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An historical and petrological assessment of Pitairlie Quarry, Angus

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OPEN REPORT OR/11/009

An historical and petrological assessment of Pitairlie Quarry, Angus

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Summary

Pitairlie Quarry, near Monikie in Angus, Scotland probably began operating in the mid 19th century, exploiting layers of sandstone and siltstone within the Dundee Flagstone Formation (part of the Old Red Sandstone Supergroup). The flaggy stone lends itself to paving, and much of the product was probably used for this purpose. Many other quarries in the local area, including the relatively well known and much bigger Carmyllie Quarry, have exploited the same geological formation to supply significant volumes of building stone in the past.

Pitairlie Quarry ceased operations in 1915 but has been recently re-opened by the Denfind Stone company. Operations at the quarry currently consist of stone recycling from spoil heaps, but the owners intend to submit a planning application to extract reserves of *in-situ* stone. This report describes the historical development of quarrying at Pitairlie and presents a petrological assessment of the stone, to inform the planning application.

Stone from the Dundee Flagstone Formation, in particular from Carmyllie Quarry, has been important historically for building and paving, both in the local area and further afield. Pitairlie stone shares many of the petrological characteristics of Carmyllie stone (though they can both vary somewhat in colour), and should in many cases provide a good substitute for Carmyllie stone where repairs are required.

Contents

1 Introduction

The British Geological Survey (BGS) has been commissioned by the Scottish Stone Liaison Group (SSLG) to investigate the building stone resource at Pitairlie Quarry. The purpose of this report is to document new and existing technical and historical information for Pitairlie stone to inform a planning application to extract new reserves of stone from the quarry.

The quarry is located at grid reference [NO 500373], just outside the village of Monikie and approximately 7 miles northeast of Dundee, in the Angus district of Scotland (Figure 1). Running east to west, the Downie Hills divide the local area into several districts. Pitairlie Quarry is located on the east side of Denfind, a winding ravine that deeply bisects the range.

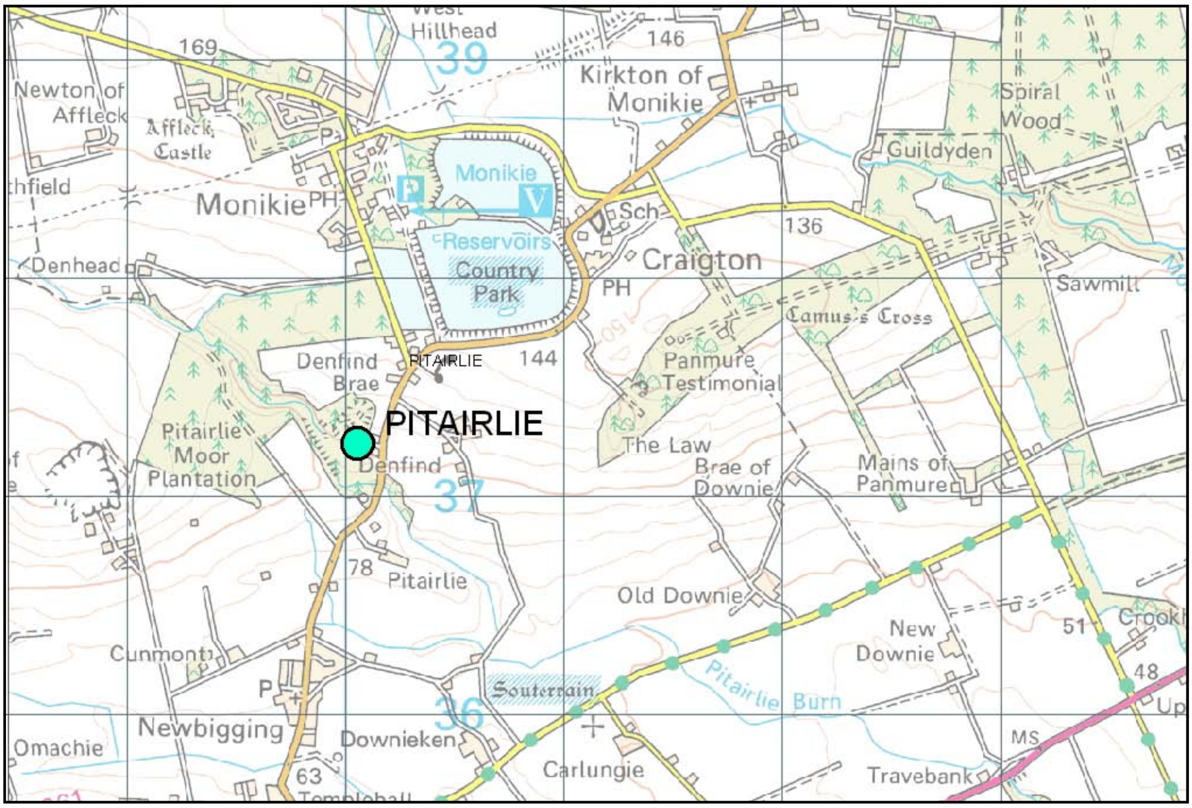


Figure 1. Current Ordnance Survey 1:50,000 scale map showing the location of Pitairlie Quarry. Grid lines are 1 kilometre apart.

The newly re-opened quarry is currently supplying material from disused spoil heaps for dry stane dyking, but reserves of *in situ* material are suitable for extraction. Exposures at the quarry display bluish grey sandstone and siltstone that locally have a well bedded, flaggy character (Figure 2).

The documented history of stone production at Pitairlie Quarry is described in Section 2. The geological setting of the quarry is described briefly in Section 3, and a petrographic assessment of samples of Pitairlie stone is presented in Section 4. In Section 5, Pitairlie stone is compared with several other stones currently used for paving in the UK, and with the historically important Carmyllie stone from the nearby Carmyllie Quarry. The results of a Compressive Strength test on two samples of Pitairlie stone are presented in Appendix 1, and a petrographic analysis of a sample of Carmyllie stone is presented in Appendix 2. Several examples of recent built-heritage conservation projects in which Pitairlie stone has been used are described in Appendix 3.

Figure 2. Exposed bedrock in Pitairlie Quarry (January 2009), illustrating the reserves of bluish grey stone. The flaggy character of the stone (i.e. a propensity to split along bedding, yielding tabular blocks) is clearly visible.

2 Historical development of Pitairlie Quarry

The historical development of operations at Pitairlie Quarry has been assessed through an examination of archival records and historical maps.

The Statistical Accounts for Scotland (1791-9) described a “a most valuable bed of pavement” (i.e. fissile stone) which begins at Leysmill Quarry on the estate of Kinblethmont, and extends south through ground holding the Carmyllie, Smithfield, Wellbank, and Duntrune quarries (Figure 3 Pitairlie Quarry lies in the same tract of land and exploits the same geological formation (see Section 3 *Geological setting of Pitairlie Quarry*).

This group of quarries is further described in David Bremnar’s *The Industries of Scotland: Their Rise, Progress, and Present Condition* (1869). There, the quarries are referred to as the Forfarshire pavement quarries - Forfarshire being an old county, which disappeared following the Local Government (Scotland) Act of 1974. The area extended from Leysmill (east) to Glamis Castle (west) and from Montreathmont Moor (north) to the Sidlaw Hills (south), all situated in the southern region of the former county. The ‘pavement’ stone produced in this region was commercially known as ‘Arbroath Pavement’. Bremnar described the material as “solid in composition, durable, and easily worked and dressed.” It was used not only for paving, but also for interior works.

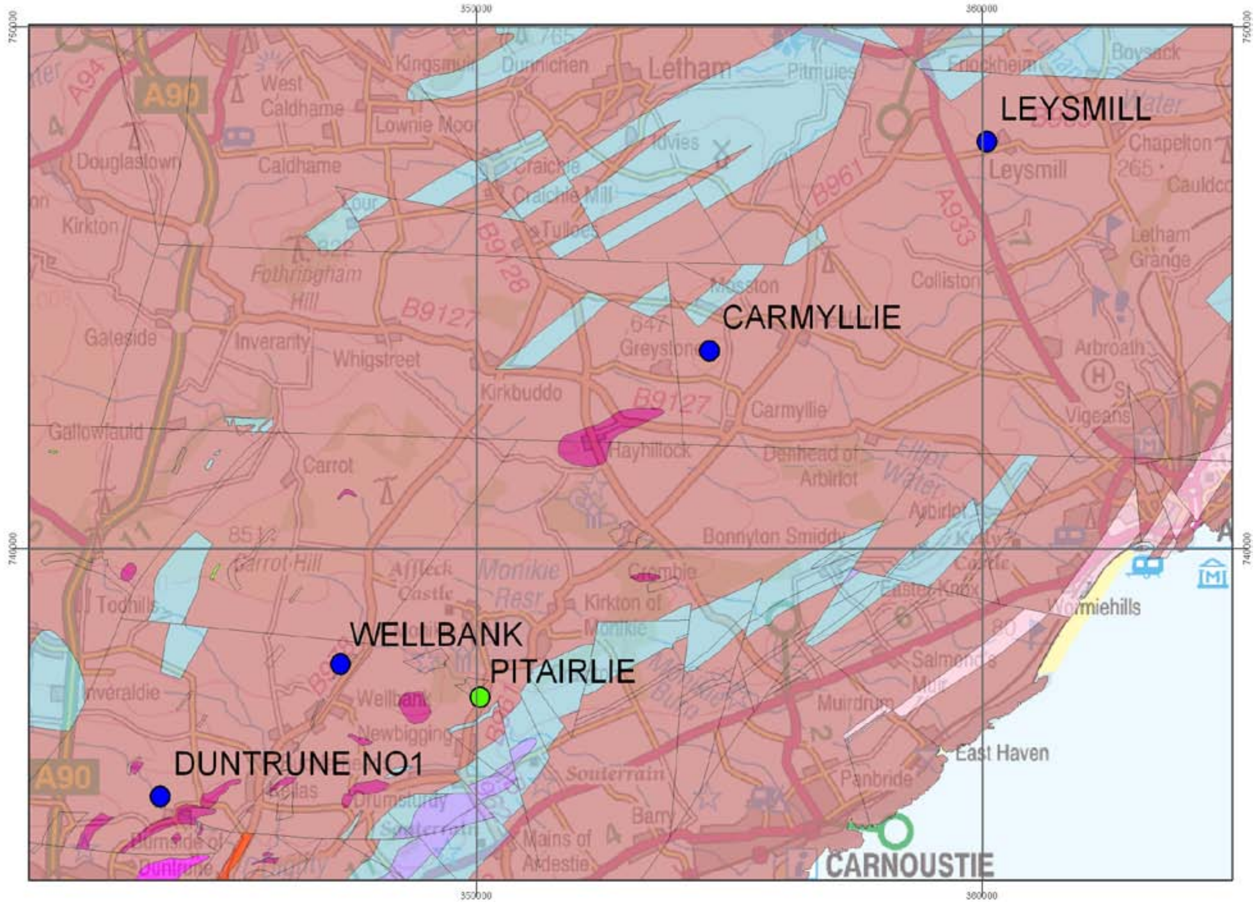


Figure 3. Location of some of the Forfarshire pavement quarries from which building stone known commercially during the 19th and 20th centuries as "Arbroath Pavement" was extracted. See Figure 9 for a key to the geological base.

