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Petrology of the sedimentary rocks from the Midland Valley of Scotland collected for BGS-NIGL detrital zircon isotopic provenance study

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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.

Contents

Summary

This report describes the mineralogy and petrology of a 11 thin sections of sedimentary rocks collected as part of a BGS-NIGL collaborative study of detrital zircon populations in the Ordovician and Silurian sandstones of the southern Midland Valley of Scotland.

1 Introduction

This report describes the mineralogy and petrology of a suite of medium- to coarse-grained sandstones and granule sandstones from the Girvan, Hagshaw Hills, Eastfield, Carmichael and North Esk/Pentland inliers of Ordovician and Silurian rocks in the southern Midland Valley of Scotland (**Figure 1**). Location details of these samples are listed in **Table 1**.

Table 1. Location details for samples of sandstone collected from the Girvan, Hagshaw Hills, Eastfield, Carmichael and North Esk/Pentland inliers of the southern Midland Valley of Scotland.

Registered Number	Rock Name	Scottish County	Location	National Grid Reference
N5065	medium-grained sandstone, March Wood Formation	Lanarkshire	HFB 173, 540 m W25 degrees N of Eastfield of Wiston Farmhouse. Eastfield Inlier	NS 9632 3356
N5066	fine-grained sandstone, Eastgate Formation	Lanarkshire	HBF 216/217, 250 m W43 degrees S of monument on Carmichael Hill, Carmichael Inlier	NS 9311 3929
N5067	microconglomerate, Parishholm Conglomerate	Lanarkshire	100 m W 10 degrees S of Parish Holm Farm. Hagshaw Hills Inlier	NS 7619 2812
N5068	granule sandstone, Hareshaw Conglomerate	Lanarkshire	Slope north-east of Glenbuck Loch, 520 m N 15 degrees W of Parish Holm Farm. Hagshaw Hills Inlier	NS 7613 2866
N5069	sandstone, Quartzite Conglomerate	Scottish Borders	North Esk Inlier, Pentland Hills	NS 1449 5907
N5070	sandstone, Igneous Conglomerate	Scottish Borders	North Esk Inlier, Pentland Hills	NS 1470 5902
N5071	very coarse-grained sandstone, Cock Rig Formation	Midlothian	North Esk Inlier, Pentland Hills	NS 1482 5864
N5072	very coarse-grained sandstone, Kilranny Conglomerate	Ayrshire	Kennedy's Pass, coastal section south of Girvan	NS 1485 9325
N5073	very coarse-grained, pebbly sandstone, Wall Member, Myoch Formation, Whitehouse Subgroup	Ayrshire	coastal section south of Girvan	NS 1680 9505
N5074	very coarse-grained, pebbly sandstone, Scart Grit	Ayrshire	Woodland Point, coastal section Girvan	NS 1690 9535
N5075	very coarse-grained, pebbly sandstone, Craigskelly Conglomerate	Ayrshire	Horse Rock, coastal section south of Girvan	NS 1790 9615

A total of 11 thin sections have been examined with the work forming part of a collaborative BGS-NIGL isotopic study on detrital zircon populations in the Ordovician and Silurian sandstones of the southern Midland Valley. The stratigraphical positions of the sandstones collected from the Hagshaw Hills, Carmichael, Eastfield and North Esk Silurian inliers are also shown on **Figure 2**. This work forms part of the British Geological Survey's Integrated Geological Survey (North) programme. The outline to the BGS-NIGL Midland Valley Dating Project can be found in Appendix 1.

2 Petrology

2.1 MARCH WOOD FORMATION

In thin section (N5065) the sandstone from the Marchwood Formation (Eastfield inlier, Table 1) is a weakly laminated, moderately sorted, compositionally immature, medium-grained rock which possesses a moderately to closely packed, clast-supported texture. The sandstone contains trace amounts of a yellow-brown to yellow-green chloritic or clay cement. However, pressure solution of detrital grains during compaction resulted in the main mode of cementation. Pressure solution also resulted in grain boundary etching and the modification of clast shape. Clastic grains are, however, typically angular to subangular in shape with a low sphericity.

The mixed clast assemblage is dominated by monocrystalline quartz and variably degraded/chloritised lithic fragments. Feldspar and micas are also common minor detrital components within this sandstone. Lithic fragments appear to have been mainly composed of a very fine-grained to cryptocrystalline igneous rocks; however sedimentary and metasedimentary rock fragments are also present. Recognisable lithologies present include very fine-grained metasandstone (psammite), biotite hornfels, felsite or cherty rock, fine-grained mica-schist, low-grade chloritic metasandstone or siltstone, very fine-grained acidic volcanic rock, hornblende-phyric andesite or dacite, basalt and siltstone. Occasional granule to small pebble-sized clasts of a chloritic siltstone (probably intraclasts) are also present. Other minor to accessory detrital components include polycrystalline quartz, muscovite, biotite, opaque minerals, plagioclase, K-feldspar, chlorite, garnet and chloritic pseudomorphs after a detrital ferromagnesian mineral or rock.

Detrital biotite and muscovite exhibit a preferred shape alignment parallel to the weakly developed/preserved sedimentary lamination. Compaction resulted in the kinking of these detrital micas and the indentation or wrapping of unstable lithic clasts around neighbouring, typically more quartzose, grains. Minor to trace amounts of a clay- to fine-silt grade matrix component within the sandstone appears to have been derived from degraded lithic clasts.

Zircon has been identified within this thin section. Small equant to rod-shaped anhedral to subhedral zircon crystals have been recognised included within plagioclase, quartz and rarely biotite. A faceted zircon crystal was also noted within a granitic lithic clast and anhedral/rounded dusty-looking zircon in a fine-grained metasedimentary rock fragment. Rounded, dusty-looking, high-relief detrital zircon grains were noted within the matrix of the sandstone.

2.2 EASTGATE FORMATION

In thin section (N5066) the sandstone from the Eastgate Formation (Carmichael inlier, Table 1) is a poorly sorted, compositionally immature, fine-grained rock which possesses a very closely packed clast-supported texture. Although fine-grained, scattered medium-grained sand grade clasts are present within this sandstone. In general this sandstone contains very or no matrix component and only trace amounts of replacive carbonate and chlorite cements. The carbonate cement appears to be replacing the unstable lithic fragments. Pressure solution of detrital grains during compaction resulted in the main mode of cementation. This process also resulted in grain boundary etching and the modification of clast shape. Clastic grains are typically angular to subangular in shape with a low sphericity. However, rare rounded, moderate sphericity grains are also present.

The mixed clast assemblage is dominated by monocrystalline quartz, feldspar (mainly plagioclase) and variably altered lithic fragments. Lithic fragments are mainly composed of a very fine-grained to cryptocrystalline igneous rocks. Recognisable lithologies include very fine-micrographic rhyolite, felsite or cherty rock, altered basalt, chloritised possibly metamorphosed basaltic rock and an originally glassy rhyolite with well-developed spherulitic textures. Other minor to accessory detrital components include polycrystalline quartz, muscovite, biotite, opaque minerals, plagioclase, K-feldspar (microcline), epidote, chlorite, sericitised plagioclase, micrographic intergrowth, garnet, tourmaline, apatite, monazite and titanite. Detrital micas, elongate lithic and quartzose grains locally exhibit a preferred shape alignment, possibly parallel to bedding.

Zircon has been identified within this thin section. Small equant to rod-shaped anhedral to subhedral zircon crystals have been recognised included within plagioclase, monocrystalline quartz and rarely biotite. Rounded, dusty-looking, high-relief detrital zircon grains have also noted within the matrix of the sandstone.

