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Source, character and weathering style of building stone in Culzean Castle & Country Park, Ayrshire

Minerals & Waste Programme

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BRITISH GEOLOGICAL SURVEY

MINERALS & WASTE PROGRAMME
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Front cover

Culzean Castle seen through Ruined Arch.

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Summary

This report describes an assessment of the source, character and weathering style of the building stone that has been used in Culzean Castle and other historic structures that lie within Culzean Castle & Country Park (CCCP), in Ayrshire. The assessment was conducted by the Building Stones team of the British Geological Survey (BGS) on behalf of National Trust for Scotland (NTS). The project was funded by Historic Scotland, and the work has been conducted under the Memorandum of Agreement (2011-2016) between Historic Scotland and Natural Environment Research Council (NERC; as represented by BGS).

The main building stone in CCCP structures is sandstone sourced locally from the Swanshaw Sandstone Formation. Descriptions of the quarries that are thought to have supplied the stone, and a brief assessment of the potential for obtaining new supplies of the same stone from these and other quarries, are presented in section 2 of this report. The results of a brief review of historical records of local quarrying activity and building history in CCCP are tabulated in an appendix and presented in section 3 as a ‘timeline’. The geological character of Swanshaw sandstone is described in section 4, and the main causes of weathering in sandstone are reviewed briefly in section 5. The character of weathering in the stonework of CCCP buildings, and some of the factors that are likely to be causing accelerated stone decay, are described in section 6. Recommendations for ‘best practice’ procedure in the long-term repair and maintenance of stonework in CCCP are presented in section 7. Key conclusions are summarised in section 8.

1 Introduction

1.1 PROJECT BACKGROUND

Culzean Castle & Country Park (shortened hereafter to CCCP or ‘the park’) includes Culzean Castle, one of the premier heritage buildings in Scotland, and more than one hundred other stone-built structures constructed between the 16th and 20th centuries. The stonework in all stone-built structures in CCCP has suffered to some degree from weathering and erosion (‘stone decay’), and many structures have been repaired at least once in the past.

In recent decades National Trust for Scotland (NTS), which manages the park, has pursued a policy of ‘planned preventative maintenance’, which involves replacing decayed stone and lost mortar, and repairing rainwater shedding systems, on a cyclical (rather than reactive) basis. However, the large number of stone-built structures in the park, their increasing age, the relative susceptibility of the main building stone to weathering and erosion, and the exposed, coastal setting of the park, present major challenges to the successful long-term conservation of the buildings on this nationally important site.

Furthermore, the main building stone used in CCCP - Swanshaw sandstone - has not been quarried locally for many years, and NTS has throughout its stewardship of the park had to use stone sourced from elsewhere to make repairs. In recent years it has increasingly been recognised that the practice of inserting blocks of ‘foreign’ stone into existing stonework can lead to accelerated stone decay and other unintended adverse consequences.

NTS is now keen to develop its best-practice procedure for the long-term repair and maintenance of structures in CCCP. Two key objectives are to understand more about the underlying causes of stone weathering and to secure a supply of new Swanshaw sandstone to use in future repairs.

BGS set out to address some of these issues in 2012, in a project funded by Historic Scotland, but the project was terminated part-way through; the outcomes achieved up to that point were delivered in a short, informal summary document. The report presented here describes the outcomes of a second project, also funded by Historic Scotland, which aims to build on the work that was begun in 2012.

1.2 GEOLOGICAL SETTING

Much of the coastal fringe of CCCP, including the ground on which Culzean Castle sits, is underlain by the Carrick Volcanic Formation (Figure 1), a succession of lavas and sediments that were deposited in the early part of the Devonian Period between 419 and 393 million years ago. This formation does not produce good building stone, and the stone has been used in only a few structures in the park. Nearly all of the stone structures in CCCP are built of sandstone from the Swanshaw Sandstone Formation, which was deposited between the late part of the Silurian Period and the early part of the Devonian Period (between 427 and 393 million years ago), and now underlies much of the park and a large swathe of the surrounding area (Figure 1).

