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Petrology and provenance of the Siluro-Devonian (Old Red Sandstone facies) sedimentary rocks of the Midland Valley, Scotland

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Foreword

This report is the published product of a study by the British Geological Survey (BGS) on the regional geology of the Midland Valley of Scotland. It is part of the Science Budget funded programme which forms part of the core programme of BGS. This core programme is designed to undertake a multidisciplinary geological survey to meet user and strategic needs for geological information.

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Summary

This report describes the composition and provenance of the sedimentary rocks of the Silurian and Devonian sedimentary sequences (Old Red Sandstone facies) of the Midland Valley of Scotland. The work forms part of a multidisciplinary project being undertaken by the British Geological Survey to examine the evolution of the Midland Valley of Scotland. This work is an integral part of the British Geological Survey's Geology and Landscape Northern Britain Programme.

Medium- to coarse-grained sandstones were analysed from the Lanark, Stonehaven, Dunnottar-Crawton, Arbuthnott-Garvock, Strathmore and Stratheden groups, as well as the Silurian inliers of the southern Midland Valley. Several general observations can be made regarding sandstone composition within central Scotland: ***(i)*** there significant differences in sandstone composition between the southern and northern Midland Valley; ***(ii)*** a negative correlation exists between the modal proportion of volcanic lithic clasts and monocrystalline quartz, with the increase in quartz reflecting an increase in the compositional maturity of the sandstones; ***(iii)*** a positive correlation can be drawn between polycrystalline quartz and monocrystalline quartz within these sandstones; ***(iv)*** a negative relationship exists between the variation in the modal volcanic lithic clasts and plagioclase possibly reflecting a decrease in the grain size of the sandstone and/or the period of transport prior to deposition (i.e. maturity); and ***(v)*** the covariation in polycrystalline quartz and metamorphic lithic clasts define a positive correlation suggesting that these two components were derived from the same source.

The clear discrimination between sandstone formations analysed from the southern and northern Midland Valley suggests that they were derived from two separate source terranes and that, in general, there was little (if any) mixing of detritus. Sandstones of the northern Midland Valley,

in general, exhibit a higher metamorphic lithic and polycrystalline quartz contents, with these components having been derived from the Dalradian Supergroup source terrane located immediately to the north of the Strathmore basin. A clear discrimination can be made between the Auchtitench Sandstone Formation (southern Midland Valley) and Gourdon Sandstone Formation (northern Midland Valley) and the remainder of the Silurian and Devonian sandstones. These formations contain a high proportion of plagioclase and volcanic lithics, consistent with the stratigraphical position of these sandstone dominated units immediately above the Duneaton Volcanic (southern Midland Valley) and Tremuda Bay Volcanic (northern Midland Valley) formations.

In the northern Midland Valley, the mean sandstone compositional data suggests that there are significant differences between the Stonehaven Group of the Stonehaven district, and the stratigraphically higher Arbuthnott-Garvock and Strathmore groups of the Aberfoyle and Strathmore districts. This along strike variation is thought to reflect changes in the geology of the source terrane from southwest to northeast. The preservation of these differences in source terrane geology within the sandstones indicates that along strike mixing of sediment was limited and that the sandstones were deposited relatively close to source.

In the southern Midland valley, the sandstones from the Cock Rig, Henshaw, March Wood, Eastgate, Greywacke Conglomerate and Swanshaw Sandstone formations are compositionally similar. Although the deposition of the Greywacke Conglomerate Formation represented a significant change in depositional environment at the base of the Lanark Group, this was not reflected in a major change in sandstone composition. This change occurs at the base of the Auchtitench Sandstone Formation, coinciding with the onset of Lower Devonian volcanism.

1 Introduction

This report describes the composition and provenance of the sedimentary rocks of the Silurian and Devonian sedimentary sequences of the Midland Valley of Scotland. The work forms part of a multidisciplinary project being undertaken by the British Geological Survey to examine the evolution of the Midland Valley of Scotland. This work is an integral part of the British Geological Survey's Geology and Landscape Northern Britain Programme.

The evolution of the Midland Valley Terrane of Scotland during Lower Palaeozoic to Devonian times, and its setting within Caledonian orogenic models has been the focus of continuing debate (Williams and Harper, 1988; McKerrow et al., 1991; Smith,1995; Phillips et al., 1998; Bluck, 2000; Phillips et al., 2004). An important part of this discussion is the sedimentology, structure and provenance of the Silurian to Devonian sedimentary rocks exposed in the southern and northern Midland Valley (Figure 1). Early provenance studies largely focused upon the conglomeratic units present within the southern (McGiven, 1967; Bluck, 1983; Heinz and Loeschke, 1988; Syba, 1989) and northern (Bluck, 1983; Haughton et al., 1990; Haughton & Halliday, 1991) parts of this terrane. Work on the Silurian rocks in the southern Midland Valley (McGiven, 1967; Bluck, 1983; Heinz and Loeschke, 1988; Syba, 1989) indicates that there is a difference between a southerly derivation direction and the source area presently exposed to the south, i.e. the Southern Uplands Terrane. Similar studies on the late Silurian to early Devonian Dunnottar and Crawton group conglomerates within the Old Red Sandstone facies of the north-eastern Midland Valley have identified the presence of a "*cryptic*" greywacke source within the Midland Valley Terrane (Haughton et al., 1990; Haughton and Halliday, 1991).

More recently, however, a number of studies have examined the composition and provenance of the sandstones which dominate the Silurian to Devonian sedimentary sequences in both the north and south of the Midland Valley (Phillips and Carroll, 1995; Phillips and Smith, 1995; Phillips et al., 1998; Phillips and Aitken, 1998; Phillips and Barron, 2000; Phillips et al., 2004). Phillips et al., (1998) demonstrated that the character of the sediment supply changed gradually upward through the Siluro-Devonian (Old Red Sandstone facies) sequence of the southern Midland Valley. They found, furthermore, that none of this sequence of sedimentary rocks contain detritus that is obviously derived from the Dalradian rocks to the north of the Midland Valley, suggesting that a barrier existed preventing it entering the Lanark Basin.

2 The Silurian to Lower Devonian rocks of the Southern Midland Valley

2.1 SILURIAN INLIERS

Strata of Llandovery and Wenlock age are exposed in several inliers along the southern side of the Midland Valley, namely the Girvan (Man and Craighead), Carmichael, Eastfield, North Esk, Hagshaw Hills and Lesmahagow inliers (Figures 1 and 2). These sedimentary rocks record an overall change from an older (Llandovery) marine sequence to younger (Wenlock) regressive terrestrial succession (Rolfe, 1960, 1961; Cocks and Toghill, 1973; Robertson, 1989). In detail the successions and their source areas vary leading Smith (1995) to suggest that the Silurian sedimentary sequences were deposited in a number of fault controlled sub-basins (also see Phillips et al., 1998).

In the Girvan area, Llandovery (cyphus Zone) conglomerates (Cocks and Toghill, 1973) thin and fine towards the south-west overstepping unconformably onto the underlying Ordovician sequence. Palaeocurrent evidence indicates that these conglomerates were derived from within the Midland Valley Terrane (Bluck, 1983, 1984). These conglomerates contain acidic igneous clasts including granite, various porphyritic microgranites and felsites, and acid lavas, less common are basic lavas, gabbros and dolerites, as well as quartzite, vein quartz, amphibolite, jasper and wacke sandstone. The presence of quartzite within these conglomerates has been used in support of there being a metamorphic basement to the northwest within the Midland Valley (Phillips et al., 1998).

In the Hagshaw Hills inlier (Figure 2) the oldest unit, the Smithy Burn Siltstone Formation, contains marine siltstones belonging to the upper Llandovery crenulata Biozone. The overlying Ree Burn Formation comprises a coarsening upwards sequence of grey mudstones and siltstones passing up into fine- to medium-grained wacke sandstones. These turbiditic sandstones were derived from the south or south-east. These are overlain by the Parishholm Conglomerate Formation which contains angular to subrounded pebbles and cobbles of fine-grained acid and basic to intermediate igneous rocks including dioritic to granitic plutonic rocks, andesite to rhyolite lavas and minor metabasalt (Table 1). Minor amounts of quartzite, chert and wacke sandstone clasts are also present (Paterson et al., 1998). Immature granule sandstones interbedded with the conglomerates contain angular, subangular to occasionally subrounded clasts of very fine-grained andesitic to rhyolitic volcanic or high-level intrusive igneous rocks, as well as monocrystalline and polycrystalline quartz. Although dominated by volcanic rocks fragments of plutonic igneous, sedimentary and metamorphic rocks are also present; including diorite or granodiorite, microgranite, granite, micrographic granite, siltstone, wacke sandstone, chert, mudstone, quartzite, chert, meta-quartz arenite, chert and psammite. The south-easterly derived Parishholm Conglomerate Formation contains a similar suite of igneous clasts to the northerly derived conglomerates of the Girvan area (Bluck, 1983; 1984). The Douglas Water Arenite, Dovestone Red Bed, Fish Bed and Gully Red Bed formations are interpreted as having been deposited within semi-permanent lakes that intermittently dried out.

The south-easterly derived Hareshaw Conglomerate Formation (McGiven, 1967) consists mainly of rounded pebbles of vein quartz and quartzite. Subordinate clasts include fine-grained and porphyritic igneous rocks, granite, metamorphic rocks, chert and mudstone. Granule to pebbly sandstones interbedded with the conglomerate are mainly composed of subangular, subrounded to occasionally rounded clasts of monocrystalline and polycrystalline quartz, as well as variably altered fragments of very fine-grained dacitic to rhyolitic volcanic rocks. Although dominated by volcanic derived detritus, fragments of sedimentary and metamorphic rocks are also present, including psammite, quartzite, quartz-schist, quartzofeldspathic mylonite, diorite or granodiorite, microdiorite and metabasaltic rock (Table 1). The Hareshaw Conglomerate Formation passes up into the alluvial sandstones of the Quarry Arenite Formation.

The basal (Llandovery, crenulata Biozone) part of the succession exposed in the Carmichael inlier (Figure 2), to the south of Lanark, comprises a sequence of shallow marine mudstones, siltstones and minor sandstones (Rolfe, 1960). These are overlain by fine- to coarse-grained, fluviatile pebbly sandstones and conglomerates of the Eastgate Formation. The poorly sorted sandstones are compositionally immature and comprise a mixed assemblage of monocrystalline quartz, feldspar (mainly plagioclase) and variably altered, very fine-grained andesitic to rhyolitic volcanic rock fragments. The Eastgate Formation includes the Fence Conglomerate Member, which is correlated with the Parishholm Conglomerate as it comprises pebbles of igneous rocks, quartzite and chert. The younger Kirk Hill Conglomerate Member of the formation contains mainly igneous derived clasts, as well as minor metamorphic and sedimentary rock fragments (Table 1). The sedimentary lithics are petrographically similar to the sandstones of the Eastgate Formation, indicating that the sequence was undergoing penecontemporaneous erosion (Phillips et al., 2004).

In the Eastfield inlier (Figure 2) fluviatile sandstones and conglomerates of the March Wood Formation are correlated with the Eastgate Formation of the Carmichael inlier (Cameron, 1997). The intercalated mudstones and siltstone at the base of the sequence are interpreted as lacustrine deposits equivalent to the fish beds in the Hagshaw Hills inlier (Peach and Horne, 1899). The medium- to coarse-grained, moderately sorted sandstones of the March Wood Formation are mainly composed of monocrystalline quartz and variably altered. very fine-grained andesitic to rhyolitic volcanic rock fragments (Table 1). Plagioclase and micas (biotite, muscovite) are also common. These heterolithic sandstones also contain clasts of very fine-grained metasandstone, biotite hornfels, felsite, fine-grained mica-schist, metasandstone (low-grade), basalt and siltstone.

In the North Esk inlier of the Pentland Hills (Figure 2), the basal part of the Llandovery to Wenlock (Molyneux, 1996) North Esk Group is represented by a mudstone-dominated sequence containing sandy siltstone and very fine-grained sandstone interbeds of the Reservoir Formation. Robertson (1989) suggested that the Reservoir Formation was deposited in an offshore marine fan environment. Bull (1995), however, interpreted the siltstones and sandstones as recording rapid deposition of distal to intermediate storm sands within a low-energy, mud-dominated shelf environment. The late Llandovery (Loydell, 2005) Deerhope Formation is dominated by finely laminated mudstones and siltstones which possibly represent ‘overbank’ deposits within a submarine fan setting. Palaeoflow directions recorded within the sandstones of the Reservoir and Deerhope formations show that they were derived from the east. The overlying Cock Rig Formation marks a sudden change in facies to medium- to coarse-grained pebbly sandstones and conglomerates. These sandstones and conglomerates are interpreted as having been deposited in submarine channels within a proximal/inner fan environment. The clast-supported conglomerates contain pebbles of andesitic to rhyolitic igneous rocks, as well as sedimentary rocks. The interbedded locally pebbly sandstones contain rounded to subrounded granule to small pebble-sized clasts of very fine-grained to cryptocrystalline acidic igneous rocks as well as metasedimentary rock fragments; including quartzite, meta-quartz arenite, andesite or dacite, felsite, chert, polycrystalline vein quartz, metasandstone (low-grade), metasiltstone, feldspathic meta-quartz arenite, glassy rhyolite, microgranite, trachyte and fine-grained sandstone (intraclasts) (Table 1).

The mudstones, siltstones and fine-grained sandstones of the overlying Wether Law Linn Formation were deposited in a shallow marine barrier environment (Robertson, 1989). The overlying terrestrial sandstones and conglomerates of the Henshaw Formation were deposited in alluvial fans. These fine- to coarse-grained sandstones are compositionally similar to the March Wood and Eastgate formations (Phillips et al., 2004). These poorly to moderately sorted, matrix-poor litharenites are mainly composed of angular to subangular grains of altered basaltic to andesitic lithic clasts, mono- and polycrystalline quartz, as well as felsitic volcanic rock fragments (Table 1). Palaeocurrent indicators in the sandstones suggest that currents flowed from the east-northeast and east-southeast (Mitchell and Mykura, 1962). The finer grained sedimentary rocks within the formation are thought to have been deposited in a playa lake (McGiven, 1967). The Henshaw Formation contains two distinct matrix- to clast-supported conglomerates, referred to as the ‘Igneous’ and ‘Quartzite’ conglomerates. These conglomeratic units are correlated with the Fence and Kirk Hill conglomerates members, respectively, of the Carmichael inlier. The older (early Wenlock) ‘Igneous’ conglomerate is characterised by the presence of very fine-grained, variably porphyritic andesite, dacite and rhyolite as well as lapilli-tuff, microgranite, trachyte, ignimbrite, tonalite, quartz-diorite, and granite pebbles (Phillips et al., 2004). Although dominated by igneous material, sedimentary (sandstone, siltstone) and metasedimentary (phyllite, meta-quartz-arenite, quartzite, biotite-hornfels) rock fragments are also common. Pebbles and cobbles within the ‘Quartzite’ Conglomerate (early to middle Wenlock) are mainly composed of polycrystalline vein quartz, quartzite and meta-quartz-arenite. However, Phillips et al. (2004) demonstrated that this conglomerate also contains a range of igneous derived clasts similar to those in the ‘Igneous’ Conglomerate. The rounded nature of the pebbles, which include broken fragments of much larger cobbles, within both the ‘Igneous’ and

'Quartzite' conglomerates suggests that they are of polycyclic origin. Palaeobasin (Bluck, 1983, 1984) and geochemical studies (Heinz and Loeschke, 1988) have shown that the Southern Uplands is not the source terrane for the southerly derived 'Igneous' and 'Quartzite' conglomerates and their correlatives. Williams and Harper (1988) suggested that the igneous material present within these conglomeratic units may have been derived from Ordovician volcanics and an older metamorphic basement which lay to the south-east of the Midland Valley, at least during early Wenlock times.

2.2 LANARK GROUP

The Silurian to Lower Devonian Lanark Group of the Southern Midland Valley (Figure 1) comprises a terrestrial redbed sequence (probably Pridoli-Lower Devonian) of sandstones and conglomerates (Bluck, 1978, 1984, 2000; Smith, 1995, Phillips et al., 1998; Browne et al., 2002; Phillips et al., 2004) with a thick interval of calc-alkaline volcanic rocks (Thirlwall, 1981, 1983; Phillips, 1994). The predominantly fluvial sandstones and alluvial fan conglomerates were deposited in a linear northeast-trending basin, referred to as the Lanark Basin (Bluck, 1978, 1984). The base of the sequence is marked by the laterally extensive Greywacke Conglomerate Formation which locally rests unconformably upon the Llandovery to Lower Wenlock marine to terrestrial sedimentary rocks of the Girvan and North Esk inliers. In the Hagshaw Hills, Lesmahagow, Carmichael and Eastfield inliers, however, there is no marked unconformity between the basal Greywacke Conglomerate Formation and the underlying older Silurian strata, but there is a sudden change in depositional facies.

The Greywacke Conglomerate Formation comprises a sequence of proximal-fan conglomerates interbedded with thin medium- to coarse-grained sandstones and microconglomerates. The vertical stacking of the alluvial fans and predominance of proximal fans indicate that subsidence kept pace or exceeded uplift of the source area during deposition of this conglomeratic formation. The conglomerates are southerly-derived and dominated by pebble to boulder sized clasts of wacke sandstone and litharenite, with some fine-grained igneous rocks and chert. The wacke sandstone clasts, although similar to the Southern Uplands sedimentary rocks, were thought by Syba (1989) to have been derived from horst blocks of flysch within the Midland Valley Terrane that have subsequently been removed by strike-slip or covered by younger strata. A minor low-grade (greenschist facies) metamorphic component present within the conglomerates includes clasts of meta-quartz-arenite, quartzite and feldspathic metasandstone (Phillips and Barron, 2000; Phillips et al., 2004). The igneous rock fragments are mainly composed of fine-grained volcanic rocks, but also include two-mica granite and feldspar-biotite-quartz-phyric rhyolite; the latter possibly derived from high-level intrusions. The lithic-rich sandstones within the Greywacke Conglomerate Formation are typically closely to very closely packed, clast-supported, matrix-poor rocks composed of angular to subangular clasts of andesitic to dacitic rock fragments and monocrystalline quartz with minor plagioclase (Table 1) (Phillips & Barron, 2000; Phillips et al., 2004). Sedimentary and metasedimentary rocks fragments are also present within these heterolithic rocks.

The overlying high energy fluviatile redbed sandstones of the Swanshaw Sandstone Formation form mainly an upward-fining sequence (Smith, 1993, 1995). Sedimentary structures present within the fine- to coarse-grained sandstones record palaeoflows towards the south-west, to the north, and to the east-northeast (Smith 1995; Phillips et al., 1998). The litharenites and quartzose litharenites which dominate the Swanshaw Sandstone Formation are heterolithic and contain small pebbles of andesitic to felsic volcanic rocks, wacke metasandstone, chert, vein quartz and silty mudstone, as well as occasional metasedimentary rock fragments (psammite and quartzite) (Table 1) (Phillips et al., 2004). A renewed input of conglomerate rich in wacke sandstone pebbles in the upper part of the formation is thought to record local uplift prior to the Lower Devonian volcanism (Smith, 1995; Phillips et al., 1998; Phillips et al., 2004). The overlying calc-alkaline basaltic to andesitic lavas of the Carrick Hills, Duneaton, Biggar and Pentland Hills volcanic formations are locally interbedded with poorly sorted volcaniclastic sandstones (Smith, 1995; Phillips et al., 1998) that contain a restricted clast assemblage dominated by haematised basalt and andesite fragments, indicating that the Lower Devonian volcanic rocks were undergoing subaerial penecontemporaneous erosion (Phillips et al., 1998).

The overlying Auchtitench Sandstone Formation mainly consists of medium- to coarse-grained volcaniclastic sandstones and conglomerates that were deposited in a fluviatile environment consisting of large, high-energy braided rivers with some proximal deposition from alluvial fans. The highly weathered sandstones and siltstones at the base of the formation contain carbonate nodules which are interpreted as having formed as patchily developed soils or salinas on the irregular surface of the volcanic terrain (Smith, 1995). In the Lanark district the basal part of the Auchtitench Formation is represented by a sequence of fine- to coarse-grained volcaniclastic sandstones known as the Wiston Grey Volcaniclastic Member. These volcaniclastic rocks immediately overlie the Biggar Volcanic Formation and are largely composed of angular to subangular, basaltic, andesitic to occasionally dacitic volcanic rock fragments (Table 1). Similar volcanic-rich sandstones occur interbedded with the fine- to coarse-grained, lithic-rich to slightly feldspathic sandstones which dominate the remainder of the Auchtitench Formation. Clasts within these more quartzose sandstones are composed of monocrystalline quartz and plagioclase with varying amounts of volcanic rock fragments (Table 1). The southerly derived coarse pebble conglomerates (4 to 5 m thick) present within the middle of the formation are almost exclusively composed of volcanic rock fragments derived from the Lower Devonian lavas, but may also include minor basaltic andesite, various porphyries, tuffaceous rock and breccia clasts (Phillips et al., 1998). The pebble to boulder content is well-rounded, indicating transport by large rivers flowing across the Lower Devonian lava fields that may have extended south of the Southern Upland Fault (Bluck, 1983).

3 The Upper Silurian to Lower Devonian rocks in the Northern Midland Valley

3.1 STONEHAVEN GROUP

The Wenlock to Ludlow (Marshall, 1991; Wellman, 1993) Stonehaven Group (Armstrong and Paterson, 1970; Browne et al., 2001) occurs at the base of the Old Red Sandstone facies sequence of the northern Midland Valley (Figure 1). The group crops out on the northern limb of the Strathmore Syncline immediately adjacent to the Highland Boundary Fault. The Stonehaven Group mainly consists of cross-bedded and horizontally laminated fluviatile sandstones which rest unconformably upon Cambro-Ordovician rocks of the Highland Border Complex (Henderson and Robertson, 1982; Curry et al., 1984). The lower formation of the group, the Cowie Formation, comprises a sequence of medium-grained quartzose sandstones with intercalated siltstones and mudstones. Intraclasts of these mud rocks within some sandstones indicates localised reworking of the overbank deposits. Pebbly to locally conglomeratic sandstones at the base of the Cowie Formation contain abundant locally derived detritus from the Highland Border Complex and adjacent polydeformed and metamorphosed Dalradian Supergroup; including mylonite, quartzite, schist/phyllite and psammite rock fragments (Phillips and Carroll, 1995). The overlying sandstones also contain a significant metamorphic/quartzose component, comprising mono- and polycrystalline quartz, staurolite and garnet, as well as metamorphic rock fragments (Table 1).

The overlying Carron Sandstone Formation may be significantly younger than the Cowie Formation with Marshall et al. (1994) and Phillips and Carroll (1995) arguing for a break in sediment composition and process between these two formations. The Carron Sandstone Formation consists mainly of locally pebbly, fine- to medium-grained sandstones with a locally substantial volcanic component. Palaeoflow directions are not known for the lower part of the formation; however, those for the upper part indicate flow toward the south-west. The lower sandstones are mainly sub-litharenites and more rarely quartz arenites. Phillips et al. (1998) identified two discrete compositional cycles within the Carron Formation characterised by a rapid increase in the metamorphic/quartzose component of the sandstones near the base, followed by a gradual increase in volcanic (andesite to dacite) related detritus. They suggested that this related to the sediment load becoming increasingly dominated by comparatively juvenile volcanic detritus, with the creation of fault scars both within the basin and along within its hinterland providing a temporary source of sediment derived from older, less volcanic-rich, polycyclic alluvium.

3.2 DUNNOTTAR-CRAWTON GROUP

The recently defined Lochovian Dunnottar-Crawton Group (Browne et al., 2002) combines the previous Dunnottar and Crawton groups of Armstrong and Paterson (1970) (after Campbell, 1913). The group comprises the Dunnottar Castle Conglomerate (oldest) (including the Downie Point Conglomerate and Strathlethan Sandstone members), Tremuda Bay Volcanic, Gourdon Sandstone (Rob’s Cove Conglomerate and Doolie Ness Conglomerate members), Whitehouse Conglomerate and Crawton Volcanic (youngest) formations. The group is mainly composed of coarse, massive and very thickly bedded conglomerates with generally minor intercalations of lithic and volcaniclastic sandstones.