2.3 PARISHHOLM CONGLOMERATE

In thin section (N5067) the granule sandstone to microconglomerate from the Parishholm Conglomerate (Hagshaw Hills inlier, Table 1) is a very poorly sorted, compositionally and texturally immature, very coarse-grained, lithic-rich rock which possesses a closely packed clast-supported texture. Clastic grains are angular, subangular to occasionally subrounded in shape with a low sphericity. Granule to small pebble-sized clasts are typically slightly more rounded than the finer grained clastic component within this sedimentary rock. The shape of the clastic grains has been locally modified due to pressure solution and grain boundary etching. Compaction also resulted in the moulding or indentation of unstable lithic clasts against neighbouring more rigid, typically quartzose, grains.

The clast assemblage is dominated by variably altered fragments of very fine-grained igneous rocks, with monocrystalline and polycrystalline quartz more common in the finer, sand-grade component to the sandstone. Although dominated by andesitic to rhyolitic volcanic or high-level intrusive rocks, fragments of sedimentary and metamorphic rocks are also present. Recognisable lithologies present include felsite, altered diorite or granodiorite, fine-grained granite/microgranite, fine-grained basaltic rock, plagioclase-phyric andesite, quartzite, chert, feldspar-phyric dacite, meta-quartz arenite, brecciated felsite/chert, feldspar-phyric dacite/rhyolite, trachytic rock, chloritised basalt, amygdaloidal basalt, granite, siltstone, matrix supported sandstone, mudstone, hornblende-feldspar-phyric dacite, micrographic granite, psammite, K-feldspar-rich (probably syenitic) granite. Other minor to accessory detrital components include polycrystalline quartz, micrographic intergrowth, microcline, chlorite, muscovite, garnet and epidote.

This very coarse-grained sandstone possesses trace amounts of a primary intergranular porosity. These pore spaces are lined, or locally filled by a very fine-grained chloritic or hematitic rim cement. Three generations of cement have been recognised within this rock; (1) an early chloritic or clay pore lining to locally pore filling cement; (2) a later, very locally developed quartz cement filling pores spaced already lined by chlorite; and (3) traces of a pore lining hematitic rim cement which post-dates the Type 1 chlorite cement, and possibly the Type 2 quartz cement. Minor hematisation of unstable detrital components may have accompanied the development of this later cement.

Zircon has been identified within this thin section. Small equant to rod-shaped anhedral to subhedral zircon crystals have been recognised included within plagioclase and variably strained quartz. Faceted zircon crystals have been noted within a dioritic/granodiorite lithic clast, K-feldspar-rich/syenitic granite, a micrograniitic rock and a fragment of feldspar-phyric dacite.

2.4 HARESHAW CONGLOMERATE

In thin section (N5068) the granule sandstone to pebbly sandstone from the Hareshaw Conglomerate (Hagshaw Hills inlier, Table 1) is a poorly to very poorly sorted, compositionally and texturally immature, coarse- to very coarse-grained, quartzose, lithic-rich rock which possesses a closely to very closely packed clast-supported texture. This sandstone has a very low primary porosity and contains very little clay matrix. Clastic grains are subangular, subrounded to occasionally rounded in shape with a low sphericity. The shape of the clastic grains has been locally modified due to pressure solution and grain boundary etching. Compaction also resulted in the moulding or indentation of unstable lithic clasts against neighbouring more rigid, typically quartzose, grains. Granule to small pebble sized clasts are typically slightly more rounded than the finer grained clastic component within this sedimentary rock.

The clast assemblage is dominated by monocrystalline and polycrystalline quartz as well as variably altered fragments of very fine-grained igneous rocks. Although dominated by dacitic to rhyolitic volcanic or high-level intrusive rocks, fragments of sedimentary and metamorphic rocks are also present. Recognisable lithologies present include muscovite-quartz-psammite, quartzite, very fine-grained quartz-schist, trachytic rock, felsite, quartz-phyric rhyolite, feldspar-phyric dacite, sheared to mylonitic quartzofeldspathic metamorphic rock, coarse grained diorite or granodiorite, microdiorite with poikilitic intergranular quartz, metamorphosed basaltic or andesitic rock, very fine-grained psammite or quartzose schist and a very fine-grained opaque-rich/graphitic phyllitic rock. Other minor to accessory detrital components include polycrystalline plagioclase, sericitised plagioclase, opaque minerals, muscovite, garnet and quartz-chlorite vein material. Both monocrystalline and polycrystalline quartz grains are strained with a well-developed undulose extinction and deformation bands.

This very coarse-grained sandstone possesses trace amounts of a clay to silt-grade matrix which appears to have been derived from the breakdown of unstable lithic clasts. Traces of a very fine-grained to cryptocrystalline quartz and Mg-chlorite/clay cements have been noted within this sandstone. However, pressure solution during compaction resulted in the main mode of cementation.

Zircon has been identified within this thin section. Rounded, dusty looking zircon crystals has been noted within the psammitic and schistose metasedimentary rock fragments. Equant to rod-shaped anhedral to subhedral zircon crystals have been recognised included within plagioclase and variably strained, monocrystalline and polycrystalline quartz.

2.5 QUARTZITE CONGLOMERATE

In thin section (N5069) a sandstone bed interbedded with the Quartzite Conglomerate (North Esk inlier, Pentland Hills, Table 1) is a poorly sorted, texturally and compositionally immature, massive, fine-grained rock which possesses a moderately packed clast-supported texture. This sandstone is characterised by the presence of a well-developed hematitic cement. Clastic grains are angular to subangular in shape with a low sphericity. However, the shape of the clastic grains has been locally modified as a result of grain boundary etching during the development of the hematitic cement.

The clast assemblage is dominated by monocrystalline quartz with subordinate amounts of altered feldspar (mainly plagioclase) and variably altered rock fragments. Feldspar and lithic fragments are variably replaced by a very fine-grained to cryptocrystalline chloritic or quartzose mosaic making it difficult to identify the range original of clast compositions. Other minor to accessory detrital components include polycrystalline quartz, felsite/cherty rock, muscovite, plagioclase, very fine-grained quartz-mica-schistose rock, epidote, tourmaline, sericitic metasandstone or metasiltstone, chloritised biotite and apatite.

No obvious zircon has been identified within this thin section.

2.6 IGNEOUS CONGLOMERATE

In thin section (N5070) a sandstone bed interbedded with the Igneous Conglomerate (North Esk inlier, Pentland Hills, Table 1) is a moderately to poorly sorted, compositionally immature, quartzose, fine- to medium-grained, rock which possesses a closely packed clast-supported texture. This sandstone contains traces of a variably developed hematitic cement and hematised clay/silt matrix. The variation in the modal proportion of this matrix defines a weakly preserved sedimentary lamination. Clastic grains are angular, subangular to rarely subrounded in shape with a low sphericity. The shape of the clastic grains has been locally modified due to pressure solution and grain boundary etching during the formation of the hematitic cement. Compaction also resulted in the kinking of detrital micas.

The clast assemblage is dominated by monocrystalline quartz with variably altered rock fragments and feldspar. The lithic clasts are variably replaced by a very fine-grained to cryptocrystalline felsitic or Mg-chloritic mosaic. Other minor to accessory detrital components include polycrystalline quartz, plagioclase, altered very fine-grained acidic igneous rock/felsite, muscovite, sericitised plagioclase, K-feldspar, opaque minerals, tourmaline, apatite, biotite, titanite/rutile, epidote.

Minor to trace secondary porosity has been noted, possibly due to the dissolution of feldspar and/or highly altered lithic clasts. Traces of a fine-silt to clay-grade matrix have been recorded within this sandstone. This matrix component may have been derived from degraded lithic clasts.