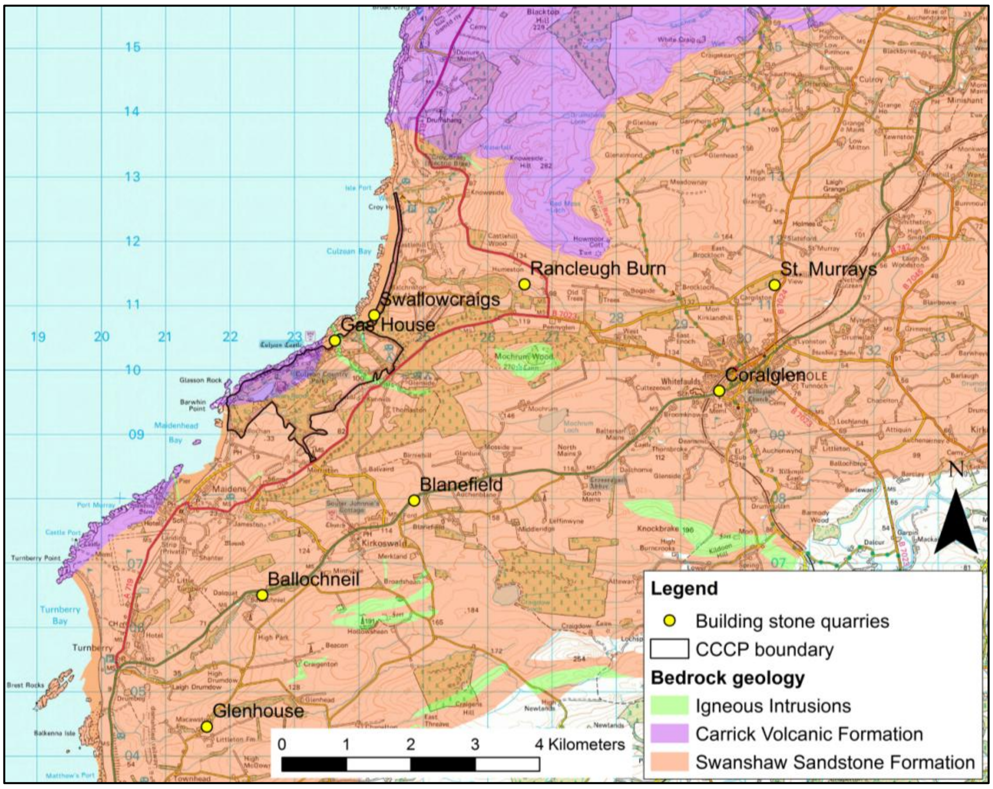

Figure 1 Bedrock geology and key localities referred to in this report

1.3 REPORT OUTLINE

The quarries that are known or suspected to have supplied the Swanshaw sandstone used in CCCP are described in section 2. All those that are still accessible were visited by BGS in 2012, with the exception of Swallowcraigs quarry which was 'rediscovered' recently by NTS and visited by BGS in 2014. The potential for obtaining new stone from each quarry is assessed briefly. The Swanshaw Sandstone Formation crops out in several other parts of the Midland Valley of Scotland, and section 2 includes an assessment (based on a desk-top review of records and a brief assessment of samples held in the BGS Rock Collection) of whether quarries in these other outcrops might provide suitable stone for repairs to CCCP buildings.

Section 3 presents a 'timeline' integrating quarrying activity in the area around CCCP and building history in the park. The timeline is based on a review of historical records, including those held by NTS and in the National Archives of Scotland.

The geological character of Swanshaw sandstone is described in section 4. The stone is described as it appears in quarries and buildings, and as it appears under the microscope. The sequence of mineral and textural changes that have occurred in Swanshaw sandstone in the geological past, and which can be deduced from microscope examination, is also described as these directly affect the way in which the stone is affected by weathering processes today.

The main causes of weathering in sandstone are reviewed briefly in section 5, then the character of weathering in CCCP buildings and some of the factors that are likely to be causing accelerated stone decay are described in section 6 using examples from the park. Recommended 'best practice' procedures for long-term repair and maintenance of stonework in CCCP are presented in section 7. Key conclusions are summarised in section 8.

