cryptocrystalline, locally mesh-textured assemblage of chlorite, bowlingite, opaque oxide and iddingsite. This chloritic assemblage is locally partly replaced by later carbonate (trace). Both pyroxene and olivine appear to have formed granular to prismatic crystals. A dusty brown mesostasis contains finely disseminated opaque minerals and occurs filling the interstitial to intersertal areas between the plagioclase laths. The remaining intergranular areas are composed of/filled by finely cryptocrystalline to radial-fibrous chloritic material.

Collectors Number: SRK48. **Registered Number:** N2574. **Location:** [NS 3393 1632] River Doon 100 m south-south-east of Nether Auchendrane. **Rock Type:** Microconglomerate with a fine-grained quartzose litharenite matrix. **Formation:** conglomeratic lens within Carrick Volcanic Formation. **Symbol:** not applicable.

Description: This thin section is of a fine-grained, immature, poorly sorted, matrix- to clast-supported, open packed microconglomerate with a fine-grained quartzose litharenite matrix. Very coarse sand- to small pebble-sized clasts are mainly composed of rock fragments. They are typically subrounded to rounded in shape with a low sphericity. However, subangular clasts are also present. The lithic clasts are dominated by sedimentary rock fragments including mudstone, siltstone and fine- to medium-grained sandstone (quartzose litharenite). All of these rock fragments possess a hematitic stained clay matrix or hematitic cement and appear to have been derived from the same source area. These larger sedimentary lithic clasts are compositionally distinct from the matrix but appear to be petrographically similar to sample N2572. Other recognisable rock fragments include: hematised, plagioclase microporphyritic basaltic rock; very fine-grained, recrystallised sandstone/metasandstone; cherty rock with quartz veins; chalcedonic quartz; and tuffaceous volcanic rock.

The thin section also contains a 2.0 to 3.0 mm layer of fine-grained sandstone which is texturally and compositionally similar to the matrix of the associated microconglomerate. The matrix to this microconglomerate is composed of a fine- to medium-grained, poorly sorted, very closely packed, immature, clast-supported, quartzose litharenite which possesses a patchily developed carbonate cement. Carbonate was noted replacing the unstable lithic clasts and locally results in the development of a more open cement-supported texture. Detrital grains within the sandstone matrix are angular, subangular to occasionally subrounded in shape with a low sphericity. They are mainly composed of variably altered rock fragments and subordinate monocrystalline quartz. The protoliths to the lithic clasts is uncertain due to carbonate replacement, but appears to have included: very fine-grained siltstone; very fine-grained volcanic or tuffaceous rock; hematised basalt; and a very fine-grained phyllitic to slaty metasedimentary rock. Other minor to accessory detrital components include opaque minerals, myrmekite/micrographic intergrowth of quartz and feldspar, white mica, K-feldspar, tourmaline and polycrystalline quartz.

The very close packing of the clasts within the matrix has locally resulted in the modification of the shape of more unstable grains and pressure solution of quartz. Carbonate replacement appears to have preferentially occurred within the sandstone matrix to this microconglomerate. However, some carbonate replacement of the larger sedimentary lithic clasts was also noted. A hematitic rim cement is patchily developed within the sandstone matrix of the microconglomerate.

Collectors Number: SRK49. **Registered Number:** N2575. **Location:** [NS 3392 1630] River Doon 100 m south-south-east of Auchendrane. **Rock Type:** fine- to medium-grained, quartzose, lithic-rich sandstone. **Formation:** conglomeratic lens within Carrick Volcanic Formation. **Symbol:** not applicable.

Description: This thin section is of a poorly to moderately sorted, fine- to medium-grained, very closely packed, matrix-poor, clast-supported, well-compacted, quartzose, lithic-rich sandstone (litharenite). This sandstone is compositionally and texturally similar to the matrix of the previously described microconglomerate (N2574), but lacks the carbonate replacement. Detrital grains are angular to subangular in shape with a low sphericity. However, grain shape has locally been modified due to the very close packing of this sandstone and apparently high degree of compaction. The clast assemblage is mainly composed of variably altered and degraded rock fragments and subordinate monocrystalline quartz clasts. The lithic clasts are composed of a range of lithologies, but are mainly composed of a very fine-grained, altered volcanic or tuffaceous rock. Other recognisable lithologies include: cryptocrystalline quart or cherty rock; chloritised tuff; very fine-grained, matrix-rich sandstone or siltstone; hematitic siltstone; very fine-grained, chloritic sandstone and siltstone ('greywacke'); rhyolite/felsite; phyllitic or slaty meta-mudstone; very fine-grained, schistose metasedimentary rock; and very fine-grained sandstone.

Minor to accessory detrital components include polycrystalline quartz, garnet, opaque and white mica. A weak shape alignment of detrital grains and traces of a replacive carbonate noted. A very fine-grained sericitic rim cement or coating developed on detrital grains was noted. Moulding and embayment of unstable lithic clasts occurred against neighbouring more rigid detrital grains. Compaction also resulted in localised pressure solution between adjacent quartz grains and flattening of siltstone clasts. Minor to trace amounts of a colourless, cryptocrystalline clay or chloritic cement was noted filling intergranular pore space.

Collectors Number: SRK50. **Registered Number:** N2576. **Location:** [NS 3389 1620] River Doon 125 m south of Nether Auchendrane. **Rock Type:** Highly altered basaltic rock comparable to N2573. **Formation:** Carrick Volcanic Formation. **Symbol:** B.

Description: This thin section is of a coarse-grained, inequigranular, aphyric, weakly amygdaloidal, hypocrystalline, highly altered basaltic rock which is petrologically similar to sample N2573. The original igneous mineralogy has largely been replaced by a cryptocrystalline chloritic assemblage. Pyroxene (± olivine) originally formed anhedral to rarely euhedral crystals which are completely replaced by chlorite and/or bowlingite. Pseudomorphs after possible olivine comprise an outer rim of opaque oxide enclosing a chloritic core which may be partially replaced by later carbonate. Elongate, lath-shaped plagioclase crystals are randomly orientated and exhibit minor replacement by chlorite and carbonate along fractures. Plagioclase forms twinned and locally weakly zoned crystals. Interstitial to intersertal areas are filled or replaced by cryptocrystalline chlorite. Rounded to irregular patches of cryptocrystalline quartz and chloritic material are common and appear to be filling vug or amygdales.

Collectors Number: SRK53. **Registered Number:** N2577. **Location:** [NS 3252 1915] River Doon, by weir, 100 m north-west of Doonfoot Bridge. **Rock Type:** Highly altered (chloritised), weakly pilotaxitic basaltic rock. **Formation:** Passage Formation. **Symbol:** flB or B.

Description: This thin section is of a medium- to coarse-grained, inequigranular, aphyric, weakly pilotaxitic, highly altered, chloritised basaltic rock. The rock comprises a network of variably aligned plagioclase laths enclosing rounded to irregular patches of cryptocrystalline chloritic material. These chloritic patches may represent highly altered glass and/or amygdales as well as occasional pseudomorphs after ferromagnesian minerals (possible pyroxene). Plagioclase forms anhedral to subhedral, twinned and zoned, lath-shaped crystals which exhibit minor alteration to chlorite and carbonate. Plagioclase also contains very fine-grained, dusty to granular inclusions of opaque minerals. Interstitial to intersertal to the feldspar is a chloritised mesostasis which contains disseminated, granular and very fine needle-like crystals of opaque minerals. Traces of quartz (locally chalcedonic) were also noted interstitial to plagioclase.

Collectors Number: SRK56. **Registered Number:** N2578. **Location:** [NS 3230 1841] tributary of River Doon, east-north-east of Longhill Bridge. **Rock Type:** Microconglomerate rich in calcareous mudstone clasts. **Formation:** Ballagan Formation. **Symbol:** not applicable.

Description: This thin section is of a poorly sorted, moderately to open packed, matrix supported, calcareous microconglomerate with a medium-grained, slightly feldspathic quartz-arenite matrix. The microconglomerate is characterised by the presence of subrounded, rounded to irregular clasts of carbonate-replaced mudstone, sandstone and occasionally siltstone. These clasts have a moderate to low sphericity. It is possible that some of the clasts may be of limestone rather than highly altered clastic sedimentary rock. The more irregular clasts have clearly had their shape modified due to pressure solution and embayment against neighbouring, more rigid, quartzose grains as a result of compaction. These calcareous clasts may be fractured (compaction-related) and partially recrystallised to a fine-grained sparry carbonate mosaic. The calcareous siltstone and sandstone clasts contain very fine-grained relict detrital clasts of quartz, tourmaline, opaque oxide and oxidised biotite. Localised stylolite development was noted in response to pressure solution along the contacts between adjacent calcareous mudstone clasts.