Zircon has been identified within this thin section. Small equant to rod-shaped anhedral to subhedral zircon crystals have been recognised included within monocrystalline and polycrystalline quartz. Large rounded, dusty looking detrital zircons have been noted within the matrix of the sandstone. Faceted, possible zircon crystals have been noted within a fragment of felsite/cherty rock. A large rounded, dusty looking zircon crystal was also noted included within muscovite.

2.7 COCK RIG FORMATION

In thin section (N5071) the granule sandstone to pebbly sandstone from the Cock Rig Formation (North Esk inlier, Pentland Hills, Table 1) is a weakly bedded, poorly sorted, compositionally and texturally immature, relatively quartzose, matrix-poor, coarse- to very coarse-grained rock which possesses a closely packed clast-supported texture. Bedding is defined by the marked variation in grain size. Erosive bases to the beds/laminae are immediately overlain by a pebbly/granule lag. A thin distorted siltstone lamina occurs between the main sandstone layers and a thin granule sandstone to microconglomeratic layer at the base of the sequence.

Granule and small pebble-sized clasts are rounded to subrounded in shape with a low sphericity. These clasts locally appear to be broken fragments of larger (probably polycyclic) grains. The granule to small pebble-sized clasts are typically more rounded than the finer grained clastic component within this sedimentary rock. These larger grains are mainly composed of fragments of very fine-grained to cryptocrystalline acidic igneous rocks as well as metasedimentary rock fragments. Recognisable lithologies present include quartzite, deformed meta-quartz arenite, feldspar-phyric andesite or dacite, felsite or cherty rock, polycrystalline strained quartz, fine-grained (low-grade) metasandstone, metasiltstone, feldspathic meta-quartz arenite, devitrified glassy rhyolite, microgranite, monocrystalline quartz, trachytic rock, chert and fine-grained sandstone (intraclasts).

The fine-grained sand-grade clasts are angular, subangular to occasionally subrounded in shape with a low sphericity. The shape of these clastic grains has been locally modified due to pressure solution and grain boundary etching. Compaction also resulted in the moulding or indentation of unstable lithic clasts against neighbouring more rigid, typically quartzose, grains. The more mixed clast assemblage in the sand-grade component of the sandstone is dominated by monocrystalline quartz, feldspar and fragments of very fine-grained igneous rocks. The range of rock fragments is similar to that forming the larger clastic grains. Other minor to accessory detrital components include polycrystalline quartz, plagioclase, biotite, green biotite, K-feldspar, muscovite, apatite, radiating crystals or spherulitic rock, hematitic cherty rock, very fine-grained psammitic rock, very fine-grained sandstone, microcline, quartz-phyric rhyolite, chlorite, rare crinoid fragments, garnet and micrographic microgranite or rhyolite.

This very coarse-grained sandstone possesses trace amounts of a replacive carbonate cement. However, pressure solution resulted in the main mode of cementation within this sedimentary rock. Development of this cement and earlier pressure solution resulted in the localised grain boundary etching and modification of clast shape. Compaction resulted in the kinking of detrital micas. A weak preferred shape alignment of elongate clasts parallel to bedding is developed within this sandstone.

Zircon has been identified within this thin section. Small equant to rod-shaped anhedral to subhedral zircon crystals have been recognised included within plagioclase and quartz.

2.8 KILRANNY CONGLOMERATE

In thin section (N5072) of a bed of granule sandstone to microconglomerate interbedded with the Kilranny Conglomerate (Girvan, Table 1) is a poorly sorted, texturally and compositionally immature, coarse- to very coarse-grained, lithic-rich, calcareous rock which possesses an open packed cement-supported texture. This sandstone is characterised by the presence of a well-developed crystalline carbonate cement. Clastic grains are angular, subangular to occasionally subrounded in shape with a low sphericity. The shape of the clastic grains has been locally modified during the development of the carbonate cement and very localised pressure solution. Rounded clasts appear to be broken fragments of larger (polycyclic) pebbles.

The clast assemblage is dominated by variably altered fragments of basaltic to microgabbroic igneous rocks with minor quartzose clasts. Recognisable lithologies present include plagioclase-pyroxene-phyric basalt, chloritised coarse-grained basalt or microgabbro, siliceous mudstone with radiolaria, variably metamorphosed microgabbroic rocks, aphyric rhyolite, plagioclase-phyric basalt, laminated sandstone/siltstone (intraclasts), chert/cryptocrystalline felsitic rock, laminated mudstone, pilotaxitic basalt, mylonitic metamafite, xenolithic altered dacite/rhyolite, variolitic basalt, microdiorite, tuffaceous/chloritic rock, polycrystalline amphibole/metamafite, schistose amphibole metamafite, epidotised basalt, mylonitic quartzofeldspathic rock and biotite hornfels. Other minor to accessory detrital components include monocrystalline quartz, chloritised rock/serpentinite, polycrystalline epidote, polycrystalline clinozoisite, opaque minerals, epidote, polycrystalline quartz, titanite, clinozoisite, amphibole, plagioclase, hornblende, actinolite, garnet, K-feldspar, rare brachiopod shell fragments and perthite.

2.9 WALL MEMBER, MYOCH FORMATION, WHITEHOUSE SUBGROUP

In thin section (N5073) the granule sandstone to pebbly sandstone from the Wall Member of the Myoch Formation (Girvan, Table 1) is a very poorly sorted, texturally and compositionally immature, coarse- to very coarse-grained, pebbly, calcareous, relatively quartzose, lithic-rich rock which possesses a closely to very closely packed clast-supported texture. Clastic grains are angular to subangular in shape with a low sphericity. Granule to small pebble-sized clasts are typically slightly more rounded than the finer grained clastic component within this sedimentary rock. The shape of the clastic grains has been locally modified due to pressure solution and grain boundary etching during the formation of a patchily developed carbonate cement.

The mixed clast assemblage is dominated by monocrystalline quartz with subordinate amounts of variably altered rock fragments and feldspar. Although dominated by mainly acidic igneous lithic clasts, fragments of sedimentary and metamorphic rocks are also present. Recognisable lithologies present include aphyric basalt, microgranitic rock, siltstone, felsite, rhyolite, metabasaltic rock, mylonitic or sheared quartz vein material, mylonitic quartzofeldspathic rock, granite or diorite, chert, quartz-phyric rhyolite, very fine-grained sandstone, variolitic basalt, chloritised rock or serpentinite and vesicular basalt or glass. Other minor to accessory detrital components include polycrystalline quartz, plagioclase, opaque minerals, biotite, apatite, chlorite and muscovite.

Compaction resulted in the kinking of detrital micas and pressure solution; the latter resulting in the main mode of cementation within this sandstone. Traces of a very fine-grained chloritic cement have also been noted.

Zircon has been identified within this thin section. Small equant to rod shaped anhedral to subhedral zircon crystals have been recognised included within monocrystalline and polycrystalline quartz.

2.10 SCART GRIT

In thin section (N5074) the pebbly sandstone from the Scart Grit (Girvan, Table 1) is a poorly sorted, compositionally immature, medium-grained, calcareous rock which possesses a closely packed clast-supported texture and low porosity. Clastic grains are angular to subangular in shape with a low sphericity. Granule to small pebble-sized clasts (up to 6 mm in size) are typically slightly more rounded than the finer grained clastic component within this sedimentary rock. These larger grains are mainly composed of variably carbonate replaced basaltic or andesitic igneous rocks. Other clasts are composed of a muscovite-bearing quartzite, monocrystalline quartz, very fine-grained cleaved phyllitic to slaty mudstone and an aphyric glassy rhyolite. A weakly developed preferred shape alignment of elongate clasts has been noted within this sample.