2 Historical sources of Swanshaw sandstone and possible sources for future building repairs

Records indicate that most (possibly all) of the sandstone used in CCCP was sourced from quarries within Cassillis Estate, which encompasses much of the local area (including the land and buildings currently forming CCCP before they were bequeathed to NTS).

All of the quarries on Cassillis Estate were inactive by the time NTS took ownership of the park (1945). Most of the stone used in repairs since then has been sourced from quarries in the north of England that produce buff sandstone deposited during the Carboniferous Period (359 to 299 million years ago). For example, a substantial proportion of the original stone used in the Robert Adam part of Culzean Castle was replaced in 1976 by buff sandstone from Springwell quarry in Northumberland, and stone from Stanton Moor quarry in Derbyshire has been used in repairs to several buildings. Brown Devonian sandstone from Callow Hill quarry in Wales has been used in some recent repairs.

As part of a best-practice approach to building conservation, NTS is keen to use Swanshaw sandstone (rather than a different stone which is likely to be less compatible) in future repairs. In recent years the Trust has begun to recycle blocks of Swanshaw sandstone from buildings in the park and has sourced small quantities of fresh stone from large blocks produced by historical quarrying activity on the coast.

There appear to be relatively few historical records that indicate which quarries supplied the stone that was used in specific CCCP buildings (more detail is provided in section 3). However, there are sufficient records to indicate that most, if not all, of the stone was sourced from a handful of quarries within a radius of c. 7 km of the park. All of these quarries – ‘Gas House’, Swallowcraigs, Ballochneil, Blanefield, Rancleugh Burn and St Murray’s – sit on the local outcrop of the Swanshaw Sandstone Formation (Figure 1 and Figure 2). Four other quarries – Coralglen, Glenhouse, Dikeneuk and Camregan – also sit on the local outcrop of Swanshaw Sandstone Formation (Figure 2) but are considered unlikely to have provided stone for use in CCCP. Brief descriptions of all these quarries are presented in section 2.1. The level of detail in each description varies according to the current accessibility of the site.

The Swanshaw Sandstone Formation crops out in several other parts of central Scotland (Figure 2), and the potential for sourcing Swanshaw sandstone from three quarries in these outcrops – Penning Hill, Wellshields and Dunduff – is assessed in section 2.2. The assessment of potential future sources of Swanshaw sandstone is based on a consideration of geological suitability and quarry accessibility; issues surrounding land ownership and permissions for renewed quarrying are not considered.