The conglomerates of the Dunnottar Castle Conglomerate Formation consist of thickly-bedded, massive or cross-bedded, clast-supported conglomerates with lenses of horizontally bedded, medium-grained sandstone. Angular to well-rounded pebble, cobble to boulder-sized clasts within these conglomerates are mainly derived from the polydeformed and metamorphosed metasedimentary rocks and post-orogenic granite plutons which intrude the Grampian terrane (Haughton and Bluck, 1989; Haughton, 1989; Phillips et al., 1998). The conglomerates are interpreted as having been deposited in large, south or south-west-flowing, braided rivers on extensive ‘wet’ alluvial fans (Haughton, 1989). In the Downie Point Conglomerate Member the clasts are mainly composed of andesitic volcanic rocks, psammite and quartzite, with much less granite and porphyritic microgranite than the other conglomerates within the Dunnottar Castle Conglomerate Formation (Table 1). Thick beds of volcaniclastic sandstone and rare volcaniclastic conglomerate interbedded with the non-volcaniclastic conglomerates were interpreted by Phillips et al. (1998) as representing periods when the background deposition of conglomerate was overwhelmed or disturbed by the introduction of large volumes of, probably locally derived, andesitic volcanic detritus. In the lower part of the Dunnottar Castle Conglomerate Formation, the Strathlethan Sandstone Member consists of medium-grained to locally pebbly, cross-bedded lithic-rich sandstones. The sandstones are mainly composed of monocrystalline quartz and andesitic to dacitic volcanic rock fragments with subordinate plagioclase (Table 1). The basal beds of the member are, however, coarser grained volcaniclastic sandstones containing angular clasts of andesitic volcanic rocks and dacite/rhyolite with rarer, rounded clasts of quartzite; the latter possibly being derived from the reworking of the underlying Downie Point Conglomerate Member (Phillips et al., 1998). Palaeoflow directions from the Strathlethan Sandstone Member are consistently toward the north-east, although there is greater variability in its upper part (Haughton, 1989). Robinson et al. (1998) record a change in imbrication fabrics within the remainder of the overlying Dunnottar Castle Conglomerate Formation from northward directed in the lower part, to south-easterly-directed in the higher parts of the sequence, with no obvious changes in clast composition. Gillen and Trewin (1987) reported low-grade metamorphic clasts, similar to Dalradian Southern Highland Group lithologies, in the conglomerates above the Strathlethan Sandstone Formation.

The overlying Tremuda Bay Volcanic Formation consists of a number of olivine-bearing trachybasalt (hawaiite) lava flows (Thirlwall, 1979; Browne et al., 2002).

The Gourdon Sandstone Formation is characterised by medium to thickly planar to cross bedded, pebbly, medium- to coarse-grained, commonly volcaniclastic sandstones. The conglomerates interbedded with these volcaniclastic sandstones, however, contain a considerable proportion of well-rounded cobbles and pebbles of metamorphic (psammite and quartzite) and granitic clasts. The Gordon Sandstone Formation contains two distinctive conglomerates, namely the Doolie Ness and Rob's Cove conglomerate members. The Rob's Cove Conglomerate Member contrasts with other conglomerates in being very poorly sorted and containing angular to subrounded clasts of a wide range of lithologies. Haughton (1988) recorded the following rock types meta-wacke sandstone, lithic sandstone, gravel conglomerate, hornblende-phyric andesite, foliated and unfoliated granodiorite, and tonalite. Other minor rock types present include metabasalt, basalt, felsite, hornfels, jasper, quartzite, vein quartz and limestone. The diversity of the clast assemblage and extreme textural immaturity of the Rob's Cove Conglomerate Member are unique (Carroll, 1995a and b). Haughton (1988) suggested that this conglomerate was derived from a cryptic source terrane hidden within the Midland Valley Terrane. Palaeocurrent data indicate that this source was possibly located to the south to south-east of Inverbervie.

The Gourdon Sandstone Formation is overlain by the Whitehouse Conglomerate Formation. This formation is mainly composed of very coarse conglomerate containing blocks (up to 1m in diameter) of metamorphic and granitic rocks derived from the Grampian terrane (see Table 1). This thickly bedded, massive or weakly cross-stratified, clast supported conglomerate passes upwards and laterally into lenses of horizontally-bedded and cross-stratified, pebbly sandstones. The clasts within the coarse fraction of the conglomerates is dominated by igneous rocks, mainly granite and porphyritic microgranite with lesser amounts of basalt and andesite. Metamorphic lithologies, such as psammite and quartz, are locally abundant. Distinctive metamorphic and sedimentary lithologies, including metabasalt, gravel conglomerate and wacke sandstone are locally abundant within the conglomerates. Browne et al. (2002) interpreted the presence of these distinctive lithologies as recording a southerly derived detritus or reworking of the underlying Rob's Cove Conglomerate Member. Overlying the Whitehouse Conglomerate Formation are the porphyritic basalt to basaltic andesite lavas of the Crawton Volcanic Formation.

3.3 ARBUTHNOTT-GARVOCK GROUP

The Lochovian to Pragian Arbuthnott-Garvock Group (Browne et al., 2002) crops out extensively on both limbs of the Strathmore Syncline and, to a lesser extent, in south-west Scotland. The group is mainly composed of sandstone with interbedded clast-supported conglomerates. In the north-east of the Midland Valley and adjacent to the Highland Boundary Fault the conglomerates contain well-rounded pebbles, cobbles and boulders of volcanic rocks, psammite and quartzite. Locally the sandstones are interbedded with siltstones and mudstones (e.g. in the Dundee and Strathallan districts). The group comprises the Catterline Conglomerate (oldest), Montrose Volcanic, Deep Conglomerate, Scone Sandstone, Craighall Conglomerate, Dundee Flagstone, Ochil Volcanic, Craig of Monievreckie Conglomerate and Ruchill Flagstone formations.

The Catterline Conglomerate Formation rests conformably upon the Crawton Volcanic Formation and is predominantly composed of thick-bedded, clast-supported cobble to pebble conglomerate with rare thick to very thick lenses of sandstone interbedded with a few thin lava flows and mudstone beds (Browne et al., 2002). The conglomerates of this formation tend to be dominated by igneous rocks, mainly granite and porphyritic microgranite with lesser amounts of basaltic to andesitic volcanic rocks. Metamorphic lithologies including psammite and quartzite are locally abundant. The matrix to the conglomerate is typically of a medium- to coarse-grained lithic sandstone, the composition of which tends to reflect that of the associated coarse clasts. These fine- to coarse-grained, quartzofeldspathic to lithic-rich sandstones are poorly sorted and comprise angular to subangular grains of monocrystalline quartz, altered feldspar and very fine-grained, aphyric andesitic to dacitic volcanic rock fragments (Table 1) (Phillips, 2004, 2007). Detrital micas (biotite, muscovite) and polycrystalline quartz are also common components. Fragments of hornblende-bearing granite, sandstone, phyllite or schist, as well as mudstone intraclasts may also be present. In the Barras Conglomerate Member of the formation the matrix to the conglomerate is entirely composed of a coarse-grained volcaniclastic pebbly sandstone. These poorly to very poorly sorted volcaniclastic sandstones are composed of angular to subangular fragments of andesitic to dacitic volcanic or high-level intrusive igneous rocks. These include plagioclase microporphyritic andesite, pilotaxitic to hyalopilitic andesitic or dacitic rock, plagioclase-pyroxene-phyric andesite or basalt, plagioclase-biotite-phyric dacite, olivine basalt. Although volcanic-rich these sandstones also contain clasts of biotite granite, psammite, biotite-muscovite-schist, meta-quartz-arenite, limestone, polycrystalline vein quartz, metasandstone, siltstone and felsite (Table 1). The metamorphic and sandstone rock fragments tend to be more rounded in shape and may represent broken fragments of larger cobbles pebbles.

The overlying Montrose Volcanic Formation consists of olivine-bearing basaltic and andesitic lavas with intercalated volcaniclastic sedimentary rocks (Phillips, 2004, 2007). The volcaniclastic or pyroclastic rocks include lapilli tuff and volcaniclastic breccia which are mainly composed of angular, ash to lapilli-grade fragments of altered basalt and andesite clasts, as well as crystal fragments. The Deep Conglomerate Formation (Carroll, 1995a and b) rests conformably upon the volcanic rocks and consists predominantly of massive, clast-supported conglomerate with well-rounded, pebble to boulder-sized clasts derived from the adjacent Grampian terrane. In the lower part these clasts are mainly composed of volcanic rocks. In the upper part of the formation the clasts are mainly composed of quartzite and psammite with lesser amounts of volcanic rock. The conglomerate locally grades up into lenticular units of trough cross-bedded, pebbly and clay-flake sandstone with thin sandy siltstone and mudstone laminations. The Craighall Conglomerate Formation of the Blairgowrie to Edzell area rests directly upon the polydeformed metamorphic rocks of the Dalradian Supergroup or locally the Lintrathen Tuff Member at the top of the Dunnottar-Crawton Group. The formation mainly consists of massive, very coarse conglomerate containing subangular to well-rounded clasts of volcanic rocks with minor psammite, quartzite and granite.

The Dundee Flagstone Formation is dominated by a sequence of medium- to coarse-grained, cross-bedded fluvial sandstones with intercalations of more thinly bedded sandstone, siltstone and mudstone representing deltaic and lacustrine deposits (Armstrong and Paterson, 1970; Browne et al., 2002). The lithic-rich, quartzose sandstones are dominated by andesitic, dacitic to rhyolitic rock fragments (biotite-feldspar-phyric dacite, pilotaxitic dacite) and monocrystalline quartz with variable amounts of plagioclase (Phillips, 2004, 2007). Although dominated by clasts of acidic volcanic or high-level intrusive rocks, sedimentary and metamorphic (schist, phyllite, metabasalt, staurolite, garnet) derived detritus may also be present (Table 1). These metamorphic lithics are typically more rounded in shape indicative of a more prolonged period of transport (polycyclic). In the finer grained sandstones detrital micas (muscovite, biotite) are aligned parallel to bedding. Aligned detrital micas also occur within the siltstones which also contain angular to subangular grains of monocrystalline quartz. The Dundee Formation rest on the basaltic to andesitic volcanic rocks of the Ochil Volcanic Formation, and interdigitates laterally with the Catterline Conglomerate Formation and volcaniclastic sandstones of the Ochil Volcanic Formation.

The Scone Sandstone Formation (Armstrong et al., 1985; Browne et al., 2002) consists largely of medium- to coarse-grained, cross-bedded, quartzose to slightly feldspathic, lithic sandstones.

These poorly to moderately sorted sandstones contain angular to subangular, to rarely subrounded grains of monocrystalline quartz, plagioclase and variably altered andesitic to dacitic rock fragments (Table 1) (Phillips, 2004, 2007). Metamorphic rock fragments may also be present including biotite-muscovite schist and psammite. On the southern limb of the Sidlaw Anticline near Arbroath the formation contains a distinctive conglomerate, the Auchmithie Conglomerate Member. This conglomerate contains clasts of acidic igneous rocks including feldspar-quartz-biotite-phyric rhyolite, ignimbritic rhyolite and granite. The fine-grained sandstone matrix to the conglomerate is poorly sorted and comprises angular to occasionally subangular clasts of monocrystalline quartz, felsite and chert (Phillips, 2004, 2007). The upper part of the Scone Sandstone Formation is transitional into the Cromlix Mudstone Formation. This transitional facies includes concretionary pedogenic limestones such as the Pittendriech Limestone.

The Craig of Monievreckie Conglomerate Formation (Browne et al., 2002) consists of clast-supported, massive, bimodally sorted conglomerates deposited by a number of coalesced alluvial fans. In the lower part of the sequence the coarse fraction comprises predominantly basaltic to andesitic volcanic lithic clasts, with lesser amounts of felsite, psammite, quartzite and semipelite. The matrix to the conglomerates is composed of medium- to coarse-grained, poorly sorted, lithic-rich sandstone containing angular to subrounded clasts of aphyric to microporphyritic andesite (Table 1). Minor amounts of mono- and polycrystalline quartz, plagioclase and metamorphic derived clasts (schist/phyllite, psammite, quartzite, garnet) may also be present (Phillips and Aitken, 1998). The proportion of non-volcanic detritus increases upwards through the formation. Sandstones are subsidiary, but include the Bofrishlie Burn Sandstone Member. These medium- to very coarse-grained volcaniclastic sandstones are largely composed of andesitic to dacitic volcanic rock fragments. The finer grained sandstones may also possess a significant proportion of monocrystalline quartz, as well as minor plagioclase, chlorite-schist/phyllite, meta-quartz-arenite, psammite and quartzite. The fine- to medium-grained pyroxene microporphyritic basaltic lavas of Balleich Lava Member locally separate the Craig of Monievreckie Conglomerate Formation from sandstones at the base (diachronous) of the overlying Ruchill Flagstone Formation.

The Ruchill Flagstone Formation consists of fine- to coarse-grained, massive sandstones with thinly interbedded silty mudstones and micaceous siltstones (Francis et al., 1970; Browne et al., 2002). The locally pebbly sandstones are heterolithic to locally volcaniclastic comprising angular to subrounded clasts of microporphyritic andesite and dacite (Table 1) (Phillips and Aitken, 1998). Minor monocrystalline quartz, plagioclase and metamorphic rock fragments (quartzite, psammite, metasiltstone, metabasalt, chlorite-schist/phyllite). Intra-formational rip-up clasts of mudstone are also common within the sandstones. The formation also contains intercalations of poorly sorted, matrix-supported conglomerate including the Callander Craig Conglomerate, Gartartan Conglomerate and Inchmurrin Conglomerate members (Phillips and Aitken, 1998). The matrix to the Inchmurrin Conglomerate Member contains clasts of very fine-grained, aphyric to microporphyritic andesite, with mono- and polycrystalline quartz occurring within the finer grained fraction. Locally the conglomerate contains rounded clasts of meta-quartz-arenite, quartzite and metasandstone. Fine- to coarse-grained sandstones and siltstones interbedded with the Inchmurrin Conglomerate Member contain angular to rounded rip-up clasts of laminated siltstone and mudstones.

3.4 STRATHMORE GROUP

The Emsian Strathmore Group (Armstrong and Paterson, 1970; Browne et al., 2002) consists mainly of locally pebbly, medium-grained, cross-bedded sandstones with important developments of moderately well-bedded, clast supported conglomerate. Rapid lateral variations in facies adjacent to the Highland Border reflect variations in depositional setting and the location with respect to local alluvial fans. The most wide spread elements of the group are represented by the Cromlix Mudstone and Teith Sandstone formations. The Cromlix Mudstone Formation (Francis et al., 1970) is characterised by a sequence of sandy or silty mudstones and siltstones with locally interbedded fine-grained, muddy sandstones. The poorly sorted, fine-grained sandstones to silty sandstones mainly comprise angular, subangular to locally subrounded clasts of monocrystalline quartz, with minor plagioclase and polycrystalline quartz within a muddy matrix. Intra-formational mudstone rip-up clasts also occur within the sandstones and dominate the locally developed mudstone breccias. In the Aberfoyle district the Cromlix Mudstone Formation contains a number of medium- to coarse-grained sandstones and conglomerate members, including the Shannochill Sandstone Member (Phillips and Aitken, 1998). These poorly sorted, clast supported, lithic sandstones are composed of volcanic (aphyric to microporphyritic andesite and dacite) and metamorphic rock fragments (quartzite, meta-quartz-arenite, chlorite-schist/phyllite, psammite) (Table 1). Fine-grained sandstone and mudstone rip-up clasts are also present. The finer grained sandstones are typically more quartzose and dominated by angular to subangular clasts of monocrystalline quartz and feldspar.

The Cromlix Mudstone Formation passes laterally and upwards into the cross-bedded, sometimes pebbly, feldspathic sandstones of the Teith Sandstone Formation. The fine- to coarse-grained, quartzofeldspathic sandstones of the Teith Sandstone Formation are mainly composed of monocrystalline quartz and feldspar (plagioclase, K-feldspar, perthite), with subordinate polycrystalline quartz (Table 1). Minor amounts of metamorphic derived detritus do occur, including metasandstone, psammite, garnet and staurolite. Along the Highland Border the Teith Sandstone Formation contains a number of conglomeratic units. In the Aberfoyle area the formation is divided into the Bracklinn Falls Conglomerate, Dalmary Sandstone and Buchlyvie Sandstone members (Phillips and Aitken, 1998). The conglomerates and coarse-grained, pebbly sandstones of Bracklinn Falls Conglomerate Member are composed of angular to subrounded clasts of andesitic volcanic rock, with subordinate amounts of metamorphic rock fragments including quartzite, mylonite, metabasalt, psammite and chlorite-schist/phyllite (Table 1). Rare carbonate sedimentary rock fragments are also present. The matrix to these conglomerates is composed of a fine- to medium-grained sandstone. The coarse-grained, pebbly sandstones and conglomerates of the Dalmary Sandstone Member are locally bimodally sorted with the larger fraction comprising andesitic volcanic and metamorphic rock fragments, as well as polycrystalline quartz. The metamorphic lithic clasts are typically more rounded in shape and comprise quartzite, chlorite-schist/phyllite, psammite, mylonitic psammite and minor metabasalt (Table 1). The finer grained sandstone matrix to the conglomerates contains a similar range of rock fragments to the coarse fraction, as well as mono- and polycrystalline quartz. The finer grained sandstones interbedded with the conglomerates of the Dalmary Sandstone Member are typically moderately to well sorted and lithic-rich. They are dominated by monocrystalline quartz with variably degraded andesitic volcanic rock fragments and altered plagioclase. Intra-formational mudstone rip-up clasts occur locally within the sandstones.

4 The Upper Devonian rocks of the Northern Midland Valley

4.1 STRATHEDEN GROUP

The Upper Devonian, Frasnian to Famennian, Stratheden Group consists mainly of fluvial sandstones with subordinate conglomerates, mudstones and only one localised volcanic unit on the island of Arran (outwith the Midland Valley of Scotland). The group comprises the Burnside Sandstone, Glenvale Sandstone and Knox Pulpit Sandstone formations (Browne et al., 2002).

The Glenvale Sandstone Formation consists of fine- to medium-grained, trough cross-stratified feldspathic sandstones with rare siliceous pebbles. These poorly sorted sandstones are mainly composed of monocrystalline quartz with variable amounts of plagioclase and felsitic or cherty rock fragments (Table 1) (Phillips, 2004). Locally these sedimentary rocks are characterised by the presence of mudstone and siltstone intraclasts.

5 Sandstone composition and provenance

5.1 ANALYTICAL TECHNIQUE

Selected samples of medium- to coarse-grained sandstone from the Lanark, Stonehaven, Dunnottar-Crawton, Arbuthnott-Garvock, Strathmore and Stratheden groups, as well as the Silurian inliers of the southern Midland Valley, have been analysed as part of a detailed petrographical provenance study. The thin sections included in this study were examined optically using a standard transmitted light petrological microscope. The modal proportion of the matrix (where present) and various detrital components within the sandstones were determined using a Swift Automatic Point Counter. The ‘raw’ data were then recalculated as modal percentages and plotted on a series of variation diagrams using a commercial spreadsheet package (Microsoft Excel). Modal compositions of the sandstones were calculated as volumetric proportions of the following categories of detrital grains (Dickinson, 1970; Dickinson and Suczek, 1979): stable quartzose grains (Q) including both monocrystalline quartz (Qm) and polycrystalline quartz (Qp); monocrystalline feldspar grains (F) 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 sandstone was taken as the sum of the unstable lithic fragments (L) plus stable polycrystalline quartz (Qp) clasts. The matrix component include primary matrix and cement, as well as partially degraded, unstable detrital material where the clast shape can no longer be recognised. Other minor components include muscovite (Mu), biotite (Bio), garnet (Gt), opaque oxides (Op), chlorite (Chl), epidote (Ep) and granitic lithic clasts (Lg). Data obtained for the Silurian and Devonian formations are plotted on a series of variation diagrams (Figures 3 to 19), and mean compositions of the sandstones are listed in Table 2.

5.2 SANDSTONE COMPOSITION

Modal compositional data obtained for the sandstones of the Lanark, Stonehaven, Dunnottar-Crawton, Arbuthnott-Garvock, Strathmore and Stratheden groups, as well as the Silurian inliers are plotted on series of variation diagrams illustrated in Figures 3 to 11. The data have been plotted on a series of log-ratio plots (Figures 7 to 11) to avoid problems of closure within the data set. These data are also plotted as a series of histograms and expanded pie charts which show the relative proportions of the main detrital components (volcanic lithic clasts, metamorphic lithic clasts, sedimentary lithic clasts, plagioclase, K-feldspar, monocrystalline quartz and polycrystalline quartz) within each sample (Figures 12 to 19). Several general observations can be made regarding sandstone composition within the central Scotland: ***(i)*** there significant differences in sandstone composition between the south and north Midland Valley

(Figures 3, 4, 5 and 6); ***(ii)*** a negative correlation exists between the modal proportion of volcanic lithic clasts and monocrystalline quartz (Figure 3a), with the increase in quartz reflecting an increase in the compositional maturity of the sandstones; ***(iii)*** a positive correlation can be drawn between polycrystalline quartz and monocrystalline quartz within these sandstones (Figure 3b); ***(iv)*** a negative relationship exists between the variation in the modal volcanic lithic clasts and plagioclase (Figure 3c) possibly reflecting a decrease in the grain size of the sandstone and/or the period of transport prior to deposition (i.e. maturity); and ***(v)*** the covariation in polycrystalline quartz and metamorphic lithic clasts define a positive correlation (Figure 3c) suggesting that these two components were derived from the same source. Similar broad trends in sandstone composition within central Scotland are also observed on the ratio plots illustrated in Figures 5, 6 and 7, and log-ratio plots shown on Figures 7 to 11. The marked change in the gradient of the trend in the covariation of volcanic lithic clasts versus monocrystalline quartz (Figures 3a, 5a and 7a) is thought to reflect a change in the grain size and maturity of the sandstones. This interpretation is supported by the fact that the coarser grained fraction within the analysed sandstones is, in general, largely composed of angular to subangular, low sphericity volcanic lithic clasts. Although there is a negative relationship between volcanic lithic clasts and plagioclase (Figure 3c), detrital plagioclase is thought to be largely derived from an igneous (volcanic) source; a conclusion supported by the presence of plagioclase phenocrysts within a significant proportion of the volcanic rock fragments. The negative relationship displayed between these two components may be interpreted as reflecting an increase in the maturity of the volcanic detritus supplied to the basin. The unstable volcanic lithic clasts will be preferentially removed from the sediment during prolonged transport/reworking, leading to a relative increase in the concentration of more stable plagioclase within the sandstone.

The clear discrimination between sandstone formations analysed from the southern and northern Midland Valley (Figures 3, 4 and 5) suggests that these formations were derived from two separate source terranes and that, in general, there was little (if any) mixing of detritus. Overall the sandstones of the northern Midland Valley have a higher metamorphic lithic and polycrystalline quartz contents (Figures 3b, 4b, 4c and 6a), with these components having been derived from the Dalradian Supergroup source terrane located immediately to the north of the Strathmore basin. Sandstone compositional data, therefore, supports the conclusion of Philips et al. (1998) and Phillips et al. (2004) that the southern Lanark and northern Strathmore sedimentary basins were separated by a major topographic feature or high during the Siluro-Devonian times. This feature divided the two basins preventing sediment dispersal from the Grampian Highlands terrane into the southern Midland Valley.

The Auchtitench Sandstone (southern Midland Valley) and Gourdon Sandstone (northern Midland Valley) formations are clearly discriminated from the remainder of the Silurian and Devonian sandstones (Figures 9, 10a, 10c and 11). These volcanic formations contain a much higher proportion of plagioclase and volcanic lithic clasts, consistent with the stratigraphical position of these sandstone dominated units immediately above the Duneaton Volcanic (southern Midland Valley) and Tremuda Bay Volcanic (northern Midland Valley) formations. The variation in plagioclase and volcanic lithics components within the sandstones define well-developed trends on both bivariant and log-ratio plots (Figures 3a, 4a, 5a, 5b, 6b, 7a, 9b and 10a). This is consistent with the variations in the maturity of these deposits with a decrease in unstable lithic components and resultant increase in more stable plagioclase and quartzose detritus occurring within the far travelled/recycled sandstones.

