Composition and provenance of sandstones and conglomerates

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Introduction

The tectonic evolution of the Midland Valley of Scotland during the Lower Palaeozoic to Devonian, and its setting within Caledonian orogenic models has been the focus of much recent debate (Williams & Harper 1988; McKerrow *et al.* 1991; Smith 1995; Phillips *et al.* 1998). Central to this debate is the sedimentology, structure and provenance of a sequence of Silurian sedimentary rocks and the overlying Lower Old Red Sandstone (Lanark Group). The Silurian sedimentary sequences are exposed in a number of inliers which occur along the southern margin of the Midland Valley of Scotland (**Figure 1**).

In general, the inliers record a transition from an older Llandovery transgressive marine sequence to a younger regressive terrestrial Lower Wenlock succession. However, there are significant differences in the detailed stratigraphy and thickness of the sequences present within the individual inliers (**Figure 2**). This variation probably reflects their deposition within in a number of small sub-basins which were developed oblique to the Southern Upland Fault during regional sinistral strike-slip (Williams & Harper 1988; Smith 1995; Phillips *et al.* 1998).

The Silurian Inliers

The Wenlock strata are subdivided into a number of formations (**Figure 2**). **March Wood, Eastgate, Henshaw** and **Cock Rig** formations, which have been sampled during this study, comprise a sequence of fine- to coarse-grained, poorly to locally moderately sorted sandstones (**Figures 3a to 3**c). The sandstones are lithologically similar and are composed of a mixed assemblage of angular to subangular basaltic to andesitic volcanic rock fragments with subordinate monocrystalline quartz and plagioclase (**Figures 3b and 3c**). Metamorphic (including metabasalt, phyllitic rock, mylonite, psammite and quartzite) and sedimentary rock fragments are a minor, but relatively common component within these sandstones. Minor to accessory detrital components include muscovite, biotite, garnet, chlorite, tourmaline, epidote, K-feldspar and amphibole.

Two distinctive conglomerates, the **'igneous'** and **'quartzite' conglomerates**, are present in some, but not all the inliers. The SE derived 'igneous' conglomerate (Henshaw Formation) is best developed in the inliers close to the Southern Upland Fault. It comprises subangular to subrounded, locally broken, granule to pebble sized clasts of fine-grained andesitic to dacitic igneous rock fragments and subordinate quartz within a medium- to coarse-grained sandstone matrix. Basalt, microgranite, rhyolite, trachyte, tonalite and felsite rock fragments are also present. Minor sedimentary and metamorphic rock fragments (meta-andesite, cleaved mudstone, psammite, quartzite, schist/phyllite and biotite-hornfels) have also been recognised.

The early to middle Wenlock 'quartzite' conglomerate is characterised by the presence of subangular to occasionally rounded quartzite rock fragments within a medium- to coarse-grained sandstone matrix. However, this heterolithic conglomerate also contains fine-grained rhyolite and dacite rock fragments as well as minor andesite, cleaved mudstone, microgranite, psammite, quartz-diorite, siltstone and mudstone. The quartzite conglomerate is best developed within the Lesmahagow inlier where it thins to the west. In contrast, in the Hagshaw Hills inlier the conglomerate thins and fines towards the north (Bluck 1983 and references therein). An isolated lens of 'quartzite' conglomerate occurs at a similar stratigraphic level in the Pentlands N Esk inlier. The variations in composition and thickness of this conglomerate suggest that it was deposited by a complex system of easterly and northerly prograding alluvial fans.

Lower Old Red Sandstone (Lanark Group)

Overlying the variably deformed LlandoveryWenlock inliers are the ?Pridoli-Lower Devonian strata of the Lanark Group which forms part of the Lower Old Red Sandstone sequence of the Midland Valley (**Figures 1** and **2**). The clastic sequence was deposited in the NE-SW-trending Lanark Basin by both axial and transverse drainage systems which supplied sediment from essentially the same source area. At the base of the Lanark Group is the laterally extensive **Greywacke Conglomerate Formation** (**Figures 2** and **4**).