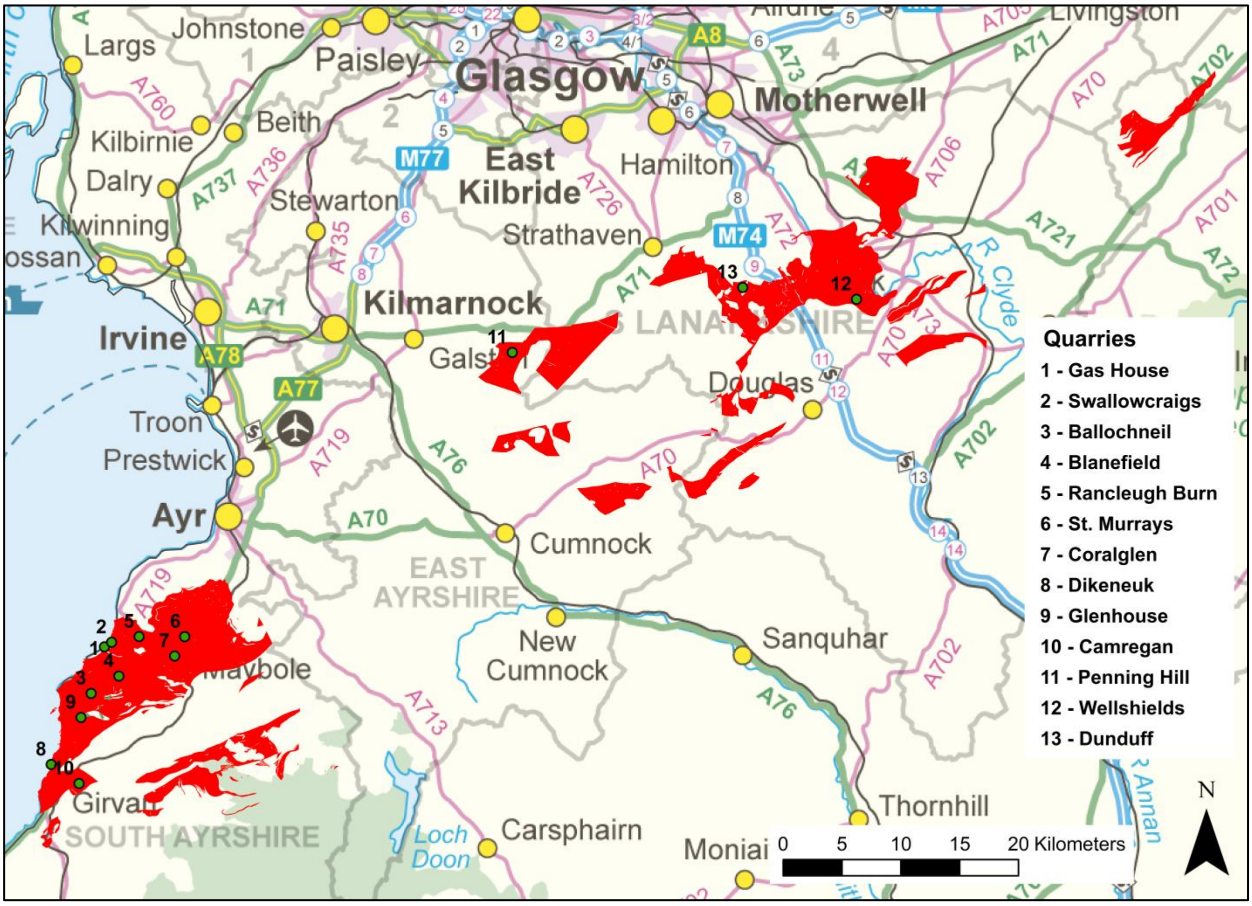

Figure 2 Outcrops of the Swanshaw Sandstone Formation in central Scotland

The extents of mapped outcrops of the Swanshaw Sandstone Formation are shown in red, and the locations and names of quarries mentioned in this report are superimposed.

2.1 QUARRIES IN THE AYRSHIRE OUTCROP OF THE SWANSHAW SANDSTONE FORMATION

2.1.1 Gas House quarry

'Gas House quarry' is an informal name (not used on published maps) given to historical stone workings in the cliff behind a small bay forming the south end of Culzean Bay (approximate location [NS 235 103]). The quarry takes its name from the Gas House building in CCCP, which faces onto the small bay. The bedrock contact between the Carrick Volcanic Formation and the Swanshaw Sandstone Formation forms the southern edge of the bay, and the workings therefore exploited the sandstone outcrops that are closest to Culzean Castle (Figure 1).

The sandstone cliff behind Culzean Bay is up to 50 metres high and extends northwards for approximately 4 km to another contact with the Carrick Volcanic Formation (Figure 1). For much of its length the cliff is heavily wooded and difficult to access, but a brief inspection suggests stone has been quarried at several (perhaps many) points along its length at least as far north as Swallowcraigs quarry (see below). Sandstone bedrock also crops out as a discontinuous platform along the foreshore, and stone may have been quarried here too (i.e. the sub-horizontal rock platforms within the intertidal zone in part may be man-made). 'Gas House quarry' therefore refers not to a single conventional quarry but to possibly many historical sites of small-scale stone extraction around the southern end of Culzean Bay (Figure 3a,b).

The sandstone outcrops consist of interbedded, metre-scale beds of uniform to bedded, medium-grained, typically orangeish buff sandstone with occasional bedding-parallel bands of cm-scale greenish mud flakes and cm-scale, orangeish brown iron-rich nodules (Figure 3c). The sandstone beds typically are essentially horizontal.

The sandstone is cut in several places by dykes (discordant sheet-like intrusions) of dolerite (dark grey to black igneous rock, sometimes known as ‘whin’). The dykes range from around 1 to 20 metres wide and the sandstone up to several metres on either side of each dyke has been ‘baked’ by the hot magma and is very hard; both the dykes and the adjacent sandstone tend to weather proud as a result. The baked sandstone may not perform in the same way as typical Swanshaw sandstone if used as a building material.