During the mid-19th century, the operations at Pitairlie Quarry employed fifty men (Bremnar). Operations continued into the 20th century. The following series of historical maps illustrates this period of development.

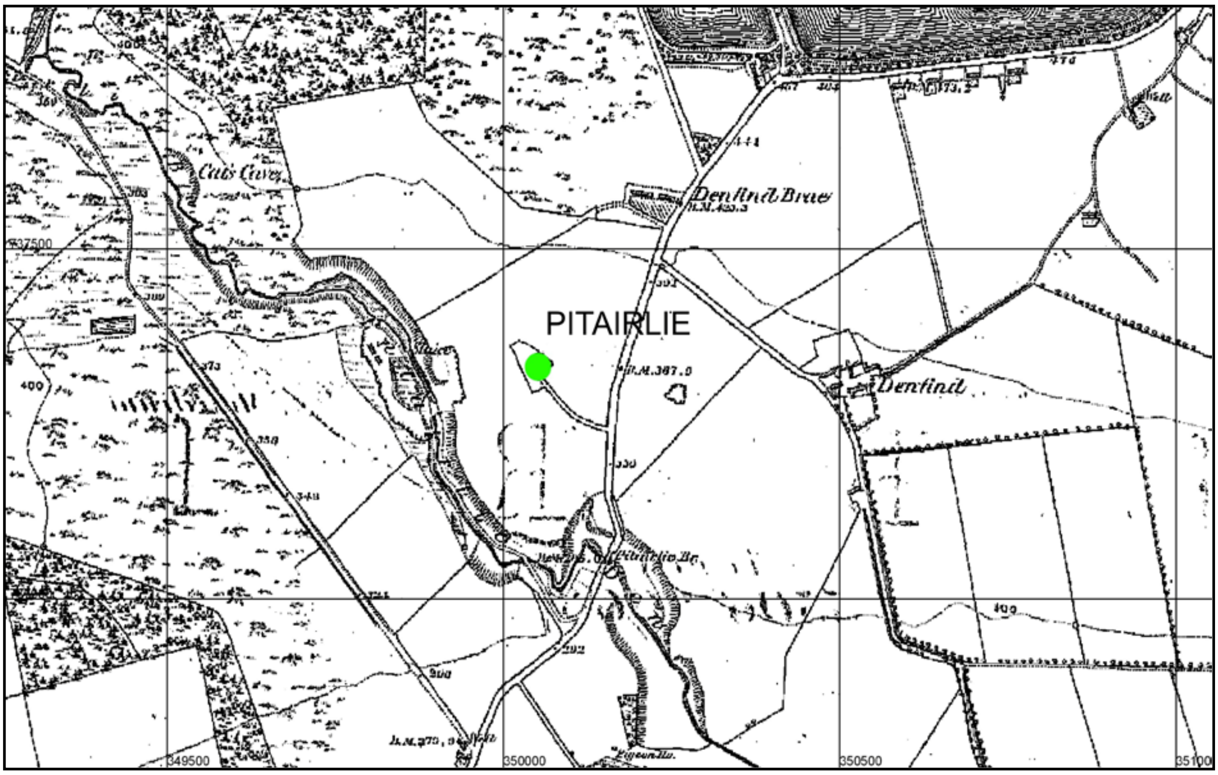


Figure 4. 1865 Ordnance Survey map. Pitairlie Quarry is fairly small at this time and unmarked.

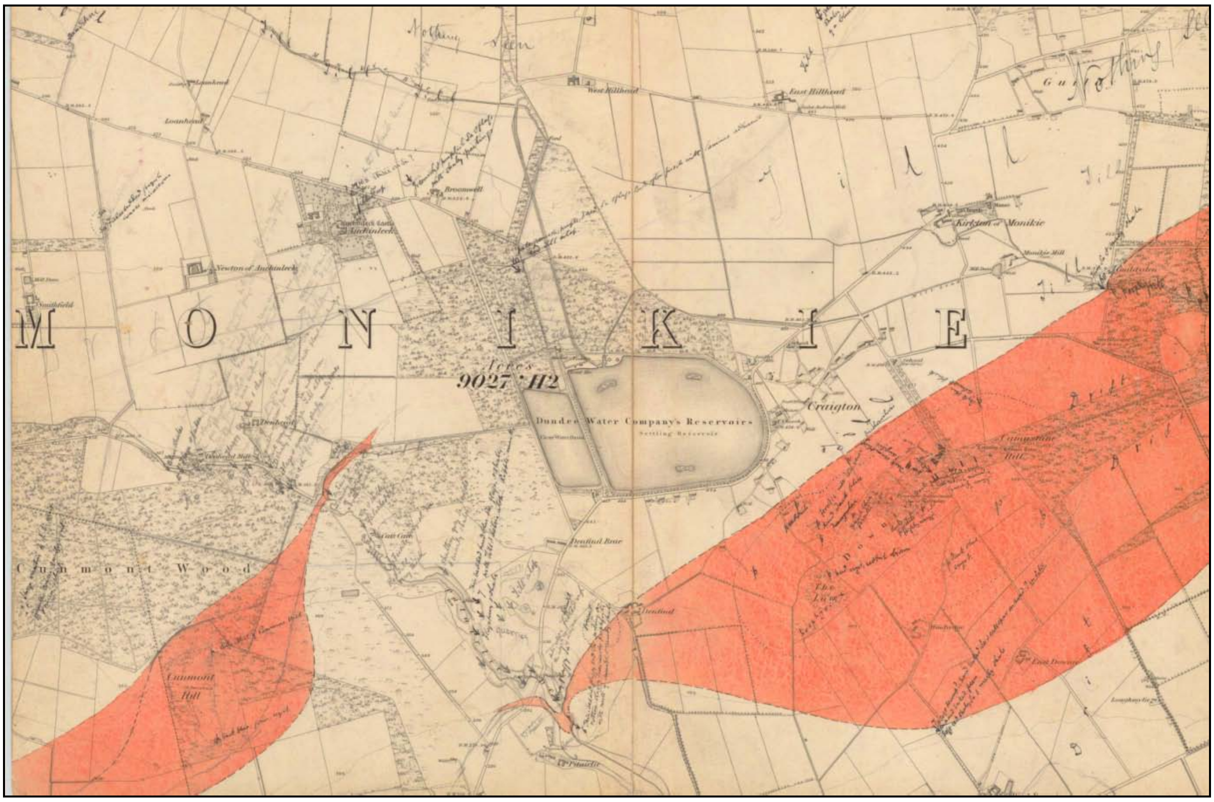


Figure 5. Hand-annotated geological field slip based on the 1865 Ordnance Survey map. This field slip describes the site of Pitairlie Quarry as consisting of "thin bedded hard blue sandstone flags and shale with till and debris atop. Ripple marks."

The greatest activity surrounding the quarry occurs between the 1865 and the 1892 (Forfarshire) Ordnance Survey maps. On the 1892 map (no image available) the quarry site located on the 1865 map is now labelled 'quarry'; however, three additional 'quarry' locations have also been identified, all along Pitairlie Den. It wasn't until the 1903 Ordnance Survey map (Figure 6) that the entire site was marked as Pitairlie Quarry.

Pitairlie Quarry ceased operations in 1915 (Illsley, 1977; p461), but Forfarshire Government returns from 1910 still identify quarrying as a significant industry in the historic parish. At this time Scotland had a total output of sandstone of 743,189 tons. The following table highlights the number of people employed in the industry at this time in the chief counties, the production in tons, and the value of the material (details from Valentine, 1912; p70).

County	Persons Employed	Output (tons)	Value (£)
Dumfries	595	102,497	44,953
Lanark	998	97,766	30,967
Fife	1063	255,078	30,027
Forfar	518	52,875	23,100

The output of Forfarshire quarries is comparatively low, however the value per ton is relatively high. From this information, Valentine (1912; p70) concluded that "Forfarshire building stone and paving stone have long enjoyed a high reputation throughout the country … many important edifices public and private in Edinburgh, Glasgow, Dundee, and other towns have been built of stone obtained from Carmyllie, Leoch, Pitairlie, Duntrune, Wellbank, Westhall, and other Forfarshire quarries."