The matrix to this microconglomerate is composed of a slightly feldspathic quartz-arenite which possesses a well developed sparry carbonate cement. The sandstone exhibits a moderately packed, clast to locally cement supported texture. The clasts within this sandstone are subangular to subrounded with a low sphericity. Grain shape has locally been modified during the development of the replacive carbonate cement. The clast assemblage is dominated by monocrystalline quartz with minor feldspar and carbonate-replaced mudstone lithic fragments. Other minor to accessory detrital components include felsite/chert, microcline, polycrystalline quartz, garnet, plagioclase, epidote and opaque minerals. Some of the monocrystalline quartz clasts possess an undulose extinction.

Collectors Number: SRK57. **Registered Number:** N2579. **Location:** [NS 3230 1843] tributary of River Doon, north-east of Longhill Bridge. **Rock Type:** Highly altered, olivine microporphyritic basaltic rock. **Formation:** dyke in Ballagan Formation. **Symbol:** omiB.

Description: This thin section is of a highly altered, inequigranular, massive, microporphyritic, weakly amygdaloidal basaltic rock. The rock has been mainly replaced by a very fine-grained to cryptocrystalline chloritic assemblage. Alteration has resulted in the variable overprinting of the original igneous texture of the rock. Olivine microphenocrysts and small intergranular crystals are pseudomorphed by carbonate. Olivine was originally anhedral to subhedral in shape and formed rounded fractured crystals. Plagioclase forms small randomly orientated, twinned and zoned, lath-shaped crystals which exhibit minor replacement by chlorite and carbonate. Interstitial glass and granular looking pyroxene are replaced by cryptocrystalline chlorite, bowlingite, opaque oxide and carbonate. Trace amounts of interstitial to intersertal quartz and small chloritised flakes of biotite were also noted within this rock.

Collectors Number: SRK58a. **Registered Number:** N2580. **Location:** [NS 3231 1849] tributary of River Doon, north-east of Longhill Bridge. **Rock Type:** Laminated, calcareous sandstone (quartz-arenite). **Formation:** Ballagan Formation. **Symbol:** not applicable.

Description: This thin section is of a fine- to medium-grained, moderately to well-sorted, compositionally mature, calcareous sandstone (quartz-arenite). The shape of the detrital grains have been modified due to the etching of grain boundaries during the development of the carbonate cement (replacive), as well as pressure solution between quartzose grains and the localised development of quartz overgrowths. The clasts appear to have originally possess a low to possibly moderate sphericity. The clast assemblage is dominated by monocrystalline quartz. Quartz is unstrained to weakly strained with locally developed planar, but typically more irregular grain boundaries. The variation in the modal proportions of the carbonate cement and a thin muddy parting preserves an original sedimentary lamination. Other minor to accessory detrital components include plagioclase, microcline, tourmaline, opaque minerals, garnet, cryptocrystalline quartz or chert, rutile and monazite. The well-developed carbonate cement locally contains anhedral to weakly subhedral rhomb-shaped crystals which may be used to suggest that the cement is or was dolomitic.

Collectors Number: SRK58b. **Registered Number:** N2580. **Location:** [NS 3231 1849] tributary of River Doon, north-east of Longhill Bridge. **Rock Type:** Laminated, calcareous pebbly sandstone (quartz-arenite). **Formation:** Ballagan Formation. **Symbol:** not applicable.

Description: This thin section is of a coarse-grained, poorly to very poorly sorted, moderately to open-packed, clast-supported, pebbly, calcareous, quartz-rich sandstone (quartz-arenite) which contains very coarse-sand, granule to occasional small pebble sized clasts of carbonate replaced mudstone or recrystallised micritic limestone. The shape of these clasts has been modified due to pressure solution and embayment against neighbouring more rigid quartzose grains. Localised stylolite development was noted associated with pressure solution between adjacent calcareous clasts. The calcareous mudstone clasts appear to have originally been rounded to subrounded in shape with a low to occasionally moderate sphericity.

The clast assemblage of the remainder of the sandstone is mainly composed of monocrystalline quartz. Other minor to accessory detrital components include plagioclase, K-feldspar, microcline, polycrystalline quartz, garnet and opaque minerals. The shape of the quartz grains has been modified due to localised pressure solution and grain boundary etching possibly associated with the development of a carbonate cement. Quartz is strained to unstrained. Compaction also resulted in localised fracturing of quartzose clasts with the fractures filled by carbonate. A sedimentary lamination present within this rock is defined/preserved by the variation in the modal proportion of carbonate and grain size of detrital clasts. Traces of a hematitic rim cement, pre-dating the main carbonate cement, was also noted. The carbonate cement appears to replace the original matrix and/or cements within this sandstone. The rock is deformed by a cataclastic fracture with localised shearing along this brittle structure resulting in the development of an oblique fabric within the carbonate vein material.

Collectors Number: SRK60. **Registered Number:** N2581. **Location:** [NS 3236 1858] tributary of River Doon, north-north-east of Longhill Bridge. **Rock Type:** Very fine-grained calcareous sandstone and conglomerate with calcareous mudstone clasts. **Formation:** Ballagan Formation. **Symbol:** not applicable.

Description: This thin section can be divided into two distinct lithologies: a layer of very fine-grained calcareous sandstone; and a layer of conglomerate containing calcareous mudstone lithic clasts. The conglomerate dominates this thin section.

The sandstone (calcareous quartz-arenite) is finely laminated with lenticular, originally clay/mud-rich partings having been replaced by secondary carbonate. The sandstone possesses an open-packed, cement-supported to locally clast-supported texture with the original matrix and unstable detrital grains having been replaced by a secondary carbonate cement. Detrital grains are subangular to subrounded with a moderate to low sphericity. The clasts are mainly composed of monocrystalline quartz. Minor to accessory detrital components include white mica, biotite, opaque minerals, plagioclase, garnet, chlorite, microcline and possible monazite.

The conglomerate is mainly composed of closely to locally moderately packed, clast-supported mudstone lithic fragments with minor siltstone and monocrystalline quartz grains set within a fine, muddy matrix. The clasts range from fine sand up to small pebble sized (> 6.0 mm in length). The calcareous mudstone clasts are irregular in shape with a low sphericity. They are shape-aligned parallel to bedding and possess irregular, embayed grain boundaries due to pressure solution between adjacent clasts. Irregular stylolites are developed along grain contacts and are denoted by a thin dark brown to honey brown seam or veinlet of clay minerals. The mudstone clasts are mainly composed of massive, cryptocrystalline carbonate which may contain small, silt-grade quartz clasts. The calcareous mudstone clasts may also be cut by irregular veinlets composed of coarser grained carbonate; these may represent carbonate filled dewatering fractures.

Collectors Number: SRK62. **Registered Number:** N2583. **Location:** [NS 3120 1933] in cliffs just to east, below Greenan Castle. **Rock Type:** Coarse-grained volcaniclastic sandstone (litharenite). **Formation:** Greenan Castle Pyroclastic Member. **Symbol:** not applicable.

Description: This thin section is of a coarse-grained, poorly sorted, moderately to open-packed, immature, lithic-rich, weakly laminated volcaniclastic sandstone (litharenite). The packing of this sandstone varies from very close to open, with the higher degree of packing occurring in the finer grained laminae. These finer grained laminae also exhibit a higher intensity of alteration/degradation of the unstable lithic clasts. Detrital grains are angular, subangular to slightly irregular in shape with a low sphericity. A weakly developed, preferred shape alignment of elongate clasts was noted. The clasts are mainly composed of chloritised basaltic rock fragments which are broadly similar in composition and exhibit minor alteration to secondary carbonate. These volcanic lithic clasts range from medium sand to granule in size and are enclosed within or coated by a thin oxide rim. Other minor to accessory detrital components include plagioclase, monocrystalline quartz, hematised rock fragments and chlorite-carbonate-quartz vein material or highly altered rock. Traces of a chloritic cement and pore-filling sparry carbonate cement were noted within this sandstone. Compaction resulted in localised pressure solution and embayment of unstable lithic clasts.

Collectors Number: SRK63. **Registered Number:** N2584. **Location:** [NS 3002 1888] shoreline, opposite middle of Holiday camp. **Rock Type:** Carbonate-replaced, laminated, mudstone and siltstone. **Formation:** Ballagan Formation. **Symbol:** not applicable.