In the northern Midland Valley, the mean compositional data determined for these sandstones suggests that there are significant differences between the Stonehaven Group of the Stonehaven area, and the stratigraphically higher Arbuthnott-Garvock and Strathmore groups of the Aberfoyle and Strathmore areas (Figures 12, 13 and 14). These stratigraphical and regional variations in sandstone composition are clearly illustrated by the variation in mono- and polycrystalline quartz (Figures 3b and 8b), plagioclase (Figure 3c) and volcanic lithic clasts (Figure 5a), and to a lesser extent metamorphic lithic clasts (Figures 4b and 6a). Results for the

Arbuthnott-Garvock Group from the Strathmore area (represented by the Whitehouse Conglomerate, Catterline Conglomerate, Dundee Flagstone, Scone Sandstone and Cromlix Mudstone formations) and Aberfoyle district (represented by the Ruchill Flagstone and Cromlix Mudstone formations, as well as the Inchmurrin Conglomerate Member) indicates that there is also an along strike variation in sandstone composition. The sandstones from the Aberfoyle district, in general, possess much higher polycrystalline quartz (Figure 3b), volcanic lithic (Figures 3c and 4a) and metamorphic lithic (Figures 5c) contents, and lower monocrystalline quartz (Figure 4b) contents than sandstones from the Strathmore district. The Ruchill Sandstone and Catterline Conglomerate formations also exhibit a systematic variation in sandstone composition reflecting changes in volcanic lithic, monocrystalline quartz, plagioclase and metamorphic lithic components (see Figures 3, 5, 7 and 8). The discrimination between the Arbuthnott-Garvock Group sandstones exposed in these two areas can also be seen on the log-ratio plots (Figures 7, 9, 10 and 11). This along strike variation is thought to reflect changes in the geology of the source terrane from southwest to northeast. The preservation of these compositional differences within the sandstones indicates that along strike mixing of sediment was limited and that the sandstones were deposited relatively close to source.

The Swanshaw Sandstone and Auchtitench Sandstone formations of the southern Midland Valley both show a systematic variation in volcanic lithic content with respect to monocrystalline quartz (Figures 5a, 7a, 9a and 9b). Similar systematic variations in sandstone composition are shown by the Ruchill Flagstone and Gourdon Sandstone formations of the northern Midland Valley (Figures 5a, 7a, 9a and 9b). Both the Auchtitench Sandstone and Gourdon Sandstone formations are dominated by volcaniclastic sandstones, with the compositional data for these rocks providing evidence of the mixing of immature (first cycle) volcanic derived detritus with sediment derived from a more quartzose (possibly polycyclic) source which included, in the case of the Gourdon Sandstone Formation, a significant proportion of older metamorphic rocks derived from the Dalradian Supergroup of the Scottish Highlands. Log ratio plots involving volcanic lithics and plagioclase (Figures 7a, 7b, 9, 10a and 11a) clearly discriminates these volcanic-rich sandstone formations from the remainder of the Midland Valley Siluro-Devonian sandstones. The volcaniclastic sandstones of the Gourdon Sandstone formation are discriminated from the older Auchtitench Sandstone Formation by their higher modal metamorphic lithic content (Figures 8a, 9c) and lower monocrystalline quartz content (Figures 5a, 6b and 8b); with these sandstones displaying a systematic variation in their metamorphic lithic content with respect to both mono- and polycrystalline quartz. The Ruchill Flagstone Formation also shows evidence of systematic variations in volcanic and metamorphic lithic, and plagioclase contents (Figures 3a, 5, 6b, 7 and 8).

The sandstones from the Cock Rig, Henshaw, March Wood, Eastgate, Greywacke Conglomerate and Swanshaw formations are compositionally similar (Figures 3 to 14). This supports the conclusions of Phillips et al. (2004) that although the Greywacke Conglomerate Formation represented a significant change in depositional environment at the base of the Lanark Group, this was not reflected in a major change in sandstone composition. The major change in sandstone composition within the Lanark Group occurred at the base of the Auchtitench Sandstone Formation, coinciding with the onset of Lower Devonian volcanism. On a number of plots the sandstones of the Swanshaw Sandstone Formation show a systematic variation in volcanic lithics and plagioclase with respect to monocrystalline quartz (Figure 6b). This reflects the increase in volcanic derived detritus upward through the formation prior to the first major phase of volcanism at the base of the Auchtitench Sandstone Formation (cf. Phillips and Smith, 1995; Phillips et al., 1998).

Sandstones from the Cowie Sandstone, Carron Sandstone, Strathlethan Sandstone and Dunnottar Castle Conglomerate formations are compositionally distinct from the sandstones of the southern Midland Valley (Figures 3 to 14), with the sandstones from the lower part of the sequence in the Stonehaven area have an overall higher polycrystalline quartz content (Figures 3b and 4c). No obvious systematic variations in sandstone composition have been recognised within the data from the Cowie Sandstone, Carron Sandstone, Strathlethan Sandstone and Dunnottar Castle Conglomerate formations (see Figures 3 to 14). This may be, at least in part, be due to the small size of the data set or due to the sediment being supplied to the basin was well mixed. The sandstones from the Stonehaven area are also compositionally distinct from the much younger sandstones of the Arbuthnott-Garvock and Strathmore groups of the Aberfoyle district. The sandstones analysed from the Cowie Sandstone, Carron Sandstone, Strathlethan Sandstone and Dunnottar Castle Conglomerate formations are discriminated by their lower metamorphic lithic content (Figures 4a, 4b and 6a) and overall lower polycrystalline quartz content (Figure 3b).

Sandstones from the Craig of Monievreckie Conglomerate, Ruchill Flagstone, Cromlix Mudstone formations, as well as the Inchmurrin Conglomerate, Shannochill Sandstone, Dalmary Sandstone and Bracklinn Falls Conglomerate members from the Aberfoyle district, in general, exhibit a similar compositional range (Figures 3 to 14). They are distinguished from the sandstones of the southern Midland Valley by their higher polycrystalline quartz content (Figures 3b, 4c, 9a, 10c and 12b) and, in general, greater modal proportion of metamorphic lithic clasts (Figures 4, 5c, 6a, 8a and 13b) reflecting their proximity to the Dalradian Supergroup of the Scottish Highlands. In detail, sandstones from the Ruchill Formation exhibit the widest compositional range (Figures 3 to 13), which is largely controlled by the modal variation in volcanic lithic and stable quartzose components.

Compositional data for the sandstones of the Strathmore district (Whitehouse Conglomerate, Scone Sandstone, Dundee Flagstone, Glenvale Sandstone, Deep Conglomerate, Teith Sandstone, Catterline Conglomerate and Cromlix Mudstone formations) shows that they are compositionally distinct from sandstones of the southern Midland Valley, and sandstones of similar age from the Aberfoyle and Stonehaven districts of the northern Midland Valley (Figures 3 to 14). However, initial results suggests that the Scone Sandstone Formation does show an apparent compositional overlap with Swanshaw Sandstone Formation of the southern Midland Valley (Figures 3c, 5 and 6a). the Ruchill Flagstone and Catterline Conglomerate formations both show a systematic variation in the proportions of volcanic lithics with respect to monocrystalline quartz (Figure 3a) and ratios of monocrystalline quartz/total lithic clasts, plagioclase/total lithic clasts, metamorphic lithic clasts/total lithic clasts and volcanic lithic clasts/total lithic clasts (Figure 5).

5.3 LITHOSTRATIGRAPHICAL VARIATION IN SANDSTONE COMPOSITION

The clear discrimination between sandstone formations analysed from the southern and northern Midland Valley (Figures 3, 4 and 5) suggests that these formations were derived from two separate source terranes and that, in general, there was little (if any) mixing of detritus. The volcanic-rich sandstones of the Gourdon Sandstone (Dunnottar-Crawton Group) and Auchtitench Sandstone (Lanark Group) formations are compositionally distinct from the remainder of the Silurian and Devonian sandstones of the Midland Valley (Figures 9a, 9c, 10c and 11a). The source of these volcanic-rich sandstone formations can be directly related to the penecontemporaneous volcanic activity. These two sandstone formations directly overly the Duneaton Volcanic and Tremuda Bay Volcanic formations, respectively. A number of ‘cycles’ in sandstone composition can be identified within the Auchtitench Sandstone Formation (Figures 16 and 17) which are characterised by an increase in quartz and plagioclase and an antithetic decrease in the modal proportion of volcanic lithic clasts (Phillips et al., 1998; Phillips et al., 2004). Phillips et al. (1998) concluded that this cyclicity reflected periods of uplift and erosion within the Lower Old Red Sandstone volcanic source terrane. A similar model may also be applicable to the Gourdon Sandstone, Catterline Conglomerate and, to a lesser extent, Ruchill Sandstone formations with seismicity associated with penecontemporaneous volcanic activity providing the required instability within the Strathmore sedimentary basin. Both the Gourdon Sandstone and Catterline Conglomerate formations exhibit a cyclicity in sandstone composition, in particular an increase in volcanic lithic clasts and antithetic decrease in monocrystalline quartz

(Figures 18 and 19) upwards through the sequence. Unlike the Auchtitench Sandstone, Catterline Conglomerate and Gourdon Sandstone formations, however, the Ruchill Sandstone Formation does not directly overlie a volcanic member. The variation in sandstone composition identified within the Ruchill Sandstone Formation (Figures 18 and 19) may be related to uplift during a minor penecontemporaneous volcanic episode (now removed), or alternatively the uplift, exposure and reworking of a suite of older volcanic-rich sandstones.

The sandstones from the Cock Rig, Henshaw, March Wood, Eastgate, Greywacke Conglomerate and Swanshaw formations are compositionally similar (Figures 3 to 14). This supports the conclusions of Phillips et al. (2004) that although the Greywacke Conglomerate Formation represented a significant change in depositional environment at the base of the Lanark Group, this was not reflected in a major change in sandstone composition. The most prominent change in sandstone composition within the Lanark Group occurred at the base of the Auchtitench Sandstone Formation, coinciding with the onset of Lower Devonian volcanism. On a number of plots the sandstones of the Swanshaw Sandstone Formation show a systematic variation in volcanic lithics and plagioclase with respect to monocrystalline quartz (Figures 3a, 3c, 5 and 6b). This reflects the increase in volcanic derived detritus upward through the formation prior to the first major phase of volcanism at the base of the Auchtitench Sandstone Formation (see Figure 16) (cf. Phillips and Smith, 1995; Phillips et al., 1998).

Sandstones from the Cowie Sandstone, Carron Sandstone, Strathlethan Sandstone and Dunnottar Castle Conglomerate formations of the Stonehaven district are compositionally distinct from the sandstones of the Silurian inliers and Devonian Swanshaw Formation of the southern Midland Valley (Figures 3 to 14). The Cowie Sandstone and Carron Sandstone formations of the Stonehaven Group are of a similar age to the sedimentary rocks exposed in the Silurian inliers of the southern Midland Valley. The clear compositional differences between these sequences, therefore, can be used to suggest that they were deposited in two separate basins (cf. Phillips et al., 1989). The major change in sandstone composition within the Stonehaven area occurs within the Dunnottar Group at the top of Dunnottar Castle Conglomerate Formation (Figures 18 and 19). This conglomeratic unit is overlain by the Tremuda Bay Volcanic Formation, with the overlying Gourdon Sandstone Formation having been derived from these calc-alkaline volcanic rocks.

As stated above, compositional data for the sandstones of the Strathmore district (Whitehouse Conglomerate, Scone Sandstone, Dundee Flagstone, Glenvale Sandstone, Deep Conglomerate, Teith Sandstone, Catterline Conglomerate and Cromlix Mudstone formations) shows that they are compositionally distinct from sandstones exposed elsewhere in the southern and northern Midland Valley (Figures 3 to 14). Although there is an apparent compositional overlap between the Scone Sandstone Formation and, older, Swanshaw Sandstone Formation of the southern Midland Valley (Figures 3c, 5 and 6a) there is no evidence to suggest that there is a direct sedimentological link between these two formations. Lithostratigraphical variations in sandstone composition within Catterline Conglomerate Formations record an increase in the proportions of volcanic lithic clasts and antithetic decrease in monocrystalline quartz (Figures 18 and 19). This variation in sandstone composition is thought to reflect the uplift and erosion of the penecontemporaneous Crawton Volcanic Formation which directly underlies the Catterline Conglomerate Formation (Figure 18). One of the sandstones from the Dundee Flagstone Formation is also rich in unstable volcanic lithic detritus (Figure 18). It is possible that this sandstone was derived from the reworking of older volcanic derived sandstones. However, small volumes of basaltic volcanic rocks do occur within the upper part of the Scone Sandstone Formation of the Strathmore district (Golledge, 2007 pers. comm.). In this area the Scone Sandstone Formation is thought to be broadly contemporaneous with the Dundee Flagstone Formation, with the flagstones representing a more distal facies. Consequently, it is possible that the locally volcanic-rich sandstones within the Dundee Flagstone Formation were derived from the uplift and erosion of penecontemporaneous volcanic rocks. Sandstones from the overlying Lower Devonian Scone Sandstone, Cromlix Mudstone, Teith Sandstone and Upper Devonian

Glenvale Sandstone formations all contain much lower concentrations of volcanic derived detritus, indicating that the volcanic influence on sandstone composition primarily occurs within the lower part of the Arbuthnott-Garvock Group (Figures 18 and 19).

5.4 SANDSTONE PROVENANCE

There is a clear discrimination between sandstone formations analysed from the southern and northern Midland Valley (Figures 3 to 14), suggesting that they were derived from two separate source terranes and that, in general, there was little (if any) evidence for mixing of detritus.

Sandstones from the March Wood, Eastgate, Cock Rig, Henshaw, Swanshaw Sandstone and Greywacke Conglomerate formations, in general, plot within the transitional, recycled orogenic fields on Figure 20. However, due to their slightly higher modal plagioclase content, data for the Eastgate and Swanshaw formations plot within mixed to dissected volcanic provenance fields on Figure 20b. The sandstones from the Silurian inliers and lower part of the Lanark Group are, therefore, interpreted as having been derived from a recycled orogenic provenance which included quartzose/metamorphic and volcanic rocks (cf. Phillips et al., 2004). Palaeocurrent data obtained for these formations suggests that the metamorphic source may have been located within the Midland Valley terrane. The marked compositional difference between the sandstones of the southern and northern Midland Valley indicates that the Dalradian or Grampian terrane was not the source for the metamorphic detritus. The compositionally distinct Auchtitench Sandstone Formation defined a trend ranging from an undissected to dissected volcanic source on Figure 20, with a small number of the analyses plotting within the mixed provenance field (Figure 20b). The compositionally and texturally immature nature of these lithic-rich sandstones supports the conclusion that they were derived from the an uplifted penecontemporaneous volcanic source, represented in outcrop by the Duneaton Volcanic Formation.

The provenance of the Arbuthnott-Garvock and Strathmore group sandstones in the Aberfoyle district was controlled by the interplay of two separate sources, namely a quartzose/metamorphic source and a volcanic source. Compositional data obtained for the sandstones of the Craig of Monievreckie Conglomerate Formation, Ruchill Formation, Cromlix Formation, Inchmurrin Conglomerate Member, Shannochill Sandstone Member, Dalmary Sandstone Member and Bracklinn Falls Conglomerate Member plot within the recycled orogenic to volcanic related fields (Figure 20). Haughton (1989, 1993) and Phillips and Carroll (1995) suggested that the Devonian sandstones may have been partially derived from gravel deposits mantling or lying in small, periodically inverted basins on the Dalradian land surface. The stable quartzose and metamorphic component within the Aberfoyle sandstones were probably derived from the low-grade Southern Highland Group of the Dalradian Supergroup exposed immediately to the north of the district. Garnet only occurs as a very minor detrital phase within these sandstones, probably due to the relatively wide nature of the Barrovian chlorite- and biotite-zones in the Aberfoyle district. The most likely source of this volcanic detritus is the contemporaneous Lower Devonian volcanic rocks which must have been undergoing penecontemporaneous uplift and erosion (cf. Phillips and Carroll, 1995; Phillips and Smith, 1995). However, the Devonian sequence of the Aberfoyle area does not contain a volcanic member. Consequently, it is possible that the volcanic component within the sandstones, in particular the Ruchill Sandstone Formation, was derived from the reworking of an of older uplifted sequence of volcanic-rich sandstones.

Sandstones from the Cowie Sandstone, Carron Sandstone, Strathlethan Sandstone and Dunnottar Castle Conglomerate formations of the Stonehaven area mainly plot within the recycled orogenic field on Figure 20. The compositionally distinct, lithic-rich sandstones of the Gourdon Sandstone Formation plot within the undissected volcanic source on Figure 20, with a small number of the analyses plotting within the lithic-rich recycled orogenic provenance field on Figure 20b. The compositionally and texturally immature nature of these lithic-rich sandstones indicates that they were derived from the an uplifted penecontemporaneous volcanic source, represented in outcrop by the Tremuda Bay Volcanic Formation.

Sandstone compositional data obtained for the Whitehouse Conglomerate, Scone Sandstone, Dundee Flagstone, Glenvale Sandstone, Deep Conglomerate, Teith Sandstone, Catterline Conglomerate and Cromlix Mudstone formations of the Strathmore district indicates that these sandstones were largely derived from a recycled orogenic provenance (Figure 20a). However, due to their slightly higher modal plagioclase content, data for the Scone Sandstone Formation plot within mixed to dissected volcanic provenance fields on Figure 20b. The stable quartzose and metamorphic component within the Strathmore sandstones were probably derived from the low-grade Southern Highland Group of the Dalradian Supergroup exposed immediately to the north of the district. Garnet and staurolite occurs as a very minor detrital phase within these sandstones. These mineral species are key index minerals of regional metamorphism recorded by the Southern Highland Group rocks exposed to the north and west of Stonehaven. The most likely source of this volcanic detritus is the contemporaneous Lower Devonian volcanic rocks (Crawton Volcanic and Montrose Volcanic formations) which must have been undergoing penecontemporaneous uplift and erosion (cf. Phillips and Carroll, 1995; Phillips and Smith, 1995). The Catterline Conglomerate and, to a lesser extent, Scone Sandstone formations both show a trend ranging from recycled orogenic (Figure 20a) or mixed (Figure 20b) to an undissected volcanic related provenance, indicative of the mixing of detritus derived from these two distinct sources.

6 Conclusions

Several general observations can be made regarding sandstone composition within the Central Scotland: ***(i)*** there significant differences in sandstone composition between the southern and northern Midland Valley; ***(ii)*** a negative correlation exists between the modal proportion of volcanic lithic clasts and monocrystalline quartz, with the increase in quartz reflecting an increase in the compositional maturity of the sandstones; ***(iii)*** a positive correlation can be drawn between polycrystalline quartz and monocrystalline quartz within these sandstones; ***(iv)*** a negative relationship exists between the variation in the modal volcanic lithic clasts and plagioclase possibly reflecting a decrease in the grain size of the sandstone and/or the period of transport prior to deposition (i.e. maturity); and ***(v)*** the covariation in polycrystalline quartz and metamorphic lithic clasts define a positive correlation suggesting that these two components were derived from the same source.

The clear discrimination between sandstone formations analysed from the southern and northern Midland Valley suggests that they were derived from two separate source terranes and that, in general, there was little (if any) mixing of detritus. Sandstones of the northern Midland Valley, in general, exhibit a higher metamorphic lithic and polycrystalline quartz contents, with these components having been derived from the Dalradian Supergroup source terrane located immediately to the north of the Strathmore basin. A clear discrimination can be made between the Auchtitench Sandstone Formation (southern Midland Valley) and Gourdon Sandstone Formation (northern Midland Valley) and the remainder of the Silurian and Devonian sandstones. These formations contain a high proportion of plagioclase and volcanic lithic clasts, consistent with the stratigraphical position of these sandstone dominated units immediately above the Duneaton Volcanic (southern Midland Valley) and Tremuda Bay Volcanic (northern Midland Valley) formations.

In the northern Midland Valley, the mean sandstone compositional data suggests that there are significant differences between the Stonehaven Group of the Stonehaven district, and the stratigraphically higher Arbuthnott-Garvock and Strathmore groups of the Aberfoyle and Strathmore districts. This along strike variation is thought to reflect changes in the geology of the source terrane from southwest to northeast. The preservation of these differences in source terrane geology within the sandstones indicates that along-strike mixing of sediment was limited and that the sandstones were deposited relatively close to source.

In the southern Midland Valley, the sandstones from the Cock Rig, Henshaw, March Wood, Eastgate, Greywacke Conglomerate and Swanshaw Sandstone formations are compositionally similar. Although the deposition of the Greywacke Conglomerate Formation represented a significant change in depositional environment at the base of the Lanark Group, this was not reflected in a major change in sandstone composition. This change occurs at the base of the Auchtitench Sandstone Formation, coinciding with the onset of Lower Devonian volcanism.

Glossary

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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Table 1. Composition of the Silurian and Devonian sedimentary rocks of the northern and southern Midland Valley, Scotland.

Formation or Member	Lithology	Major components	Minor components	Trace to accessory components
March Wood Formation	litharenite	basaltic to andesitic volcanic rock fragments with subordinate monocrystalline quartz	polycrystalline quartz, biotite-microporphyritic dacite, mica-rich phyllitic/schistose rock (locally graphitic or oxide-rich), psammite, variably haematised basalt, very low-grade (sub-greenschist facies) metasiltstone or mudstone, granite, meta-quartz arenite, biotite schistose rock, felsite, very fine-grained sandstone, mudstone	muscovite, biotite, garnet, oxidised biotite, perthite, micrographic intergrowth, chlorite, tourmaline, epidote, K-feldspar (including microcline)
Westgate Formation: Eastgate Sandstone member	litharenite	volcanic rock fragments, monocrystalline quartz, subordinate feldspar (mainly plagioclase)	quartz-chlorite schistose rock, hematised mudstone or tuff, mica-rich phyllite, very fine-grained sandstone, felsite, amphibole-phyric andesite, quartzite, very fine-grained psammite, quartzose mylonite, metabasalt, trachyte, mylonitic metabasalt, fine-grained ‘wacke’ sandstone or metasandstone, mudstone, siltstone, chert	Polycrystalline quartz, opaque minerals, muscovite, micrographic intergrowth, variably altered biotite, perthite, epidote, K-feldspar, tourmaline, garnet, zircon, chlorite pseudomorphs after ferromagnesian minerals
Westgate Formation: Kirk Hill Conglomerate Member	conglomerate to microconglomerate (granule to pebble sized clasts)	igneous rock fragments including: chloritised basalt/basaltic andesite, feldspar-quartz-phyric dacite, plagioclase-phyric andesite, feldspar-quartz-biotite-phyric rhyolite, cryptocrystalline acidic volcanic rock, biotite-granite to granodiorite, tonalite, lapilli tuff, trachyte	quartzite, feldspathic sandstone	
	sandstone matrix	basaltic volcanic rock fragments, monocrystalline quartz	basalt, very fine-grained sandstone, chert, cryptocrystalline quartz, mica-rich phyllite or schist	polycrystalline quartz, garnet, plagioclase, chlorite, muscovite, opaque minerals

Table 1. continued.

Formation or Member	Lithology	Major components	Minor components	Trace to accessory components
Cock Rig Formation	conglomerate to microconglomerate (granule to pebble sized clasts)	dacite & rhyolite volcanic rock fragments	trachyte, microgranite/tonalite with a well developed micrographic intergrowth, low-grade metasandstone, andesite, microdiorite, dacitic tuff, quartzite, quartz-feldspar-phyric rhyolite (porphyry), feldspathic metasandstone, meta-quartz arenite	andesite, jaspery chert, feldspathic quartzite, vein quartz, haematised sandstone, rare oolitic limestone
Cock Rig Formation	sandstone matrix	mono- & polycrystalline quartz, andesitic/felsitic volcanic rock fragments		chloritised biotite, plagioclase, garnet, chlorite, ooids, crinoid fragments, shell fragments, muscovite, micrographic intergrowth, opaque minerals, K-feldspar, zircon, chalcedonic quartz, chert
Henshaw Formation: Igneous Conglomerate	conglomerate to microconglomerate	andesitic, dacitic to possibly rhyolitic volcanic rock fragments, subordinate mono- & polycrystalline quartz	hyalopilitic rhyolite, quartz-feldspar-biotite-phyric dacite (porphyry), chloritised amygdaloidal andesite or basalt, haematised volcanic rock, haematised lapilli-tuff, microgranite, ignimbrite, pilotaxitic trachyte, tonalite or quartz diorite, granite, very fine-grained sandstone, coarse siltstone, volcaniclastic sandstone, feldspathic sandstone, fine-grained sandstone and coarse siltstone with a chloritic matrix	meta-quartz arenite, mica-rich phyllitic or schistose rock, plagioclase, micrographic intergrowth, opaque minerals, tourmaline, perthite, K-feldspar, biotite, muscovite, epidote, quartz-chlorite vein material, rare very fine-grained biotite hornfels
Henshaw Formation: Quartzite Conglomerate	conglomerate to microconglomerate	dacite to rhyolite volcanic rock fragments, polycrystalline quartz, quartzite, monocrystalline quartz	haematised andesite, weakly amygdaloidal andesite, feldspar microporphyritic dacite, sheared/mylonitised polycrystalline quartz, carbonate-haematite rock, cleaved mudstone or tuff, altered microgranite or quartz diorite, fine-grained psammite, haematitic siltstone, fine-grained feldspathic sandstone, laminated mudstone, altered volcaniclastic sandstone	
	sandstone matrix	mono- & polycrystalline quartz	felsic volcanic rock fragments	muscovite, tourmaline, epidote, sericitised feldspar, cleaved chloritic mudstone, psammite, micaceous phyllite

Table 1. continued.