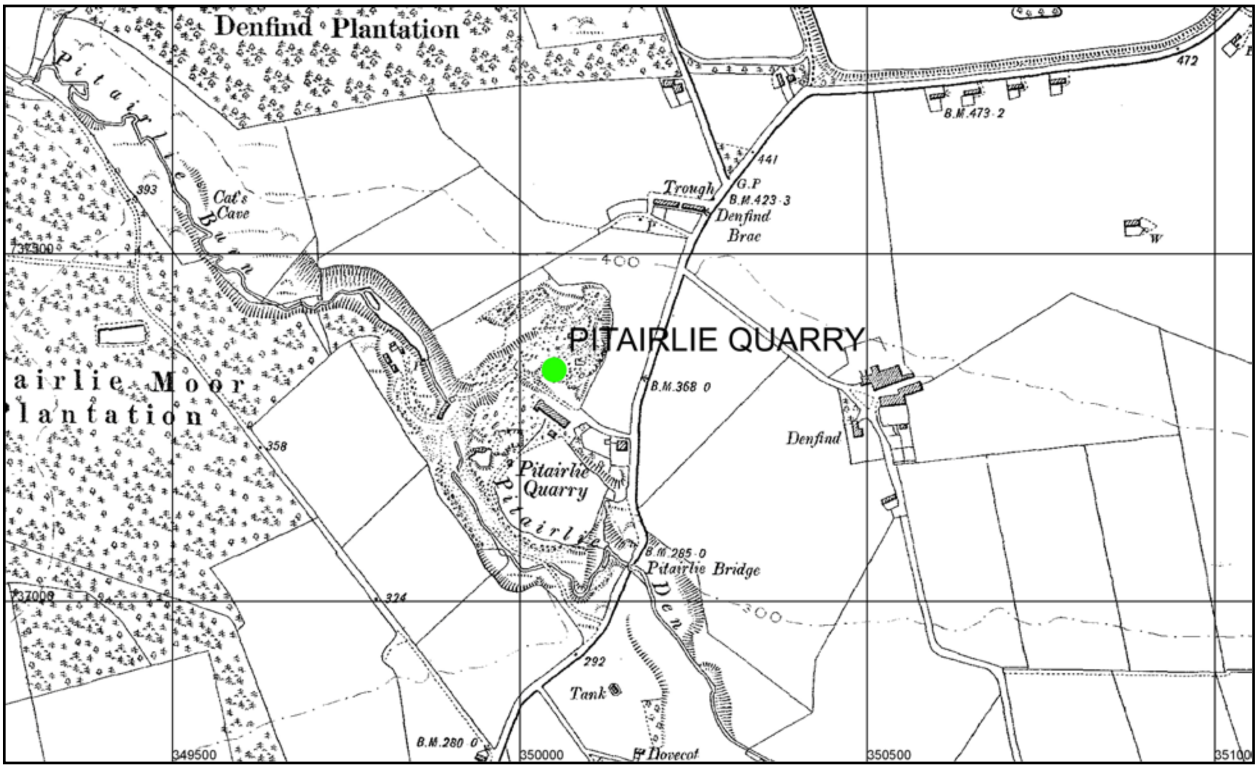


Figure 6. 1903 Ordnance Survey map. Pitairlie Quarry has expanded to occupy a large area of the Denfind ravine, known as Pitairlie Den. The late 19th century was the era of greatest expansion for the quarry site.

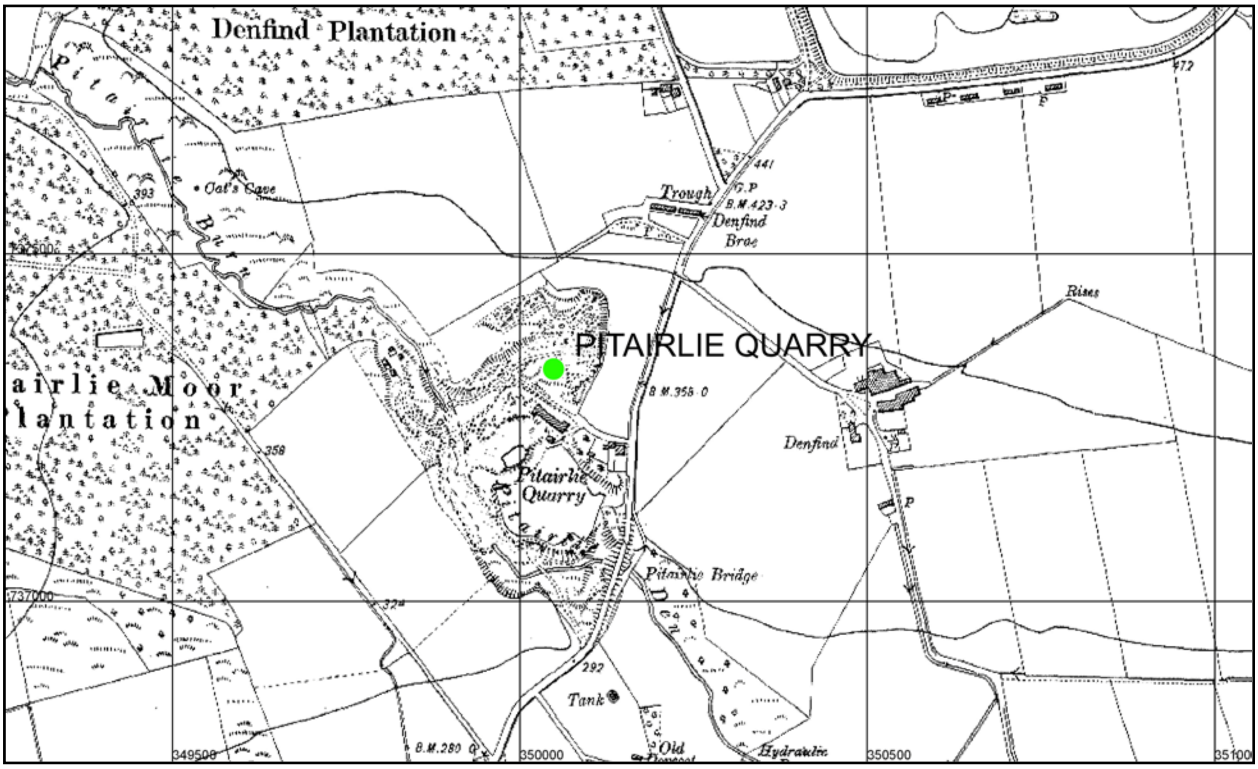


Figure 7. 1923 Ordnance Survey map. Pitairlie Quarry shows little or no expansion from the 1903 map. The quarry had ceased operating in 1915.

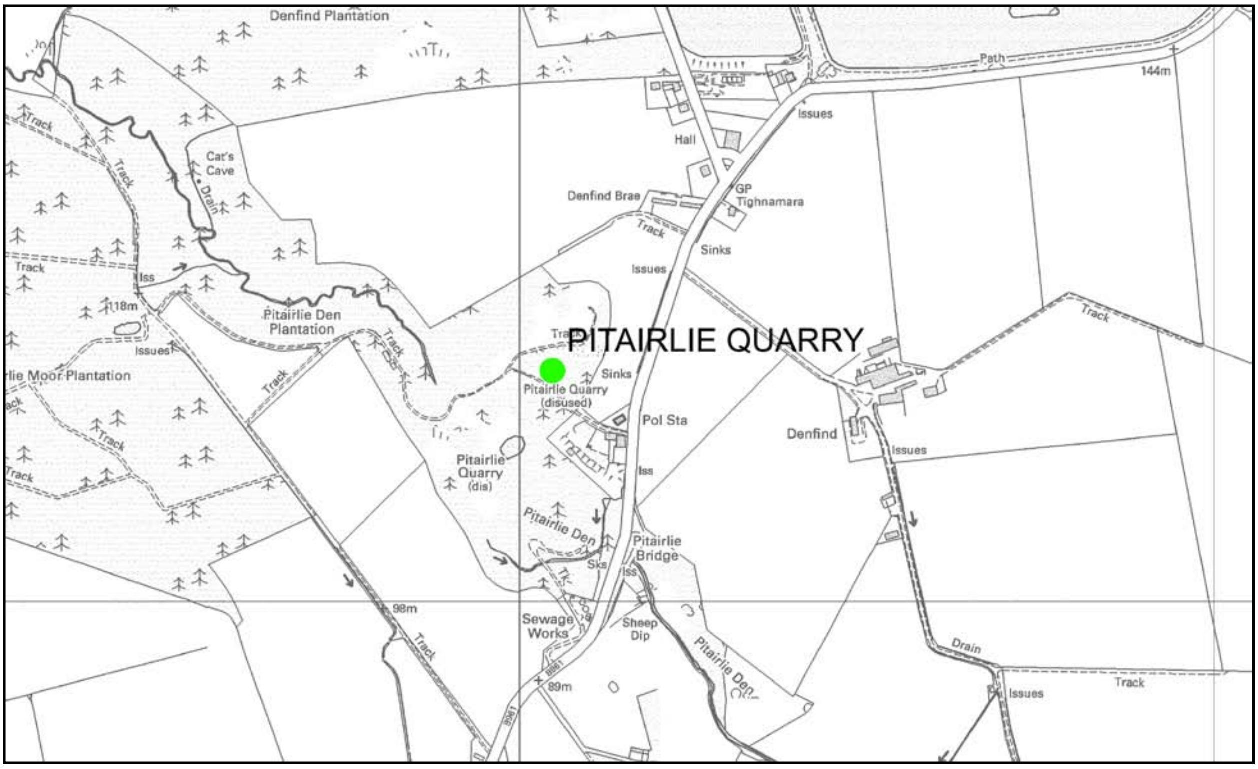


Figure 8 Present day 1:25,000 scale Ordnance Survey map with two sites labelled ‘Pitairlie Quarry (disused)’.