Description: This thin section is of a finely laminated, calcareous mudstone and siltstone in which the clay/mud fraction has been completely replaced by massive very fine-grained, micritic carbonate. Silty layers and bases to laminae were originally graded and contain silt to fine sand-grade clasts of monocrystalline quartz. Other accessory detrital components observed within these slightly more coarse-grained laminae include white mica, carbonate-replaced mudstone rip-up clasts, tourmaline, opaque minerals and plagioclase. Small irregular to dusty looking opaque material may represent carbonaceous plant remains. One complete ostracod valve has been recognised. This very fine bioclast/fossil is filled by clay. Small scale erosional surfaces are preserved at the base of these coarse siltstone laminae. Other sedimentary structures preserved/recognised within this sample include grading, minor soft sediment deformation and a weak convolute lamination. Fractures and an irregular vug/void within the rock are filled by clear, sparry carbonate.

Collectors Number: SRK64a. **Registered Number:** N2585. **Location:** [NS 3278 1830] River Doon, 250 m south-east of Doonbank Farm. **Rock Type:** Fragmented/brecciated calcareous rock. **Formation:** Kinnesswood Formation. **Symbol:** not applicable.

Description: This thin section is of a fragmented or brecciated, very fine-grained calcareous rock which contains irregular patches of clear sparry carbonate apparently forming the cement/matrix. The fine-grained calcareous rock exhibits a dusty appearance in plane polarised light. It occurs as irregular, angular to subangular fragments which locally contain fine- to medium-sand grade monocrystalline quartz grains. These quartz grains are angular, subangular to occasionally subrounded in shape and may represent relict detrital grains and/or diagenetic quartz crystals. These calcareous rock fragments may also contain slightly darker coloured, rounded to subrounded clasts of micritic carbonate. The remainder of the sample is composed of fine- to medium-grained sparry carbonate which possesses an anhedral granular texture. Fine-grained, granular looking carbonate was noted forming rims upon the calcareous rock fragments with the centre of the fractures/vugs filled by more coarse-grained sparry carbonate.

Collectors Number: SRK65. **Registered Number:** N2586. **Location:** [NS 3275 1826] River Doon, 250 m south-east of Doonbank Farm. **Rock Type:** Calcareous microconglomerate containing clasts of micritic carbonate rock. **Formation:** Kinnesswood Formation. **Symbol:** not applicable.

Description: This thin section is of a very poorly sorted, open-packed, very coarse-grained, calcareous pebbly sandstone or microconglomerate which contains granule to pebble-sized clasts of a very fine-grained to micritic carbonate rock. These clasts are subrounded to slightly irregular in shape with a low to moderate sphericity. The shape of these clasts has, however, been modified during compaction which resulted in pressure solution and embayment of these unstable lithic fragments against neighbouring more rigid quartzose grains. The carbonate rock fragments occur in distinct layers and are variably shape-aligned parallel to a weak sedimentary lamination. Other granule to pebble-sized clasts are occasionally composed of a very fine-grained possibly tuffaceous rock, strained polycrystalline quartz and hematised cherty rock.

The remainder of the sandstone consists of angular, subangular to rounded, low to moderate sphericity clasts set in a well-developed carbonate cement. The sandstone has an open packed and cement-supported texture. The shape of the detrital grains has locally been modified during the development of the carbonate cement; the latter appears to be replacing the original matrix and/or unstable detrital grains. The detrital grains appear to have originally been rounded to subrounded in shape. They are mainly composed of monocrystalline quartz. Other minor to accessory detrital components include polycrystalline quartz, plagioclase, sheared vein quartz or quartz mylonite, K-feldspar, tourmaline and muscovite/white mica. Clasts of deformed vein quartz or quartz mylonite are a common minor detrital component. Etching of clast grain boundaries was noted apparently associated with the development of the carbonate cement.

Collectors Number: SRK67. **Registered Number:** N2587. **Location:** [NS 3099 1779] 400 m north-east of Balig Farm. **Rock Type:** Highly altered, plagioclase-pyroxene microporphyritic basalt or basaltic andesite. **Formation:** Carrick Volcanic Formation. **Symbol:** plpmiB^B/A^B or B^B/A^B.

Description: This thin section is of a fine-grained, massive to weakly pilotaxitic, inequigranular, microporphyritic to weakly macroporphyritic, hypocrystalline, slightly feldspathic basalt or basaltic andesite. The phenocrysts are mainly composed of plagioclase with subordinate pseudomorphs after pyroxene microphenocrysts. Pyroxene originally formed anhedral to subhedral, locally embayed to skeletal crystals which are completely replaced by chlorite and/or bowlingite. Small Fe-oxide and iddingsite pseudomorphs after possible orthopyroxene and/or olivine are also present. Plagioclase forms anhedral to subhedral, twinned and zoned, lath-shaped to prismatic equant crystals. Larger plagioclase phenocrysts locally possess a sieve-textured core with irregular to worm-like inclusions of chloritised glass. Plagioclase occurs as single isolated phenocrysts and as clusters of several (3 to 4) crystals. Feldspar may also exhibit a preferred shape-alignment defining a weakly developed pilotaxitic fabric.

The groundmass is fine-grained and massive in appearance. It is mainly composed of randomly orientated plagioclase laths with interstitial to intersertal chloritised pyroxene and a dusty looking mesostasis. Minor relict clinopyroxene was noted within the groundmass. However, interstitial granular looking pyroxene is typically altered to chlorite (± bowlingite). The mesostasis locally forms rims upon plagioclase and contains numerous very fine-grained inclusions of opaque minerals/oxide. Coarser grained granular to needle-like crystals of opaque minerals are also present within the groundmass.

Collectors Number: SRK68. **Registered Number:** N2588. **Location:** [NS 3248 1915] just south of River Doon by sea weir. **Rock Type:** Fine-grained, quartz-rich sandstone (quartz-arenite) with small patches of replacive carbonate cement. **Formation:** Lawmuir Formation. **Symbol:** not applicable.

Description: This thin section is of a fine-grained, closely packed, relatively compositionally mature, quartzose, massive sandstone which contains small pockets or patches of a replacive carbonate cement. Detrital grains are subangular to subrounded in shape with a low sphericity. The shape of the clasts is locally modified by the pressure solution of quartz and localised development of early quartz overgrowths. The clast assemblage is mainly composed of monocrystalline quartz. Other minor to accessory detrital components include polycrystalline quartz, degraded/altered rock fragments (protolith uncertain), K-feldspar, plagioclase, opaque minerals, white mica, epidote, variably chloritised biotite, chlorite and apatite.

Minor kinking of detrital micas was noted. Pressure solution appears to result in the main form of cementation within this sandstone. However, minor amounts of a pore-filling, intergranular, cryptocrystalline to very fine-grained radial-fibrous feldspathic or clay matrix or cement is also present. This matrix component is variably replaced by red-brown, hematite-stained carbonate. Carbonate includes rhomb-shaped crystals which may be either dolomite or pseudomorphs after dolomite (calcified dolomite).

Collectors Number: SRK69. **Registered Number:** N2589. **Location:** [NS 3170 1838] River Doon tributary, west of Longhill Bridge. **Rock Type:** Coarse-grained, feldspathic, quartz-rich sandstone (quartz-arenite). **Formation:** Kinnesswood Formation. **Symbol:** not applicable.

Description: This thin section is of a coarse-grained, poorly sorted, open-packed, cement-supported, slightly feldspathic, calcareous quartz-rich sandstone (feldspathic quartz-arenite) which possesses a well-developed carbonate cement. The medium- to coarse-grained sparry carbonate cement has a granular appearance and slightly dusty appearance in plane polarised light. The clastic grains are angular, subangular to subrounded in shape with a low sphericity. However, the shape of the clasts have been modified due to grain boundary etching as a result of the development of the carbonate cement. The detrital grains appear to have originally been subrounded to rounded in shape.

Detrital grains range up to 1.7 mm in size. The detrital assemblage is mainly composed of monocrystalline quartz with minor K-feldspar (including microcline). Other minor to accessory detrital components include polycrystalline quartz, plagioclase, opaque minerals, garnet, biotite, felsite, tuffaceous volcanic rock, mesoperthite and muscovite. Compaction resulted in minor fracturing of quartz clasts with the fractures filled by carbonate and localised pressure solution between adjacent quartz and quartz-feldspar grains. The carbonate cement locally possess a red-brown hematitic stain, or included relicts of the original clay matrix.

Collectors Number: SRK72. **Registered Number:** N2590. **Location:** [NS 3164 1828] River Doon tributary, west of Longhill Bridge. **Rock Type:** Laminated, fine- to medium-grained, calcareous sandstone. **Formation:** Kinnesswood Formation. **Symbol:** not applicable.