Formation or Member	Lithology	Major components	Minor components	Trace to accessory components
Greywacke Conglomerate Formation	litharenite	andesitic to dacitic rock fragments, monocrystalline quartz, plagioclase	felsite, very fine-grained sandstone, white mica-chlorite phyllite, fine-grained psammite, quartz-chlorite schist, cleaved mudstone, siltstone, crenulated phyllite, quartzite, chloritised basalt, granite	polycrystalline quartz, muscovite, biotite, polycrystalline epidote, chlorite, micrographic intergrowth, K-feldspar, microcline, white mica, garnet, tourmaline, zircon, chlorite pseudomorphs after ferromagnesian minerals
Greywacke Conglomerate Formation	conglomerate	fine-grained wacke sandstone, litharenite, coarse siltstone	chloritised basalt, mudstone, chert, fine-grained siltstone, devitrified glass or tuffaceous rock, cleaved siltstone or mudstone, jasper, cataclasite, polycrystalline vein quartz, quartzite, meta-quartz arenite, tourmaline-bearing granite, two mica granite, feldspar-biotite-quartz-phyric rhyolite, feldspathic metasandstone, quartzose sandstone, fine-grained carbonate rock, felsite	biotite, polycrystalline quartz, opaque minerals
Swanshaw Sandstone Formation	litharenite	altered volcanic lithic clasts, monocrystalline quartz, plagioclase	very fine-grained schist, pilotaxitic trachyte, quartz-microporphyritic rhyolite, chert/cryptocrystalline quartz, dacite, altered variolitic basalt, amphibole-phyric andesite, chloritised basalt/metabasalt, fine-grained sandstone, siltstone, psammite, quartzite, fine-grained hornfels	polycrystalline quartz, biotite, muscovite, K-feldspar, perthite, microcline, chlorite, carbonate, carbonate rock, tourmaline, amphibole, opaque minerals, apatite, deformed vein quartz or quartz mylonite, chlorite pseudomorphs after ferromagnesian minerals
	microconglomerate	sedimentary & low-grade metasedimentary rock fragments, including: mudstone, siltstone, quartzose sandstone, psammite, quartzite, fine-grained wacke sandstone	tuffaceous & volcanic rocks, fine-grained sandstone to coarse siltstone, mudstone, siltstone, foliated metasiltstone, plagioclase-phyric basalt, recrystallised sandstone/metasandstone, chert, chalcedonic quartz, quartz-phyric rhyolite (porphyry), fine-grained quartzose litharenite	polycrystalline quartz, K-feldspar, muscovite, tourmaline, micrographic intergrowth, opaque minerals

Table 1. continued.

Formation or Member	Lithology	Major components	Minor components	Trace to accessory components
Swanshaw Sandstone Formation	quartzose litharenite	monocrystalline quartz, variably degraded volcanic rock fragments	rhyolite, felsite, mudstone, haematised metabasalt, chert, quartzite, cleaved mudstone, biotite-schist, white mica-rich phyllite or schist, trachytic rock, chloritic sandstone and siltstone, phyllite/slate, very fine-grained microgranite/rhyolite, haematised mudstone & siltstone	polycrystalline quartz, plagioclase, sericitised rock or feldspar, opaque minerals, tourmaline, titanite/rutile, white mica, garnet, biotite, K-feldspar, chloritic pseudomorphs after ferromagnesian minerals, staurolite
Biggar Volcanic Formation	litharenite	andesitic volcanic rock fragments, including: plagioclase-phyric basaltic andesite, plagioclase-amphibole-phyric andesite, aphyric andesite and dacite, feldspar-biotite-phyric dacite, amygdaloidal pilotaxitic andesite	plagioclase	monocrystalline quartz, devitrified glass, opaque minerals, altered feldspar, zircon, muscovite, mudstone, fine siltstone
Auchtitench Sandstone Formation	lithic-rich to feldspathic sandstone	monocrystalline quartz, plagioclase, andesitic to dacitic volcanic rock fragments		microcline, polycrystalline quartz, epidote, garnet, perthite, felsite, opaque minerals, tourmaline, chlorite, rutile, white mica/muscovite, amphibole, chlorite after detrital ferromagnesian minerals, quartz-chlorite rock or vein material, rare metasedimentary and quartzite rock fragments
	volcaniclastic sandstone	basaltic andesitic to dacitic volcanic rock fragments, including: plagioclase-phyric basaltic andesite, plagioclase-amphibole-phyric andesite, aphyric andesite and dacite, feldspar-biotite-phyric dacite, amygdaloidal pilotaxitic andesite	plagioclase	monocrystalline quartz, devitrified glass, opaque minerals, zircon, chloritised biotite, muscovite, mudstone, fine siltstone

Table 1. continued.

Formation or Member	Lithology	Major components	Minor components	Trace to accessory components
Cowie Formation	quartz arenite to litharenite	monocrystalline quartz, plagioclase, rock fragments; including mylonite, quartzite, mudstone, siltstone, felsite, chert	polycrystalline quartz	muscovite, staurolite, opaque minerals, epidote, tourmaline, apatite, chlorite pseudomorphs after a ferromagnesian mineral
	litharenite	monocrystalline quartz, polycrystalline quartz, rock fragments	plagioclase, K-feldspar	opaque minerals, muscovite, biotite, chlorite, staurolite, garnet, tourmaline, amphibole, zircon, apatite
Cowie Formation: Castle of Cowie Member	sandstone to silty sandstone	monocrystalline quartz	polycrystalline quartz, biotite, muscovite	chlorite, chlorite pseudomorphs after a ferromagnesian mineral, opaque minerals, tourmaline
Cowie Formation: Cowie Harbour Conglomerate Member	litharenite and microconglomerate	monocrystalline quartz, plagioclase, andesitic to dacitic volcanic rock fragments; including microporphyritic andesite, hornblende-phyric andesite, biotite-hornblende phyric dacite, pyroxene-hornblende phyric basaltic andesite		opaque minerals, K-feldspar, polycrystalline quartz, biotite, chlorite, apatite, zircon, tourmaline
	siltstone	monocrystalline quartz		plagioclase, muscovite, biotite, opaque minerals, chlorite, rock fragments, amphibole, zircon, apatite
Carron Sandstone Formation	quartz arenite and litharenite	monocrystalline quartz, andesitic to dacitic volcanic rock fragments, metamorphic rock fragments; including semipelite, psammite, quartzite, schist	plagioclase, polycrystalline quartz	K-feldspar, opaque minerals, biotite, muscovite, chlorite, garnet, epidote, tourmaline, zoisite, zircon, apatite, epidote, mudstone rip-up clasts
Dunnottar Castle Conglomerate Formation	litharenite	andesitic to dacitic volcanic rock fragments, monocrystalline quartz	plagioclase, metamorphic rock fragments; including schist/phyllite, psammite, quartzite	polycrystalline quartz, muscovite, biotite, opaque minerals, K-feldspar, perthite, clinozoisite, garnet, tourmaline, zoisite, apatite, epidote
	conglomerate	volcanic rock fragments; including microporphyritic andesite and dacite	monocrystalline quartz, plagioclase	polycrystalline quartz, K-feldspar, biotite, opaque minerals garnet, tourmaline, epidote

Table 1. continued.

Formation or Member	Lithology	Major components	Minor components	Trace to accessory components
Gourdon Sandstone Formation	pebbly sandstone to microconglomerate	basaltic to andesitic volcanic and metamorphic rock fragments; including hematised basalt, hematised basaltic andesite, hornblende-phyric andesite, fine microgabbro, chloritised basalt, metabasalt, cleaved meta-mudstone, plagioclase-biotite-phyric andesite/dacite, aphyric andesite, meta-wacke sandstone, meta-siltstone, variolitic metabasalt, glassy tuffaceous rock, olivine-phyric basalt	plagioclase, monocrystalline quartz	opaque minerals, biotite, chlorite, pseudomorphs after hornblende and pyroxene, apatite, clinozoisite, polycrystalline quartz, opaque pseudomorphs after biotite, hornblende, plagioclase, granite with well developed micrographic texture, myrmekite/micrographic intergrowth
	litharenite	basaltic, andesitic to dacitic volcanic; including hematised basalt, hematised basaltic andesite, hornblende-phyric andesite, fine microgabbro, chloritised basalt, plagioclase-biotite-phyric andesite/dacite, aphyric andesite	plagioclase, monocrystalline quartz, and metamorphic rock fragments; including metabasalt, cleaved meta-mudstone, meta-wacke sandstone, meta-siltstone, variolitic metabasalt, psammite, quartzite, epidotised metabasalt	opaque minerals, biotite, chlorite, pseudomorphs after hornblende and pyroxene, apatite, clinozoisite, polycrystalline quartz, opaque pseudomorphs after biotite, pyroxene, hornblende, epidote-chlorite rock, tourmaline, chlorite-quartz rock, myrmekite/micrographic intergrowth, zircon, white mica
Gourdon Sandstone Formation: Doolie Ness Conglomerate Member	pebbly sandstone	andesitic to dacitic volcanic rock fragments	plagioclase, monocrystalline quartz, metamorphic rock fragments; including meta-wacke sandstone, biotite hornfels, cleaved meta-mudstone, meta-siltstone, variolitic metabasalt	opaque minerals, biotite, hornblende, polycrystalline quartz, white mica, felsite, chlorite, apatite
Gourdon Sandstone Formation: Rob's Cove Conglomerate Member	conglomerate	wacke sandstone		
Whitehouse Conglomerate Formation	pebbly sandstone	volcanic rock fragments; including aphyric to porphyritic andesite, basaltic andesite, dacite, chloritised basalt, chloritised/sericitised glass	metamorphic rock fragments; including chloritised basalt, metabasalt, psammite, quartzite, biotite hornfels, biotite psammite, felsic rock, meta-wacke sandstone, mylonite, quartz-epidote rock	monocrystalline quartz, plagioclase, polycrystalline quartz, biotite, muscovite, epidote

Table 1. continued.

Formation or Member	Lithology	Major components	Minor components	Trace to accessory components
Dunnottar Castle Conglomerate Formation: Downie Point Conglomerate Member	pebbly litharenite to microconglomerate	volcanic rock fragments; including feldspar-phyric andesite/dacite, plagioclase-hornblende-phyric andesite, feldspar-quartz-phyric dacite/rhyolite, plagioclase-phyric basaltic andesite		
	sandstone matrix	monocrystalline quartz, andesitic to dacitic volcanic rock fragments		plagioclase, polycrystalline quartz, K-feldspar, perthite, muscovite, garnet, biotite, opaque oxide, apatite, clinozoisite, epidote, chlorite pseudomorphs after a ferromagnesian mineral
Dunnottar Castle Conglomerate Formation: Strathlethan Sandstone Member	litharenite	monocrystalline quartz, andesitic to dacitic volcanic rock fragments	plagioclase, quartzite, schist, biotite-bearing psammite	micrographic intergrowth, biotite, chlorite, epidote, zoisite, apatite
Catterline Conglomerate Formation	wacke sandstone	monocrystalline quartz	altered feldspar, polycrystalline quartz	muscovite, altered biotite, altered granitic rock fragments, opaque minerals, apatite, plagioclase, chlorite, tourmaline
	quartzose litharenite	andesitic to dacitic volcanic rock fragments, monocrystalline quartz	plagioclase, hornblende-bearing granitic rock, very fine-grained sandstone, siltstone, phyllitic or schistose biotite-bearing metasedimentary rock, siltstone and mudstone intraclasts, possible serpentinite	polycrystalline quartz, muscovite, biotite, hematised/oxidised biotite, chlorite, garnet, opaque minerals, hematised rock, sericitised rock or feldspar, microcline perthite
	volcaniclastic microconglomerate	andesitic to dacitic volcanic or high level intrusive igneous rocks; including plagioclase microporphyritic andesite, pilotaxitic to hyalopilitic andesitic or dacitic rock, plagioclase-pyroxene-phyric andesitic or basaltic rock, plagioclase-biotite-phyric dacite, olivine basalt	fine-grained quartzose lithic sandstone, sericitised biotite granitic rock, psammite, biotite-muscovite-schistose rock, chloritised micaceous psammite, meta-quartz-arenite, polycrystalline carbonate/limestone, biotite micaceous psammite, vein quartz, sericitic metasandstone, very fine-grained quartzose sandstone, siltstone, felsite	

	sandstone matrix	monocrystalline quartz, andesitic to dacitic volcanic rock fragments, plagioclase	biotite	monocrystalline quartz, polycrystalline biotite, polycrystalline quartz, plagioclase, chlorite, muscovite/white mica and opaque minerals

Table 1. continued.

Formation or Member	Lithology	Major components	Minor components	Trace to accessory components
Montrose Volcanic Formation	lapilli-tuff and volcaniclastic conglomerate (breccia)	altered basaltic to andesitic volcanic rock fragments, plagioclase crystal fragments	plagioclase crystal fragments	
Dundee Flagstone Formation	quartzose litharenite	dacitic to rhyolitic volcanic rock fragments, monocrystalline quartz	plagioclase	polycrystalline quartz, biotite, garnet, chlorite, opaque minerals, apatite, muscovite, hematised rock or biotite, staurolite, microcline, epidote, sericitised rock, very fine-grained sedimentary rock, very fine-grained micaceous schistose rock, rutile, chloritised metabasaltic rock
	siltstone	monocrystalline quartz	biotite, muscovite	chlorite, plagioclase, opaque minerals, microcline, apatite
	pebbly sandstone to microconglomerate	andesitic, dacitic to rhyolitic volcanic rock fragments; including biotite-feldspar-phyric dacite, pilotaxitic dacite		
	sandstone matrix	monocrystalline quartz, andesitic to rhyolitic volcanic rock fragments	plagioclase	polycrystalline quartz, muscovite, very fine-grained sedimentary rock, biotite, chlorite, felsite, hematised rock
Scone Sandstone Formation	quartzose to slightly feldspathic litharenite	monocrystalline quartz, plagioclase, altered andesitic to dacitic volcanic rock fragments	very fine-grained slaty or schistose metasedimentary rock, biotite-muscovite schist, psammite	K-feldspar, microcline, felsite, cherty rock, polycrystalline quartz, hematised rock, garnet, muscovite, opaque minerals, tourmaline, biotite, chlorite, perthite, epidote, staurolite, sericitised rock
Scone Sandstone Formation: Auchmithie Conglomerate Member	conglomerate	feldspar-quartz-biotite-phyric rhyolite, ignimbritic rhyolite, altered granitic rock		
	quartzose litharenite	monocrystalline quartz, chert, felsitic rock fragments		muscovite, biotite, opaque minerals, polycrystalline quartz, K-feldspar, plagioclase, chloritised biotite, staurolite
Scone Sandstone Formation: Trappean Conglomerate	conglomerate	plagioclase-amphibole porphyritic andesitic rock		

Table 1. continued.

Formation or Member	Lithology	Major components	Minor components	Trace to accessory components
Cromlix Mudstone Formation	mudstone	monocrystalline quartz		plagioclase, muscovite/white mica, opaque minerals, variably chloritised biotite, chlorite
	sandstone	monocrystalline quartz	polycrystalline quartz, plagioclase	muscovite, microcline, very fine-grained rock fragments, carbonate, garnet, biotite, metasedimentary rock fragments, opaque minerals
Teith Sandstone Formation	quartzofeldspathic sandstone	monocrystalline quartz, feldspar (plagioclase, K-feldspar, perthite)	polycrystalline quartz	opaque minerals, muscovite/white mica, chlorite, felsitic rock fragments, biotite, fibrolite-bearing metasedimentary rock, metasandstone, garnet, staurolite, apatite, rutile
Glenvale Sandstone Formation	calcareous sandstone	monocrystalline quartz	plagioclase, chert, felsitic volcanic rock fragments	polycrystalline quartz, muscovite, microcline, biotite, opaque minerals, micrographic intergrowth, very fine-grained metasedimentary rock, devitrified glassy volcanic rock, sericitic slaty rock, tourmaline, zircon

Table 2. Sandstone compositional data for the Silurian and Devonian sedimentary rocks of the northern and southern Midland Valley, Scotland.

Swanshaw Sandstone Formation, New Cumnock district									
Component	Mean	Standard Error	Median	Standard Deviation	Sample Variance	Range	Min	Max	Count
Qm	21.91	3.40	25.54	10.21	104.16	26.85	6.74	33.59	9.00
Qp	5.50	1.00	5.60	3.01	9.05	7.38	1.88	9.26	9.00
Pl	7.72	1.37	6.19	4.10	16.77	12.33	3.03	15.36	9.00
Ksp	0.36	0.09	0.44	0.27	0.07	0.78	0.00	0.78	9.00
Ls	3.51	0.85	3.51	2.55	6.49	7.88	0.00	7.88	9.00
Lm	12.88	1.60	14.45	4.79	22.98	13.19	4.86	18.05	9.00
Lv	23.04	3.10	19.01	9.29	86.22	25.94	12.18	38.12	9.00
Duneaton Volcanic Formation, New Cumnock district									
Component	Mean	Standard Error	Median	Standard Deviation	Sample Variance	Range	Min	Max	Count
Qm	0.47	0.26	0.37	0.52	0.27	1.14	0.00	1.14	4.00
Qp	0.06	0.03	0.06	0.07	0.00	0.12	0.00	0.12	4.00
Pl	4.29	2.65	2.02	5.29	27.99	11.24	0.95	12.19	4.00
Ksp	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	4.00
Ls	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	4.00
Lm	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	4.00
Lv	79.09	4.80	79.06	9.60	92.11	17.85	70.19	88.04	4.00
Auchtitench Sandstone Formation, New Cumnock district									
Component	Mean	Standard Error	Median	Standard Deviation	Sample Variance	Range	Min	Max	Count
Qm	12.80	2.49	9.96	12.70	161.32	36.24	0.30	36.54	26.00
Qp	2.08	0.36	1.77	1.85	3.44	6.09	0.00	6.09	26.00
Pl	10.80	1.18	8.99	6.02	36.23	20.45	0.77	21.22	26.00
Ksp	0.53	0.10	0.47	0.52	0.27	1.68	0.00	1.68	26.00
Ls	0.15	0.05	0.00	0.27	0.07	0.89	0.00	0.89	26.00
Lm	1.09	0.18	1.05	0.93	0.86	2.91	0.00	2.91	26.00
Lv	55.28	4.88	63.61	24.90	619.95	76.45	13.14	89.60	26.00
Cock Rig Formation, North Esk Inlier, Pentland Hills									
Component	Mean	Standard Error	Median	Standard Deviation	Sample Variance	Range	Min	Max	Count
Qm	25.05	5.38	22.47	10.76	115.85	25.24	15.02	40.26	4.00
Qp	9.84	1.55	8.93	3.11	9.65	7.14	7.19	14.33	4.00
Pl	3.67	1.47	3.80	2.94	8.67	7.07	0.00	7.07	4.00
Ksp	0.47	0.13	0.46	0.26	0.07	0.55	0.21	0.76	4.00
Ls	2.19	0.81	2.37	1.62	2.61	3.36	0.33	3.69	4.00
Lm	9.73	3.42	9.88	6.83	46.67	13.28	2.94	16.22	4.00
Lv	38.05	3.88	37.78	7.77	60.34	18.76	28.94	47.71	4.00

Table 2. continued.

Henshaw Formation, Igneous Conglomerate Member, North Esk Inlier, Pentland Hills									
Component	Mean	Standard Error	Median	Standard Deviation	Sample Variance	Range	Min	Max	Count
Qm	8.41	2.29	7.68	4.59	21.04	10.60	3.84	14.45	4.00
Qp	6.34	1.34	5.43	2.69	7.23	5.83	4.35	10.17	4.00
Pl	2.78	0.60	3.28	1.20	1.44	2.55	1.01	3.56	4.00
Ksp	0.51	0.09	0.51	0.18	0.03	0.40	0.31	0.71	4.00
Ls	10.09	3.73	7.52	7.46	55.72	16.56	4.37	20.93	4.00
Lm	5.58	2.05	4.17	4.10	16.82	9.11	2.44	11.55	4.00
Lv	55.77	1.37	54.56	2.74	7.49	5.74	54.10	59.84	4.00
Henshaw Formation, Quartzite Conglomerate Member, North Esk Inlier, Pentland Hills									
Component	Mean	Standard Error	Median	Standard Deviation	Sample Variance	Range	Min	Max	Count
Qm	4.84	2.02	4.84	2.86	8.17	4.04	2.81	6.86	2.00
Qp	34.74	8.81	34.74	12.46	155.13	17.61	25.93	43.54	2.00
Pl	5.70	5.60	5.70	7.93	62.82	11.21	0.10	11.31	2.00
Ksp	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	2.00
Ls	2.25	0.24	2.25	0.34	0.12	0.48	2.01	2.49	2.00
Lm	20.00	12.16	20.00	17.20	295.84	24.32	7.84	32.16	2.00
Lv	23.94	5.51	23.94	7.79	60.66	11.01	18.43	29.45	2.00
Greywacke Conglomerate Formation, North Esk Inlier, Pentland Hills									
Component	Mean	Standard Error	Median	Standard Deviation	Sample Variance	Range	Min	Max	Count
Qm	26.77	0.59	26.51	1.02	1.04	1.99	25.91	27.89	3.00
Qp	6.06	1.70	6.75	2.95	8.71	5.78	2.82	8.60	3.00
Pl	3.18	0.51	2.92	0.88	0.77	1.70	2.46	4.15	3.00
Ksp	0.18	0.06	0.15	0.10	0.01	0.20	0.10	0.30	3.00
Ls	2.07	1.38	1.33	2.38	5.68	4.59	0.15	4.74	3.00
Lm	12.97	5.44	10.69	9.43	88.94	18.44	4.90	23.34	3.00
Lv	14.46	0.81	13.80	1.40	1.97	2.56	13.51	16.07	3.00
Marchwood Formation, Eastfield Inlier, Lanark district									
Component	Mean	Standard Error	Median	Standard Deviation	Sample Variance	Range	Min	Max	Count
Qm	23.07	4.56	18.59	7.90	62.34	13.76	18.43	32.18	3.00
Qp	4.82	0.48	4.67	0.83	0.69	1.64	4.08	5.72	3.00
Pl	7.22	2.38	4.90	4.12	16.99	7.20	4.78	11.98	3.00
Ksp	0.40	0.06	0.40	0.10	0.01	0.20	0.31	0.51	3.00
Ls	0.67	0.40	0.61	0.70	0.49	1.39	0.00	1.39	3.00
Lm	8.59	0.34	8.78	0.60	0.36	1.14	7.92	9.06	3.00
Lv	36.69	5.70	40.45	9.87	97.50	18.64	25.48	44.12	3.00
Westgate Formation, Eastgate Sandstone Member, Carmichael Inlier, Lanark area									
Component	Mean	Standard Error	Median	Standard Deviation	Sample Variance	Range	Min	Max	Count
Qm	27.78	2.28	27.86	5.58	31.10	15.75	21.10	36.85	6.00
Qp	5.51	0.35	5.61	0.86	0.74	2.41	4.40	6.81	6.00
Pl	13.84	0.46	13.89	1.13	1.27	3.11	12.49	15.60	6.00
Ksp	0.47	0.12	0.40	0.29	0.08	0.81	0.20	1.01	6.00
Ls	0.30	0.10	0.30	0.25	0.06	0.70	0.00	0.70	6.00
Lm	8.51	0.84	7.91	2.05	4.21	5.78	5.72	11.50	6.00
Lv	25.10	1.98	26.61	4.84	23.46	12.84	18.27	31.12	6.00

Table 2. continued.