Figure 4. Tinto Hill from immediately SW of the Southern Upland Fault. The Tinto Rhyolite (Devonian) is intruded into the Greywacke Conglomerate Formation; the March Wood Formation of the Eastfield Inlier forms the sloping ground at the foot of Tinto Hill.

The Greywacke Conglomerate Formation thins and fines towards the NW and was deposited in alluvial fans interbedded with sandstones which preserve palaeocurrent indicators of a source region to the SE (Bluck 1983). In the Hagshaw Hills area mean palaeoflow indicate that the formation was mainly derived from the E, with only a minor component being derived from the S (Syba 1989). 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 Greywacke Conglomerate Formation passes upwards into predominantly red bed, high energy fluviatile sandstones of the overlying **Swanshaw Formation** (**Figure 2**). The Swanshaw Formation records an overall upward-fining sequence with a renewed input of coarse conglomerate towards the top of the formation; possibly the result of local uplift prior to the subsequent volcanic episode. The sandstones contain a mixed detrital assemblage of andesitic to felsic rock fragments, quartz and feldspar (**Figure 3d**). Other rock fragments present include 'greywacke' metasandstone, silicified red sandstone, chert, and silty mudstone, as well as rare higher grade, foliated metasedimentary rock fragments (psammite and quartzite).

The stratigraphically overlying **Duneaton, Biggar and Pentland Hills volcanic formations** (**Figure 2**) consist of a suite of calc-alkaline, basaltic to andesitic lavas (subaerial) with minor intercalated tuffs and volcaniclastic sandstones and breccias (Smith 1995; Phillips *et al.* 1998). These Lower Devonian (410-415 Ma, Rb-Sr whole rock-mineral ages; Thirlwall 1988) lavas have geochemical characteristics comparable to basalts erupted in a volcanic island-arc setting (Thirlwall 1981, 1983) and possess a strong 'within plate' continental component (Phillips et al. 1998). The interbedded sedimentary rocks are poorly sorted and poorly bedded. They contain a restricted, clast assemblage dominated by angular, locally derived basaltic and andesitic volcanic rock fragments (with minor feldspar, pyroxene and hornblende crystal fragments).

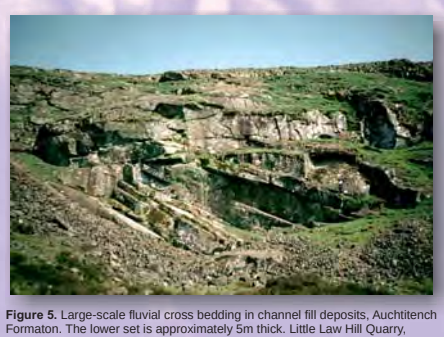

Figure 5. Large-scale fluvial cross bedding in channel fill deposits, Auchtitench Formaton. The lower set is approximately 5m thick. Little Law Hill Quarry, Roberton, Lanark district

The succeeding **Auchtitench Formation** (**Figure 2**) is dominated by a sequence of fine- to coarse-grained, lithic-rich sandstones. At the base of the formation, highly weathered sandstones and siltstones contain carbonate nodules/clasts and are interpreted as having formed as patchily developed soils or salinas on the irregular surface of the volcanic terrain. The overlying fluviatile sandstone succession is typically less altered/weathered and contains intercalated pebbly sandstones and 4 to 5 m thick conglomeratic units. Sandstone dominated channel-fill deposits, large-scale crossed bedded units (**Figure 5**) and small-scale fining- as well as coarsening-upward sequences have been recognised. The locally volcaniclastic sandstones are composed of angular to subangular clasts of andesitic to dacitic volcanic rock fragments, monocrystalline quartz and plagioclase (**Figure 3e**). Minor to accessory detrital components include K-feldspar, opaque minerals, tourmaline, garnet, white mica, chlorite, amphibole and epidote. The coarse pebble conglomerates are composed almost exclusively of Lower Devonian-type andesite/dacite volcanic rock and breccia clasts. These southerly derived conglomerates form thick coarsening upward sequences, with the presence of large (up to > 1 m in length) boulders and high degree of rounding of clasts being indicative of transport and deposition within a large river system (Bluck 1983).