All of the stone that is exposed today is weathered to some degree, and the full colour range and character of unweathered stone is difficult to determine. However, most of the exposed stone remains strongly cohesive, and fresh sandstone from any of the exposures forming Gas House quarry should provide a good match for much of the Swanshaw sandstone that has been used in CCCP. A small volume of stone for repairing the Waste Chute in CCCP has been extracted recently by NTS masons from boulders on the Gas House quarry foreshore (Figure 3d).

Much of this section of shore and adjacent cliffs is a Site of Special Scientific Interest (SSSI) and this may limit the potential for extracting new stone. Nevertheless, Gas House quarry is the closest and most accessible historical source of Swanshaw sandstone, and has the potential to be an important source of new stone.

2.1.2 Swallowcraigs quarry

Swallowcraigs Quarry is sited on the densely wooded cliff behind Culzean Bay, approximately 1 km northeast of Culzean Castle at [NS 2424 1085]. Unlike Gas House quarry, the site has the form of a conventional quarry with a substantial worked face.

The site is on two levels with the upper level apparently forming the main quarry.

The lower level consists of a northwest-facing vertical face up to ~8 metres high and ~15 metres long, the base of which is within 10 metres of the beach and 2-3 metres above it (Figure 3e). This face may have been quarried in the past but probably less recently than the upper level.

The upper level has a northwest-facing, curved (concave) back wall ~25 metres wide, ~8 metres deep (within the curve), and ~9 metres high (Figure 3f). The back wall is near-vertical and consists entirely of exposed rock. A narrow, roughly level path provides access along the base of the back wall, and a heavily vegetated talus slope beneath the path terminates in the cliff forming the lower level. The base of the upper level back wall is roughly 20 metres above beach level.

The worked face of the upper level is near-vertical but irregular in detail, comprising variably protruding and recessed beds and blocks of sandstone. All of the stone has a patina of light brown dust, probably precipitated from rainwater run-off. The face contains the remains of many vertical drill holes (presumably part of the quarrying process), and is intersected by bedding joints and steep joints that are typically spaced at intervals of 0.5 to 2 metres. There are no obvious marks that would suggest blasting has been used to extract stone.

The stone has the character of typical Swanshaw sandstone. The freshest stone surfaces are generally greenish buff but in detail can display alternating centimetre-scale bands (parallel to bedding) of olive-green and greyish buff stone. Bands up to ~20 centimetres thick and rich in gravel- to cobble-grade, greenish-grey mud flakes occur infrequently.

The sandstone beds typically dip very gently (~10º) towards north but locally are essentially horizontal. The beds range up to around 1 metre thick and the tops of some beds consist of a mudstone layer up to ~10 centimetres thick. The sandstone can be thinly to thickly parallel-bedded or cross-bedded, and occasionally displays contorted or slumped bedding.

All of the exposed stone is weathered (producing a dull thud when struck with a hammer).

At the north end of the curved quarry face the sandstone is cut by a cluster of moderately steep granulation seams (thin bands of crushed sandstone representing a small geological fault). Granulation seams were not seen in the main part of the quarry face.

Swallowcraigs quarry is reasonably accessible on foot and has the potential to provide sandstone that is a good match for the buff Swanshaw sandstone that has been used in CCCP. However, the lack of a vehicle track, the steepness of the worked faces and the slopes above and below them, the densely wooded environment, and the weathered nature of the exposed stone mean that a substantial effort would be required to obtain a significant supply of fresh new stone from the site. Much of this section of shore and adjacent cliffs is a Site of Special Scientific Interest (SSSI); Swallowcraigs quarry may sit within the boundary of the SSSI and this might limit the potential for extracting new stone.

2.1.3 Ballochneil quarry

Ballochneil quarry sits entirely within an area of woodland on the south side of Milton Burn, approximately 2 km south-west of Kirkoswald (grid reference [NS 2250 0650]).

The quarry consists of a single broadly semi-circular pit c. 120 metres long, 50 metres wide, and up to c. 30 metres deep. The floor and the steep sides and back-wall are almost entirely concealed beneath spoil heaps and dense vegetation. Steep slopes on three sides and an unbridged stream on the north side preclude easy access to the site.