Finer grained sand-grade clasts are angular, subangular to rarely subrounded in shape with a low sphericity. However, rare clasts of moderate sphericity have been noted. The clast assemblage is dominated by monocrystalline and polycrystalline quartz with subordinate amounts of variably altered rock fragments. Lithic clasts are composed of a similar range of lithologies as the coarser grained granule to small pebble-sized grains. A crude bimodal grain size distribution is present within this sandstone with a break in clast size separating the coarser granule and finer sand-grade clasts. Other minor to accessory detrital components include very fine-grained quartz-mica-schist, muscovite, glassy rock/chert, opaque minerals, muscovite, apatite, epidote, tourmaline and zircon.

The finer grained lithic clasts are variably degraded and incorporated into the matrix component of this sandstone. Compaction resulted in the kinking of detrital micas and pressure solution; the latter resulting in the main mode of cementation within this sandstone. Traces of a very fine-grained replacive carbonate cement have been noted.

Zircon has been identified within this thin section. Small equant to rod-shaped anhedral to subhedral zircon crystals have been recognised included within quartz. Larger rounded, dusty looking detrital zircons have been notes within the matrix of the sandstone.

2.11 CRAIGSKELLY CONGLOMERATE

In thin section (N5075) the coarse-grained sandstone to granule sandstone interbedded with the Craigskelly Conglomerate (Girvan, Table 1) is a poorly to very poorly sorted, texturally and compositionally immature, relatively quartzose, lithic-rich, coarse- to very coarse-grained rock which possesses a closely packed clast-supported texture and low porosity. Clastic grains are angular, subangular to locally subrounded in shape with a low sphericity. However, granule sized clasts are typically slightly more rounded in shape than the finer grained component within this sedimentary rock.

The mixed clast assemblage is dominated by monocrystalline and polycrystalline quartz and rock fragments. The lithic clasts are mainly composed of variably altered, very fine-grained igneous rocks. However, sedimentary and metamorphic rock fragments are also present. Recognisable lithologies include basalt, quartz-phyric rhyolite, siltstone, variolitic basalt, quartz-zoisite rock, aphyric rhyolite or dacite, felsite, chert, quartz-feldspar-phyric rhyolite with well developed spherulitic textures, muscovite-bearing quartzite or psammite, chloritic rock or serpentinite, very fine-grained phyllitic micaceous rock, pilotaxitic/trachytic rock, quartz-chlorite vein material and fine-grained psammite. Other minor to accessory detrital components include plagioclase, biotite, opaque minerals, chlorite, muscovite, zircon, rutile, apatite, tourmaline, titanite, epidote and garnet. A weakly developed preferred shape alignment of elongate clasts has been noted within this sample.

Compaction resulted in the kinking of detrital micas and pressure solution; the latter resulting in the main mode of cementation within this sandstone. Traces of a very fine-grained to cryptocrystalline chloritic cement have also been noted.

Zircon has been identified within this thin section. Small equant to rod shaped anhedral to subhedral zircon crystals have been recognised included within monocrystalline and polycrystalline quartz. A zircon crystal was also noted included within muscovite. Larger rounded, dusty looking detrital zircons have been notes within the matrix of the sandstone.

3 Samples selected for isotopic analysis

The sandstones from the following lithostratigraphical units have been selected for detailed isotopic analysis of their detrital zircon populations (**Table 2**): (1) March Wood Formation; (2) Parishholm Conglomerate; (3) Hareshaw Conglomerate; (4) Cockrig Formation; (5) Wall Member of the Myoch Formation; and (6) Craigskelly Conglomerate. The selected samples all contain zircon in thin section as isolated detrital grains and/or included crystals within larger quartz, feldspar and/or lithic clasts.

Table 2. Details of sandstone samples from the Midland Valley selected for isotopic analysis.

Sample	Selection	Formation	Inlier	Age	Comments
N5065	✓	March Wood Formation	Eastfield Inlier	Mid Wenlock	Zircon seen in thin section. Will provide information on provenance for strata of Mid Wenlock age and from the eastern Midland Valley
N5066	✗	Eastgate Formation	Carmichael Inlier	Mid Wenlock	Zircon present in thin section. Rejected as March Wood Formation sample of comparable age and composition
N5067	✓	Parishholm Conglomerate	Hagshaw Hills Inlier	Lower Wenlock	Zircon present in thin section. Will provide information on provenance for strata of Lower Wenlock age and from the central Midland Valley and highlight any temporal changes in provenance comparison with younger Hareshaw Conglomerate
N5068	✓	Hareshaw Conglomerate	Hagshaw Hills Inlier	Mid Wenlock	Zircon present in thin section. Will provide information on provenance for strata of Mid Wenlock age and from the central Midland Valley and highlight any temporal changes in provenance comparison with older Parishholm Conglomerate
N5069	✗	Quartzite Conglomerate	North Esk Inlier	Mid Wenlock	No zircons seen in thin section
N5070	✗	Igneous Conglomerate	North Esk Inlier	Lower Wenlock	Few small zircons present in thin section
N5071	✓	Cock Rig	North Esk Inlier	Upper Llandovery	Zircon present in thin section. Will provide information on provenance for strata of Upper Llandovery age and from the north-eastern Midland Valley
N5072	✗	Kilranny Conglomerate	Girvan	Ashgill/Caradoc	No zircons seen in thin section
N5073	✓	Wall Member, Myoch	Girvan	Ashgill/Cara	Zircon present in thin section. Will provide information on provenance for strata of

		Formation		doc	Ashgill/Caradoc age and from the lowest part of the sedimentary succession in the western Midland Valley
N5074	✗	Scart Grit	Girvan	Lower Llandovery	Few zircons seen in thin section, sample already selected of comparable age
N5075	✓	Craigskelly	Girvan	Lower Llandovery	Zircon present in thin section. Will provide information on provenance for strata of Lower Llandovery age and from the western Midland Valley

These sandstones will allow comparisons to be made between the Ordovician to Silurian sedimentary sequences present within each of the main Lower Palaeozoic inliers in the Southern Midland Valley. Furthermore, they provide detailed information on the spatial and temporal changes in the sandstone provenance within the southern Midland Valley of Scotland from latest Ordovician (Ashgill-Caradoc) to late Silurian (Mid-Wenlock) times. These data will also enable comparisons to be made with detrital zircon populations found within the Ordovician Portpatrick Formation sandstone of the adjacent Southern Uplands terrane.

4 Figures

Figure 1. Simplified geological map of the Midland Valley of Scotland showing the distribution of Silurian inliers and the Siluro-Devonian Lanark Group. 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; CMF, Carmichael Fault; PF, Pentland Fault, CCF, Crossgatehall Fault.

Figure 2. Generalised vertical sections through the Silurian inliers and Siluro-Devonian sequences and contemporaneous volcanic rocks of the New Cumnock, Lanark and Pentland Hills districts. The stratigraphical positions of the sandstones collected from the Hagshaw Hills, Carmichael, Eastfield and North Esk Silurian inliers of the southern Midland Valley are also shown.

5 Tables

Table 1. Location details for samples of sandstone collected from the Girvan, Hagshaw Hills, Eastfield, Carmichael and North Esk/Pentland inliers of the southern Midland Valley of Scotland.

Table 2. Details of sandstone samples from the Midland Valley selected for isotopic analysis.

6 Plates

Plate 1. (a) medium-grained sandstone containing aligned detrital micas and an elongate mudstone lithic clast, March Wood Formation, East Field inlier (sample N5065; plane polarised light; objective x2.5); **(b)** fine- to medium-grained sandstone, Eastgate Formation, Carmichael inlier (sample N5066; plane polarised light; objective x2.5); **(c)** microconglomerate, Parishholm Conglomerate, Hagshaw Hills inlier (sample N5067; plane polarised light; objective x1.0); **(d)** granule sandstone to pebbly sandstone, Hareshaw Conglomerate, Hagshaw Hills inlier (sample N5068; plane polarised light; objective x1.0).