No record has been found of any named buildings or structures that were constructed using building stone extracted from Pitairlie Quarry. However, information of this sort does exist for the nearby Carmyllie Quarry, which supplied similar stone in significant volumes to the local area as well as further afield. According to Bremnar (1849), Carmyllie Quarry first supplied stone for use as roofing slate. At first, the slates were carted in great quantities to Dundee and neighbouring areas. The slates were also shipped to Leith and brought into Edinburgh. It was not until the beginning of the 19th century that Carmyllie Quarry began to produce paving stone. Bremnar listed the following additional uses for Carmyllie stone: steps, copes; cisterns for paper-makers, chemical works, and bleach-fields; and columns, balustrades, and other architectural ornaments. The stone was widely exported across the United Kingdom, to many countries in Europe, to the United States, and to Australia and other colonies (that existed at the time of the book's publication in 1849). It was noted that many towns across Scotland were paved with Carmyllie stone, but the towns were not named; however, the following buildings were noted as having Carmyllie stone paving: the new University of Glasgow; the New College, Edinburgh; the Bank of Scotland, Edinburgh; all principal buildings in Aberdeen; and Perth railway station (Bremnar, 1849; p416-420).

The lack of historical records precludes any firm conclusions regarding the degree to which Pitairlie stone was exported and used at this time. However, as it is likely that Pitairlie and Carmyllie quarries were in operation more-or-less simultaneously during the latter part of the 19th century, and exploited the same geological formation, it seems reasonable to assume that Pitairlie stone may have been transported widely and put to a similar range of uses as Carmyllie stone.

3 Geological setting of Pitairlie Quarry

The geology of the southern part of Angus (south of the Highland Boundary Fault) is dominated by sedimentary rocks of the Old Red Sandstone Supergroup, which are of Early Devonian age (416-397 million years old). They consist mainly of sandstones and conglomerates, with some siltstones. The Old Red Sandstone has been quarried in numerous places throughout Angus, mostly as small quarries providing building stone to the local area.

The geology of the area around Pitairlie Quarry is dominated by the Dundee Flagstone Formation, a stratigraphic unit within the Old Red Sandstone Supergroup. The Dundee Flagstone Formation consists of cross-bedded sandstones and flaggy sandstones interbedded with minor siltstones and mudstones. These sedimentary rocks are interdigitated with lava flows (i.e. igneous rocks) of the Ochil Volcanic Formation.

'Carmyllie type' flagstones (i.e. 'Arbroath Pavement") were extracted from the Dundee Flagstone Formation at Pitairlie Quarry, Carmyllie Quarry and a cluster of other historically active quarries in the area (Figure 9). There are no currently active quarries extracting building stone from this geological formation.

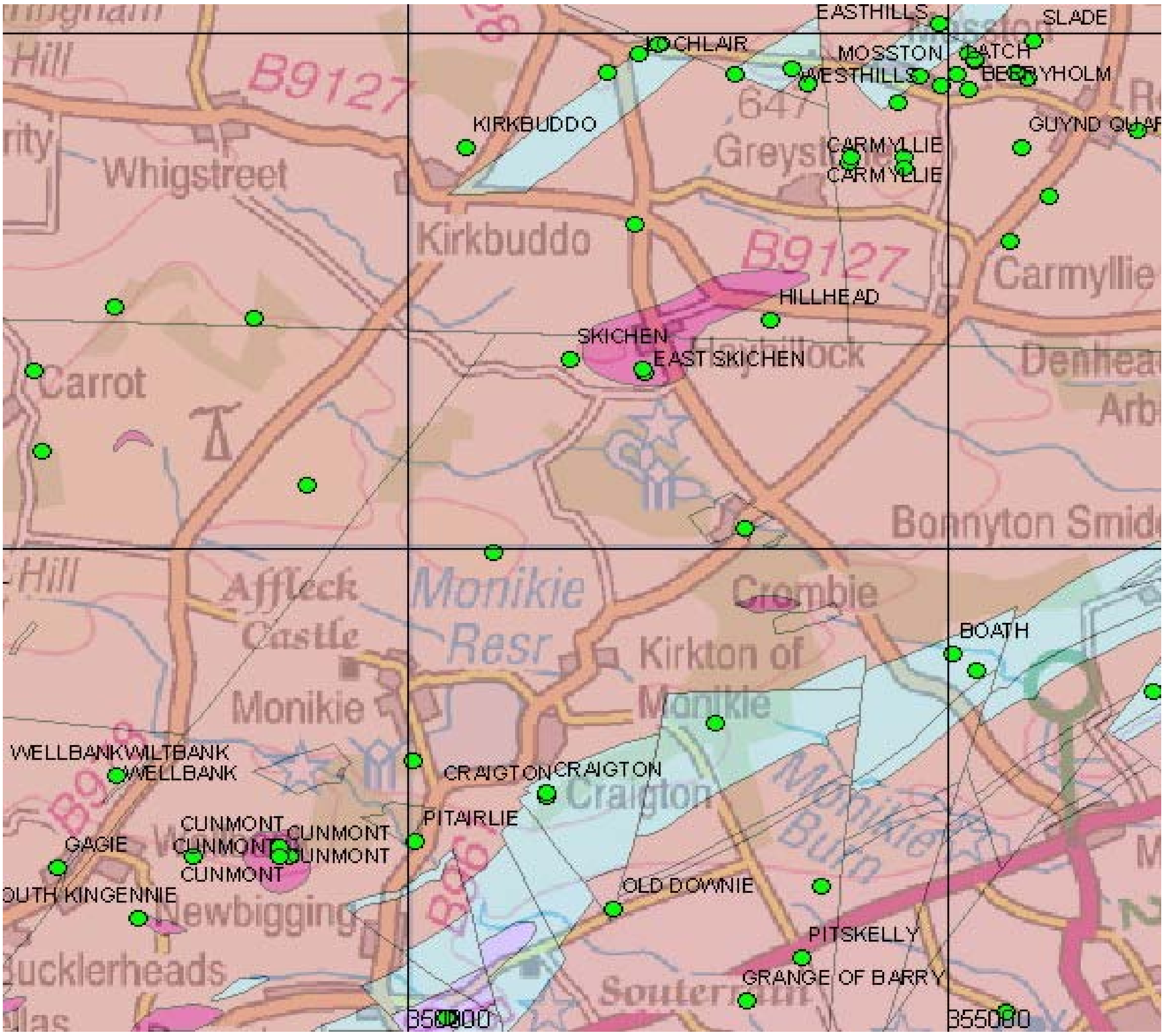


Figure 9 Geological map showing the location of Pitairlie Quarry and other nearby quarries. Bedrock units at outcrop (from the BGS digital geological map of Great Britain [DiGMapGB50]) are colour-coded as follows: pink - Dundee Flagstone Formation; blue - Ochil Volcanic Formation (lavas); bright pink - intrusions of microdiorite (Devonian). Green dots and associated names are quarries (from the BGS database of historical and currently active UK quarries).

4 Description of Pitairlie stone samples

4.1 INTRODUCTION

Three samples of stone from Pitairlie Quarry were collected during a visit to the site in January 2009. A thin section (a slice of the stone cut thin enough to be transparent, so it can be analysed using a petrological microscope) was prepared from each sample. A petrographic analysis has been performed on these and two other thin sections of stone from Pitairlie Quarry already held within the BGS Building Stone Archive, which contains stone samples from current and historic quarries.

Sample details are summarised in the table below. The exposed bedrock in the quarry is approximately 80% sandstone and 20% siltstone. The five samples are broadly representative of the exposed lithologies; samples MC11362, MC11363, MC8685 and MC8686 are classified as fine-sand-grade sandstone and MC11361 as siltstone. The samples have been classified according to the BGS Rock Classification Scheme (Hallsworth & Knox, 1999).

BGS sample number	Stone type	Sample media	Source
MC11361	Siltstone	Hand specimen, thin section	Collected from Pitairlie Quarry during site visit.
MC11362	Sandstone (fine-sand-grade lithic-arenite)	Hand specimen, thin section	Collected from Pitairlie Quarry during site visit.
MC11363	Sandstone (fine-sand-grade lithic-arenite)	Hand specimen, thin section	Collected from Pitairlie Quarry during site visit.
MC8685	Sandstone (fine-sand-grade lithic-arenite)	Thin section	Thin section from BGS collection
MC8686	Sandstone (fine-sand-grade lithic-arenite)	Thin section	Thin section from BGS collection

Four of the five samples (MC11362, MC11363, MC8685 and MC8686) are essentially similar and are described together; a separate description is provided for MC11361.

A Compressive Strength test has been performed on MC11362 and MC11363. The methodology and results are described in Appendix 1, and the significance of the results is discussed in Section 5.

4.2 METHODOLOGY

The petrographic descriptions are based on macroscopic and microscopic examination of the samples. For each sample, a macroscopic examination was performed with the unaided eye and by binocular microscope. A precise colour description was obtained by comparing the sample surface with a standard Munsell® Rock Colour Chart. A microscopic examination was performed on a thin section using a polarizing microscope and following the procedures set out in British Standard BS EN 12407:2000 (*Natural stone test methods – Petrographic examination*). Before preparing thin sections, the stone samples were impregnated with blue resin to highlight pore spaces. The thin sections have been cut perpendicular to the bedding fabric of the stone, and are positioned to be as representative as possible of each sample.

The thin section description includes details of the proportions of rock components (the various types of detrital grains, the various types of mineral cement, and pore space). These are estimates based on a visual assessment of the proportion of thin section area that the component occupies, expressed as a percentage.

All the thin section images in this report were taken in plane-polarized light; pore spaces appear blue. The field of view in all images is the same (c.3.3 mm across), so the characteristics of each sample can be compared directly.

4.3 PETROGRAPHIC DESCRIPTIONS OF PITAIRLIE QUARRY STONE

4.3.1 Sandstone

Hand specimen description (based on samples MC11362 and MC11363)

Both hand specimens are 150 mm x 100 mm x 80 mm in size and consist of fine-sand-grade (see Figure 12), bluish-grey sandstone. The Munsell colour code of the dry, fresh stone lies between 5 BG 6/1 and 10 BG 5/1. This is a hard, strongly cohesive stone. MC11362 shows some well developed bedding laminations, whereas MC11363 is relatively uniform (i.e. lacks a discernible fabric). Aligned white mica flakes concentrated along bedding surfaces are likely to contribute to the fissility of the stone (i.e. its propensity to split along bedding). Moderate reaction with hydrochloric acid (10% HCl) indicates that one or more carbonate minerals is present, and a water bead test indicates low permeability. These stone samples display only fresh, unweathered surfaces.