Exposed bedrock is restricted almost entirely to just two small parts of the quarry: an area on the steep back wall approximately 7 metres wide by 3 metres high (Figure 3g), and an over-deepened part of the floor approximately 6 metres wide and 3.5 metres high (Figure 3h).

The stone exposed in both these areas is similar and typical of Swanshaw sandstone: purplish grey to greenish grey and buff, faintly bedded, fine- to medium-grained sandstone with occasional purplish grey mud flakes 5 to 10 cm in size. The sandstone beds are typically around 1 metre thick and include cross-bedded and parallel bedded layers. In places, the stone has weathered to orangeish buff and purplish brown.

Ballochneil quarry is still accessible on foot today and has the potential to provide a substantial quantity of Swanshaw sandstone that would be a good match for much of the stone used in CCCP. However, renewed extraction of sandstone at this quarry would be challenging. The quarry is around 100 metres from the A77 road and separated from it by woodland and a stream several metres wide; there is currently no vehicle track to the quarry and no bridge over the stream. Furthermore, significant quantities of soil, vegetation, quarry spoil and weathered stone would need to be cleared to gain access to fresh bedrock.

2.1.4 Blanefield quarry

Blanefield Quarry is recorded as a gravel pit in the BGS Database of Mines and Quarries (also known as the ‘BritPits’ database) and its location is placed at [NS 2486 0797], immediately south of the A77 and roughly halfway between the hamlet of Blanefield and Kirkoswald village.

Today, no trace of either a stone quarry or gravel pit can be seen on the ground, though aerial photographs show what could be the outline of a former quarry c. 150 x 150 metres in plan in a field at this location; it must be concluded that the quarry has been filled. The quarry is not shown on any Ordnance Survey (OS) maps dating back to 1859, suggesting it had been filled before that date. The site is within the outcrop of the Swanshaw Sandstone Formation, and dimension stone sourced from Blanefield Quarry is likely to have had the characteristics of typical Swanshaw sandstone.

There is essentially no potential for renewed extraction of stone from Blanefield quarry.

2.1.5 Rancleugh Burn quarry

Rancleugh Burn quarry consists of a scoop c. 20 x 20 metres in plan which has been cut into the steep slope forming the north side of Rancleugh Burn, at grid reference [NS 2657 1133].

The site is now heavily overgrown and difficult to access (Figure 3i). Within the scoop, bedrock is still exposed in a vertical quarried face of around 5x5 metres, and this is likely to have been the focus of historical dimension stone extraction.

The exposed stone is highly weathered but appears to have the characteristics of typical Swanshaw sandstone. Most of the stone is orangeish buff but there are also bedding-parallel layers of reddish brown and greenish grey stone. The sandstone forms cross-bedded layers throughout the exposure, with foresets typically 10-30 cm thick (Figure 3j). Mud flakes, iron nodules, and clasts of quartz and granite are present.

Rancleugh Burn is identified as a dimension stone quarry in the BritPits database and is marked on the 1859 OS map as a “freestone quarry”. However, its small size suggests the stone may have been used to supply local needs only (e.g. bridges and houses).

The quarry is around 300 metres from the A719 road, and can be accessed on foot either from the north through a pasture field or from the east along the side of Rancleugh Burn. The quarry has the potential to provide Swanshaw sandstone that would be a good match for much of the stone used in CCCP. However, producing a reasonable quantity of fresh stone would require vehicular access and the removal of substantial amounts of vegetation, weathered stone and overburden.

2.1.6 St Murray’s quarry

St Murray’s quarry is on the north-west side of the B7024 road, approximately 1 km north of Maybole at grid reference [NS 3046 1132]. The site today consists of a large pit occupying an area of c. 100 x 80 m in plan, and bounded on all sides (other than at the access track) by vertical rock faces up to c. 10 m high (Figure 3k). OS maps show a second quarry around 100 metres north of the main site, with a single, east-facing worked face approximately 50 metres long. The second quarry sits entirely within St Murray’s Plantation with no obvious means of access, and aerial photographs show it to be densely wooded; it clearly has been disused for some time.