Description: This thin section is of a poorly sorted, moderately to open packed, clast- to cement-supported, fine- to medium-grained, laminated, compositionally immature, calcareous sandstone which possesses a well-developed carbonate cement. The cement is replacing the original matrix and unstable detrital components within this sandstone. Carbonate forms anhedral crystals (≤ 0.8 mm in size) which include or overgrow detrital grains. Lithic clasts appear to have formed a common minor component within this sandstone. The outlines of these highly altered/replaced rock fragments can still be recognised. Detrital grains are subangular to subrounded in shape with a low to occasionally moderate sphericity. The detrital assemblage was originally composed of monocrystalline quartz with subordinate rock fragments and minor feldspar clasts. The composition of the rock fragments is uncertain due to alteration, however they may have include a very fine-grained tuffaceous rock.

Other minor to accessory detrital components include plagioclase, muscovite, K-feldspar, microcline, chloritised biotite, opaque minerals, polycrystalline quartz, chloritised rock or chlorite pseudomorphs after a ferromagnesian minerals. Compaction resulted in localised pressure solution between adjacent quartz grains. Traces of a chloritic matrix are also present and may have been partially derived from degraded/altered rock fragments. The sedimentary lamination present within this preserved by a change in grain size from fine- to medium-grained sand.

Collectors Number: SRK73. **Registered Number:** N2591. **Location:** [NS 3218 1797] old quarry, 600 m east-north-east of Burton Farm. **Rock Type:** Brecciated limestone or carbonate replaced sandstone. **Formation:** Kinnesswood Formation. **Symbol:** not applicable.

Description: This thin section is of a fractured carbonate-replaced sandstone or limestone. The fractures are filled by texturally zoned, cryptocrystalline to very fine-grained (c. 0.2-0.3 mm in size) quartz. The quartz forms a cement to the fractured calcareous rock which forms angular to irregular fragments. The calcareous rock is mainly composed of dusty looking (in plane polarised light), cryptocrystalline or micritic carbonate as well as slightly coarser grained sparry carbonate. The carbonate rock also contains angular to rounded quartz grains which probably represent relict monocrystalline detrital grains. A crudely developed banding and mottling was noted within some of the calcareous rock fragments. Relict quartz grains were also noted within the cryptocrystalline quartz.

Collectors Number: SRK2. **Registered Number:** N2540. **Location:** [NS 3302 1708] Newark Estate, small quarry 300 m north of Glen Imm. **Rock Type:** Pilotaxitic plagioclase-pyroxene macroporphyritic basalt. **Formation:** Carrick Volcanic Formation. **Symbol:** flplpmaB^{B} or B^{B}.

Description: This thin section is of a fine-grained, inequigranular, hypocrystalline, altered, feldspathic, macroporphyritic basalt with weakly seriate plagioclase phenocrysts. Alteration and hydration resulted in the development of a very fine-grained assemblage of chlorite, carbonate, Fe-oxide, iddingsite and bowlingite. The phenocrysts are mainly composed of plagioclase with subordinate chlorite-carbonate pseudomorphs after pyroxene. Plagioclase forms subhedral to euhedral, twinned, lath-shaped to occasionally equant crystals which range up to 3.5 mm in length. Feldspar occurs as single isolated crystals and clusters of several, locally stacked phenocrysts. Plagioclase also exhibits a preferred shape alignment defining a weakly developed pilotaxitic fabric.

The groundmass is fine- to medium-grained and massive in appearance. It is composed of randomly orientated plagioclase laths with interstitial chloritised, granular pyroxene and dusty looking mesostasis. The mesostasis contains very fine-grained, granular to dusty looking opaque crystals. Small irregular patches of very fine-grained, radial-fibrous chlorite was noted within the groundmass.

Collectors Number: SRK3. **Registered Number:** N2541. **Location:** [NS 3239 1694] Newark Estate, 100 m west of Newarkhill Farm. **Rock Type:** Highly altered, pilotaxitic olivine-pyroxene-plagioclase microporphyritic basalt. **Formation:** Carrick Volcanic Formation. **Symbol:** flopplmiB or B.

Description: This thin section is of a medium- to coarse-grained, inequigranular, hypocrystalline, highly altered, microporphyritic basaltic rock which comprises the assemblage plagioclase, chlorite, opaque minerals, carbonate, bowlingite and iddingsite. Phenocrysts of olivine are completely pseudomorphed by a cryptocrystalline assemblage of chlorite, bowlingite, opaque and iddingsite. These pseudomorphs consist of an outer rim of an opaque mineral enclosing a core of chloritic material. Fractures within the original relict olivine are preserved by thin seams or veinlets of opaque oxide. The bulk of the rock is composed of aligned plagioclase laths which define a well-developed pilotaxitic fabric which wraps around the microphenocrysts. The plagioclase is fractured and exhibits minor alteration to chlorite. Traces of interstitial to intersertal mesostasis are present. Interstitial pyroxene and glass have been completely replaced by a pale green chloritic assemblage. Minor to trace amounts of interstitial to intersertal feldspar were also noted.

Collectors Number: SRK5. **Registered Number:** N2542. **Location:** [NS 3190 1665] Newark Estate, 650 m south-west of Newarkhill Farm. **Rock Type:** Highly altered, weakly pilotaxitic, plagioclase-pyroxene macroporphyritic basalt. **Formation:** Carrick Volcanic Formation. **Symbol:** flplmaB or B.

Description: This thin section is of a fine- to very fine-grained, highly altered, amygdaloidal, inequigranular, hypocrystalline, macroporphyritic basaltic rock which comprises the assemblage plagioclase, chlorite, bowlingite, opaque minerals and quartz. The phenocrysts are mainly composed of plagioclase with minor chlorite/bowlingite pseudomorphs after a ferromagnesian mineral (pyroxene, ± olivine). The pseudomorphs may also contain trace amounts of opaque oxide and, in some cases, quartz. Plagioclase forms anhedral to weakly subhedral, twinned crystals which are variably rounded due to resorption. Primary plagioclase is variably recrystallised to albite. It occurs as single isolated crystals as well as clusters of 3 to 4 crystals. Larger plagioclase phenocrysts (up to 3.0-4.0 mm in length) may contain very fine-grained, rounded to worm-like inclusions of altered glass and dusty opaque minerals. Plagioclase is locally fractured and exhibits minor alteration to chlorite. The variable alignment of plagioclase phenocrysts defines a weakly developed pilotaxitic fabric.

The groundmass is very fine-grained and massive in appearance. It is mainly composed of randomly orientated plagioclase laths which chloritised intergranular pyroxene and mesostasis. The mesostasis locally forms rims upon plagioclase laths and contains very fine-grained opaque crystals. Elongate to needle-like opaque crystals are also present within the groundmass. Irregular patches of chloritic material may represent amygdales.

Collectors Number: SRK8. **Registered Number:** N2543. **Location:** [NS 3166 1615] Newark Estate, 650 m west-north-west of High Midton. **Rock Type:** Highly altered, pilotaxitic, weakly olivine-plagioclase microporphyritic basalt. **Formation:** Carrick Volcanic Formation. **Symbol:** floplmiB or B.

Description: This thin section is of a highly altered, inequigranular, aphyric to weakly microporphyritic, hypocrystalline, fine-grained basaltic rock which consists of the assemblage plagioclase, chlorite, opaque minerals, quartz, bowlingite and carbonate. The phenocrysts within this microporphyritic basalt are only slightly coarser grained than the groundmass. These phenocrysts are mainly composed of pseudomorphs after olivine (± pyroxene) with only minor to occasional plagioclase crystals. The ferromagnesian minerals are completely replaced by a cryptocrystalline assemblage of chlorite, bowlingite, quartz and trace amounts of carbonate. The original shape and fractures within olivine are preserved by thin seams or veinlets of opaque oxide. Plagioclase phenocrysts are anhedral to subhedral in shape and exhibit minor alteration to chlorite (± albite). These phenocrysts are variably aligned parallel to a pilotaxitic fabric present within the groundmass.

The groundmass is mainly composed of aligned plagioclase laths defining a well-developed pilotaxitic fabric. Interstitial to intersertal areas are filled by chloritised pyroxene, granular opaque minerals and a variably altered mesostasis. The mesostasis locally forms a rim upon plagioclase and contains very fine-grained, dusty looking inclusions of opaque minerals. Irregular vugs and amygdales are texturally zoned and composed of cryptocrystalline to radial fibrous chlorite with an outer rim of cryptocrystalline quartz.