Plate 2. (a) fine-grained sandstone with a hematitic cement, Quartzite Conglomerate, North Esk inlier (sample N5069; plane polarised light; objective x2.5); **(b)** medium-grained sandstone, Igneous Conglomerate, North Esk inlier (sample N5070; plane polarised light; objective x2.5); **(c)** granule sandstone, Cockrig Formation, North Esk inlier (sample N5071; plane polarised light; objective x1.0); **(d)** granule sandstone to pebbly sandstone, Kilranny Conglomerate, Girvan (sample N5072; plane polarised light; objective x1.0).

Plate 3. (a) coarse-grained sandstone, Wall Member, Myoch Formation, Girvan (sample N5073; plane polarised light; objective x2.5); **(b)** coarse-grained, pebbly sandstone, Scart Grit, Girvan (sample N5074; plane polarised light; objective x1.0); **(c)** granule sandstone, Craigskelly Conglomerate, Girvan (sample N5075; plane polarised light; objective x2.5).

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.

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

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

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

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

Equigranular – all crystals are approximately the same size.

Inequigranular – crystals of substantially different grain size. Common variety, *porphyritic* texture consists of large crystals of a particular mineral or minerals set in a finer grained groundmass. Porphyritic texture can be subdivided into: (a) *microporphyritic*, phenocrysts equal to or less than 2.0 mm in size; and (b) *macroporphyritic*, phenocrysts greater than 2.0 mm in size.

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

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

Andesite – An intermediate volcanic rock, usually porphyritic, consisting of plagioclase (frequently zoned from labradorite to oligoclase), pyroxene, hornblende and/or biotite.

Basalt – A volcanic rock consisting essentially of calcic plagioclase and pyroxene. Olivine and minor feldspathoids may also be present.

Basaltic andesite – A volcanic rock with plagioclase compositions expected for andesites but containing ferromagnesian minerals more commonly found in basalts.

Dacite – A volcanic rock composed of quartz and sodic plagioclase with minor amounts of biotite and/or hornblende and/or pyroxene.

Gabbro – A coarse-grained plutonic rock composed essentially of calcic plagioclase, pyroxene and Fe-oxides. If olivine is an essential constituent it is referred to as an olivine-gabbro – if quartz, a quartz-gabbro.

Peridotite – A collective term for ultramafic rocks consisting essentially of olivine with pyroxene and/or amphibole.

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

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

Rhyolite – A collective term for silicic volcanic rocks consisting of phenocrysts of quartz and K-feldspar, often with minor plagioclase and biotite, in a microcrystalline or glassy groundmass.

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

Granite – A medium- to coarse-grained plutonic rock consisting essentially of quartz, K-feldspar and plagioclase in variable amounts usually with hornblende and/or biotite.

Accessory – A minor constituent of rocks which is present only in small amounts, for example the minerals apatite, zircon, titanite.

Appendix 1 Outline proposal for the BGS-NIGL Midland Valley dating project

Project Title: Do the Lower Palaeozoic sedimentary sequences within the Midland Valley terrane preserve evidence for an older arc complex and Grenvillian basement along the Laurentian margin of the Scottish Caledonides ?

Objectives of the project: The project is designed to generate absolute ages (U-Pb ages laser ablation) for the detrital zircon populations contained within the major sandstone and conglomeratic units of the Lower Palaeozoic sedimentary sequence of the Midland Valley terrane.

Working hypothesis or model to be tested: Detritus supplied to the Ordovician and Silurian sedimentary basins within the Midland Valley terrane was not derived from a contemporaneous island arc complex as suggested by Bluck (1983, 2000, 2001), but was derived from much older, possibly Precambrian, terranes as proposed by Smith (1995), Phillips *et al*., (1998), Stone and Evans (2001) and Phillips *et al*., (2004). These terranes may have been unrelated to the Laurentian continent to the north of the Midland Valley, and possibly included fragments of Grenvillian and/or Avalonian origin. The potential presence of such terranes within sedimentation range of the Laurentian margin during the Ordovician and Silurian would indicate more complex history for the Iapetus Ocean than is commonly supposed. In particular, it would emphasise the early date at which terranes rifted from Gondwana and migrated northwards across the ocean..

Manner in which isotope results are expected to contribute to the objectives: Current models for a fore-arc environment in the Southern Uplands and Midland Valley are founded upon the belief that the remains of the Palaeozoic island-arc are preserved within the contemporaneous Ordovician and Silurian sedimentary sequences of the Midland Valley terrane (Bluck 1983, 2000, 2001). This remains untested by geochronological methods. Recent studies have revealed that the provenance of these sedimentary rocks was more complex (Phillips and Smith 1995; Phillips and Barron 2000; Phillips 1998, 1999, 2000) and included a potentially much older metasedimentary and granitic source(s), as well as a basaltic, andesitic to dacitic volcanic terrane. Isotopic data obtained for detrital zircon populations present within the major sandstone and conglomeratic units within the Ordovician and Silurian sedimentary sequences of the Midland Valley will provide critical age constraints on the sources which contributed detritus to these Lower Palaeozoic basins (Phillips *et al*., in press). From this study two possible outcomes are envisaged: **(1)** that Ordovician volcanic material is present, supporting the existence of a contemporaneous arc founded upon an older continental crust; or **(2)** no Ordovician ages are found and that these sedimentary rocks were derived from much older volcanic and metamorphic terranes which are potentially unrelated to Laurentia. This will not prove that a contemporaneous (Ordovician-Silurian) volcanic source is not represented somewhere within the Scottish Caledonides, but would cast serious doubt upon the fore-arc model, especially when taken in conjunction with recent work in the adjacent Southern Uplands terrane (Phillips *et al*., 2003).

Project Description: Detritus supplied to the Ordovician and Silurian sedimentary basins within the Midland Valley terrane was not derived from a contemporaneous island arc complex as suggested by Bluck (1983, 2000, 2001), but was derived from much older, possibly Precambrian, terranes as proposed by Smith (1995), Phillips *et al*., (1998), Stone and Evans (2001), Phillips *et al*., (2003) and Phillips *et al*., (2004). These terranes may have been unrelated to the Laurentian continent to the north of the Midland Valley, and may have included fragments of Grenvillian and/or Avalonian origin (Phillips *et al*., 2004). Phillips *et al*., (2003) have characterised one of these terranes, demonstrating that an Avalonian arc terrane, founded upon Grenvillian continental crust, supplied detritus to the Southern Uplands sedimentary basin during the Ordovician. This evidence indicates a more complex history for the evolution of the Laurentian margin and the Iapetus Ocean than is commonly supposed. In particular, it emphasises the previously unknown and very early date at which these terranes rifted from Gondwana and migrated northwards across the ocean. Furthermore, the results of Phillips *et al*., (2003) and Phillips *et al*., (2004) suggest that the southern margin of Laurentia was composed of a diverse assemblage of potentially unrelated (suspect) terranes. Consequently, the Lower Palaeozoic sedimentary rocks present within the Midland Valley terrane may have a radically different provenance to those now identified within the juxtaposed Southern Uplands terrane. Dating of these sedimentary rocks, with well-established lithoclast suites, may also hold the key to unravelling the timing of accretion and origin of these suspect terranes.