Thin section description (based on samples MC11362, MC11363, MC8685, MC8686)

Detrital (granular) components

The detrital grain assemblage is dominated by quartz (34%) and lithic grains (i.e. rock fragments; 20%), the latter consisting of very-fine-grained volcanic and metamorphic rock types. A small proportion of the quartz grains are polycrystalline (representing quartz that had recrystallised prior to the formation of this sedimentary rock). Feldspars (15%)are present in twinned and untwinned varieties. There are also small proportions of biotite (5%), opaque iron oxide (4%), chlorite (3%), and muscovite (2%), and the minerals tourmaline, epidote, garnet and zircon are present in trace amounts. MC8686 has a greater proportion of iron oxides than the other samples.

Apart from quartz (which is essentially chemically inert), many of the detrital grains show signs of secondary alteration. Most of the feldspar grains display a turbid texture, showing they have undergone alteration. Some lithic grains with a 'ragged' appearance are partly altered to clay. Chlorite has replaced biotite locally.

Intergranular components

Silica overgrowths on quartz constitute around 3% of the stone. The overgrowths commonly manifest as euhedral (i.e. crystal-shaped, rather than abraded) terminations on quartz grains, and they locally bind adjacent grains thereby contributing to the cohesion of the stone. Sparry calcite (6%), which formed after the quartz overgrowths, occupies intergranular spaces and in places is seen to have replaced feldspar. A small proportion (1%) of secondary clay occupies pore space.

Texture

Elongate detrital grains are aligned parallel to bedding, and define a well developed fabric (see the thin section images below). Most detrital grains are subangular to subrounded, well sorted, and of fine-sand grade. Pore space occupies approximately 7% of the thin section area in samples MC11362 and MC11363, but significantly less (1-2%) in MC8585 and MC8586. Some intragranular pore space (c. 1-2% of the stone) has developed in MC11362 and MC11363 due to selective dissolution of the detrital grains. Pore spaces are small (≤0.15 mm) and not well connected, hence the stone has low permeability.

Comments

All four samples are very similar in terms of the types and proportions of detrital constituents, however samples MC8585 and MC8586 have notably lower porosity than MC11362 and MC11363. The differences in porosity are attributed to the varying degrees to which the calcite cement (and, to a lesser extent, detrital grains) has dissolved. Calcite is susceptible to dissolution in the near-surface environment, and the stone in Pitairlie Quarry is likely to have suffered calcite dissolution to varying degrees and on a range of scales.

Silicate detrital grains are bound by well developed grain contacts, typically of 'long' and 'pressure solution' type. Adjacent quartz grains are locally bound by silica overgrowths.

Rock classification

Based on grain-size and the proportions of detrital grain types, the stone is **fine-sand-grade lithic-arenite**.

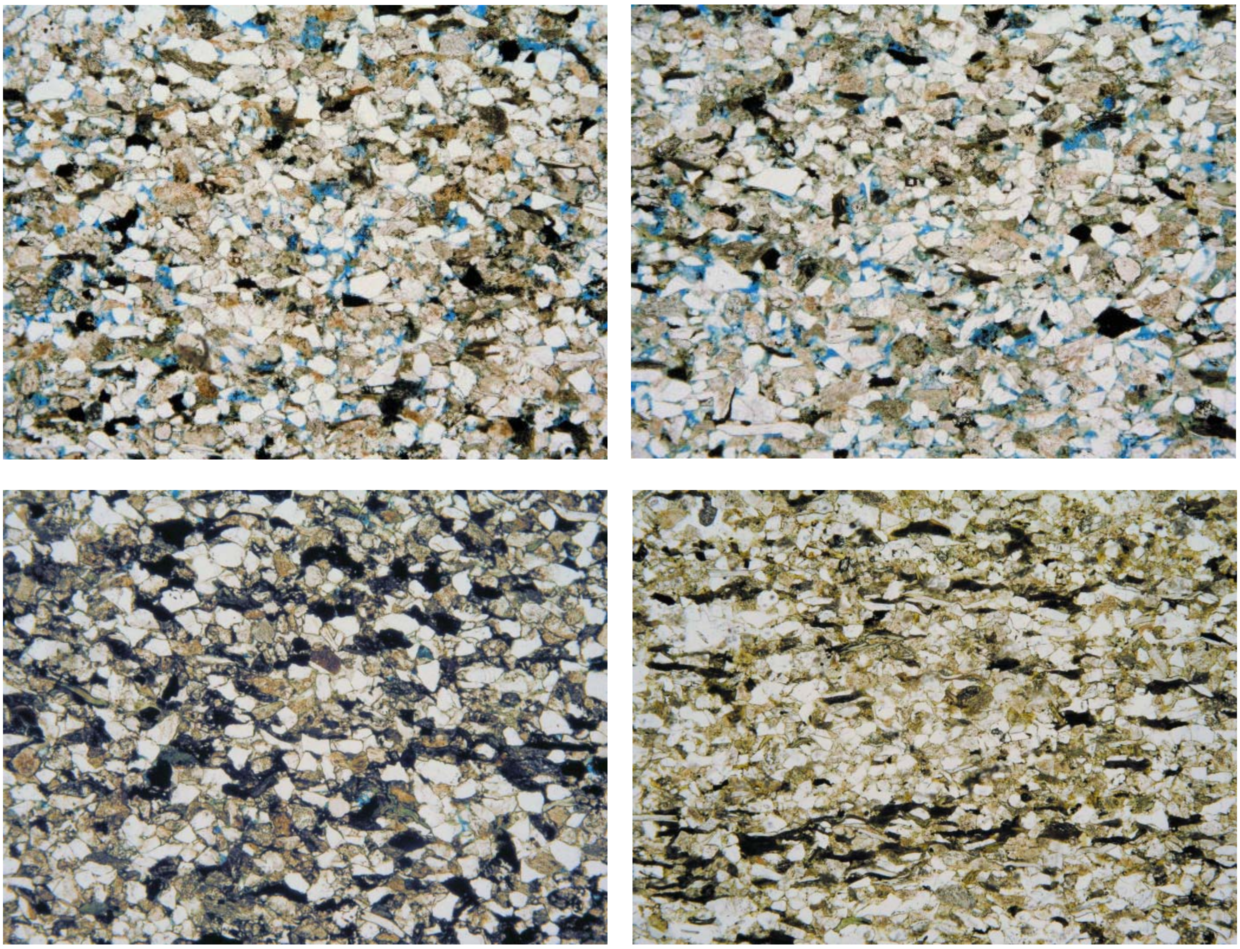


Figure 10. Thin section images of Pitairlie sandstone samples. Clockwise from top left: MC11362, MC11363, MC8685, and MC8686. The field of view is 3.3mm. Pore spaces appear blue. The four samples are broadly similar in terms of the type and proportion of detrital components. Variations in the proportion of pore space reflect variations in the degree to which the calcite cement has dissolved.

4.3.2 Siltstone

Hand specimen description (based on sample MC11361)

The sample is a piece of bluish-grey siltstone, 60 mm x 50 mm x 15 mm in size. The Munsell colour code of the dry, fresh stone is close to 5 BG 5/1. This is a hard, strongly cohesive stone, and shows a well developed laminated fabric of alternating darker and lighter layers up to 3 mm thick. These laminae are cross bedded on a mm scale. Moderate reaction with hydrochloric acid (10% HCl) indicates that calcite is present, and a water bead test indicates very low permeability. The sample displays only fresh, unweathered surfaces.

Thin section description (based on sample MC11361)

Detrital (granular) components

The detrital grain assemblage is dominated by quartz (30%) and lithic grains (25%), the latter consisting of very-fine-grained volcanic and metamorphic rock types. Feldspars (15%) occur as both twinned and untwinned varieties, and many feldspar grains display a turbid texture associated with secondary alteration. There are also small proportions of detrital muscovite (8%), opaque oxide (5%), biotite (5%) and chlorite (4%). Chlorite has replaced biotite locally. Detrital epidote is present in trace amounts.

Intergranular components

Post-deposition overgrowths on quartz and feldspar grains are developed locally, comprising around 1% of the stone. A cement of sparry calcite (6%), which formed after the quartz and feldspar overgrowths, has formed in intergranular spaces.

Texture

The stone has a banded character in thin section, reflecting the laminated appearance of the hand specimen. Elongate detrital grains are aligned parallel to the banding. The banding is defined by variations in grain-size, sorting and mineral proportions. Finer grained bands typically contain a smaller proportion of quartz. Detrital grains are angular to subrounded and poorly sorted overall, but moderately sorted within individual bands. The grain-size ranges from silt-grade to very-fine-sand grade, but the stone is dominantly of silt-grade. Pore space occupies approximately 1% of the thin section area, but ranges from virtually zero to approximately 2% on the thin section scale (see Figure 11). Pore spaces are very small ($\leq$0.03 mm) and not connected in the plane of the thin section; hence, this stone has very low permeability.

Comments

Quartz and feldspar grains are bound by well developed grain contacts, typically of ‘long’ and ‘pressure solution’ type. Calcite in interstitial spaces is also acting to cement the granular framework. The majority of the pore space in this sample is intragranular (i.e. formed within the detrital grains, by dissolution) and has not formed due to calcite dissolution.

Rock classification

Based on overall grain-size and the proportions of detrital grain types, the sample is classified as **siltstone**.