Greywacke Conglomerate Formation, Lanark district									
Component	Mean	Standard Error	Median	Standard Deviation	Sample Variance	Range	Min	Max	Count
Qm	19.20	0.16	19.20	0.22	0.05	0.31	19.05	19.36	2.00
Qp	6.51	0.89	6.51	1.26	1.58	1.78	5.62	7.40	2.00
Pl	5.80	0.48	5.80	0.68	0.47	0.97	5.32	6.28	2.00
Ksp	0.15	0.05	0.15	0.07	0.01	0.10	0.10	0.20	2.00
Ls	0.30	0.10	0.30	0.14	0.02	0.20	0.20	0.40	2.00
Lm	12.00	0.97	12.00	1.37	1.87	1.94	11.03	12.97	2.00
Lv	35.93	1.08	35.93	1.53	2.33	2.16	34.85	37.01	2.00
Swanshaw Sandstone Formation, Lanark district									
Component	Mean	Standard Error	Median	Standard Deviation	Sample Variance	Range	Min	Max	Count
Qm	31.29	1.32	30.38	6.19	38.38	20.61	24.38	45.00	22.00
Qp	7.80	0.84	6.97	3.96	15.70	19.89	3.46	23.35	22.00
Pl	11.30	0.72	11.59	3.37	11.38	12.51	2.69	15.20	22.00
Ksp	0.81	0.08	0.79	0.39	0.16	1.53	0.00	1.53	22.00
Ls	1.03	0.18	1.03	0.85	0.73	2.86	0.00	2.86	22.00
Lm	6.87	0.36	6.69	1.70	2.90	7.82	2.58	10.40	22.00
Lv	16.51	1.60	17.41	7.49	56.08	30.06	4.96	35.02	22.00
Auchtitench Sandstone Formation, Wiston Grey Volcaniclastic Member, Lanark district									
Component	Mean	Standard Error	Median	Standard Deviation	Sample Variance	Range	Min	Max	Count
Qm	0.34	0.13	0.20	0.23	0.05	0.40	0.20	0.60	3.00
Qp	0.07	0.07	0.00	0.12	0.01	0.20	0.00	0.20	3.00
Pl	4.29	1.73	3.42	3.00	8.99	5.80	1.83	7.63	3.00
Ksp	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	3.00
Ls	1.39	1.34	0.10	2.32	5.36	4.06	0.00	4.06	3.00
Lm	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	3.00
Lv	79.87	5.56	80.20	9.63	92.78	19.26	70.08	89.34	3.00
Auchtitench Sandstone Formation, Lanark district									
Component	Mean	Standard Error	Median	Standard Deviation	Sample Variance	Range	Min	Max	Count
Qm	41.49	3.16	40.87	6.33	40.04	15.33	34.44	49.77	4.00
Qp	5.14	0.59	5.46	1.17	1.38	2.58	3.53	6.11	4.00
Pl	17.83	3.10	19.30	6.19	38.33	14.48	9.12	23.59	4.00
Ksp	0.98	0.22	0.86	0.45	0.20	0.99	0.60	1.59	4.00
Ls	0.03	0.03	0.00	0.05	0.00	0.10	0.00	0.10	4.00
Lm	3.33	0.38	3.52	0.76	0.57	1.67	2.30	3.98	4.00
Lv	12.46	0.76	12.74	1.52	2.31	3.36	10.49	13.86	4.00
Cowie Sandstone Formation, Stonehaven district									
Component	Mean	Standard Error	Median	Standard Deviation	Sample Variance	Range	Min	Max	Count
Qm	17.19	3.47	17.47	11.52	132.81	30.44	1.04	31.47	11.00
Qp	10.40	2.07	11.38	6.85	46.97	20.05	0.00	20.05	11.00
Pl	4.37	1.38	2.73	4.58	21.00	11.46	0.00	11.46	11.00
Ksp	0.50	0.17	0.29	0.55	0.30	1.52	0.00	1.52	11.00
Ls	0.61	0.34	0.00	1.14	1.30	3.71	0.00	3.71	11.00
Lm	9.86	4.58	4.97	15.20	231.06	53.48	0.00	53.48	11.00
Lv	23.82	8.03	14.22	26.63	709.19	74.95	1.41	76.36	11.00

Table 2. continued.

Carron Sandstone Formation, Stonehaven district									
Component	Mean	Standard Error	Median	Standard Deviation	Sample Variance	Range	Min	Max	Count
Qm	17.79	4.56	12.83	15.11	228.41	43.21	2.26	45.47	11.00
Qp	6.78	1.68	7.00	5.57	30.99	15.03	0.17	15.20	11.00
Pl	11.21	1.59	11.06	5.26	27.67	18.15	3.13	21.28	11.00
Ksp	0.75	0.20	0.72	0.66	0.44	2.29	0.00	2.29	11.00
Ls	0.55	0.27	0.14	0.89	0.80	2.84	0.00	2.84	11.00
Lm	5.53	1.28	5.98	4.23	17.92	10.82	0.00	10.82	11.00
Lv	40.21	7.66	42.51	25.39	644.74	76.83	5.43	82.26	11.00
Dunnottar Castle Conglomerate Formation, Strathlethan Sandstone Member, Stonehaven district									
Component	Mean	Standard Error	Median	Standard Deviation	Sample Variance	Range	Min	Max	Count
Qm	12.31	3.94	15.49	9.65	93.06	21.94	0.00	21.94	6.00
Qp	3.80	1.20	5.47	2.95	8.70	6.11	0.00	6.11	6.00
Pl	9.82	2.64	7.59	6.48	41.93	17.85	4.61	22.45	6.00
Ksp	0.62	0.18	0.61	0.44	0.19	1.21	0.00	1.21	6.00
Ls	0.18	0.10	0.08	0.25	0.06	0.61	0.00	0.61	6.00
Lm	6.99	2.46	7.02	6.02	36.30	16.06	0.33	16.39	6.00
Lv	43.49	11.24	32.39	27.54	758.33	66.45	20.06	86.51	6.00
Dunnottar Castle Conglomerate Formation, Stonehaven district									
Component	Mean	Standard Error	Median	Standard Deviation	Sample Variance	Range	Min	Max	Count
Qm	14.63783	3.72	17.83	8.31	69.01	20.99	0.57	21.56	5.00
Qp	5.78413	1.44	6.83	3.23	10.43	8.21	0.19	8.41	5.00
Pl	10.57217	1.55	9.05	3.48	12.08	8.45	8.07	16.52	5.00
Ksp	1.11581	0.58	0.68	1.31	1.71	3.19	0.00	3.19	5.00
Ls	0.19	0.09	0.16	0.21	0.04	0.47	0.00	0.47	5.00
Lm	7.42	2.05	8.54	4.58	20.95	12.39	0.00	12.39	5.00
Lv	41.69	7.85	33.39	17.56	308.45	42.74	28.52	71.26	5.00
Gourdon Sandstone (Castle Hill) Formation, Stonehaven district									
Component	Mean	Standard Error	Median	Standard Deviation	Sample Variance	Range	Min	Max	Count
Qm	0.74	0.23	0.52	0.81	0.65	2.93	0.00	2.93	12.00
Qp	0.11	0.04	0.10	0.12	0.02	0.30	0.00	0.30	12.00
Pl	13.81	1.95	13.13	6.75	45.63	25.70	4.25	29.95	12.00
Ksp	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	12.00
Ls	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	12.00
Lm	4.41	1.62	1.79	5.62	31.59	16.40	0.00	16.40	12.00
Lv	61.95	2.83	60.03	9.80	96.00	32.91	43.86	76.77	12.00

Table 2. continued.

Component	Mean	Standard Error	Median	Standard Deviation	Sample Variance	Range	Min	Max	Count
Gourdon Sandstone Formation, Stonehaven district									
Qm	1.18	0.37	0.71	1.42	2.03	5.12	0.00	5.12	15.00
Qp	0.27	0.11	0.20	0.43	0.18	1.43	0.00	1.43	15.00
Pl	13.96	1.62	14.11	6.26	39.14	25.70	4.25	29.95	15.00
Ksp	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	15.00
Ls	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	15.00
Lm	7.17	2.42	2.37	9.37	87.76	30.09	0.00	30.09	15.00
Lv	59.27	2.98	58.60	11.54	133.14	37.41	39.36	76.77	15.00
Ruchill Flagstone Formation, Inchmurrin Conglomerate Member, Aberfoyle district									
Component	Mean	Standard Error	Median	Standard Deviation	Sample Variance	Range	Min	Max	Count
Qm	25.09	3.33	27.78	7.44	55.33	18.70	15.77	34.47	5.00
Qp	12.46	1.56	11.67	3.50	12.22	9.39	8.79	18.18	5.00
Pl	6.36	0.91	5.99	2.03	4.13	4.64	4.28	8.93	5.00
Ksp	0.30	0.08	0.31	0.19	0.04	0.50	0.00	0.50	5.00
Ls	0.80	0.41	0.52	0.92	0.85	2.22	0.18	2.40	5.00
Lm	12.91	2.18	12.94	4.88	23.83	11.98	8.32	20.30	5.00
Lv	24.29	3.98	20.96	8.89	79.06	21.94	18.08	40.02	5.00
Ruchill Flagstone Formation, Aberfoyle district									
Component	Mean	Standard Error	Median	Standard Deviation	Sample Variance	Range	Min	Max	Count
Qm	19.71	3.84	21.53	12.16	147.80	38.20	1.30	39.50	10.00
Qp	12.07	2.83	11.22	8.96	80.23	29.53	0.40	29.93	10.00
Pl	6.62	1.09	5.98	3.45	11.90	10.83	1.40	12.24	10.00
Ksp	0.30	0.11	0.25	0.33	0.11	1.00	0.00	1.00	10.00
Ls	0.69	0.28	0.25	0.88	0.77	2.40	0.00	2.40	10.00
Lm	8.59	1.99	7.47	6.28	39.44	21.16	1.00	22.16	10.00
Lv	37.89	7.77	31.00	24.57	603.56	70.14	10.10	80.24	10.00
Teith Sandstone Formation, Dalmary Sandstone Member, Aberfoyle district									
Component	Mean	Standard Error	Median	Standard Deviation	Sample Variance	Range	Min	Max	Count
Qm	17.19	4.14	17.49	8.29	68.67	20.23	6.79	27.01	4.00
Qp	13.29	1.25	12.81	2.51	6.28	5.92	10.82	16.73	4.00
Pl	7.82	1.23	7.70	2.46	6.06	5.54	5.17	10.70	4.00
Ksp	0.15	0.07	0.15	0.13	0.02	0.31	0.00	0.31	4.00
Ls	0.58	0.21	0.61	0.41	0.17	0.92	0.10	1.02	4.00
Lm	15.25	2.57	15.74	5.14	26.47	12.21	8.66	20.87	4.00
Lv	34.33	3.25	34.09	6.50	42.23	15.74	26.71	42.45	4.00
Cromlix Mudstone Formation, Aberfoyle district									
Component	Mean	Standard Error	Median	Standard Deviation	Sample Variance	Range	Min	Max	Count
Qm	23.97	5.73	29.46	9.93	98.57	17.44	12.51	29.95	3.00
Qp	17.09	3.57	20.60	6.18	38.24	10.77	9.95	20.72	3.00
Pl	11.98	6.75	8.44	11.69	136.64	22.56	2.46	25.02	3.00
Ksp	0.20	0.15	0.10	0.26	0.07	0.49	0.00	0.49	3.00
Ls	1.09	0.99	0.20	1.72	2.97	3.08	0.00	3.08	3.00
Lm	10.78	4.44	7.94	7.69	59.08	14.56	4.93	19.49	3.00
Lv	22.92	7.45	16.85	12.91	166.58	23.57	14.17	37.74	3.00

Table 2. continued

Swanshaw Sandstone Formation, Ayr area									
Component	Mean	Standard Error	Median	Standard Deviation	Sample Variance	Range	Min	Max	Count
Qm	21.42	1.94	20.73	6.44	41.50	18.33	11.53	29.87	11.00
Qp	6.58	0.70	6.72	2.31	5.34	7.80	2.99	10.79	11.00
Pl	6.88	1.01	6.45	3.35	11.20	10.87	0.81	11.68	11.00
Ksp	1.26	0.23	1.46	0.75	0.56	2.46	0.00	2.46	11.00
Ls	6.42	3.02	2.86	10.01	100.21	32.06	0.82	32.89	11.00
Lm	4.68	1.22	3.51	4.05	16.44	13.06	0.62	13.68	11.00
Lv	20.74	4.14	16.18	13.74	188.83	47.41	8.92	56.33	11.00
Whitehouse Conglomerate Formation, Strathmore district									
Component	Mean	Standard Error	Median	Standard Deviation	Sample Variance	Range	Min	Max	Count
Qm	15.17	1.89	14.59	3.77	14.23	9.08	11.22	20.30	4.00
Qp	6.81	1.42	6.31	2.85	8.11	6.60	4.01	10.61	4.00
Pl	7.46	1.27	7.06	2.54	6.43	5.50	5.11	10.61	4.00
Ksp	0.80	0.29	0.60	0.57	0.33	1.22	0.40	1.62	4.00
Ls	3.11	0.74	3.12	1.47	2.16	3.60	1.30	4.90	4.00
Lm	3.67	0.27	3.86	0.53	0.28	1.14	2.90	4.04	4.00
Lv	23.83	2.80	24.30	5.61	31.46	12.39	17.17	29.56	4.00
Catterline Conglomerate Formation, Strathmore district									
Component	Mean	Standard Error	Median	Standard Deviation	Sample Variance	Range	Min	Max	Count
Qm	11.09	1.79	12.95	7.37	54.34	19.90	0.30	20.20	17.00
Qp	4.86	0.66	5.78	2.70	7.31	9.15	0.10	9.25	17.00
Pl	7.91	1.01	7.77	4.16	17.33	15.05	0.80	15.85	17.00
Ksp	0.74	0.17	0.52	0.68	0.47	2.31	0.00	2.31	17.00
Ls	3.83	1.28	1.93	5.27	27.79	22.24	0.00	22.24	17.00
Lm	5.99	1.15	5.21	4.73	22.34	18.67	0.00	18.67	17.00
Lv	35.26	3.46	33.47	14.28	203.87	45.55	14.71	60.26	17.00
Dundee Flagstone Formation, Strathmore district									
Component	Mean	Standard Error	Median	Standard Deviation	Sample Variance	Range	Min	Max	Count
Qm	16.75	10.38	16.75	14.67	215.28	20.75	6.37	27.12	2.00
Qp	5.73	2.03	5.73	2.87	8.26	4.06	3.70	7.76	2.00
Pl	9.35	4.73	9.35	6.68	44.69	9.45	4.62	14.08	2.00
Ksp	1.03	0.21	1.03	0.30	0.09	0.42	0.82	1.24	2.00
Ls	2.89	1.66	2.89	2.35	5.52	3.32	1.23	4.55	2.00
Lm	3.10	0.53	3.10	0.75	0.56	1.05	2.57	3.62	2.00
Lv	41.18	22.96	41.18	32.46	1053.96	45.91	18.22	64.13	2.00

Table 2. continued.

Scone Sandstone Formation, Strathmore district									
Component	Mean	Standard Error	Median	Standard Deviation	Sample Variance	Range	Min	Max	Count
Qm	23.19	2.40	21.82	5.38	28.90	12.21	17.98	30.19	5.00
Qp	8.01	0.48	8.15	1.08	1.16	2.82	6.20	9.01	5.00
Pl	12.19	2.09	11.61	4.68	21.92	11.95	5.35	17.30	5.00
Ksp	1.04	0.16	1.05	0.37	0.14	1.00	0.49	1.49	5.00
Ls	0.96	0.19	0.85	0.43	0.19	0.96	0.52	1.48	5.00
Lm	4.62	1.40	4.25	3.12	9.76	7.42	1.57	8.99	5.00
Lv	15.49	2.85	13.97	6.38	40.67	16.02	10.59	26.61	5.00
Cromlix Mudstone Formation, Strathmore district									
Component	Mean	Standard Error	Median	Standard Deviation	Sample Variance	Range	Min	Max	Count
Qm	14.44	4.03	16.54	6.99	48.82	13.49	6.65	20.14	3.00
Qp	8.57	2.68	10.95	4.64	21.50	8.30	3.22	11.52	3.00
Pl	4.20	1.10	5.11	1.90	3.62	3.46	2.01	5.48	3.00
Ksp	0.85	0.39	0.80	0.67	0.44	1.33	0.20	1.53	3.00
Ls	5.30	2.79	5.41	4.84	23.41	9.67	0.40	10.08	3.00
Lm	5.05	1.93	6.61	3.35	11.22	6.13	1.21	7.34	3.00
Lv	19.64	5.34	19.39	9.24	85.44	18.48	10.52	29.00	3.00
Kinnesswood Formation, Strathmore district									
Component	Mean	Standard Error	Median	Standard Deviation	Sample Variance	Range	Min	Max	Count
Qm	45.07	2.85	44.55	5.69	32.39	13.60	38.80	52.40	4.00
Qp	8.45	1.22	7.72	2.44	5.96	5.58	6.40	11.98	4.00
Pl	2.51	0.34	2.27	0.68	0.46	1.50	2.00	3.50	4.00
Ksp	0.78	0.31	0.50	0.62	0.39	1.30	0.40	1.70	4.00
Ls	4.15	4.15	0.00	8.30	68.88	16.60	0.00	16.60	4.00
Lm	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	4.00
Lv	0.66	0.46	0.30	0.93	0.86	2.04	0.00	2.04	4.00

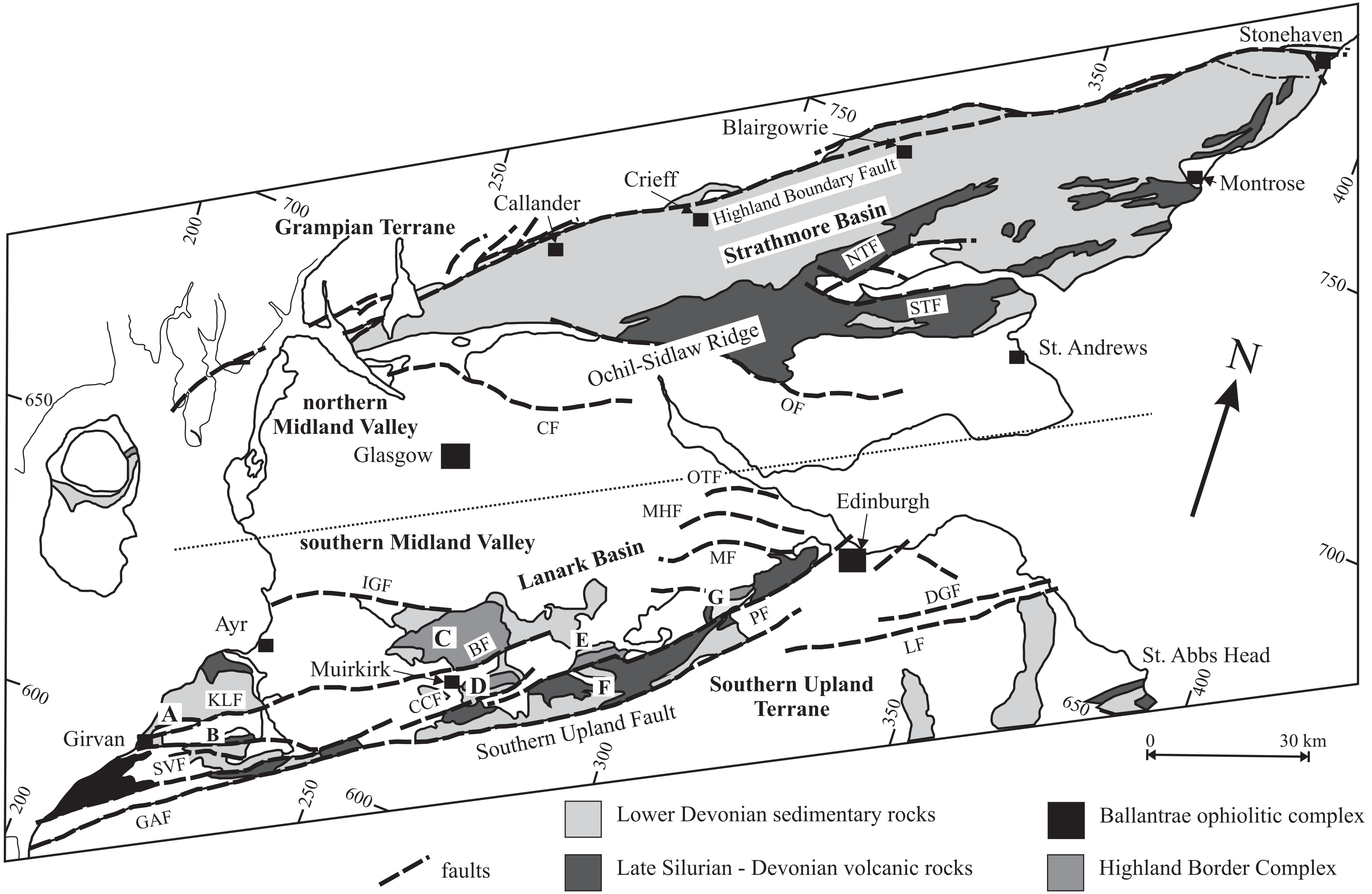

Figure 1. Simplified geological map or the Midland Valley of Scotland showing the distribution of Silurian and Devonian sedimentary rocks. Silurian inliers: A, Craighead; B, Girvan Main; C, Lesmahagow; D, Hagshaw Hills; E, Carmichael; F, Eastfield; G, Pentland Hills (North Esk). Faults: SVF, Stinchar Valley Fault; GAF, Glen App Fault; KLF, Kerse Loch Fault; BF, Bankend Fault; CCF, Carmacoup Fault; IGF, Inchgotrick Fault; PF, Pentland Fault; DGF, Dunbar-Gifford Fault; LF, Lammermuir Fault; MF, Murieston Fault; MHF, Middleton Fault; OTF, Ochiltree Fault; CF, Campsie Fault; OF, Ochil Fault; STF, South Tay Fault; NFT, North Tay Fault.

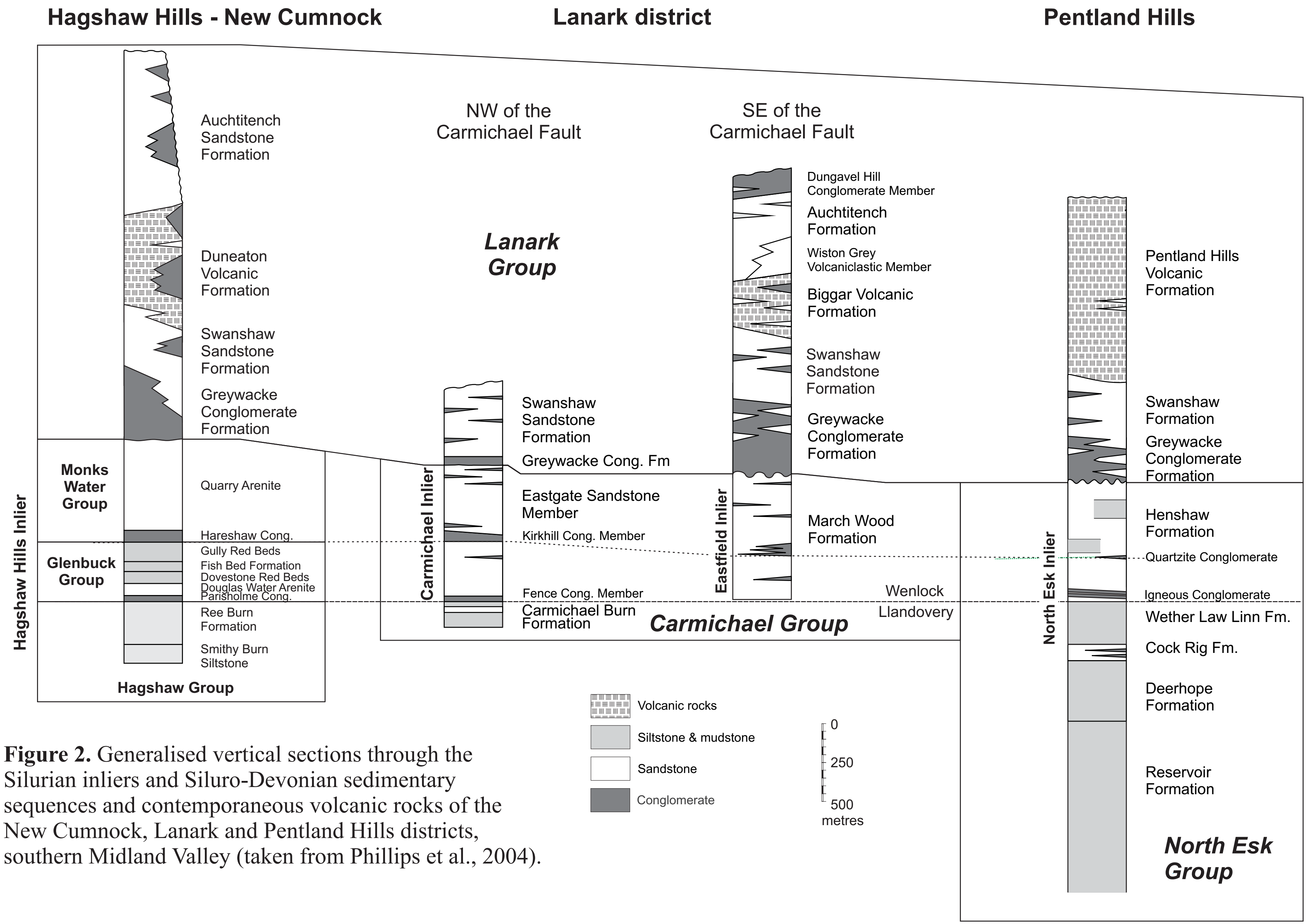

Figure 2. Generalised vertical sections through the Silurian inliers and Siluro-Devonian sedimentary sequences and contemporaneous volcanic rocks of the New Cumnock, Lanark and Pentland Hills districts, southern Midland Valley (taken from Phillips et al., 2004).