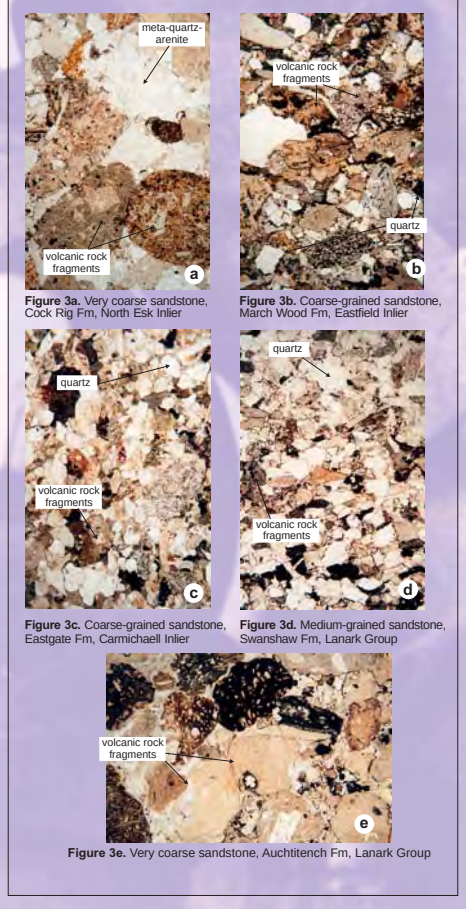

Figure 3a. Very coarse sandstone, Cock Rig Fm, North Esk Inlier

Figure 3b. Coarse-grained sandstone, March Wood Fm, Eastfield Inlier

Figure 3c. Coarse-grained sandstone, Eastgate Fm, Carmichaell Inlier

Figure 3d. Medium-grained sandstone, Swanshaw Fm, Lanark Group

Figure 3e. Very coarse sandstone, Auchtitench Fm, Lanark Group

Figure 3. Thin section photomicrographs

In the Girvan and Pentland Hills areas there is a marked angular unconformity between this conglomeratic formation and underlying Silurian strata. However, in the Hagshaw Hills, Lesmahagow, Carmichael and Eastfield inliers (**Figure 1**) the Greywacke Conglomerate Formation records a marked change in sedimentary facies and rest conformably upon the Silurian rocks with a irregular erosional contact at its base.

The Greywacke Conglomerate Formation comprises a sequence of conglomeratic units interbedded with thin medium- to coarse-grained sandstones. The typically lithic-rich sandstones are mainly composed andesitic to dacitic volcanic rock fragments with subordinate monocrystalline quartz and plagioclase. Minor trachyte, granite, felsite, psammite, quartzite, phyllite, schistose metasedimentary rock fragments are also present. Minor to accessory detrital components include muscovite, variably hematised biotite, epidote, K-feldspar, opaque minerals and garnet. The conglomerates are characterised by the presence of pebble to boulder sized clasts of 'greywacke' sandstone, but also contain subordinate chert, quartzite and fine-grained volcanic rock fragments.