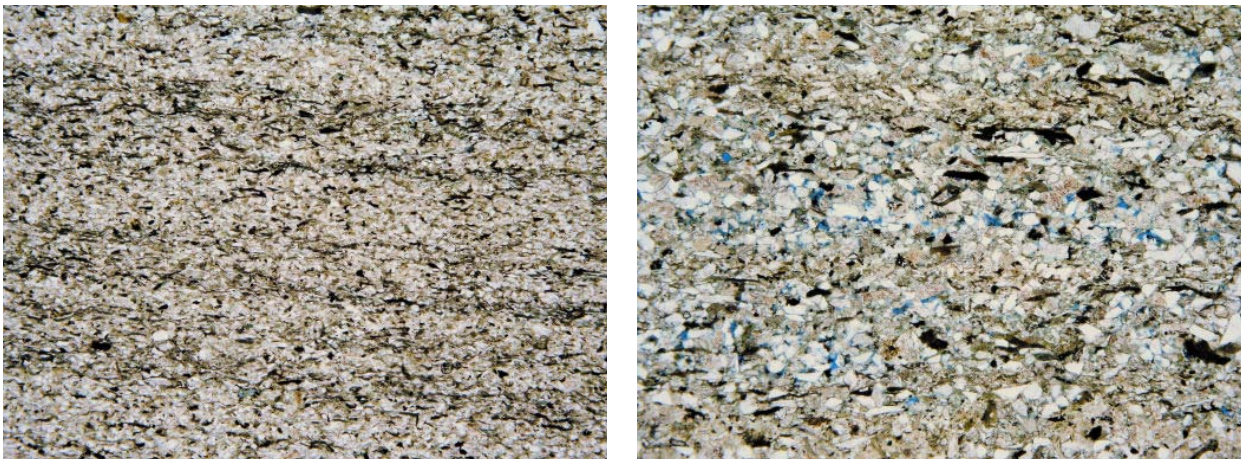


Figure 11 Thin section images of the Pitairlie siltstone sample (MC11361). The field of view is 3.3mm. Pore spaces appear blue.

Phi units	Clast or crystal size in mm. Log scale	Sedimentary clasts		Volcaniclastic fragments	Crystalline rocks, igneous, metamorphic or sedimentary
		boulders	G R A V E L	blocks and bombs	very-coarse-grained very-coarse-crystalline
-8	256	cobbles			
-6	64	pebbles		lapilli	
-4	16				coarse-grained coarse-crystalline
-2	4	granules			
-1	2	very-coarse-sand	S A N D	coarse-ash-grains	medium-grained medium-crystalline
0	1	coarse-sand			
1	0.5 (1/2)	medium-sand			
2	0.25 (1/4)	fine-sand			fine-grained fine-crystalline
3	0.125 (1/8)	very-fine-sand			
5	0.032 (1/32)	silt	M U D	fine-ash-grains	very-fine-grained very-fine-crystalline
8	0.004 (1/256)	clay			cryptocrystalline

Figure 12. BGS grain-size classification scheme (based on Wentworth, 1922).

From Hallsworth and Knox, 1999. BGS © NERC.

5 Discussion

5.1 A COMPARISON OF PITAIRLIE AND CARMYLLIE STONE

Two main variants of the stone from Pitairlie Quarry have been described.

- A bluish-grey, fine-sand-grade lithic-arenite, represented by samples MC11362, MC11363, MC8585 and MC8586.
- A bluish-grey siltstone, represented by sample MC11361, which features a laminated fabric.

A petrographic description for a sample of Carmyllie stone from the BGS collection is presented in Appendix 2. The samples of Pitairlie sandstone and Carmyllie stone are closely similar in a number of respects. They are hard, strongly cohesive stones of fine-sand-grade. They contain similar types and proportions of detrital constituents (suggesting they share the same sediment source, which would be consistent with the fact that both come from the same geological formation), and both are classified as the lithic-arenite type of sandstone. However, the Carmyllie stone sample has significantly more carbonate cement (~18%) and less pore space (~1%) than the Pitairlie samples.

The two stones are sufficiently similar in colour that Pitairlie stone should in many situations provide an acceptable colour match for Carmyllie stone. The fine-sand-grade lithic-arenite variety of Pitairlie stone is closely similar to the sample of Carmyllie stone from the BGS collection, and should provide a good substitute in repairs to Carmyllie stone. The weathered surfaces of samples of Carmyllie stone and Pitairlie stone held within the BGS collections are typically brownish, suggesting that weathering may act to reduce the differences in colour displayed by the fresh stones.

5.2 COMPARISON OF PITAIRLIE STONE AND CURRENTLY AVAILABLE PAVING STONES

To make it suitable for paving, a natural stone should have: low permeability, to minimise water penetration and growth of biogenic matter; good cohesion, to provide resistance to wear; a fissile character, so it will split readily along bedding planes to form tabular blocks; and sufficient compressive and flexural strength to cope with any load that it is expected to bear (e.g. large vehicles).

The characteristics of several currently available stones on the UK market that are commonly used for paving are compared with Pitairlie stone in Table 1. These have been selected to be representative of the range of currently available paving stones that have similarities to (and might compete with) Pitairlie stone.

Representative photomicrographs of each stone are presented in plates 1 and 2.

Stone name	Colour range	Grain size	Permeability	Stone cohesion	Bedding/Fissility	Compressive strength	Flexural strength
Ladycross	Pale grey to buff	very fine sand grade	Very low	Strongly cohesive	Laminae size layers but not well developed; moderately fissile	Not known	Not known
West Stone sandstone	Bluish grey to buff	Fine to medium sand grade	Moderately low	Strongly cohesive	Uniform; not fissile	110MPa	10.92MPa
Crossland Hill	Buff	Medium sand grade	Low	Strongly cohesive	Uniform; not fissile	132 MPa	15.0 - 18.9 MPa
Scoutmoor	Greenish to bluish grey	very fine sand grade	Very low	Strongly cohesive	Well laminated; fissile	186 MPa	25.7 MPa
Forest of Dean Green	Bluish to greenish grey	Fine to medium sand grade	Moderately low	Strongly cohesive	Uniform; not fissile	110 MPa	Not known
Bolton wood	Buff	Fine sand grade	Low	Strongly cohesive	Uniform; not fissile	Not known	Not known
Delph Stone	Buff	Very fine sand grade	Low	Strongly cohesive	Uniform; not fissile	Not known	Not known
Pennant/ Forest Pennant	Bluish, Greenish and Purplish Grey.	Medium sand grade	Moderately low	Strongly cohesive	Uniform; not fissile	122 MPa	Not known
Caithness Flagstone	Dark Grey	Silt to clay grade (shale)	Very low	Strongly cohesive	Well laminated; fissile	150 MPa	37.2 Mpa
Greenmoor Rustic	Greyish green	Very fine sand grade	Very low	Strongly cohesive	Well laminated; fissile	Not known	17 MPa
Pitairlie Siltstone	Bluish Grey	Silt grade	Very low	Strongly cohesive	Well laminated; fissile	Not known	Not known
Pitairlie Sandstone	Bluish Grey	Fine sand grade	Very low	Strongly cohesive	Laminae size layers but not well developed; moderately fissile	78 – 98 MPa	Not known

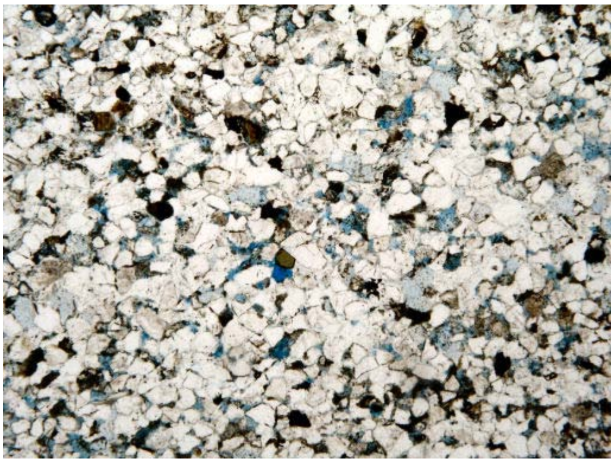
Table 1. A comparison of selected attributes of Pitairlie stone and currently available stones commonly used in the UK for paving. Values for the compressive strength of Pitairlie stone are from Appendix 1. Other reported values for compressive strength and flexural strength are from the websites of the Building Research Establishment (BRE) or individual stone suppliers. Details of the methodology used in these tests are not always provided; it is assumed for the purposes of this report that the methodology used has been essentially the same in all cases and that the data can be compared directly. 'Not known' indicates the information is not provided by either of these sources. MPa = MegaPascals.

The observations in Table 1 were made from samples of stone held within the BGS Building Stone Archive. These samples may not be representative of the quarry as a whole or of the stone that is currently being produced. The comparison is therefore intended to provide only a broad indication of the qualities and relative merits of each stone. The ‘fissility’ of the stone (i.e. its propensity to part on parallel surfaces, along bedding) is inferred from the observed bedding character of the stone samples and does not necessarily reflect the ease with which quarried blocks of the stone can be split into slabs. Well bedded and laminated stones are expected to split with greater ease than those with a more uniform character – the latter may need to be sawn into slabs suitable for paving.

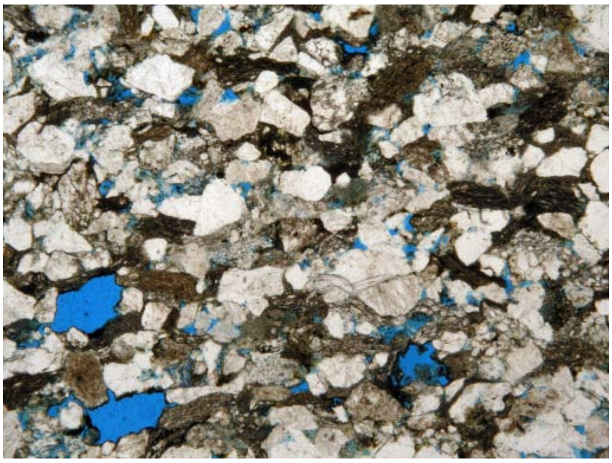
‘Compressive strength’ is the capacity of a natural stone to withstand a force directed normal to bedding; a compressive strength test typically involves subjecting a stone to a distributed, compressive load and measuring the size of the applied force at the moment of failure (crushing). ‘Flexural strength’ is the capacity of a natural stone to resist deformation under load; a flexural strength test typically involves subjecting a material to a point load, such that it bends, and measuring the size of the applied force at the moment of rupture (fracturing). Good compressive strength is an important attribute of stone that will be required to support a distributed load (e.g. mullions), while good flexural strength is an important property of paving stone. Compressive strength values for two samples of Pitairlie sandstone (Appendix 1 and Table 1) are significantly lower than the reported values for several other stones, and this may limit the range of uses to which the stone is suited. There are currently no flexural strength data for any samples of Pitairlie stone. More compressive strength data (especially for siltstone samples) and new flexural strength data (siltstone and sandstone) should be obtained for Pitairlie stone to fully assess its suitability for a range of uses.