The main quarry is listed in the BritPits database as a dimension stone quarry, and it is obvious that a large volume of stone has been extracted in the past. Most of the exposed rock face is covered in a relatively thick patina of dust and organic matter, making it difficult to examine the stone. The stone is generally reddish grey apart from a relatively small section of exposure on the west side of the quarry where the stone appears to be predominantly greyish buff. Unlike other quarries in the Swanshaw Sandstone Formation that have been visited as part of this project, the stone in St Murray’s quarry has a generally consistent colour, though in other respects it has all the characteristics of typical Swanshaw sandstone; the St Murray’s stone can be considered a generally reddish grey variant of Swanshaw sandstone.

The sandstone beds are typically c. 1 m thick, broadly horizontal, and are locally cross-bedded and finely laminated. Small geological faults (which manifest as sets of closely spaced, steeply inclined, narrow ribs that tend to stand slightly proud of the sandstone and are sometimes known as *granulation seams*), mud flakes and coloured spots/nodules are all developed locally (Figure 3l).

Access to the quarry is straightforward; a track from the B7024 road leads into the quarry through a locked gate; the quarry floor is gravelled-over so vehicles potentially can be driven directly to the quarried faces. The site is currently used as a shooting range by a local rifle club.

Renewed extraction of stone at St Murray’s quarry would be more straightforward that at most of the other quarries visited as part of this study, given the good access and lack of vegetation obstructing the rock face. However, stone with the character of St Murray’s stone has been used in only a small number of buildings in CCCP, notably the Victorian additions forming the east and west wings of Culzean Castle, the Orangery, Camellia House, and Filter House. Reddish brown sandstone is also a component of some rubble walling, for example in Swan Pond Cottage and Gas House; this reddish brown stone may not come from St Murray's quarry originally but St Murray's quarry stone would probably be a good substitute.

Many of the sandstone buildings in the town of Maybole consist of reddish to purplish grey Swanshaw sandstone. Much of this probably came from Coralglen quarry (see below), though some is likely to be from St Murray's quarry. Any new stone produced from St Murray's quarry might find a ready market in building repairs in Maybole (and the surrounding area).

2.1.7 Coralglen quarry

Coralglen quarry was located in the town of Maybole at grid reference [NS 2960 0967]; however, the quarry has been filled for many years and the site is now occupied by housing. BGS has no samples of stone from Coralglen quarry and no record of when the quarry was active. However, the main building stone in Maybole is sandstone with a more intense reddish brown colour than stone from St Murray's quarry, and this stone is probably from Coralglen quarry.

Other than some of the stone blocks used in rubble walling, none of the buildings in CCCP contain stone with the intense reddish brown colour that appears to be characteristic of Coralglen quarry. Most of the sandstone buildings in Maybole post-date nearly all the buildings in CCCP, and Coralglen quarry may have opened after most of the buildings in CCCP had been constructed.

Coralglen quarry is no longer accessible and there is essentially no possibility of obtaining new stone from the site.

2.1.8 Dikeneuk quarry

Dikeneuk quarry (which is also referred to as 'Dykeneuk' and 'Girvan Mains') is located on the coast at Chapeldonan, c. 3 km north of Girvan (grid reference [NS 1910 0046]). The site, which is no longer active, is identified as a dimension stone quarry in the BGS BritPits database but BGS has no samples of stone from the quarry. The quarry sits within the main Ayrshire outcrop of the Swanshaw Sandstone Formation and therefore may have produced stone of broadly similar character to that used in CCCP.

The site, which was not visited as part of this study, consists of three broadly circular pits, each roughly 30 metres wide. The pits are now flooded and it is unlikely that the site could provide a significant source of new stone.

2.1.9 Glenhouse quarry

Glenhouse quarry is around 2 km south-east of Turnberry, near Littleton Farm and Chapelton Burn (grid reference [NS 2164 0445]). The site, which was not visited as part of this study, is identified as a dimension stone quarry in the BGS BritPits database, but BGS does not hold any samples of the stone. Aerial photographs suggest the site consists of a small worked outcrop on the south side of the wooded banks holding Chapelton Burn, and is likely to have supplied stone for local use only; the site appears to be still accessible, though overgrown.