Current models for a fore-arc environment in the Southern Uplands and Midland Valley are founded upon the belief that the remains of the Palaeozoic island-arc are preserved within the contemporaneous Ordovician and Silurian sedimentary sequences of the Midland Valley terrane (Bluck 1983, 2000, 2001). This contemporaneous volcanic island-arc is thought to have shed volcanic and plutonic igneous detritus into the adjacent Lower Palaeozoic sedimentary basins (Bluck 1983, 2000, 2001). However, this model remains untested by geochronological methods. Recent detailed studies have revealed that the provenance of these sedimentary rocks was far more complex (Phillips and Smith 1995; Phillips and Barron 2000; Phillips 1998, 1999, 2000; Phillips *et al*., 2004) and included a potentially much older metasedimentary (up to amphibolite facies) and plutonic and high-level intrusive granitic source(s), as well as a basaltic, andesitic to dacitic volcanic terrane. This regional analysis of provenance is ongoing. Isotopic data obtained for detrital zircon populations present within the major sandstone and conglomeratic units within the Ordovician and Silurian sedimentary sequences of the Midland Valley will provide critical age constraints on these identified source terranes.

From this study two possible outcomes are envisaged: **(1)** that Ordovician volcanic material is present, supporting the existence of a contemporaneous arc founded upon an older Laurentian or Grenvillian continental crust; or **(2)** no Ordovician ages are found and that these sedimentary rocks were derived from much older volcanic and metamorphic terranes which are potentially unrelated to Laurentia. An alternative strike-slip model may then be invoked in which the source terrane was composed of an complex assemblage of an older (possibly Precambrian, Phillips *et al*., 2004) dismembered volcanic arc, as well as a plutonic igneous and metamorphic complex (Smith 1995; Phillips *et al*., 1988; Stone and Evans 2001). This will not prove that a contemporaneous (Ordovician-Silurian) volcanic source is not represented somewhere within the Scottish Caledonides, but would cast serious doubt upon the fore-arc model, especially when taken in conjunction with recent work in the adjacent Southern Uplands terrane (Phillips *et al*., 2003). Consequently, the proposed project is of critical importance to our understanding of the evolution of the Midland Valley terrane and its position within the wider Caledonian orogen.

The project is designed to generate age profiles for the detrital zircon populations contained within the major sandstone and conglomeratic units of the Lower Palaeozoic sedimentary sequence of the Midland Valley terrane. It is proposed that zircon populations should be extracted and dated from 5 samples of sandstone from these clastic sequences. It is intended that the analysis of the detrital zircons will be made using the laser ablation technique which is better suited to provenance studies than TIMS analysis. Detailed petrological studies have already been carried out on these sequences and have identified the main source terranes which supplied detritus to these Ordovician and Silurian sedimentary basins within the Midland Valley of Scotland (Phillips and Smith 1995; Phillips 1998, 1999, 2000; Phillips and Barron 2000; Phillips *et al*., 2004). The morphology of the detrital zircons will be examined using a standard petrological microscope and cathodoluminescence SEM analysis. These can then be compared with zircons included within the lithic clasts present within the sandstones and conglomerates. This will provide a direct link between the dated detrital zircons and their original granitic plutonic, volcanic or metasedimentary source and, therefore, providing an age constraint for these source terranes.

The U-Pb age data obtained will place age constrains on the granitic, volcanic and metamorphic source terranes and, therefore, allow the validity of the previously published models for the Pre-Carboniferous evolution of the Midland Valley terrane to be assessed. The data will also provide important information on the composition and age of the basement to the Midland Valley, which can then be utilised in the modelling activities of the upper crust as part of the Digital Geoscience Spatial Model of the Midland Valley. Ultimately, this research project will enable a more detailed model of the Midland Valley terrane to be erected and its role within the broader Caledonian-Appalachian orogen to be established.

References: Current and recent research relevant to this proposal.

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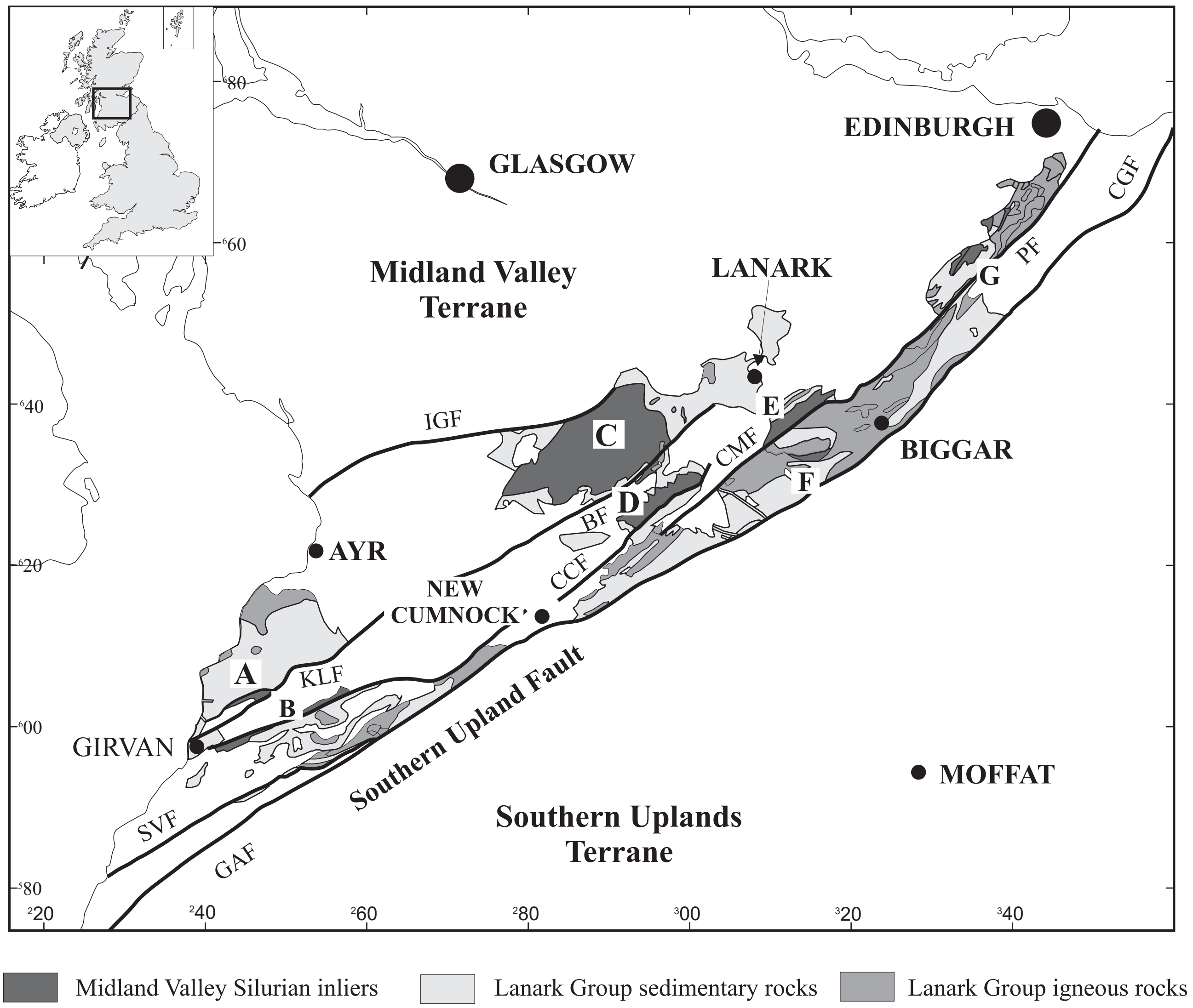