Several of the stones in Table 1 are buff, and Pitairlie stone obviously would not be a good substitute for these where colour is important. The Forest of Dean and Pennant stones have a broadly similar colour to Pitairlie stone, but they are not fissile and their coarser grain-size may be associated with higher permeability than Pitairlie stone. Caithness flagstone is significantly finer grained and lacks a blueish tinge.

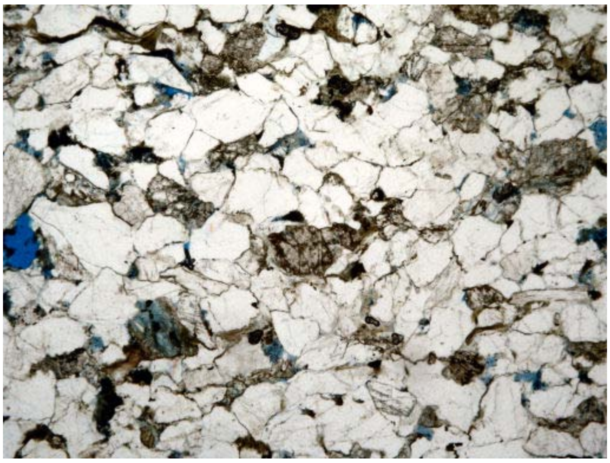
Scoutmoor and Greenmoor Rustic stones are the most similar to Pitairlie stone in terms of colour, permeability and fissility, though they are typically greenish grey rather than bluish grey. These northern England stones are, however, a poorer match for Carmyllie stone than the samples of Pitairlie which we have examined, and they do not have a history of use in the areas of Scotland where Carmyllie stone has been extensively used.



Ladycross

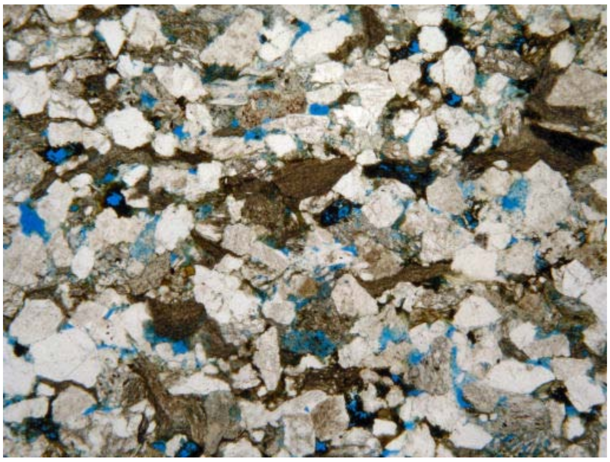


West Stone Sandstone

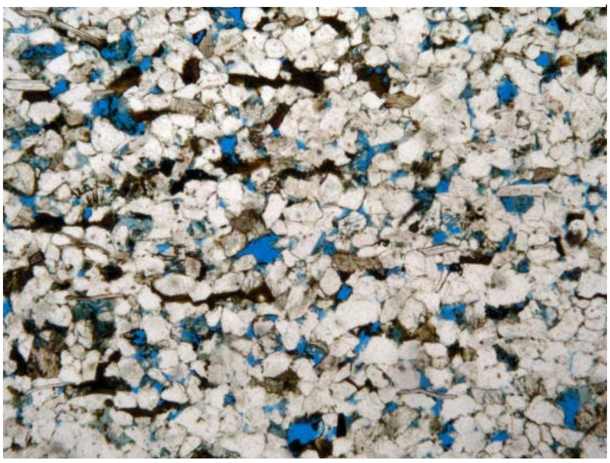


Crossland Hill

Scoutmoor

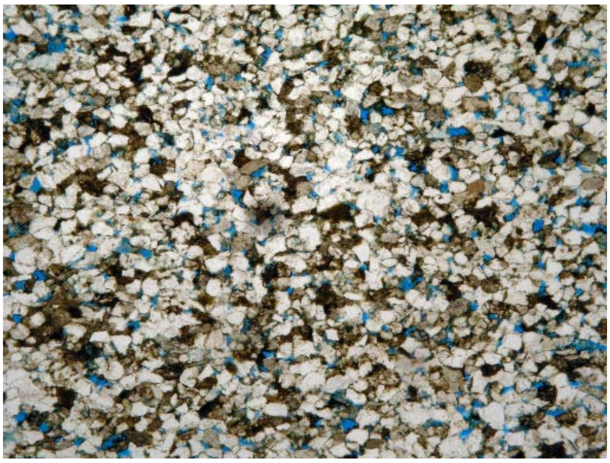


Forest of Dean Green

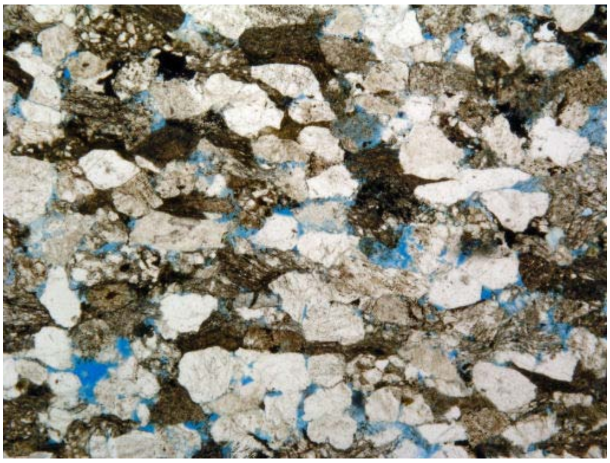


Bolton wood

Plate 1. Photomicrographs of a selection of currently available UK stones commonly used for paving. Images are 3.3mm wide, porosity highlighted in blue dye resin.

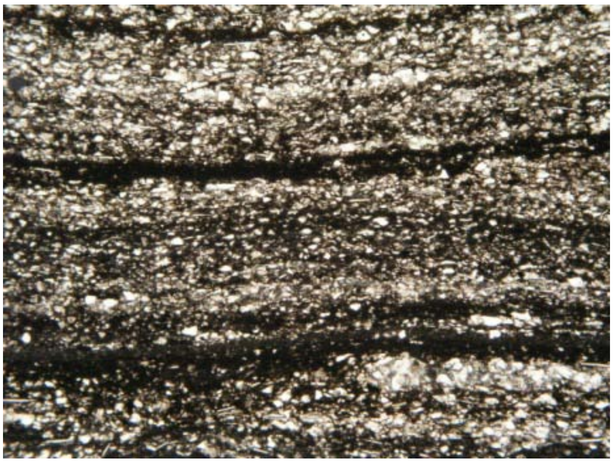


Delph Stone



Pennant/Forest Pennant

Greenmoor rustic



Caithness Flagstone

Pitairlie Siltstone (MC11361)

Pitairlie Sandstone (MC11362)

Plate 2. Photomicrographs of a selection of currently available UK stones that are commonly used for paving in the UK, and the two varieties of Pitairlie stone for comparison. Images are 3.3mm wide, porosity highlighted in blue dye resin.

6 Conclusions

Pitairlie Quarry probably began operating in the mid 19th century, exploiting layers of sandstone and siltstone within the Dundee Flagstone Formation (part of the Old Red Sandstone Supergroup). Many other quarries in the local area, including the relatively well known and much bigger Carmyllie Quarry, have exploited the same geological formation to supply significant volumes of building stone in the past. The stone was known historically as 'Arbroath Pavement'. All the quarries are now closed (Pitairlie Quarry closed in 1915), and no quarries currently extract building stone from this geological formation.

A lack of historical records precludes any firm conclusion regarding the degree to which Pitairlie stone was exported and how it was used. However, Pitairlie and Carmyllie quarries probably were in operation more-or-less simultaneously during the latter part of the 19th century, and they exploited the same geological formation. It therefore seems reasonable to assume that Pitairlie stone would have been transported widely and put to a similar range of uses as Carmyllie stone.

Pitairlie stone shares many of the petrological characteristics of Carmyllie stone (though both vary somewhat in colour), and should in many cases provide the best available substitute for Carmyllie stone where repairs are required.

Reclaimed Pitairlie stone has been used in several important recent conservation projects in Edinburgh, as a substitute for Carmyllie stone (Aitcheson House) and as a replacement for "Arbroath Pavement" type stone (Scotsman Steps and steps at Edinburgh Castle).

Based on a preliminary assessment, around 80% of the stone exposed in Pitairlie Quarry is fine-sand-grade sandstone and the remainder is siltstone. These two stone types are distinguished mainly by grain-size, being broadly similar in terms of the type and proportions of mineral components. Pitairlie stone is typically bluish grey and has the range of petrological qualities that typically make a good paving stone – a moderately fissile character, low permeability and good cohesion (providing resistance to wear). In one or more of these respects it compares favourably to several other stones that currently are commonly used in the UK for paving.

More geotechnical data (e.g. compressive strength and flexural strength) are needed to assess fully the range of uses to which the stone is suited. Two compressive strength values reported for Pitairlie sandstone in this report (78-98 MPa) are relatively low, and there are currently no reported values for flexural strength.

This study has not included an assessment of how readily the stone currently exposed in the quarry splits along bedding, what the typical thickness and size of newly excavated split stone blocks would be, and what volume of exploitable stone of suitable character remains (i.e. the magnitude of the reserve).