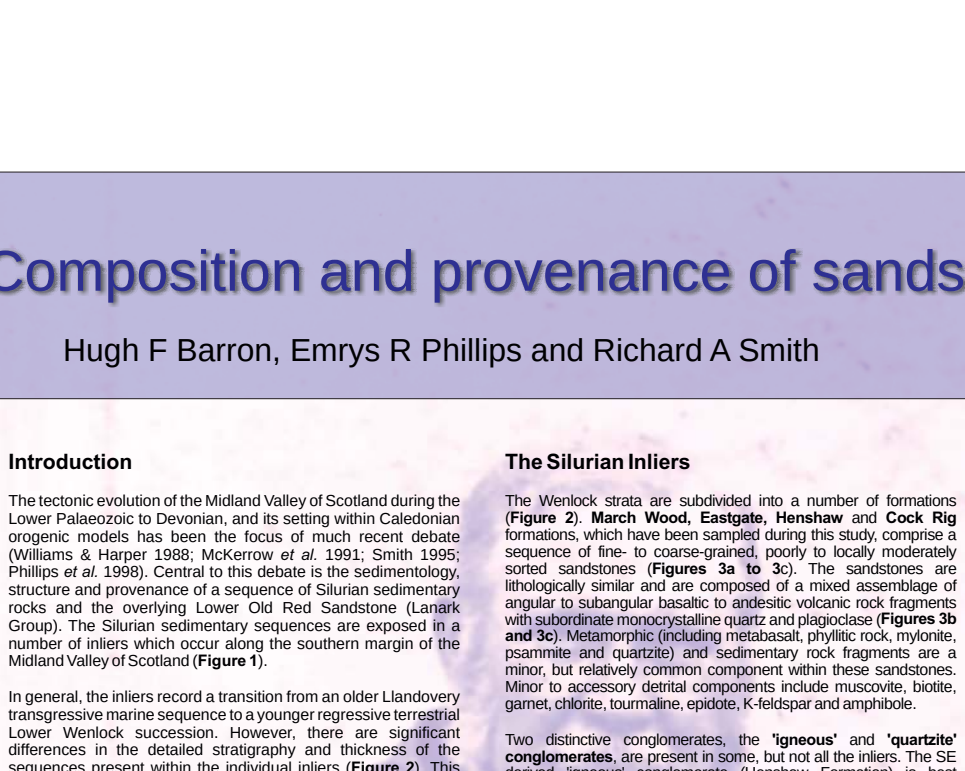

Figure 1. Simplified geological map of the Lanark Basin of the south Midland Valley showing the distribution of the Silurian inliers and the Siluro-Devonian Lanark Group. **Study Areas**: 1 - New Cumnock; 2 - Lanark; 3 - Pentland Hills. **Silurian inliers**: A, Craighead; B, Girvan Main; C, Lesmahagow; D, Hagshaw Hills; E, Carmichael; F, Eastfield; G, Pentland Hills. **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; CGF, Crossgatehall Fault.