Collectors Number: SRK9. **Registered Number:** N2544. **Location:** [NS 3172 1679] Newark Estate, 800 m west-south-west of Newarkhill Farm. **Rock Type:** Highly altered, pilotaxitic, weakly olivine-plagioclase microporphyritic basalt (comparable to sample N2543). **Formation:** Carrick Volcanic Formation. **Symbol:** floplmiB or B.

Description: This thin section is of a medium- to coarse-grained, hypocrystalline, highly altered, feldspathic basaltic rock which comprises an inequigranular assemblage of plagioclase, chlorite, carbonate, opaque minerals, iddingsite and bowlingite. Microphenocrysts are composed of plagioclase and pseudomorphs after olivine. These pseudomorphs are composed of an outer rim of opaque oxide and/or iddingsite enclosing a core of chlorite/bowlingite. The chloritic cores to these pseudomorphs are locally replaced by later carbonate. Olivine occurs as single isolated crystals and clusters of several anhedral microphenocrysts. Plagioclase forms anhedral to subhedral, twinned and occasionally zoned phenocrysts which may exhibit preferential alteration of their cores to chlorite (± carbonate). Plagioclase phenocrysts are aligned parallel to the pilotaxitic fabric present within the groundmass.

The groundmass is feldspathic and composed of closely packed, aligned plagioclase laths with chloritic pseudomorphs after intergranular pyroxene (± olivine). The remaining interstitial to intersertal areas are filled by a dusty looking (in plane polarised light), feldspathic mesostasis which contains numerous inclusions of opaque oxide. Small granular to needle-like crystals of opaque oxide are also present within the groundmass. The patchy replacement of the groundmass by carbonate locally overprints the primary igneous texture of the rock.

Collectors Number: SRK10. **Registered Number:** N2545. **Location:** [NS 3148 1616] Newark Estate, 800 m west-north-west of High Midton. **Rock Type:** Pilotaxitic, plagioclase-pyroxene-olivine macroporphyritic basalt or basaltic andesite. **Formation:** Carrick Volcanic Formation. **Symbol:** flplpomaB^{B}/A^{B} or B^{B}/A^{B}.

Description: This thin section is of a fine- to very fine-grained, weakly altered, pilotaxitic, macroporphyritic basalt or basaltic andesite which comprises an inequigranular assemblage of plagioclase, clinopyroxene, olivine and opaque minerals. Alteration and hydration of this primary minerals assemblage resulted in the development of carbonate, chlorite, bowlingite, iddingsite and quartz.

The phenocrysts are mainly composed of plagioclase with minor carbonate-chlorite (± quartz) pseudomorphs after olivine and pyroxene. Olivine originally formed anhedral, rounded crystals with pyroxene forming subhedral microphenocrysts. Traces of relict clinopyroxene were noted within this basalt to basaltic andesite. Plagioclase phenocrysts range from 0.3 up to 4.5 mm in length and may locally possess an irregular rim containing very small, rounded to irregular inclusions of altered glass. Plagioclase typically forms anhedral to subhedral, twinned and oscillatory zoned, elongate to lath shaped crystals. However, occasional equant plagioclase crystals are also present. Plagioclase exhibits minor alteration to chlorite and carbonate. The shape alignment of the plagioclase phenocrysts defines the pilotaxitic fabric developed within this basaltic rock. Some rounding of plagioclase phenocrysts, due to resorption, was noted.

The groundmass is fine-grained, massive to weakly pilotaxitic and composed of randomly orientated plagioclase laths with intergranular chloritised pyroxene and glass. Minor to trace amounts of an interstitial to intersertal, dusty looking mesostasis is also present. Granular to needle-like opaque crystals are a common minor to accessory component within the groundmass. The groundmass also contains trace interstitial quartz.

Collectors Number: SRK12. **Registered Number:** N2546. **Location:** [NS 3113 1594] small quarry, 600 m north of High Pinmore. **Rock Type:** Highly altered, plagioclase-olivine-pyroxene macroporphyritic basalt. **Formation:** Carrick Volcanic Formation. **Symbol:** plopmaB or B.

Description: This thin section is of a fine-grained, highly altered, massive, feldspathic, hypocrystalline, macroporphyritic basalt which comprises an inequigranular assemblage of plagioclase, opaque minerals, chlorite, iddingsite, bowlingite and quartz. Phenocrysts are mainly composed of plagioclase ranging from 0.2 up to 2.8 mm in size with minor chlorite and opaque pseudomorphs after olivine. Occasional chlorite pseudomorphs after pyroxene microphenocrysts are also present. Plagioclase forms anhedral to subhedral, twinned, lath-shaped to equant crystals which exhibit variable rounding due to resorption. They occur as single crystals as well as clusters of several microphenocrysts. Plagioclase exhibits minor alteration to chlorite along fractures.

The groundmass is massive and mainly composed of small, randomly orientated plagioclase laths with opaque + chlorite pseudomorphs after intergranular pyroxene (± olivine). The remainder of the interstitial to intersertal areas are filled by cryptocrystalline chloritic material.

Traces of anhedral, granular to rod-shaped opaque crystals, a feldspathic mesostasis and interstitial quartz were noted within the groundmass.

Collectors Number: SRK14. **Registered Number:** N2547. **Location:** [NS 3124 1588] 550 m north-north-east of High Pinmore. **Rock Type:** Highly altered, olivine-plagioclase microporphyritic basaltic rock. **Formation:** Carrick Volcanic Formation. **Symbol:** oplmiB or B.

Description: This thin section is of a medium- to coarse-grained, hypocrystalline, highly altered, microporphyritic basaltic rock which comprises an inequigranular assemblage of plagioclase, chlorite, opaque oxide, carbonate, iddingsite and bowlingite. The phenocrysts within this basalt are only slightly coarser grained than the groundmass. They are mainly composed of opaque + carbonate pseudomorphs after anhedral to subhedral olivine (≤ 0.9 mm in size) and occasional slightly larger plagioclase microphenocrysts. Olivine pseudomorphs are composed of a core of carbonate enclosed within a rim of opaque oxide and/or iddingsite. Plagioclase forms anhedral, twinned crystals which exhibit minor alteration to carbonate. The larger plagioclase phenocrysts may possess a dusty, possibly sieve textured core.

The groundmass is massive to very weakly pilotaxitic and composed of small plagioclase laths with minor intergranular chlorite + carbonate + opaque oxide pseudomorphs after pyroxene (± olivine). The remaining interstitial phase are replaced by secondary carbonate. Needle-like and anhedral granular opaque crystals are common within the groundmass.

Collectors Number: SRK27. **Registered Number:** N2559. **Location:** [NS 3300 1737] 350 m, south-south-west of Doonside. **Rock Type:** Hematised, plagioclase-olivine-pyroxene macroporphyritic basaltic rock. **Formation:** Carrick Volcanic Formation. **Symbol:** plopmaB or B.

Description: This thin section is of a fine- to medium-grained, hypocrystalline, hematised, weakly pilotaxitic, macroporphyritic basaltic rock which comprises an inequigranular assemblage of plagioclase, opaque minerals, carbonate, chlorite, white mica, iddingsite and quartz. The weakly developed pilotaxitic fabric present within this basalt is defined by the preferred shape alignment of plagioclase phenocrysts. The phenocrysts are mainly composed of plagioclase and finer-grained granular looking olivine. Occasional carbonate + quartz pseudomorphs after pyroxene and/or olivine microphenocrysts are also present. Pseudomorphs after olivine are composed of a rounded to irregular core of cryptocrystalline chloritic material enclosed within a rim of opaque oxide and/or iddingsite. In some cases olivine is completely replaced by opaque oxide. Plagioclase forms twinned, anhedral to subhedral, typically elongate to lath-shaped phenocrysts as well as occasional more equant crystals. Plagioclase may exhibit minor alteration to carbonate.

The groundmass is fine-grained and mainly composed of equant to lath-shaped, randomly orientated plagioclase with a dusty brown, inclusion-rich mesostasis. Needle-like and granular opaque crystals are relatively common. Small pockets of carbonate replacement were noted within the groundmass. The remaining interstitial to intersertal areas are filled by trace amounts of a cryptocrystalline chloritic assemblage.

Collectors Number: SRK15. **Registered Number:** N2548. **Location:** [NS 3104 1524] Pinmore Burn, 100 m south of High Pinmore. **Rock Type:** Lithic-rich, volcaniclastic sandstone (litharenite). **Formation:** Swanshaw Sandstone Formation. **Symbol:** not applicable.