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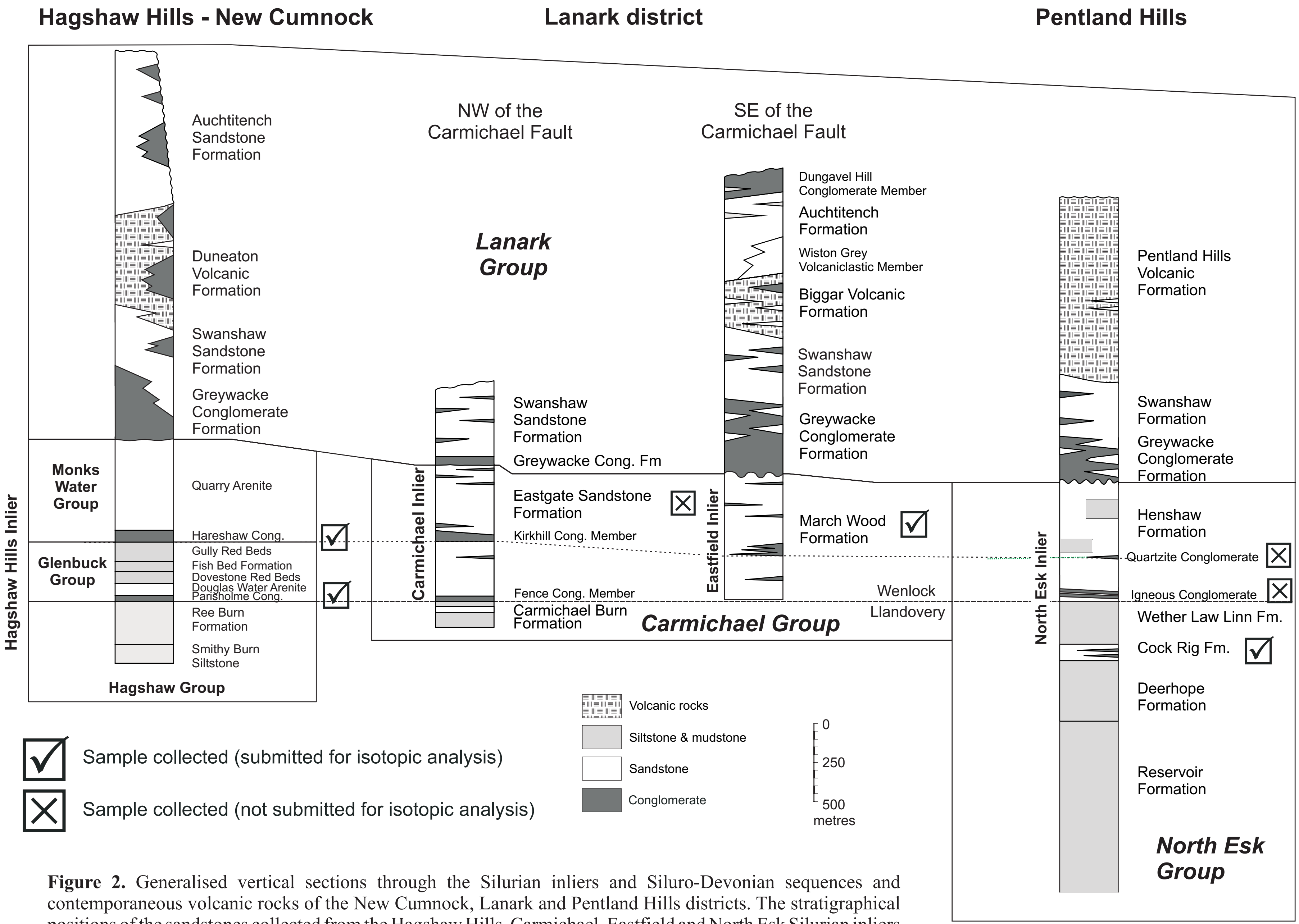

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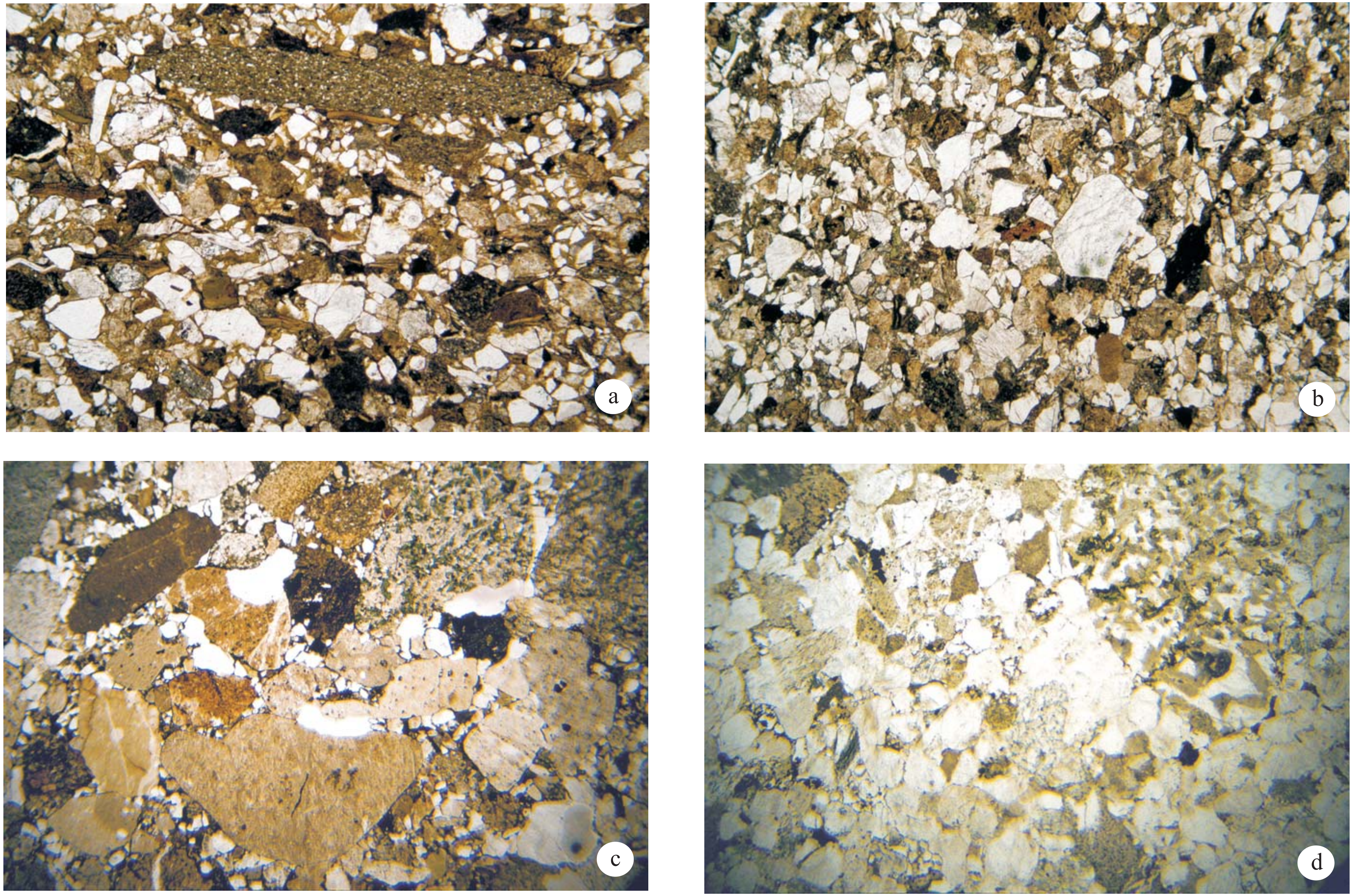