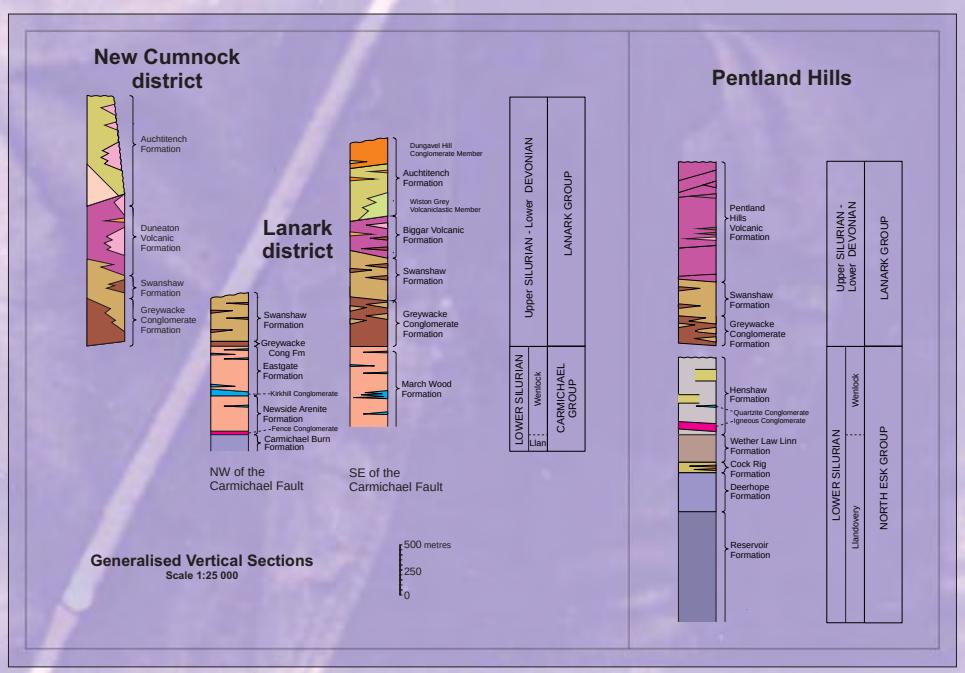

Figure 2. Generalised vertical sections of the Silurian inliers and Lanark Group from the New Cumock, Lanark and Pentland Hills areas.

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Background and left: Dr John Horne and Dr Benjamin Neeve Peach outside the Inchnadamph Hotel, Assynt, British Association Meeting, September 1912
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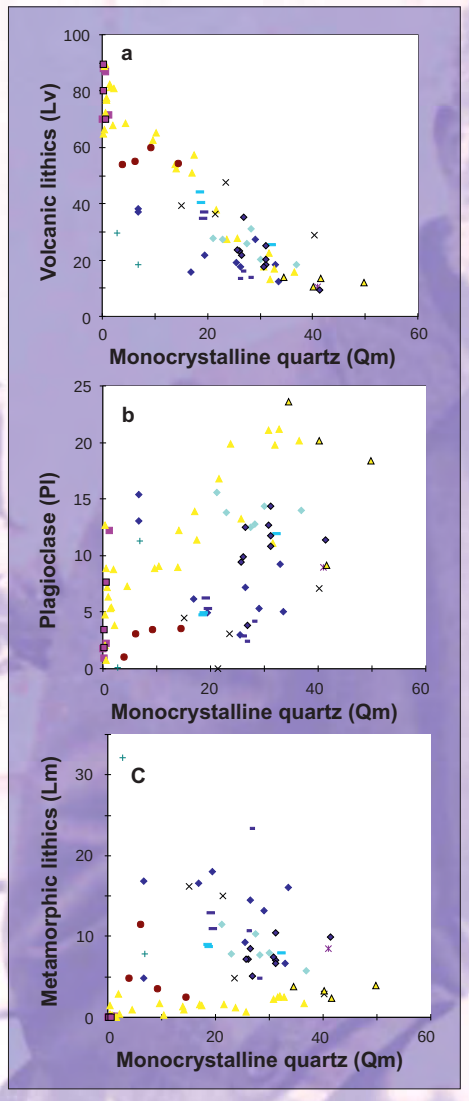
from the Silurian inliers and the Lanark Group, Midland Valley