Description: This thin section is of a moderately to poorly sorted, moderately packed, compositionally immature, grain-supported, lithic-rich, volcaniclastic sandstone (litharenite) which possesses a well-developed chloritic rim cement. This cement also fills the intergranular pore space and locally appears to 'wrap around' the detrital grains. The detrital grains are angular, subangular to subrounded in shape with a low to moderate sphericity. Elongate clasts exhibit a weakly developed preferred shape alignment. The bulk of the clast assemblage is composed of variably altered (chloritised or hematised), very fine-grained, basaltic to andesitic rock fragments. Although altered these rocks may contain feldspar microphenocrysts and pseudomorphs after hornblende. Traces of detrital monocrystalline quartz and a single small pebble-sized clast of weakly cleaved siltstone are also present. Other accessory detrital components include opaque minerals, sericitised feldspar, oxidised biotite and chloritic pseudomorphs after a detrital ferromagnesian mineral(s).

Collectors Number: SRK16. **Registered Number:** N2549. **Location:** [NS 3118 1496] Pinmore Burn, 100 m south of Low Pinmore. **Rock Type:** Heterolithic microconglomerate. **Formation:** Swanshaw Sandstone Formation. **Symbol:** not applicable.

Description: This thin section is of a coarse-grained, poorly to very poorly sorted, immature, lithic-rich, heterolithic microconglomerate with a medium-grained sandstone matrix. The coarse sand, granule to pebble-sized clasts are subangular to subrounded in shape with a low sphericity. They are mainly composed of a very fine-grained tuffaceous rock or mudstone and fine-grained, recrystallised sandstone or metasandstone with minor to trace polycrystalline quartz/felsite and coarse- to medium-grained sandstone. The microconglomerate, in general, has an open-packed, matrix to locally clast-supported texture. In contrast, the sandstone matrix to the microconglomerate is closely packed, clast-supported, immature and poorly sorted.

Detrital grains are angular to rounded in shape with a low to moderate sphericity. They are mainly composed of monocrystalline quartz and lithic fragments; the latter include the same range of lithologies as the larger clasts. The apparently volcanic to tuffaceous rock fragments are variably altered making identification of their original protolith difficult. Sedimentary or low-grade metasedimentary rock fragments are a common component within this microconglomerate. Other minor to accessory detrital components include cherty rock, white mica/muscovite, polycrystalline quartz and feldspar. The shape of the unstable lithic clasts has been modified due to compaction (± alteration) resulting in embayment against neighbouring more rigid grains. A hematitic cement is variably developed in the sandstone matrix replacing the original matrix component as well as degraded lithic clasts.

Collectors Number: SRK17a. **Registered Number:** N2550. Location: [NS 3121 1496] Pinmore Burn, 100 m south of Low Pinmore. **Rock Type:** Very coarse-grained, pebbly sandstone or microconglomerate. **Formation:** Swanshaw Sandstone Formation. **Symbol:** not applicable.

Description: This thin section is of a very coarse-grained, poorly to very poorly sorted, texturally immature, heterolithic, closely to very closely packed, matrix-poor, clast-supported pebbly sandstone (litharenite) or microconglomerate. The clasts are typically angular to subrounded in shape with occasional subrounded and rounded grains. They also possess a low sphericity. The close to very close packing of the clasts coupled with compaction has resulted in embayment and moulding of unstable grains against neighbouring more rigid grains.

The clast assemblage is dominated by very fine-grained tuffaceous volcanic rock or mudstone and very fine- to medium-grained sandstone to very low-grade metasandstone. Siltstone lithic clasts are also common and may possess a weakly developed cleavage. Other minor to accessory detrital components include monocrystalline quartz, felsite, hematised rock, polycrystalline quartz and tourmaline. A weak shape alignment of elongate clasts was also noted. Trace amounts of a hematitic matrix or cement present within this microconglomerate appears to be partially derived from the breakdown of unstable hematised rock fragments. Traces of an earlier chloritic cement were also recognised. This early cement is partially replaced by secondary hematitic oxide.

Collectors Number: SRK17b. **Registered Number:** N2551. **Location:** [NS 3121 1496] Pinmore Burn, 100 m south of Low Pinmore. **Rock Type:** Medium- to coarse-grained, lithic-rich sandstone. **Formation:** Swanshaw Sandstone Formation. **Symbol:** not applicable.

Description: This thin section is of a medium- to coarse-grained, poorly to moderately sorted, immature, moderately packed, matrix- to very locally clast-supported, lithic-rich sandstone (litharenite). The matrix appears to be partially derived from degraded lithic clasts and is variably replaced by hematitic oxide. Detrital grains are angular to subangular in shape with a low to occasionally moderate sphericity. Occasional subrounded grains are also present with elongate clasts showing a weakly developed preferred shape alignment. The sandstone possesses a crude bimodal sorting with a distinct break between medium-sand grade and very coarse to granule-sized clasts which give the rock its ‘pebbly’ appearance.

The detrital assemblage is mainly composed of variably altered or degraded, sedimentary and tuffaceous volcanic rock fragments as well as monocrystalline quartz clasts. The sedimentary and possibly very low-grade metasedimentary rocks range from fine-grained siltstone to very fine-grained sandstone. Other minor to accessory detrital components include polycrystalline quartz, tourmaline, very fine-grained quartzite or psammite, hematised rock, white mica, K-feldspar, garnet, sheared vein quartz, plagioclase and felsitic rock. Localised etching of grain boundaries and pressure solution between adjacent quartz grains has been recognised. Traces of a cryptocrystalline chloritic and quartzose cements were noted.

Collectors Number: SRK18. **Registered Number:** N2552. **Location:** [NS 3128 1486] Pinmore Burn, 250 m south-east of Low Pinmore. **Rock Type:** Medium-grained, quartzose, lithic-rich sandstone (litharenite). **Formation:** Swanshaw Sandstone Formation. **Symbol:** not applicable.

Description: This thin section is of a medium-grained, moderately to poorly sorted, very closely packed, clast-supported, texturally immature, quartzose, lithic-rich sandstone (litharenite). Detrital grains are angular to subangular in shape with a low to moderate sphericity. They are mainly composed of variably degraded lithic clasts and monocrystalline quartz. The lithic clasts are composed of a variety of variably altered, very fine-grained to cryptocrystalline volcanic/tuffaceous rock fragments, siltstone to very fine-grained sandstone and subordinate metasedimentary rock fragments. The precise composition/protolith of some of the rock fragments has been masked by alteration. Recognisable rock fragments include: cherty rock; white mica-rich phyllitic or very fine-grained schistose rock; and very fine-grained biotite-schist.

Other minor to accessory detrital components include muscovite, polycrystalline quartz, biotite, tourmaline, plagioclase, opaque minerals, K-feldspar and chloritic pseudomorphs after a ferromagnesian minerals. Compaction resulted in the kinking of detrital micas and modification of the shape of more unstable lithic clasts. These lithic clasts may exhibit replacement by a turbid, brown to honey-brown hematitic clay-rich assemblage. The minor amounts of matrix component within this sandstone appears to have been derived from the breakdown of unstable lithic clasts. Traces of cryptocrystalline chloritic and quartzose cements are recorded. The very close packing and alteration of this sandstone locally makes the identification of individual grain boundaries difficult.

Collectors Number: SRK19. **Registered Number:** N2553. **Location:** [NS 3168 1552] Upper Brae Glen Plantation, 400 m west of Midton. **Rock Type:** Medium-grained, slightly calcareous, quartzose, lithic-rich sandstone (litharenite). **Formation:** Swanshaw Sandstone Formation. **Symbol:** not applicable.

Description: This thin section is of a medium-grained, slightly calcareous, compositionally immature, moderately packed, clast-supported, poorly to moderately sorted, quartzose, lithic-rich sandstone (litharenite). This rock possesses a moderately to well-developed hematitic stained (honey brown) carbonate cement. Carbonate appears to have replaced the original fine-grained (mud) components within the sandstone as well as unstable lithic clasts. The carbonate initially formed a fine rim or coating on quartzose grains, then filled and/or replaced the intergranular porosity or a matrix, respectively. A thin hematitic clay cement or coating was noted on some detrital grains.