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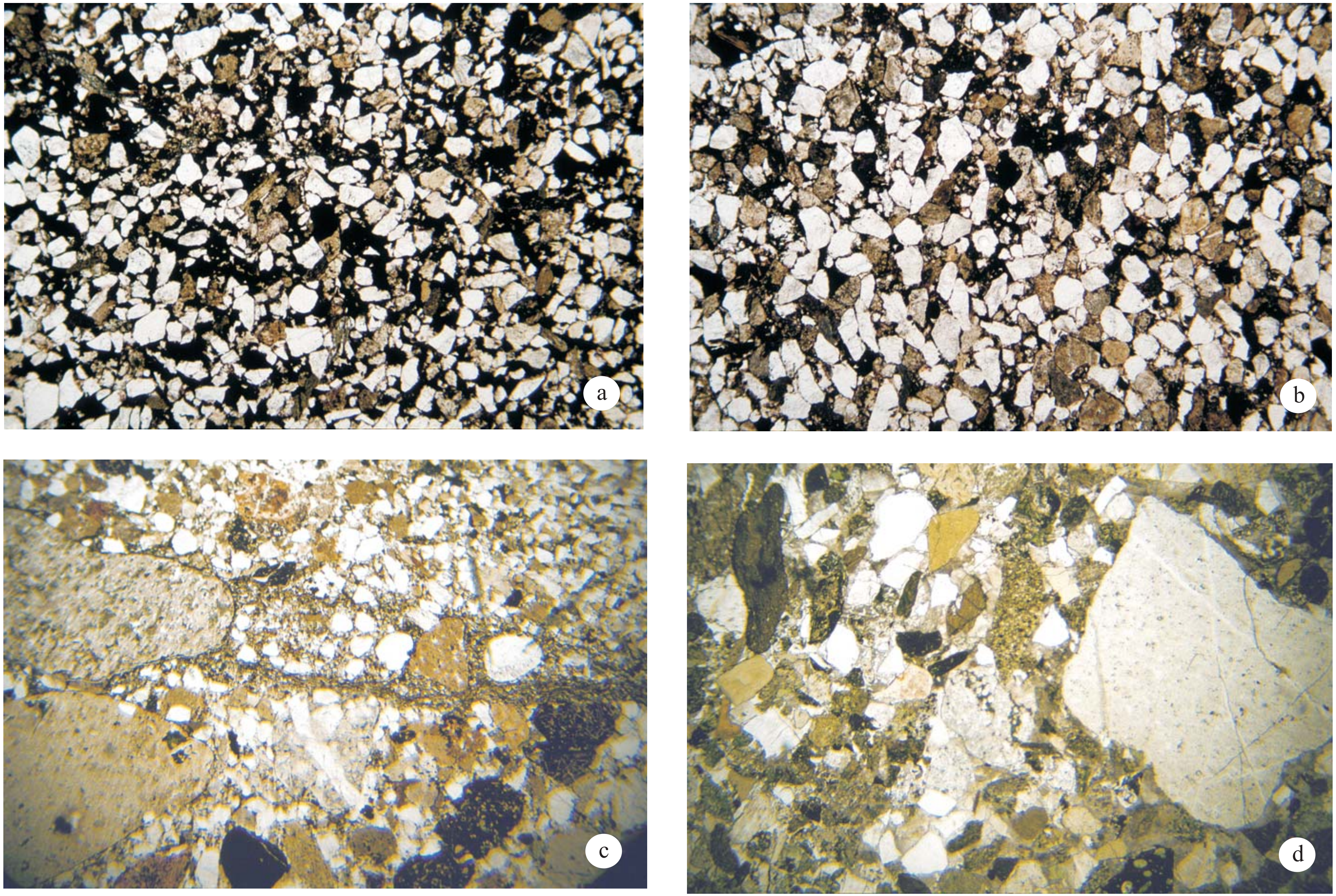
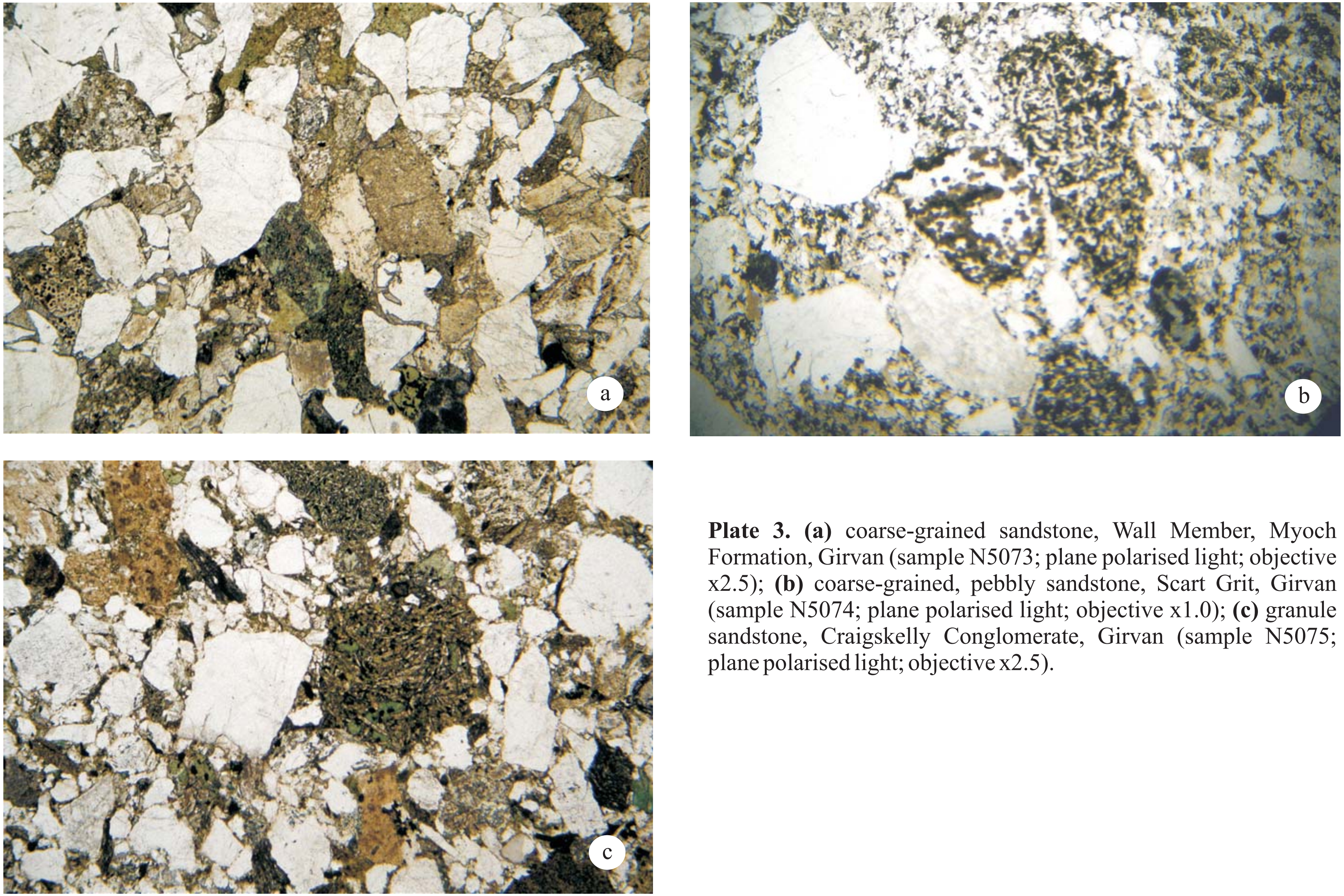


Plate 2. (a) fine-grained sandstone with a hematitic cement, Quartzite Conglomerate, North Esk inlier (sample N5069; plane polarised light; objective x2.5); **(b)** medium-grained sandstone, Igneous Conglomerate, North Esk inlier (sample N5070; plane polarised light; objective x2.5); **(c)** granule sandstone, Cockrig Formation, North Esk inlier (sample N5071; plane polarised light; objective x1.0); **(d)** granule sandstone to pebbly sandstone, Kilranny Conglomerate, Girvan (sample N5072; plane polarised light; objective x1.0).



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