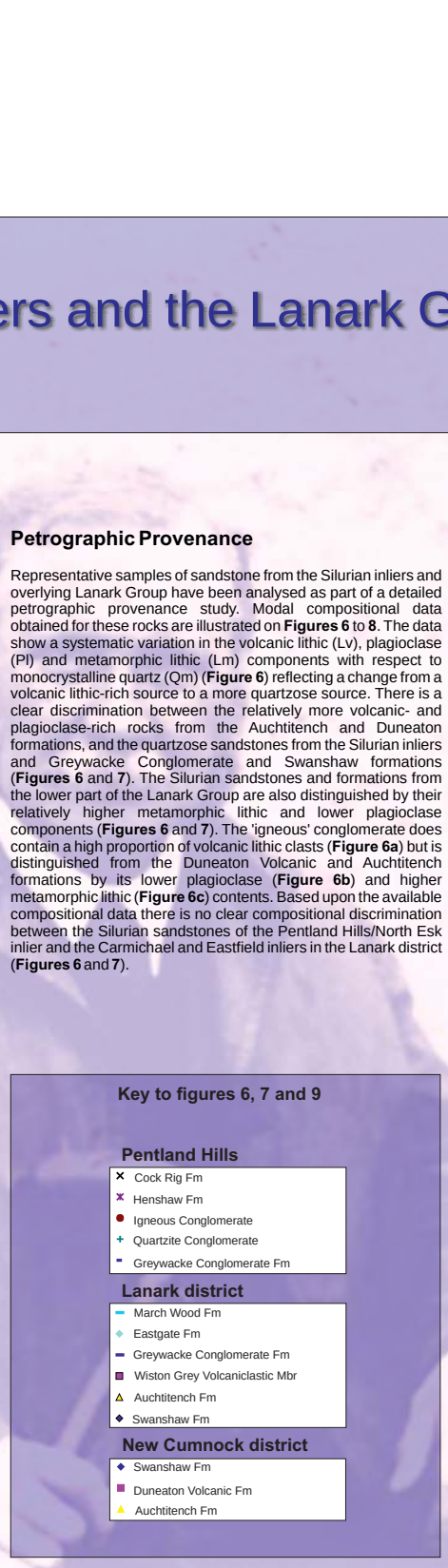


Figure 6. Variation in a) volcanic lithics, b) plagioclase and c) metamorphic lithics with respect to monocrystalline quartz within Silurian and Lanark Group sandstones

Petrographic Provenance

Representative samples of sandstone from the Silurian inliers and overlying Lanark Group have been analysed as part of a detailed petrographic provenance study. Modal compositional data obtained for these rocks are illustrated on **Figures 6** to **8**. The data show a systematic variation in the volcanic lithic (Lv), plagioclase (Pl) and metamorphic lithic (Lm) components with respect to monocrystalline quartz (Qm) (**Figure 6**) reflecting a change from a volcanic lithic-rich source to a more quartzose source. There is a clear discrimination between the relatively more volcanic- and plagioclase-rich rocks from the Auchtitench and Duneaton formations, and the quartzose sandstones from the Silurian inliers and Greywacke Conglomerate and Swanshaw formations (**Figures 6** and **7**). The Silurian sandstones and formations from the lower part of the Lanark Group are also distinguished by their relatively higher metamorphic lithic and lower plagioclase components (**Figures 6** and **7**). The 'igneous' conglomerate does contain a high proportion of volcanic lithic clasts (**Figure 6a**) but is distinguished from the Duneaton Volcanic and Auchtitench formations by its lower plagioclase (**Figure 6b**) and higher metamorphic lithic (**Figure 6c**) contents. Based upon the available compositional data there is no clear compositional discrimination between the Silurian sandstones of the Pentland Hills/North Esk inlier and the Carmichael and Eastfield inliers in the Lanark district (**Figures 6** and **7**).