The clastic grains are angular, subangular to occasionally subrounded in shape with a typically low sphericity. The lithic clasts, in general, are more rounded in shape than the quartzose grains. The detrital assemblage is mainly composed of variably altered sedimentary and tuffaceous or volcanic rock fragments as well as monocrystalline quartz. The shape of the lithic fragments has been modified due to compaction with the more unstable grains becoming embayed against, or moulded around, neighbouring more rigid clasts. Recognisable lithologies include: very fine-grained schistose rock; fine-grained siltstone or metasiltstone; felsite; cherty rock; trachytic rock; and weakly cleaved mudstone. Fragments of fine- to very fine-grained sedimentary or very low-grade metasedimentary rocks are a common component within this sandstone. Other minor to accessory detrital components include plagioclase, polycrystalline quartz, chloritised rock, garnet, opaque minerals, K-feldspar and chloritic pseudomorphs after a ferromagnesian mineral.

Collectors Number: SRK20b. **Registered Number:** N2554. **Location:** [NS 3184 1547] Upper Brae Glen Plantation, 200 m west of Midton. **Rock Type:** Laminated, medium- to very coarse-grained, lithic-rich sandstone (litharenite). **Formation:** Swanshaw Sandstone Formation. Symbol: not applicable.

Description: This thin section is of a laminated, medium- to very coarse-grained, poorly sorted, closely packed, clast-supported, lithic-rich, relatively quartzose sandstone (litharenite). The detrital grains are subangular, subrounded, to occasionally rounded in shape with a low sphericity. The clast assemblage is mainly composed of lithic clasts and monocrystalline quartz with minor amounts of polycrystalline quartz. The lithic clasts are mainly composed of: very fine grained or cryptocrystalline tuffaceous rock or cherty-looking mudstone; felsitic volcanic rock; and subordinate fine-grained sedimentary or very low-grade metasedimentary rock fragments. Other minor to accessory detrital components include plagioclase, carbonate rock, tourmaline, deformed vein quartz or quartz mylonitic rock, schistose sedimentary rock, white mica and opaque minerals.

The very close packing of this sandstone locally makes the identification of individual grain boundaries difficult. The clay-grade matrix forms a minor component and appears to have, at least in part, been derived from degraded lithic clasts. The sedimentary lamination is defined/preserved by a marked change in grain size resulting alternating fine- and medium-grained sandstone laminae. The matrix is variably replaced by a hematitic stained, red-brown carbonate mineral. This replacive carbonate cement is well-developed and in one of the coarser grained sandstone layers results in a moderate to open-packed, cement-supported texture.

Collectors Number: SRK21. **Registered Number:** N2555. **Location:** [NS 3174 1550] Upper Brae Glen Plantation, 300 m west of Midton. **Rock Type:** Conglomerate. **Formation:** Swanshaw Sandstone Formation. **Symbol:** not applicable.

Description: This thin section is of a poorly sorted, lithic-rich conglomerate. The thin section is dominated by a few large granule to pebble-sized (c. 1.5 cm) lithic clasts. These clasts are mainly composed of fine-grained sandstone to coarse-grained siltstone rock fragments which are altered/recrystallised or have undergone low-grade metamorphism. These large clasts are subrounded to rounded in shape with a low sphericity. Recognisable lithologies include: tuffaceous or cherty mudstone; very fine-grained psammite; quartzite; and fine-grained wacke sandstone.

The matrix to the conglomerate is a coarse-grained, very poorly sorted, closely to very closely packed, lithic-rich sandstone (litharenite) which possesses minor amounts of a replacive hematitic stained carbonate cement. Carbonate appears to be replacing the original fine-grained components in the sandstone as well as the more unstable lithic components. The very close packing and compaction of the sandstone locally results in pressure solution and embayment of the lithic clasts against neighbouring more rigid grains. The clast assemblage of the sandstone is dominated by lithic clasts, which include a similar range of lithologies to the larger detrital grains, with subordinate to minor monocrystalline quartz. The alteration of the lithic clasts, including carbonate replacement, makes identification of individual clast boundaries difficult. Accessory detrital components include polycrystalline quartz, cleaved mudstone and/or tuffaceous rock.

Collectors Number: SRK22b. **Registered Number:** N2556. **Location:** [NS 3190 1546] Upper Brae Glen Plantation, 150 m south-west of Midton. **Rock Type:** Calcareous, medium- to coarse-grained, lithic-rich sandstone (litharenite). **Formation:** Swanshaw Sandstone Formation. **Symbol:** not applicable.

Description: This thin section is of a medium- to coarse-grained, poorly to very poorly sorted, close- to open-packed, texturally immature, lithic-rich sandstone (litharenite) with a well-developed, but patchy, replacive carbonate cement. Carbonate appears to be replacing the original matrix and unstable lithic components. Small pockets or patches of a hematitic-stained carbonate are also present. Where carbonate replacement is most intense the sandstone possesses an open, cement-supported texture. Locally, carbonate replacement may result in the overprinting of the primary clastic texture of the rock. Another distinctive feature of this sandstone is the presence of irregular, elongate, flattened, colourless Mg-chloritic aggregates or pseudomorphs after rock fragments. This cryptocrystalline material also contains radiating, very fine-grained, fibrous to spherulitic aggregates of chlorite or clay minerals.

Detrital grains are angular to subangular in shape with a low sphericity. However, occasional subrounded to rounded clasts are also present. The clast assemblage is mainly composed of variably altered/degraded lithic clasts and monocrystalline quartz; the latter also includes embayed (partially resorped) crystal fragments. The lithic clasts are mainly composed of a very fine-grained volcanic rock and very fine-grained siltstone or mudstone. Other minor to accessory detrital components include microcline, plagioclase, polycrystalline quartz, opaque minerals, white mica, foliated very fine-grained quartzose schist, variably chloritised or hematised biotite, chert, very fine-grained metasandstone or psammite and hematised very fine-grained basalt or metabasaltic rock. Carbonate pseudomorphs after original detrital grains were also noted. Compaction resulted in the kinking of detrital micas and localised embayment of lithic grains against neighbouring more rigid clasts. A thin hematitic coating or rim cement was noted developed upon some detrital grains.

Collectors Number: SRK23. **Registered Number:** N2557. **Location:** [NS 3192 1546] Upper Brae Glen Plantation, 125 m south-west of Midton. **Rock Type:** Medium-grained, quartzose, lithic-rich sandstone (litharenite). **Formation:** Swanshaw Sandstone Formation. **Symbol:** not applicable.

Description: This thin section is of a medium-grained, poorly sorted, texturally immature, closely packed, clast-supported, quartzose, lithic-rich sandstone (litharenite) with a patchily developed Fe-stained, replacive carbonate cement. Traces of a cryptocrystalline chloritic cement, quartz overgrowths and hematitic rims or coatings are also present within this sandstone. The thin section is 'plucked', locally obscuring the original texture of the rock.

Detrital grains are angular, subangular to occasionally subrounded in shape with a low sphericity. The clast assemblage is mainly composed of a very fine-grained to cryptocrystalline tuffaceous rock or cherty mudstone and siltstone or very low-grade metasiltstone. However, the composition of the lithic clasts has largely been obscured by later alteration and overall grain size of the sandstone. Other minor to accessory detrital components include polycrystalline quartz, chlorite, white mica, opaque minerals, plagioclase, hematised biotite, cherty rock and variably chloritised biotite.

Collectors Number: SRK26. **Registered Number:** N2558. **Location:** [NS 3250 1686] Newark Estate, 100 m south of Newarkhill Farm. **Rock Type:** Altered, fine-grained, lithic-rich sandstone (litharenite). **Formation:** Sandstone and conglomerate lens within the Carrick Volcanic Formation. **Symbol:** not applicable.

Description: This thin section is of a fine-grained, moderately sorted, very closely packed, massive, clast-supported, matrix-poor, lithic-rich sandstone (litharenite) which possesses a patchily developed replacive carbonate cement. The rock also contains occasional granule to small pebble-sized clasts. The detrital grains are angular to subangular in shape with a low sphericity. The clast assemblage is mainly composed of altered lithic clasts and monocrystalline quartz with subordinate plagioclase. The lithic clasts are mainly altered to a cryptocrystalline chloritic assemblage. Chlorite also forms minor to trace amounts of cement. This cement and chloritised lithic clasts are variably or patchily replaced by secondary carbonate.

Minor to accessory detrital components include hematised biotite, chlorite, muscovite, felsite, garnet, opaque minerals, very fine-grained phyllitic rock and chlorite pseudomorphs after ferromagnesian minerals. Irregular patches (trace) of hematitic staining or replacement of the chloritic cement was recorded. Alteration and very close packing of the sandstone locally makes identification of individual clast boundaries difficult. The granule to small pebble sized clasts are subrounded in shape with a low sphericity and are composed of a very fine-grained hyalopilitic/pilotaxitic andesitic rock.