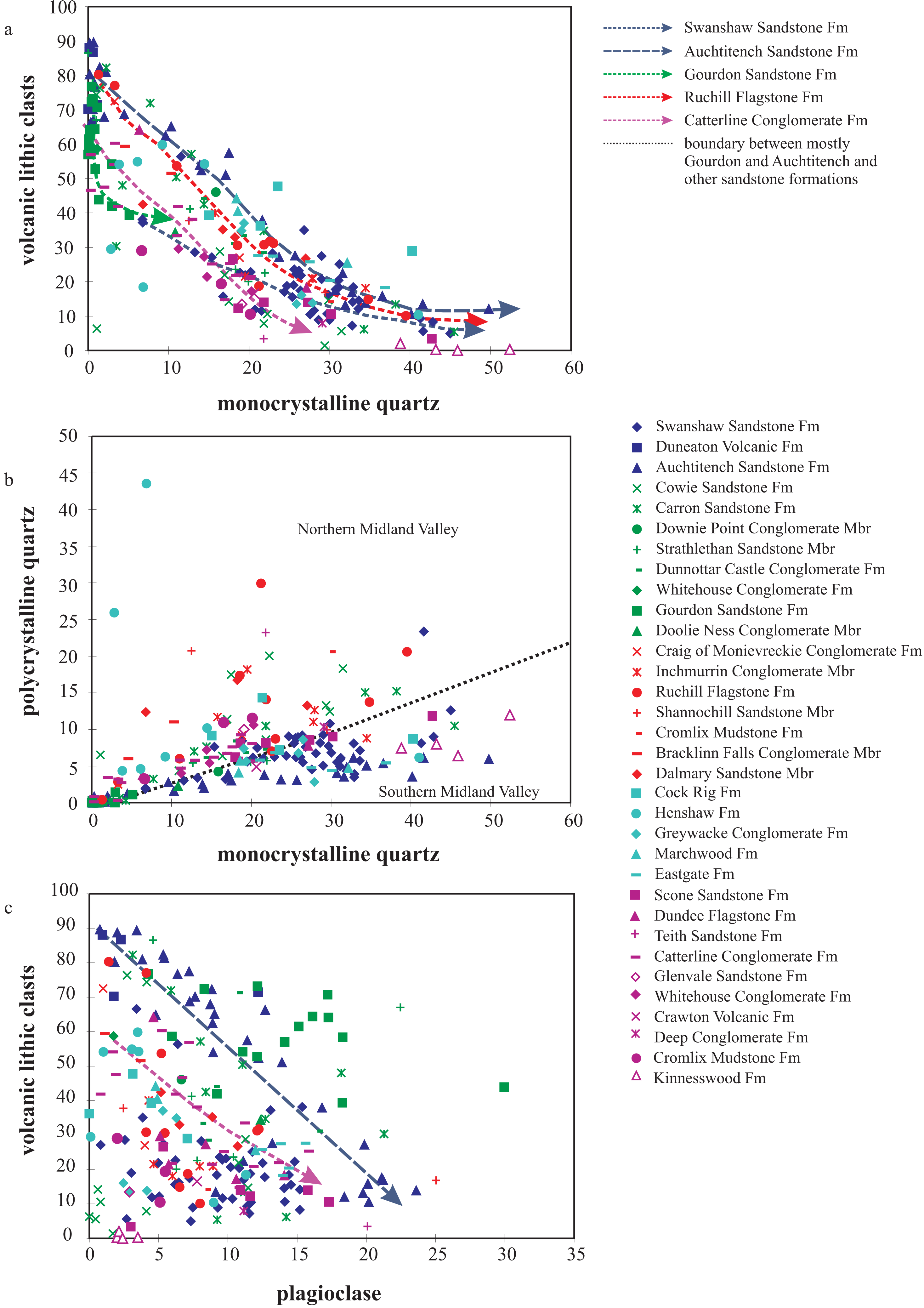

Figure 3. Bivariant plots showing the variation in: **(a)** volcanic lithic clasts versus monocrystalline quartz; **(b)** polycrystalline quartz versus monocrystalline; and **(c)** volcanic lithic clasts versus plagioclase.

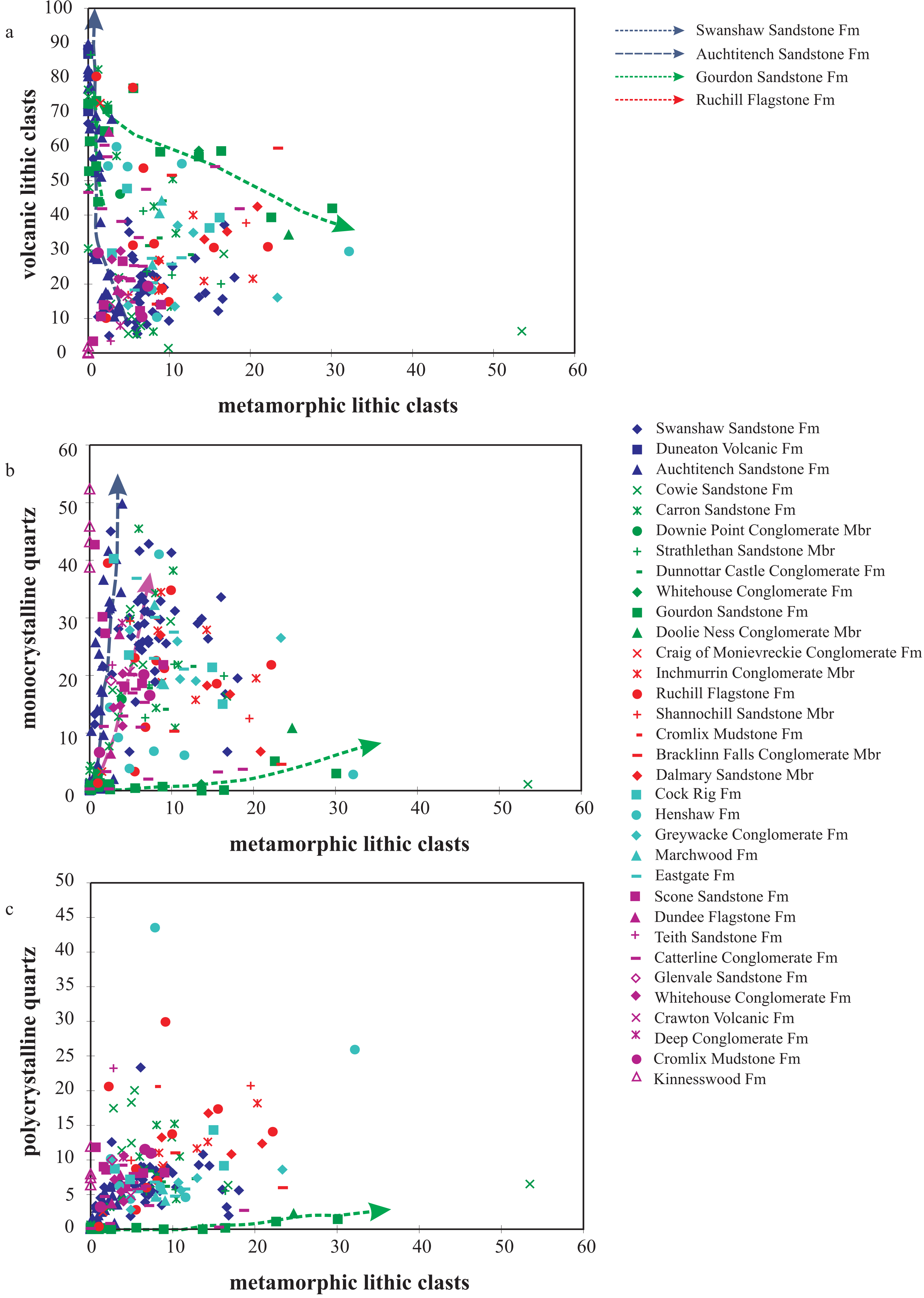

Figure 4. Bivariant plots showing the variation in: **(a)** volcanic lithics versus metamorphic lithics; **(b)** monocrystalline quartz versus metamorphic lithic clasts; and **(c)** polycrystalline quartz versus metamorphic lithic clasts.

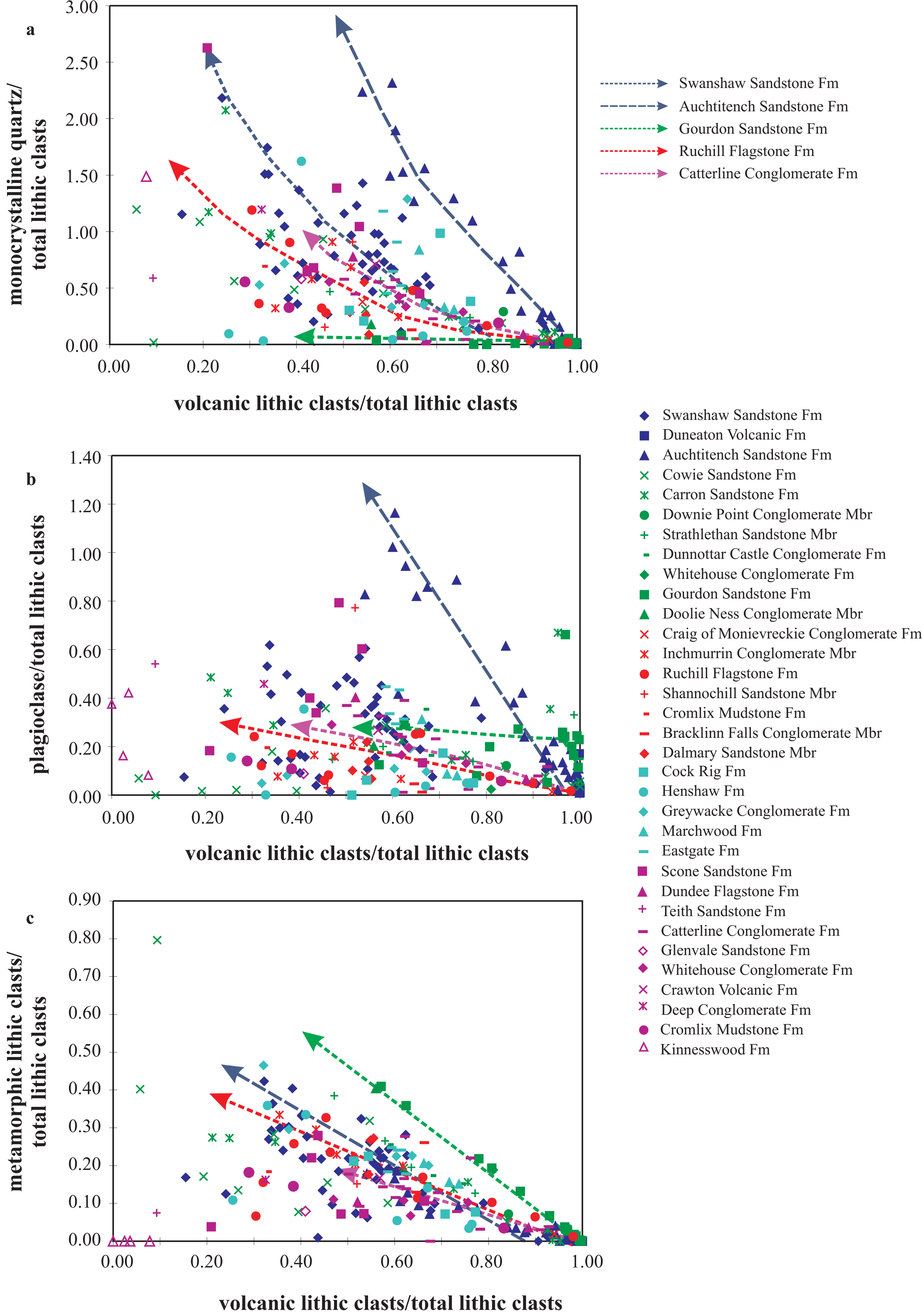

Figure 5. Bivariant plots showing the variation in: **(a)** monocrystalline quartz/total lithic clasts versus volcanic lithics/total lithic clasts; **(b)** plagioclase/total lithics versus volcanic lithics/total lithics; and **(c)** metamorphic lithics/total lithics versus volcanic lithics/total lithics.

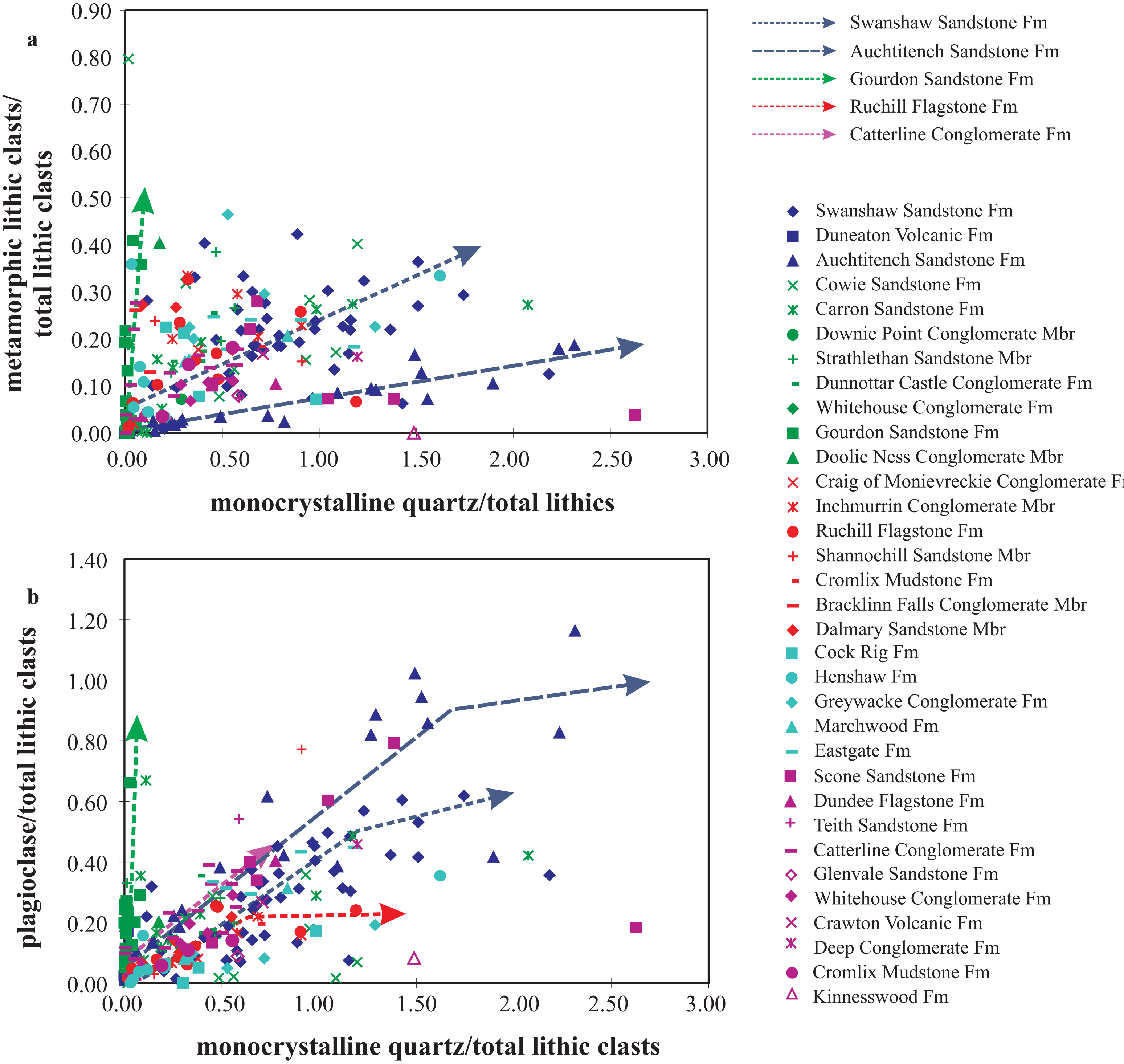

Figure 6. Bivariant plots showing the variation in: **(a)** metamorphic lithics/total lithic clasts versus monocrystalline quartz/total lithic clasts; and **(b)** plagioclase/total lithic clasts versus monocrystalline quartz/total lithics.

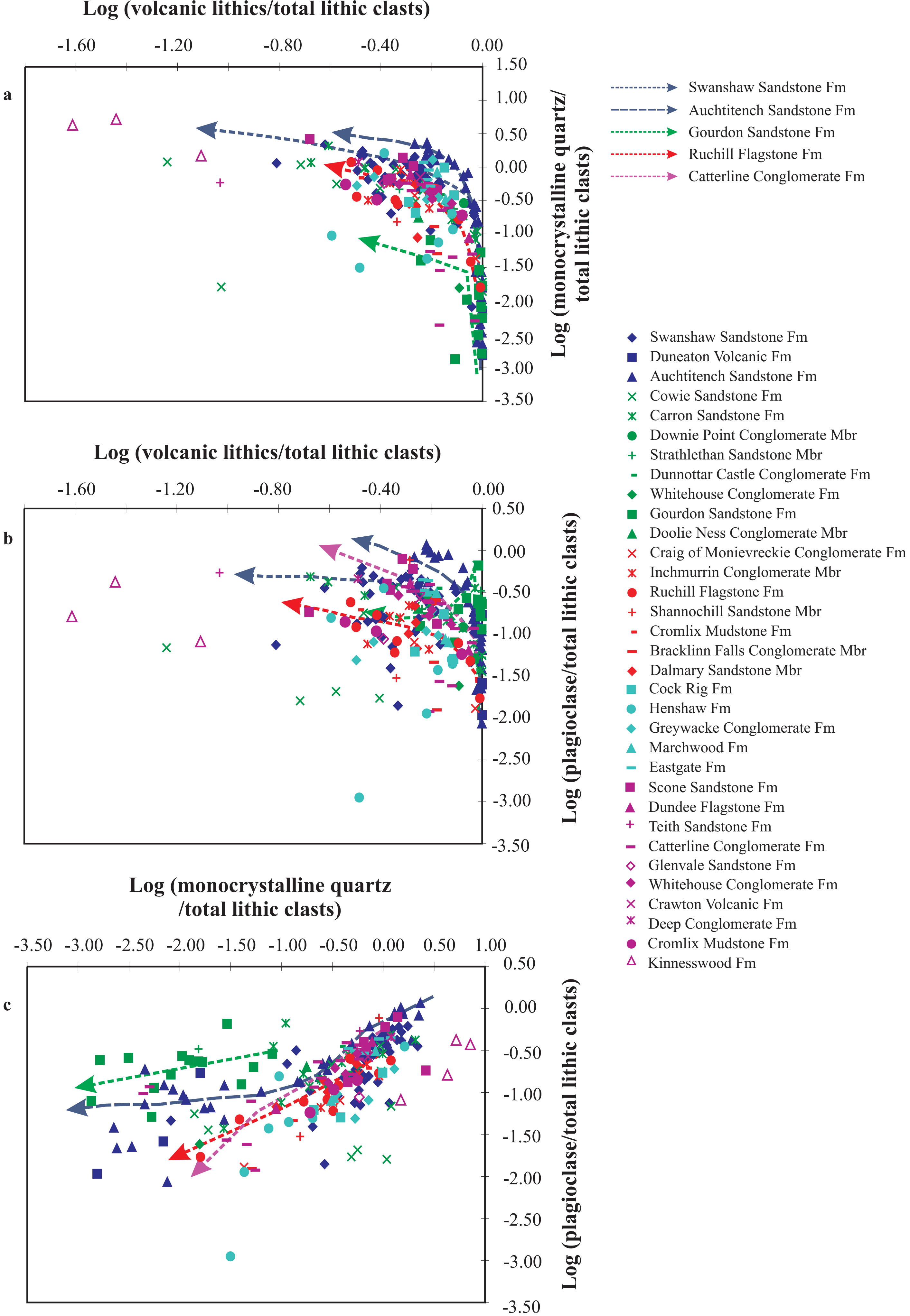

Figure 7. Log ratio plots showing the variation in: **(a)** Log (volcanic lithic clasts/total lithic clasts) versus Log (monocrystalline quartz/total lithic clasts); **(b)** Log (volcanic lithic clasts/total lithic clasts) versus Log (plagioclase/total lithic clasts); and **(c)** Log (monocrystalline quartz/total lithic clasts) versus Log (plagioclase/total lithic clasts).

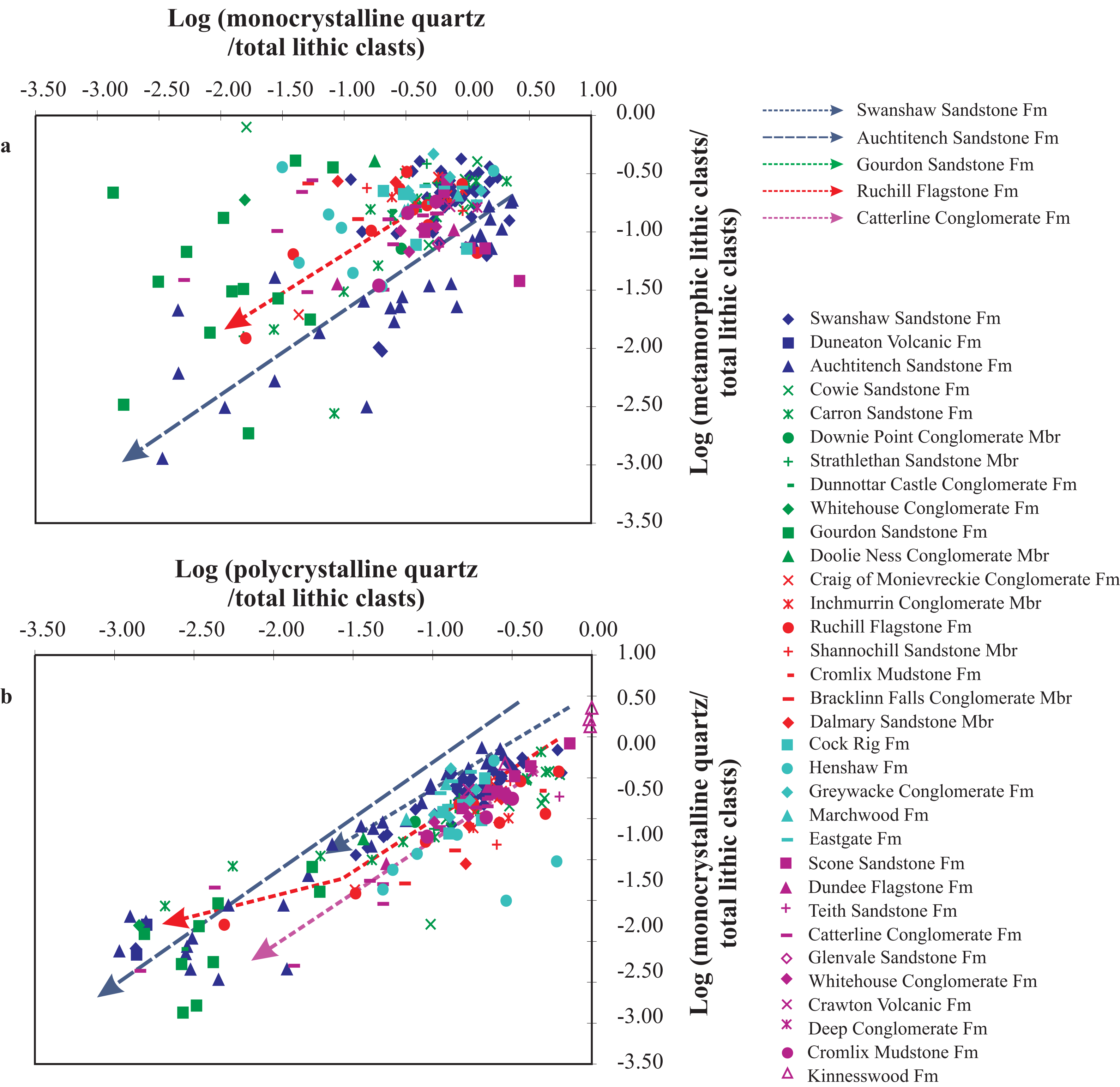

Figure 8. Log ratio plots showing the variation in: **(a)** Log (monocrystalline quartz/total lithic clasts) versus Log (metamorphic lithics/total lithic clasts); and **(b)** Log (polycrystalline quartz/total lithic clasts) versus Log (monocrystalline quartz/total lithic clasts).