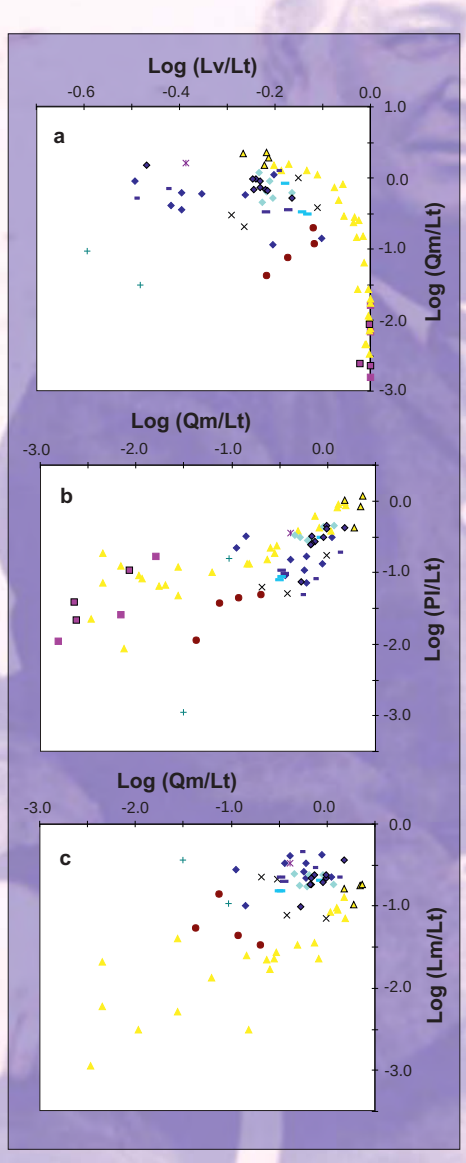


Figure 7. Log-ratio plots of sandstone compositional data from the Silurian inliers and Lanark Group

Lithostratigraphic variations in the main detrital components clearly indicate that a major change in sandstone composition occurs at the base of the Duneaton Volcanic Formation or Auchtitench Formation where this volcanic horizon is absent (**Figure 8**). Importantly, sandstones from the lower part of the Lanark Group are compositionally similar to the underlying Silurian sedimentary rocks (**Figures 6** to **8**). This relationship shows that there is no major break in sandstone composition at the base of the Lower Old Red Sandstone and suggests that the Silurian sandstones and the lower part of the Lanark Group were derived from the same source area. The quartz, feldspar and lithic contents of these sandstones suggest that they were largely derived from a recycled orogenic source (**Figure 9**). In contrast, sandstones from the Duneaton and Auchtitench formations have compositions comparable to sandstones derived from volcanic source area (**Figure 9**). The approximately linear change from undissected to dissected reflects the variation in the degree of erosion in the source area resulting in an decrease in the volcanic lithic component and increase in detrital feldspar and quartz.

Discussion

The results of this petrographic provenance study clearly indicate that the sandstones exposed within the various Silurian inliers are compositionally similar and were probably derived from the same recycled orogenic source. Palaeobasin analysis (Bluck 1983, 1984) and provenance studies (this study; Heinz & Loeschke 1988) have shown that the Southern Upland Terrane which presently lies to the SE is not the source. The recycled orogenic source area to the Midland Valley Silurian sedimentary sequences was composed of an older (?Cambro-Ordovician) andesitic to dacitic volcanic terrane, quartzose metamorphic rocks and granitic plutonic rocks as well as possibly penecontemporaneous sedimentary rocks. There is no clear evidence to suggest that the Grampian Terrane was the source of the metamorphic detritus which argues for a barrier within the Midland Valley preventing such detritus entering the Silurian/Lanark basin. Available palaeocurrent data indicates that this older volcanic/metamorphic terrane was located to the SE of the Midland Valley at least during Wenlock times (*cf.* Williams & Harper 1988).

The absence of any major compositional break at the base of the overlying Lower Old Red Sandstone Lanark Group can be used to suggest that this source area continued to supply detritus into the developing NE-SW-trending Lanark basin. 'Greywacke' sandstone clasts within the southerly to easterly derived Greywacke Conglomerate Formation were initially thought to be derived from the Silurian strata of the Southern Uplands (see Bluck 1983, 1984). However, Syba (1989) demonstrated that these greywacke sandstones are compositionally distinct from those of the Southern Uplands. She concluded that they may have been derived from horst blocks of flysch within the Midland Valley Terrane which have since been removed by strike-slip or covered by younger strata. An alternative hypothesis is that these 'greywacke' sandstones record the presence of sedimentary basins developed upon the volcanic/metamorphic source area to the Midland Valley Silurian sedimentary sequences. These basins may have been inverted/uplifted during late Wenlock regional sinistral strike-slip (Phillips *et al.* 1998) resulting in a sudden influx of 'greywacke' sandstone detritus into, and localised deformation of the Midland Valley Silurian sub-basins.