Glossary

Alkali – A prefix given to rocks which contain either: (a) modal feldspathoids and/or alkali amphibole or pyroxenes; or (b) normative feldspathoids or acmite.

Alkali basalt – Term originally used for basalts containing accessory feldspathoids. These rocks typically contain a Ti-augite and olivine as their main ferromagnesian phases. Now defined geochemically using the Total Alkali-Silica diagram as a variety of basalt.

Alkali gabbro – A variety of gabbro which is alkaline in character due to the presence of analcime or nepheline and ferromagnesian phases such as barkevikite, kaersutite and/or Ti-augite.

Andesite – An intermediate volcanic rock, usually porphyritic, consisting of plagioclase (frequently zoned from labradorite to oligoclase), pyroxene, hornblende and/or biotite. Now defined modally on a Quartz-Alkali feldspar-Plagioclase-Feldspathoid diagram or geochemically using the Total Alkali-Silica diagram.

Basalt – A volcanic rock consisting essentially of calcic plagioclase and pyroxene. Olivine and minor feldspathoids may also be present. Now defined modally on a Quartz-Alkali feldspar-Plagioclase-Feldspathoid diagram or geochemically using the Total Alkali-Silica diagram.

Basaltic andesite – A volcanic rock with plagioclase compositions expected for andesites but containing ferromagnesian minerals more commonly found in basalts. Now defined geochemically using the Total Alkali-Silica diagram.

Benmoreite – Defined geochemically as the sodic variety of trachyandesite using the Total Alkali-Silica diagram.

Camptonite – A variety of lamprophyre composed of phenocrysts of combination of olivine, kaersutite, Ti-augite and Ti-biotite in a matrix of the same minerals (except olivine) with plagioclase and sometimes subordinate alkali feldspar and feldspathoids.

Crinanite – A variety of olivine-analcime dolerite or gabbro composed of olivine, Ti-augite and labradorite with minor analcime. Although it has less analcime and more olivine than teschenite the two names have been used interchangeably.

Dacite – A volcanic rock composed of quartz and sodic plagioclase with minor amounts of biotite and/or hornblende and/or pyroxene. Now defined modally on a Quartz-Alkali feldspar-Plagioclase-Feldspathoid diagram or geochemically using the Total Alkali-Silica diagram.

Dolerite – A rock of intermediate grain size between a basalt and gabbro (i.e. synonym for microgabbro), and composed of essentially plagioclase, pyroxene and opaque minerals. Often contains an ophitic texture. If olivine is present may be called an olivine-dolerite; if quartz, a quartz-dolerite.

Felsite – A rock term initially used for the microcrystalline groundmass of porphyries. Now commonly used for microcrystalline rocks of granitic composition (i.e. dacite to rhyolite).

Hawaiite – Defined geochemically as the sodic variety of trachybasalt using the Total Alkali-Silica diagram.

Kersantite – A variety of lamprophyre consisting of phenocrysts of Mg-biotite, with or without hornblende, olivine or pyroxene in a groundmass of the same minerals plus plagioclase and occasionally alkali feldspar.

Monchiquite – A variety of lamprophyre similar to camptonite except that the groundmass is feldspar-free and composed of combinations of glass and feldspathoids, especially analcime.

Mugearite – Defined geochemically as the sodic variety of basaltic trachyandesite using the Total Alkali-Silica diagram.

Olivine-basalt – A commonly used term for a basalt containing olivine as an essential constituent.

Quartz-dolerite – A variety of dolerite composed mainly of plagioclase and pyroxenes with interstitial quartz. The rock has tholeiitic affinities and its pyroxenes are usually sub-calcic augite accompanied by pigeonite or orthopyroxene.

Teschenite – A variety of analcime gabbro consisting of olivine, Ti-augite, labradorite and analcime.

Tholeiitic basalt – Commonly used term for a variety of basalt composed of labradorite, augite, hypersthene or pigeonite with olivine (often showing reaction relationship) or quartz, and often with interstitial glass.

Trachyandesite – A term originally used for volcanic rocks intermediate in composition between trachyte and andesite and containing equal amounts of alkali feldspar and plagioclase. Later used for volcanic rocks containing feldspathoids as well as alkali feldspar and plagioclase. Now defined geochemically using the Total Alkali-Silica diagram.

Trachybasalt – Term mainly used for basaltic volcanic rocks containing labradorite and alkali feldspar. Now defined geochemically using the Total Alkali-Silica diagram.

Trachyte – A volcanic rock consisting essentially of alkali feldspar. Now defined modally on a Quartz-Alkali feldspar-Plagioclase-Feldspathoid diagram or geochemically using the Total Alkali-Silica diagram.

Crystallinity – (a) holocrystalline, an igneous rock composed of 100% crystals; (b) holohyaline, an igneous rock composed of 100% glass; and (c) hypocrystalline, intermediate between the two end-members and can be described more precisely by stating the relative proportions of crystals and glass.

Microcrystalline – crystals can be identified with a petrological microscope. Crystals only just large enough to show polarisation colours (< 0.01 mm in size) are called microlites.

Cryptocrystalline – crystals are too small to be identified even with the petrological microscope.

Grain size – (a) coarse-grained, crystals > 5.0 mm in size; (b) medium-grained, crystals 1.0 to 5.0 mm in size; (c) fine-grained, crystals < 1.0 mm in size.

Equigranular – all crystals are approximately the same size.

Inequigranular – crystals of substantially different grain size. Common variety, porphyritic texture, can be subdivided into: (a) microporphyritic, phenocrysts ≤ 2.0 mm in size; and (b) macroporphyritic, phenocrysts > 2.0 mm in size.

Seriate texture – continuous range in crystal size of principal minerals.

Trachytic texture – sub-parallel alignment of microcrystalline feldspar in the groundmass of a holocrystalline or hypocrystalline rocks. Sub-divided into pilotaxitic texture and hyalopilitic texture depending on whether the material between the feldspar is crystalline or glassy. Trachytoid texture, alignment of tabular, bladed or prismatic crystals which is visible to the naked eye. The terms flow and fluxion texture are sometimes used as synonyms for trachytic and trachytoid textures. However, they are best avoided due to their genetic implications.

Grain size – (a) clay < 0.0039 mm in size; (b) silt, 0.0039 to 0.0625 mm in size; (c) fine sand, 0.0625 to 0.25 mm in size; (d) medium sand, 0.25 to 0.5 mm in size; (e) coarse sand, 0.5 to 1.0 mm in size; (f) very coarse sand, 1.0 to 2.0 mm in size; (g) granules 2.0 to 4.0 mm in size; (h) pebbles 4.0 to 64 mm in size.

Rounded – Describes the smoothness of the surface of a grain. The terms well-rounded, rounded, subrounded, subangular, angular, very angular are used to describe the increasingly angular/irregular/rough nature of the surface of detrital grains.

Sphericity – Describes the how closely a detrital grain approximates to a sphere. The terms low sphericity, moderate sphericity and high sphericity are used to describe how spherical (ball-like) the detrital grains are.

Sorting – Well sorted describes a deposit in which all the detrital grains are of approximately uniform size. In reality most fragmentary deposits contain a range of grain sizes and can be described as moderately sorted, poorly sorted or in extreme cases unsorted.

Packing – Describes, as the term suggests, how closely the individual detrital grains are packed together within a fragmentary deposit. The term closely packed is used where all the grains are in contact and there is very little obvious matrix or cement; moderately packed and open packed are used with an increase in the porosity, matrix and/or cement.

Clast supported – Describes a fragmentary deposit where all the detrital grains are in contact.

Matrix supported – Describes a fragmentary deposit where the detrital grains are, to varying degrees, isolated/supported within a finer grained matrix.

Cement supported – Describes a fragmentary deposit where the detrital grains are, to varying degrees, isolated/supported within the cement.

Cement – The material bonding the fragments of clastic sedimentary rocks together and which was precipitated between the grains after deposition.

Porosity – The volume of voids expressed as a percentage of the total volume of the sediment or sedimentary rock.

Matrix – Material, usually clay minerals or micas, forming a bonding substance to grains in a clastic sedimentary rock. The matrix material was deposited with the other grains or developed authogenically by diagenesis or slight metamorphism. Also used more generally for finer grained material in any rock in which large components are set.

Detritus – A general term for fragmentary material, such as gravel, sand, clay, worn from rock by disintegration. Detrital grains in clastic sedimentary rocks may be composed of single mineral grains (e.g. monocrystalline quartz, plagioclase), polycrystalline mineral grains (e.g. polycrystalline quartz) or lithic fragments including sedimentary, igneous and metamorphic rock fragments.

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