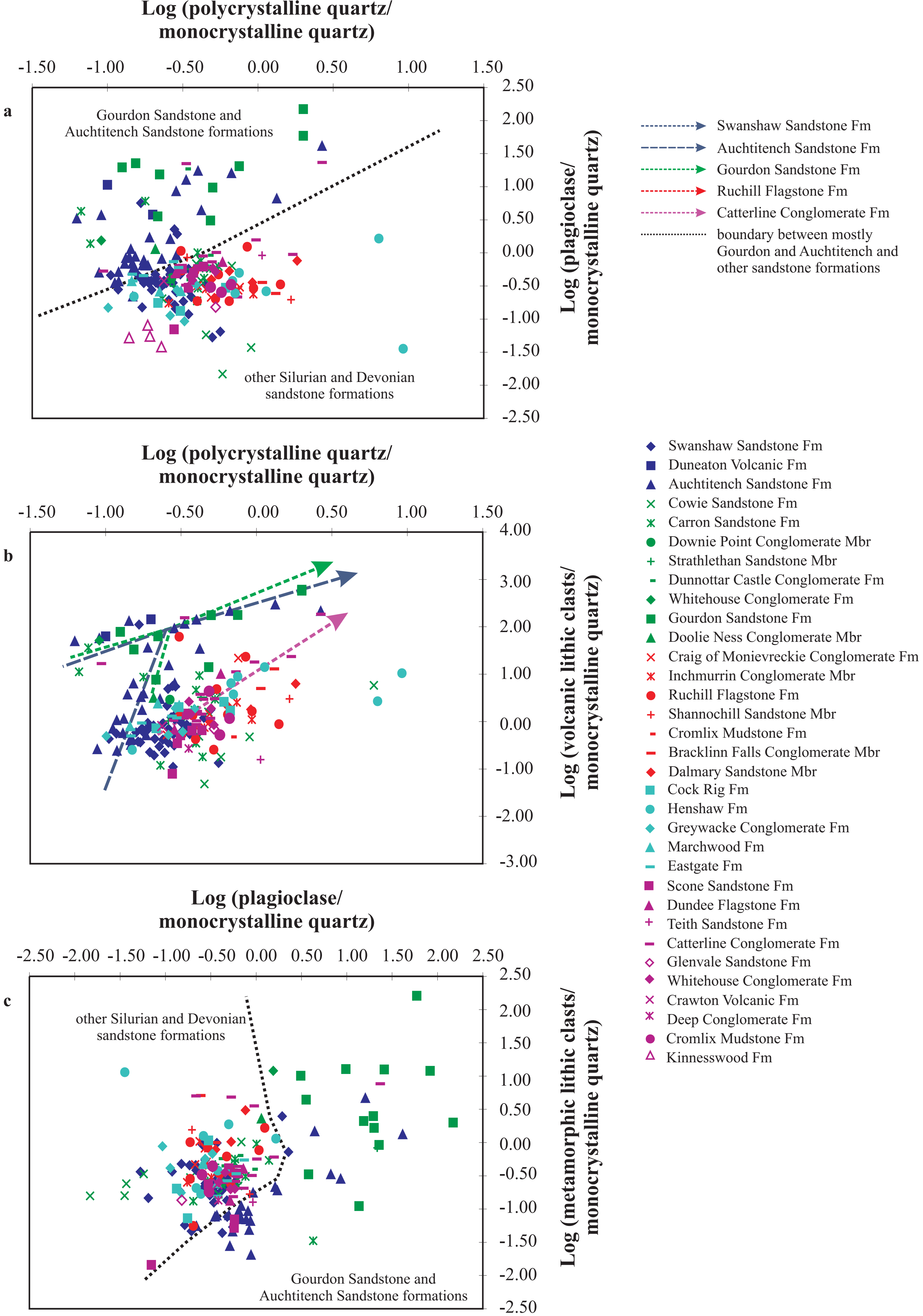

Figure 9. Log ratio plots showing the variation in: **(a)** Log (polycrystalline quartz/monocrystalline quartz) versus Log (plagioclase/monocrystalline quartz); **(b)** Log (polycrystalline quartz/monocrystalline quartz) versus Log (volcanic lithic clasts/monocrystalline quartz); and **(c)** Log (plagioclase/monocrystalline quartz) versus Log (metamorphic lithic clasts/monocrystalline quartz).

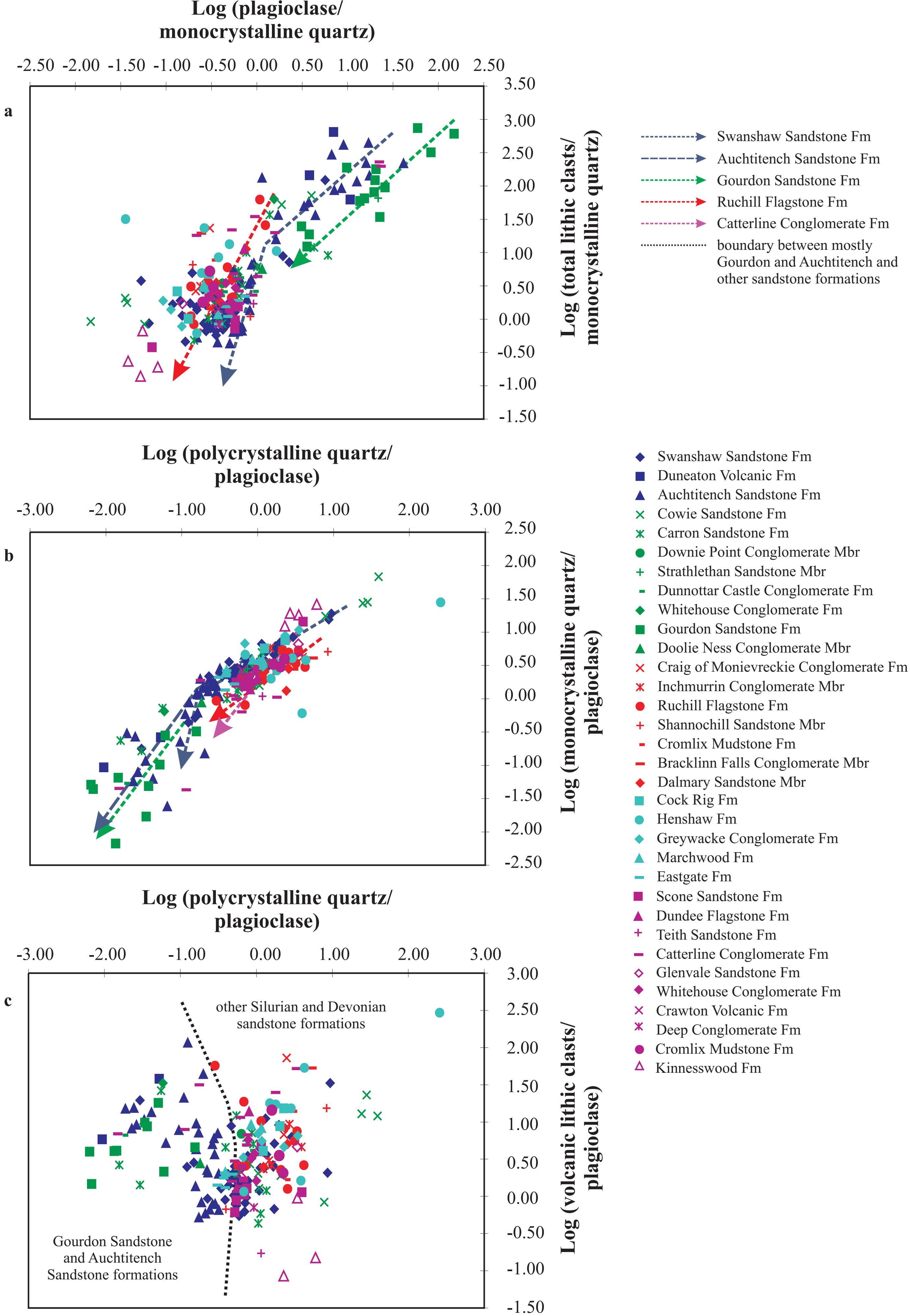

Figure 10. Log ratio plots showing the variation in: **(a)** Log (plagioclase/monocrystalline quartz) versus Log (total lithic clasts/monocrystalline quartz); **(b)** Log (polycrystalline quartz/plagioclase) versus Log (monocrystalline quartz/plagioclase); and **(c)** Log (polycrystalline quartz/plagioclase) versus Log (volcanic lithic clasts/plagioclase).

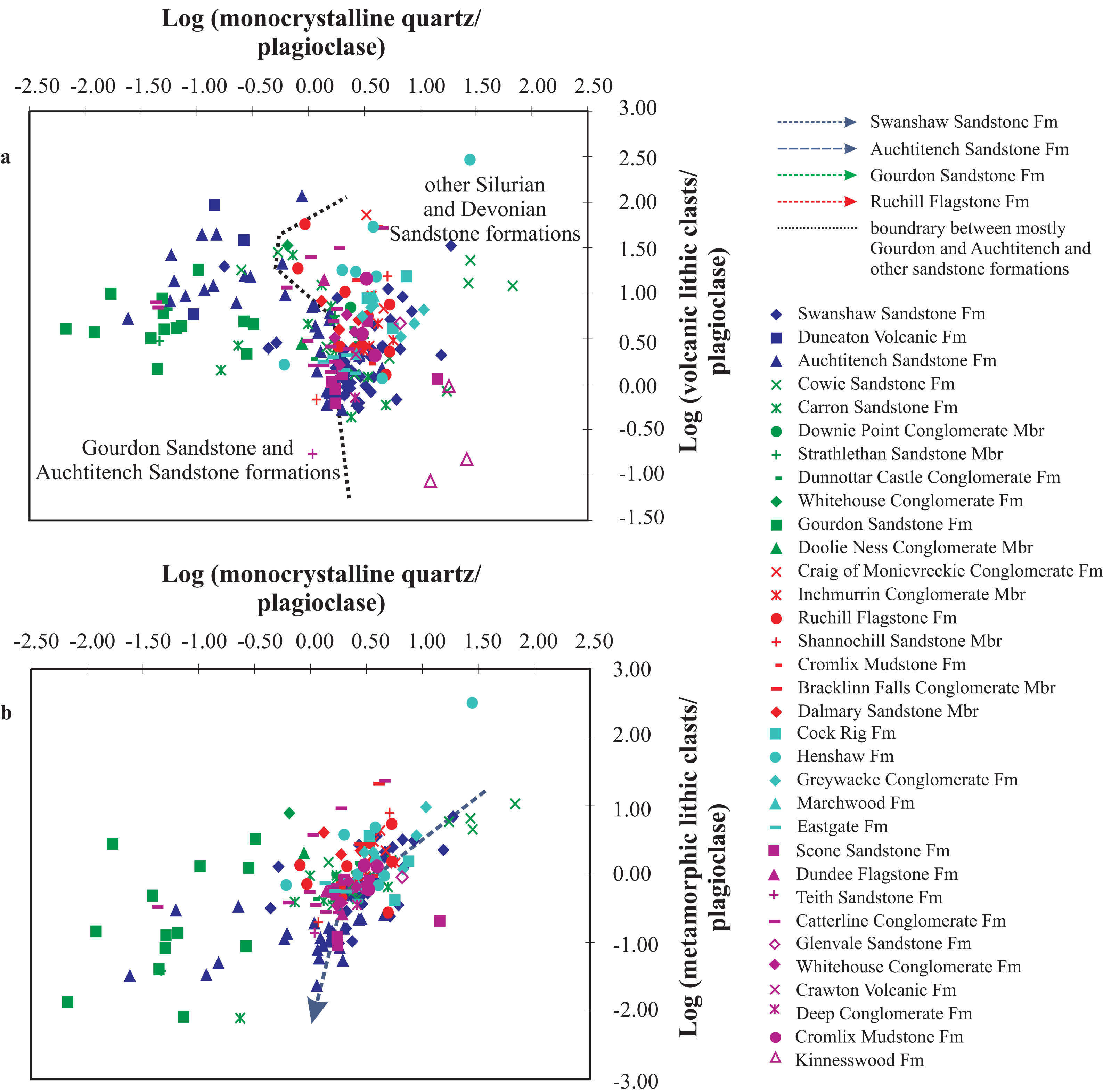

Figure 11. Log ratio plots showing the variation in: **(a)** Log (monocrystalline quartz/plagioclase) versus Log (volcanic lithic clasts/plagioclase); and **(b)** Log (monocrystalline quartz/plagioclase) versus Log (metamorphic lithic clasts/plagioclase).

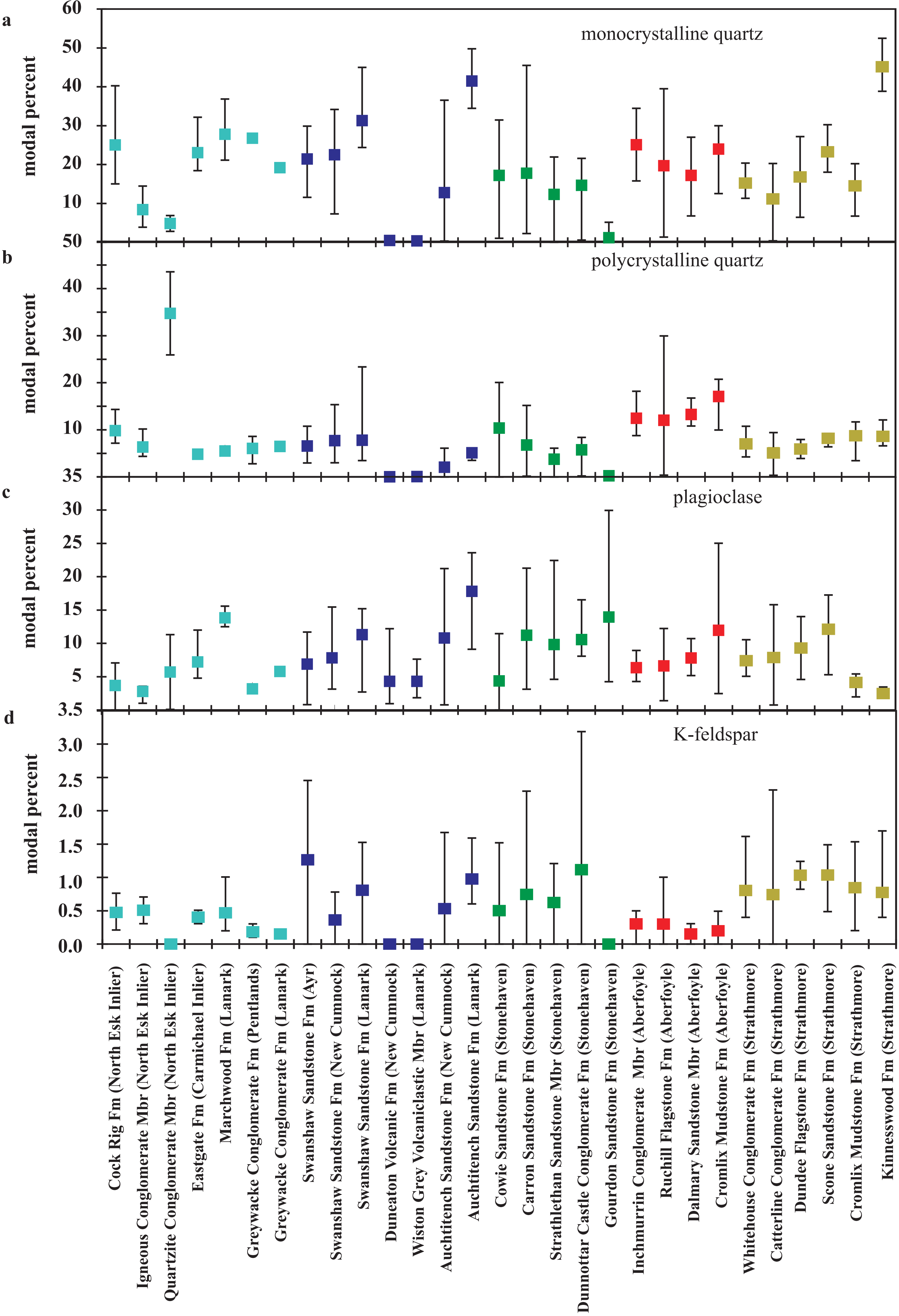

Figure 12. Mean sandstone compositional data for the Silurian and Devonian sedimentary rocks exposed in the north and south of the Midland Valley: **(a)** monocrystalline quartz; **(b)** polycrystalline quartz; **(c)** plagioclase; and **(d)** K-feldspar. Error bars define the range in sandstone composition.

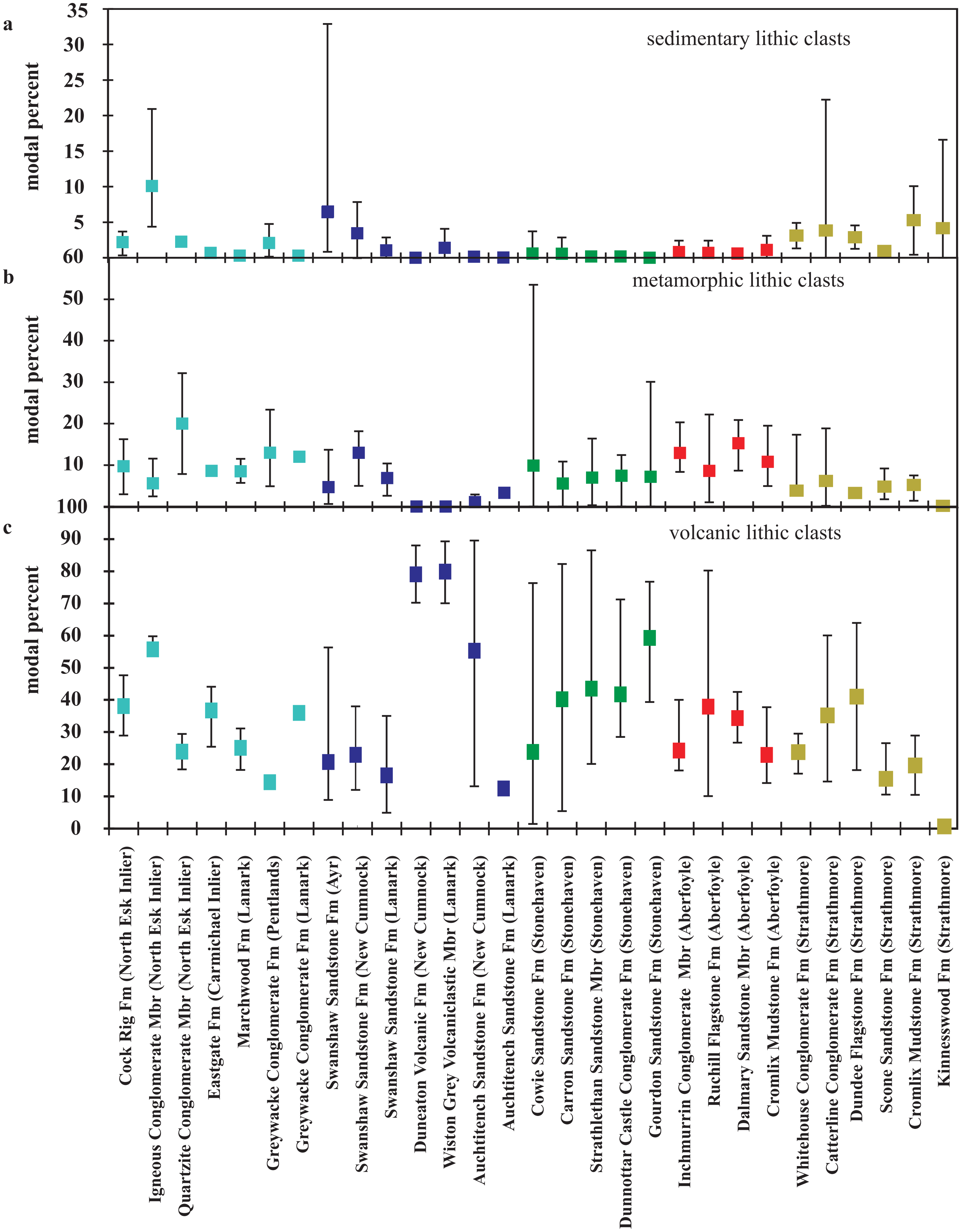

Figure 13. Mean sandstone composition data for the Silurian and Devonian sedimentary rocks exposed in the north and south of the Midland Valley: **(a)** sedimentary lithic clasts; **(b)** metamorphic lithic clasts; and **(c)** volcanic lithic clasts.

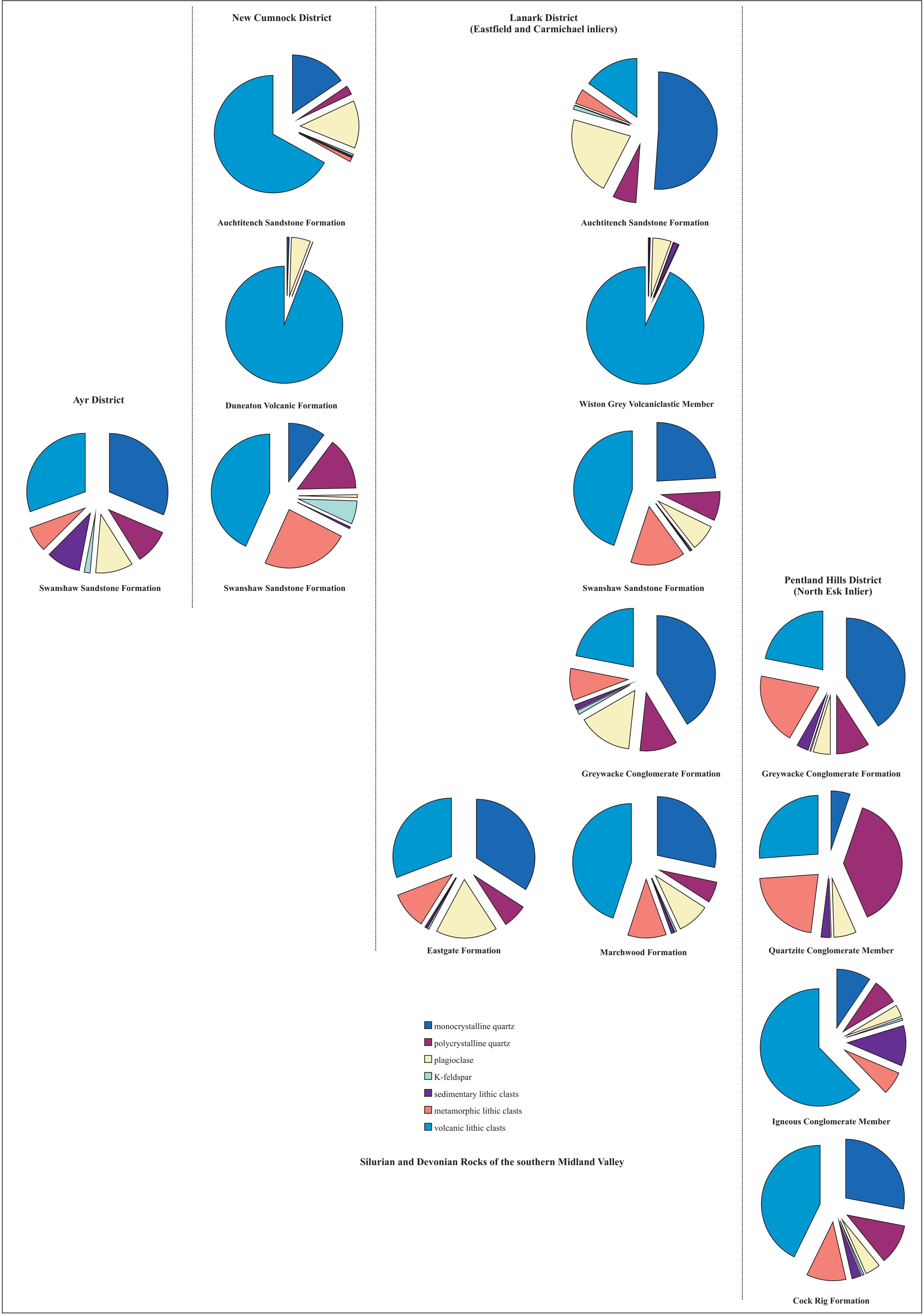

Figure 14. Pie charts showing the variation in mean sandstone composition for the Silurian and Devonian sedimentary rocks of the southern Midland Valley.