References

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

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Appendix 1 Compressive Strength tests

INTRODUCTION

A Compressive Strength test was performed on two samples of sandstone collected from Pitairlie Quarry. The tests were conducted in the British Geological Survey Engineering Geology laboratory at Keyworth, Nottingham. Compressive strength is the capacity of a natural stone to withstand a force directed normal to bedding.

METHODOLOGY

The test technique is based on that described in ASTM (1995), test C170-90. A cylindrical core sample, of 50 mm nominal diameter, was drilled from the block sample so the axis of the cylinder was perpendicular to the bedding. The test specimen was cut and the ends surface ground so they were flat and parallel to within 20 µm. The test sample length was nominally the same as the diameter. The specimens were weighed and measured, then allowed to dry in the laboratory. A 2000-kN compression machine was set up for the size of the specimen used. Both platens had a Rockwell hardness of not less than HRC58. The lower platen included a spherical seat. The spherical seat was lubricated with oil. The specimen, platens and spherical seating were accurately centred. The loading rate during the test did not exceed 690 kPa/sec. The load was measured using a 330 kN RDP load cell S/N 470876 with RDP E525 digital indicator.

RESULTS

Compressive strength (σ_C) = W/(1000 x A) MPa

where: W is the maximum load (kN)

A is the area of the load bearing surface of the sample (m^2).

The results are presented below.

Sample	Received identification	Weight g	Dimensions Length mm	Diameter mm	Nominal density mg/cm^3	Load at failure kN	Time to failure secs	Compressive strength MPa
EGLLJ157/1	MC11362	240.09	50.16	49.73	2.46	184.2	170	94.8
EGLLJ157/2	MC11363	235.58	50.13	49.66	2.43	152.0	147	78.5

Samples were tested air dried. Compressive Strength tests were conducted by David Entwisle, BGS Keyworth.

Abbreviated terms

kN – Kilo Newtons (1kN = 1000 Newtons). Measurement of force.

µm – Microns (1 micron = 0.000001 metres). Measurement of distance.

kPa/sec – Kilo Pascals per second. (Rate at which pressure is applied).

MPa – Mega Pascals (1 Megapascal = 1000 Pascals)

mg/cm^3 – Measure of stone density

Appendix 2 Petrographic analysis of Carmyllie Quarry flagstone

The BGS Building Stones Collection holds just one thin section of stone from Carmyllie Quarry - BGS sample MC8609. A petrographic description of this sample is provided here to enable a comparison with the petrographic analyses of the two varieties of Pitairlie stone presented in Section 5 of this report. The degree to which the sample is representative of typical Carmyllie stone is not known.

Macroscopic description

The sample is a piece c. 450 mm x 180 mm x 35 mm of grey, very-fine-sand-grade sandstone. The Munsell colour code of the dry, fresh stone is close to 10 BG 5/1. The stone is hard and strongly cohesive, and displays a well developed flaggy fabric defined by bedding-parallel layers. White mica grains are discernible on surfaces parallel to bedding. A vigorous reaction with hydrochloric acid (10% HCl) shows that a significant proportion of calcite is present, and a water bead test indicates very low permeability. Weathered surfaces of the sample are slightly more brown than the fresh stone, closer to Munsell colour code 7.5 Y 4/2.

Microscopic description

<u>Detrital components</u>

The detrital grain assemblage is dominated by quartz (30%) and lithic grains (25%), the latter consisting of very-fine-grained volcanic and metamorphic rock types. Feldspars comprise 12% of the stone and commonly show a turbid texture due to alteration. Small proportions of muscovite (3%), opaque oxide (3%), biotite (4%) and chlorite (5%) are also present, with a trace of detrital tourmaline. Chlorite has replaced biotite locally.

<u>Intergranular components</u>

Overgrowths on grains of quartz and feldspar comprise 1-2% of the stone. A relatively abundant cement of sparry calcite (18%) formed after the silicate overgrowths and pervades the stone. A small proportion of clay (c.1%) infills pore space locally.

<u>Texture</u>

The thin section displays a strong alignment of the detrital grains, with elongate quartz, mica and lithic grains aligned parallel to bedding. Detrital grains are typically angular to subrounded, moderately sorted, and of very-fine-sand grade. Pore space is scarce, occupying approximately 1% of the thin section area. Pore spaces are very small ($\leq$0.03 mm) and typically not connected in the plane of the thin section; hence, this stone has very low permeability.

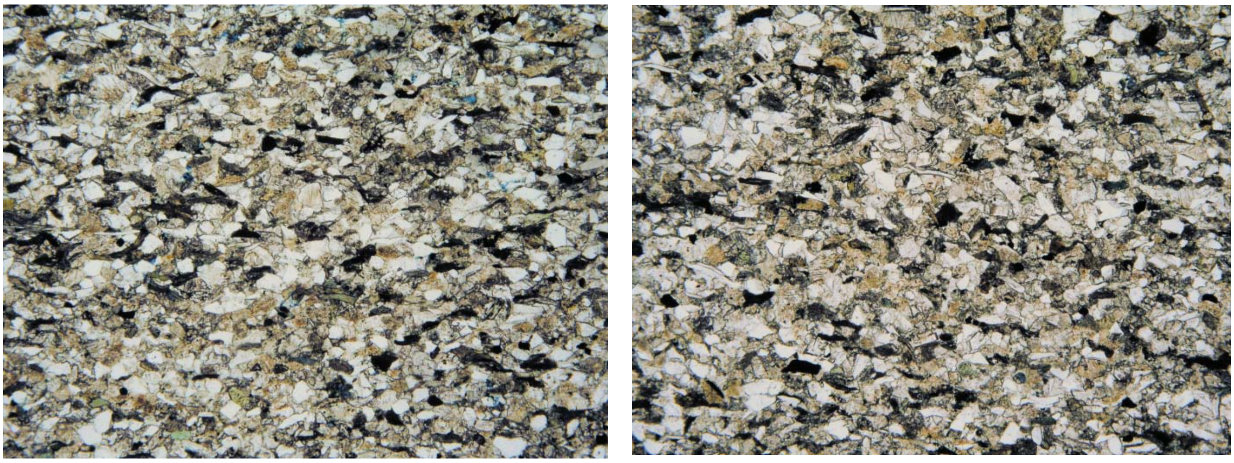
<u>Comments</u>

The detrital grains are bound by well developed grain contacts, typically of ‘long’ and ‘pressure solution’ type. The overgrowths on detrital grains and the sparry calcite cement will contribute to stone cohesion.

Some other hand samples of Carmyllie stone from the BGS Building Stones Collection display a range of colour from grey to lilac/purple. Variation within this colour range is seen between different blocks as well as within individual samples which have a patchy appearance with grey and purplish grey patches.

<u>Rock classification</u>

Based on grain-size and the proportions of detrital grain types, the sample is classified as **very-fine-sand-grade lithic-arenite**.



Thin section images of BGS sample MC8609 (Carmyllie stone). The field of view is 3.3mm. Pore space appears blue.

Appendix 3 Case studies from recent conservation projects

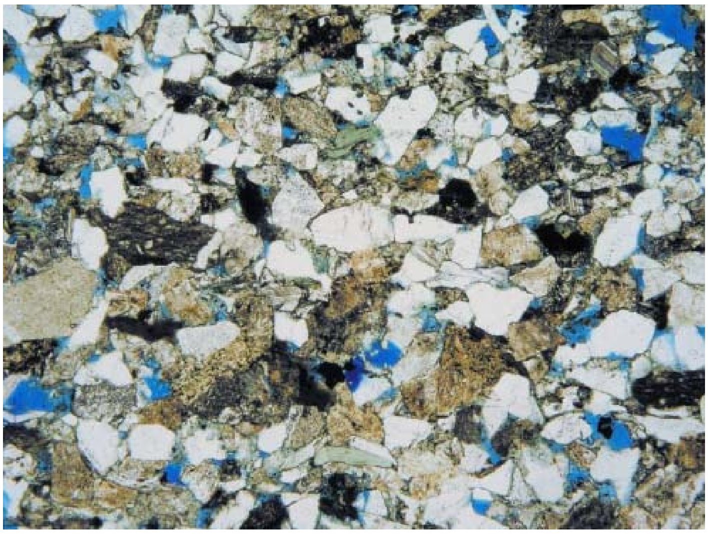
ACHESON HOUSE

Acheson House is an early 17th century building located on the Royal Mile, Edinburgh. The building has undergone extensive restoration since its initial construction, with the latest taking place in the 1930s. At this time, the full roof structure and sarking was fully renewed; however, it is likely that the roof covering was retained. The 1930s restoration also introduced lead flashings and rhones, neither of which were likely to have been original features. Recently, Simpson & Brown Architects have re-tiled the roof with stone from Pitairlie Quarry. Some of the original material was retained, but the roof as presently completed comprises mostly new stone. This is the first roof in Scotland to have locally sourced sandstone flags in over 60 years.

SCOTSMAN STEPS FLAGSTONES

In November 2009, BGS was commissioned to undertake a petrographic analysis and stonematching assessment for the flagstones of the Scotsman Steps, Northbridge, Edinburgh. This assessment concluded that the flagstones featured within the steps were very likely to be Carmyllie type flagstone, which would have been extracted from one of the many quarries near Carmyllie in Angus. As none of these quarries are currently active, the report identified the newly available material from Pitairlie Quarry as the closest matching stone for use in repairing the steps.

EDINBURGH CASTLE



In September 2010, BGS was commissioned to undertake a building stone assessment for repairs to Edinburgh Castle, which included a stonematching exercise for the flagstone steps that lead up to the historic cannon, Mons Meg. The report noted the similarity between the stone sample from the flagstone steps and Carmyllie type flagstone, and concluded that the most appropriate currently available replacement stone would be from Pitairlie Quarry, even though the sample from the castle was significantly coarser grained than Pitairlie stone. A thin section photomicrograph of the sample from the steps up Mons Meg is shown above. The image has a field of view 3.3 mm wide, and pore space is highlighted with blue resin.