The major change in sandstone composition and provenance occurs well within the Lower Old Red Sandstone sequence at the base of the Duneaton Volcanic Formation. Onset of this volcanic episode was preceded by uplift and the renewed influx of 'greywacke' conglomerate near the top of the Swanshaw Formation. The rapid development of volcanic pile and the lack of extra-basinal clasts indicate that volcanism dramatically changed the drainage pattern and cut off the older volcanic/metamorphic source terrane. The volcaniclastic sandstones of the Duneaton Volcanic and Auchtitench formations were clearly derived from the Devonian volcanic rocks which were undergoing penecontemporaneous uplift and erosion. The approximately linear increase in the quartz and feldspar components within the sandstones of the Auchtitench Formation may simply reflect an increase in the maturity of the sediment. Alternatively, the increase in the stable quartzose/metamorphic components may record the recycling of older, relatively quartz-rich sandstones, e.g. from the Swanshaw Formation, exposed due to faulting in the volcanic hinterland.

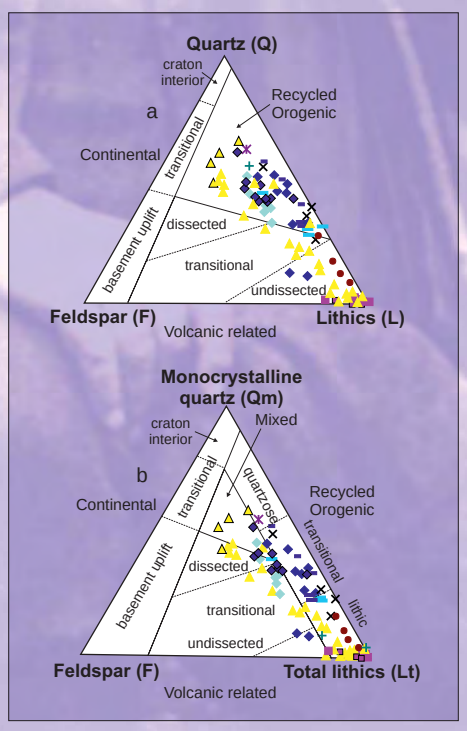


Figure 9. Discrimination diagrams for determining the provenance of sandstones

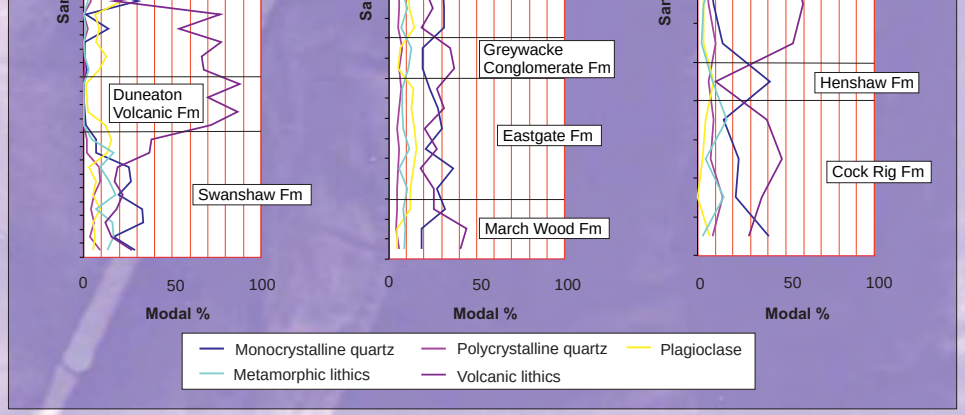


Figure 8. Lithostratigraphical variation in sandstone composition from the New Cumnock, Lanark and Pentland Hills areas

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