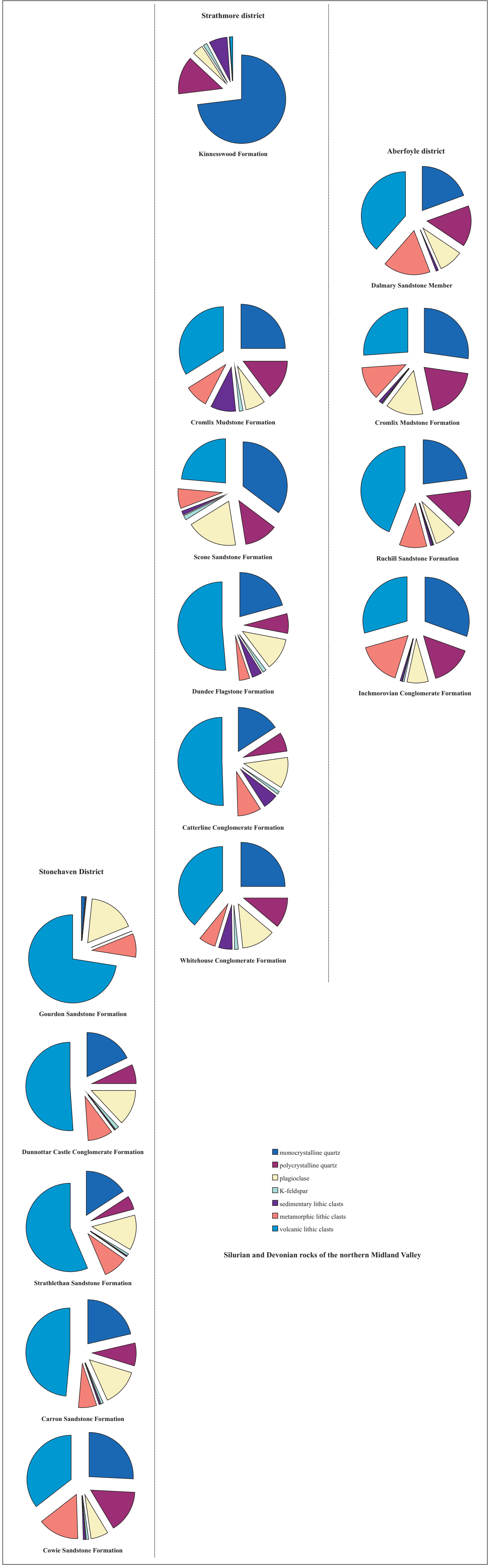

Figure 15. Pie charts showing the variation in mean sandstone composition for the Silurian and Devonian sedimentary rocks of the northern Midland Valley.

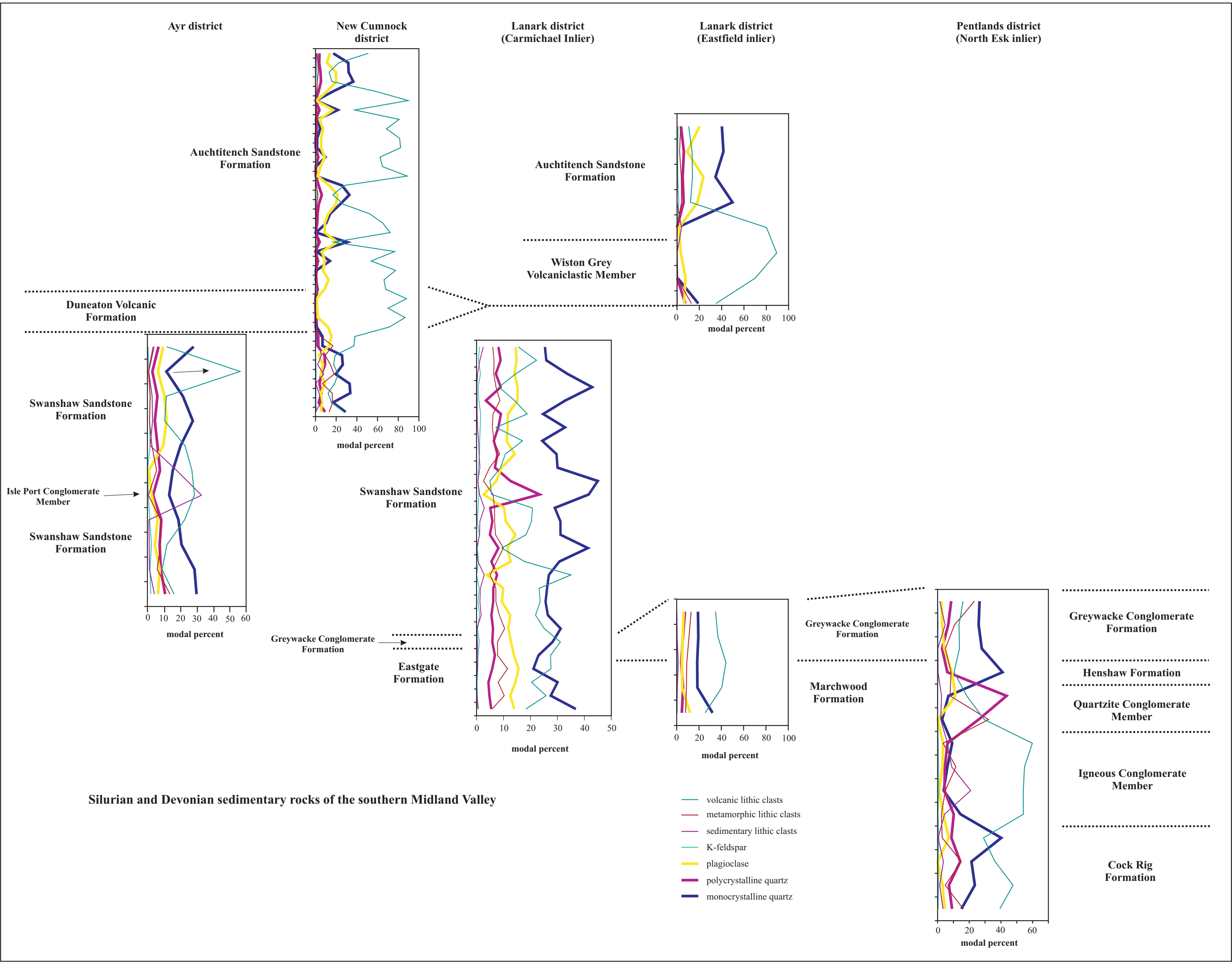

Figure 16. Lithostratigraphical variation in mono- and polycrystalline quartz, plagioclase, K-feldspar, metamorphic, sedimentary and volcanic lithic clast contents of the sandstones from the Silurian and Devonian sedimentary rocks of the southern Midland Valley.

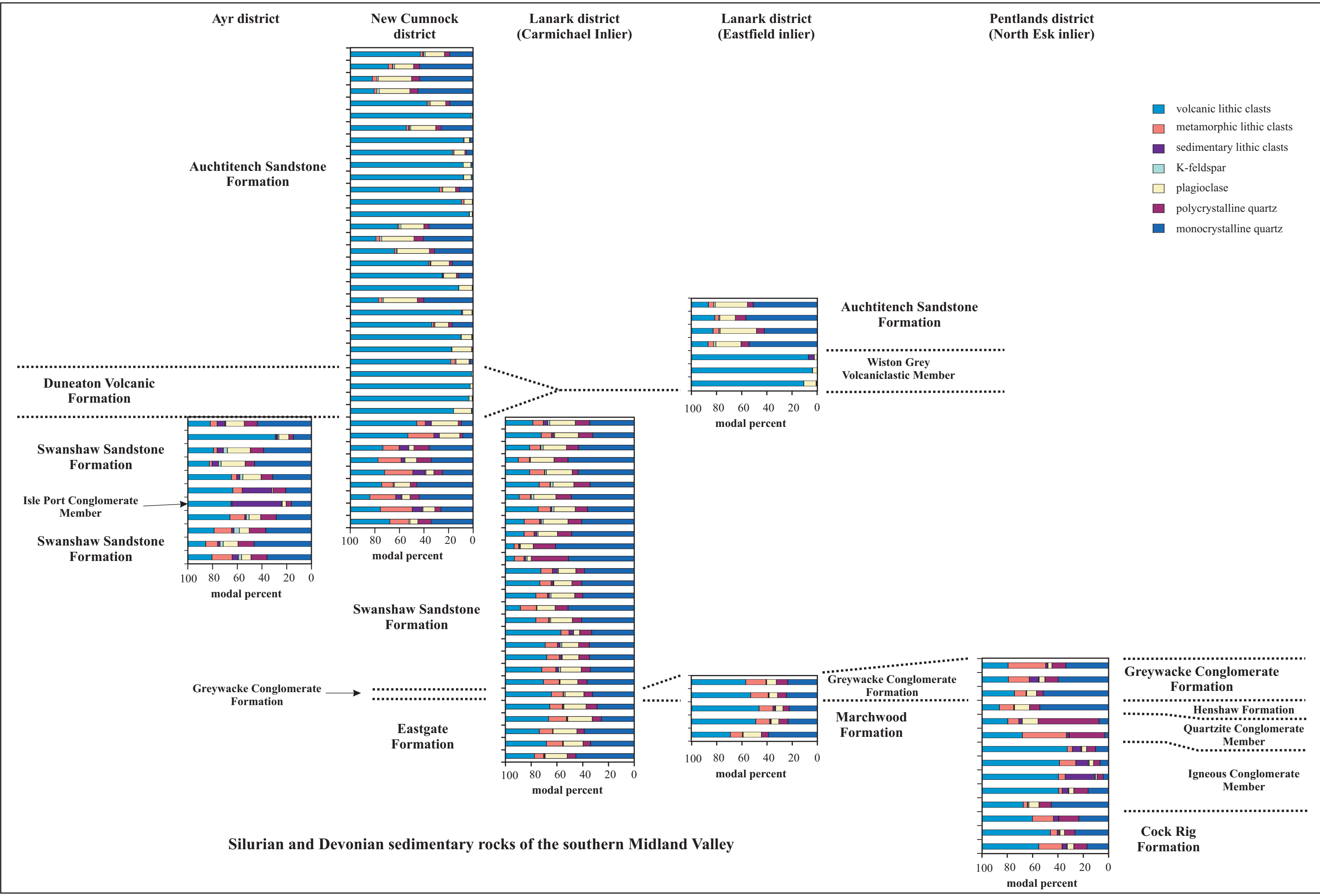

Figure 17. Bar charts showing the lithostratigraphical variation in mono- and polycrystalline quartz, plagioclase, K-feldspar, metamorphic, sedimentary and volcanic lithic clast contents of the sandstones from the Silurian and Devonian sedimentary rocks of the southern Midland Valley.

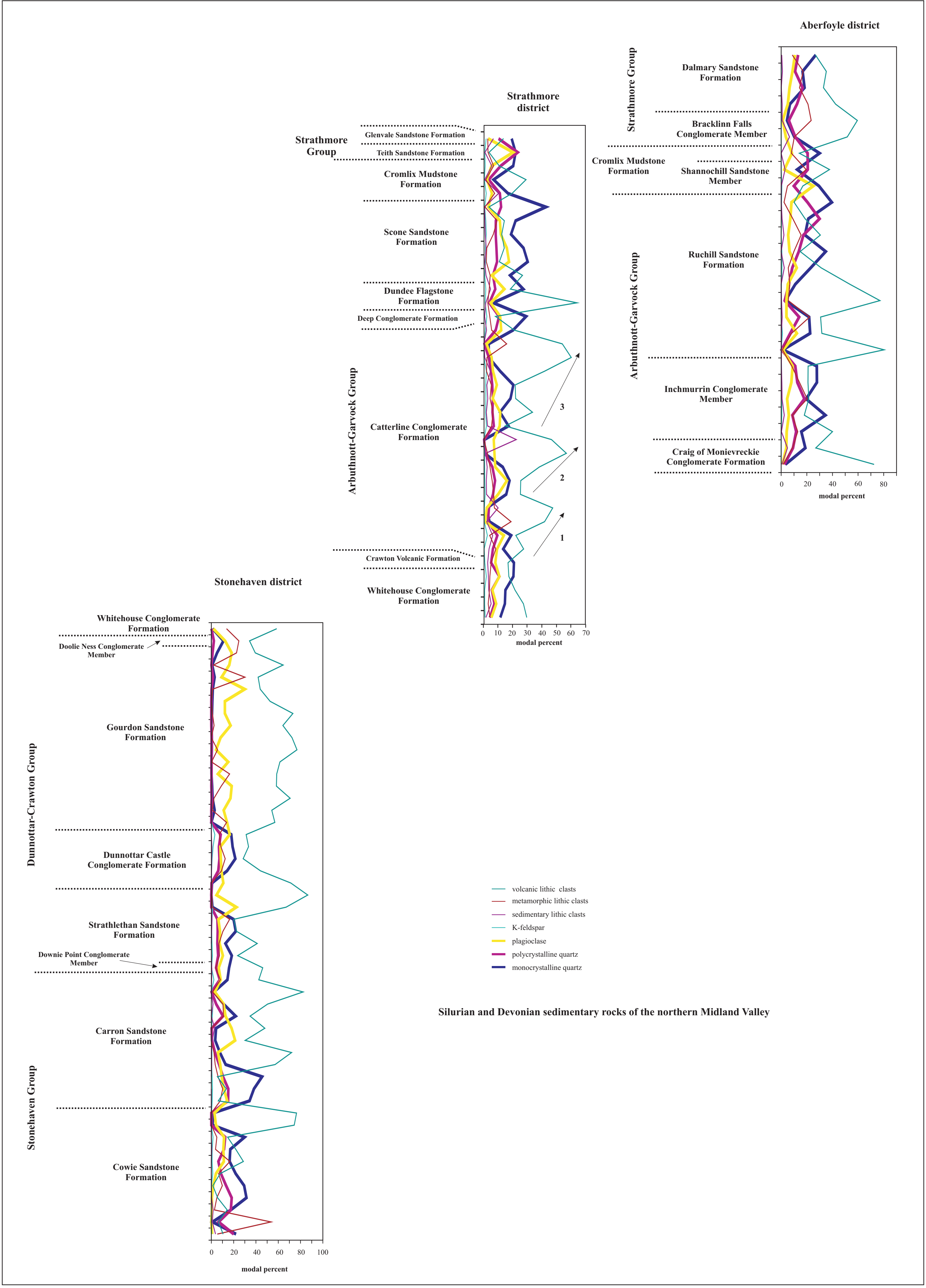

Figure 18. Lithostratigraphical variation in mono- and polycrystalline quartz, plagioclase, K-feldspar, metamorphic, sedimentary and volcanic lithic clast contents of the sandstones from the Silurian and Devonian sedimentary rocks of the northern Midland Valley.

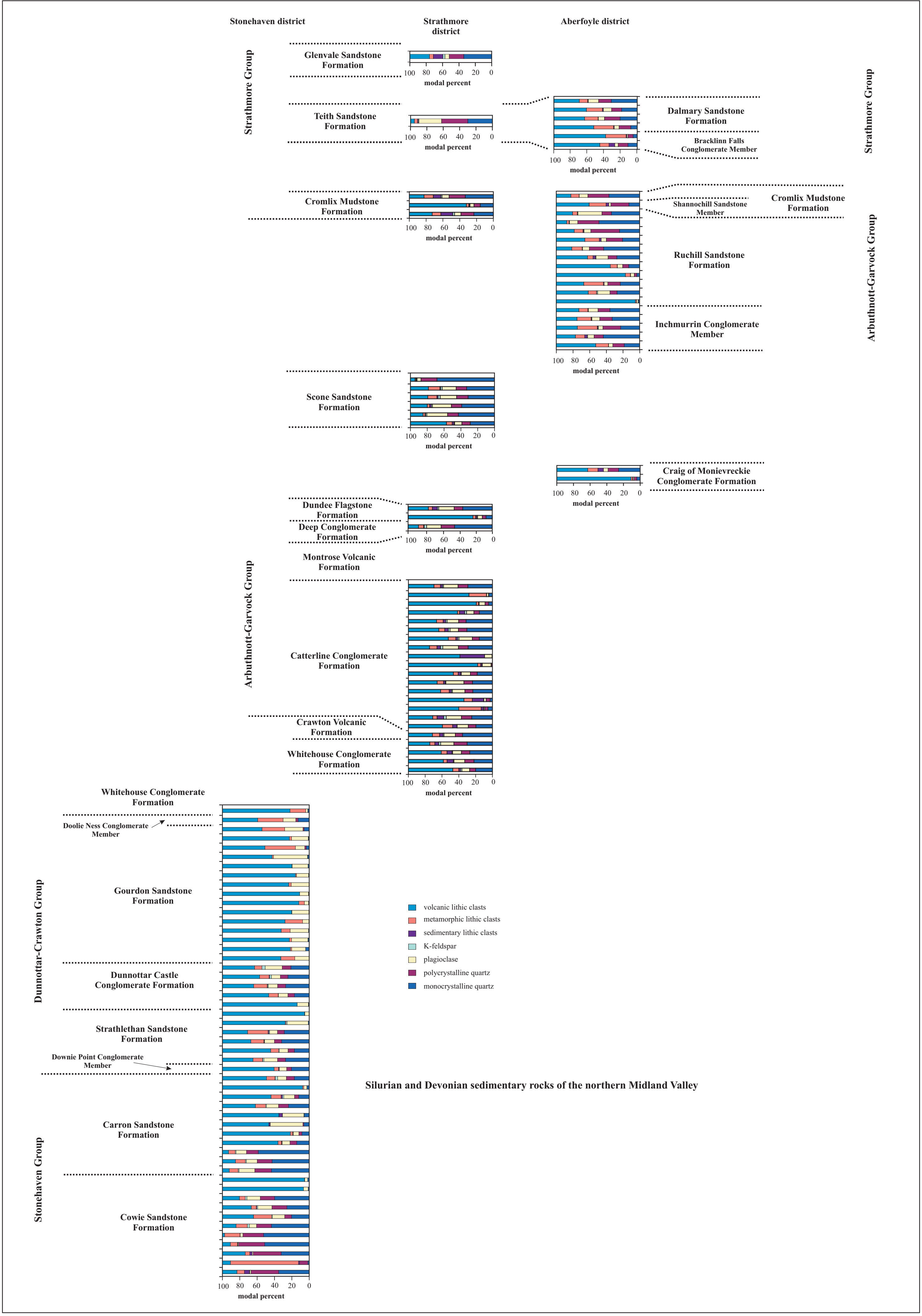

Figure 19. Bar charts showing the lithostratigraphical variation in mono- and polycrystalline quartz, plagioclase, K-feldspar, metamorphic, sedimentary and volcanic lithic clast contents of the sandstones from the Silurian and Devonian sedimentary rocks of the northern Midland Valley.

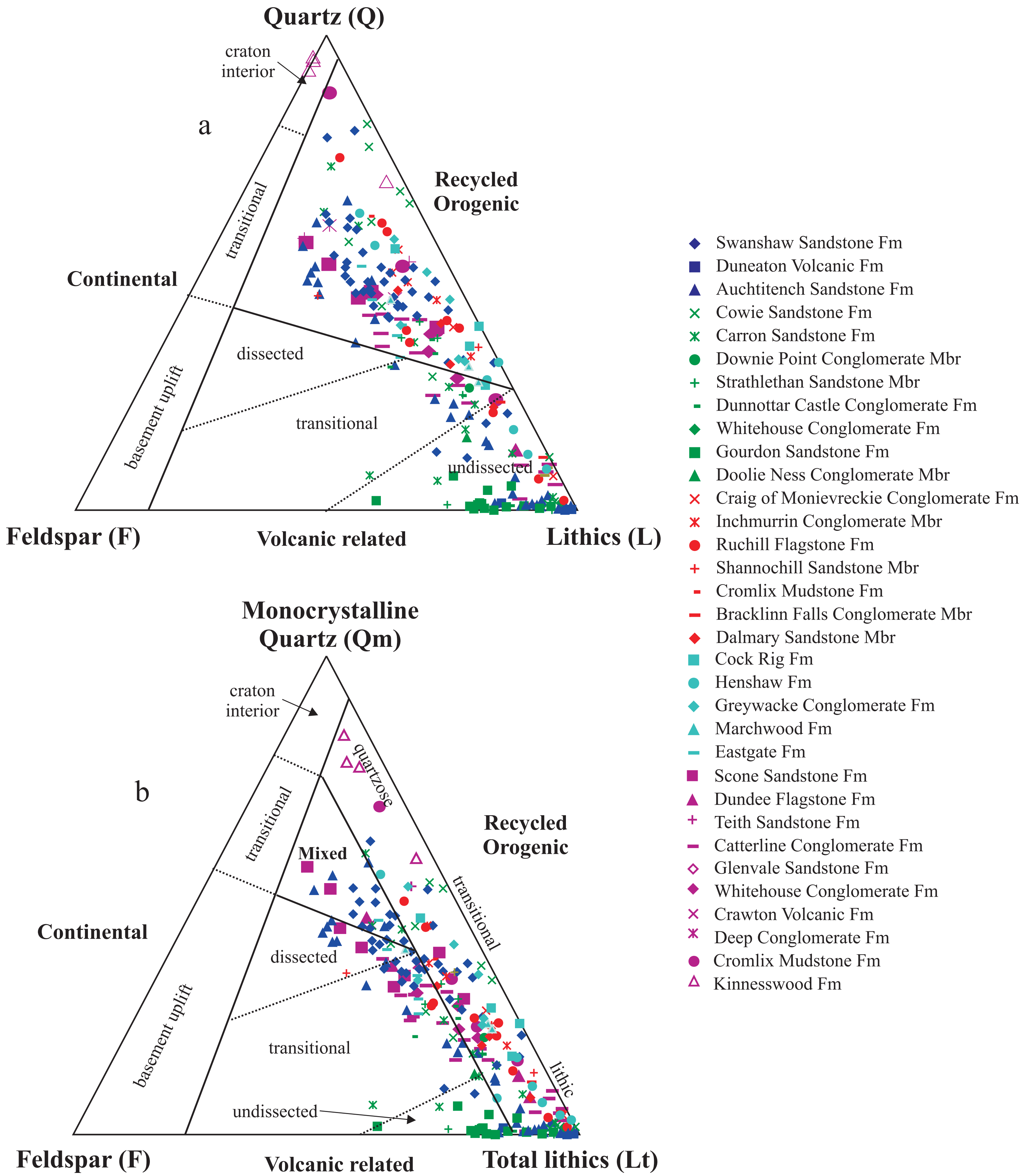

Figure 20. Ternary diagrams for determining sandstone provenance (after Dickinson & Suczek, 1979): **(a)** quartz-feldspar-lithic clasts; **(b)** monocrystalline quartz-feldspar-total lithic clasts.