Glenhouse quarry is recorded on the 1859 OS map with the words "Old Quarry (freestone)"; an outline of the pit indicating its shape and size is not shown. These details suggest that it was not of a significant size and was already disused by the mid-19th century.

2.1.10 Camregan Quarry

Camregan Quarry is around 3 km north-east of Girvan, in Camregan Glen (grid reference [NX 2147 9884]). The site, which was not visited as part of this study, is identified as a dimension stone quarry in the BGS BritPits database, but BGS does not hold any samples of the stone. Aerial photographs suggest the site consists of a small worked outcrop on the north-east side of the wooded banks of Killoup Burn, and is likely to have supplied stone for local use only; the site appears to be still accessible, though overgrown.

Camregan Quarry is recorded on the 1859 OS map with the words “Freestone Quarry”, which may suggest that it was active at this time. An outline of the pit, indicating its shape and size, is not shown on the map. The 1897 OS map does not feature the quarry, suggesting extraction had ceased by this time.

2.2 QUARRIES IN OTHER OUTCROPS OF THE SWANSHAW SANDSTONE FORMATION

The BGS BritPits database contains records for two former dimension stone quarries in outcrops of the Swanshaw Sandstone Formation in other parts of Scotland. These quarries are too distant to have been a source of the stone used in CCCP. Neither quarry was visited as part of this study.

Only quarries believed to have produced dimension stone historically have been considered in this assessment. The BritPits database contains details of other quarries that produced Swanshaw sandstone for a different or unidentified use, and these could be considered as part of a wider assessment.

2.2.1 Penning Hill quarries

Stone from the Swanshaw Sandstone Formation was formerly produced from several pits on Penning Hill, which is around 2 km south-east of Darvel in East Ayrshire (grid reference [NS 583 356]); the pits are referred to collectively as ‘Penning Hill quarries’.

Aerial photographs of the site show numerous rock outcrops with associated pits and delves spread across the hillside. The terrain is mainly open moorland at around 250 metres elevation, and the workings appear to be relatively free of vegetation. A rough vehicle track leads to the quarries from Tulloch farm.

The BGS Rock Collection includes five samples of sandstone from Penning Hill quarries and the adjacent ground. Three of these are closely similar and consist of dark purplish grey, fine-grained sandstone; this stone is significantly finer-grained and darker than the Swanshaw sandstone used in CCCP. The two other samples are strongly cohesive, reddish grey sandstone; the character of this stone suggests it may have been “baked” by nearby intrusions of igneous rock.

The Penning Hill quarries might provide a relatively accessible source of Swanshaw sandstone, but the stone is unlikely to be an ideal match for most of the stone used in CCCP.

2.2.2 Wellsheilds quarry

Stone from the Swanshaw Sandstone Formation was formerly produced from Wellsheilds quarry, which is around 4 km south of Lanark in South Lanarkshire (grid reference [NS 8756 3999]).

Aerial photographs of the site show a single square pit c. 20 m x 20 metres, which appears to be partly overgrown by trees, grass and shrubs. Exposed rock on the east side presumably represents a quarried rock face. The quarry is c. 80 metres from a paved road, and has no obvious access track.

The BGS Rock Collection includes one sample of sandstone from Wellshields quarry; the stone consists of bluish grey, coarse-grained sandstone and is unlikely to provide a good match for most of the sandstone used in CCCP.

2.2.3 Dunduff quarry

Dunduff quarry, 2 km southeast of Kirkmuirhill in South Lanarkshire (grid reference [NS 7790 4100]), is the only quarry that is currently extracting stone from the Swanshaw Sandstone Formation. The quarry is large and is currently operated as an aggregate quarry by Patersons Quarries Ltd; however, the BGS Building Stone collection contains several samples of stone from Dunduff quarry, suggesting it previously produced dimension stone. It may be possible to obtain dimension stone block from the quarry operator on request.

The BGS Rock Collection includes six samples from Dunduff quarry. They are all closely similar and consist of dark purplish grey, fine-grained, strongly cohesive sandstone. The stone is significantly finer-grained, darker and generally less permeable than the Swanshaw sandstone used in CCCP, and therefore is unlikely to be an ideal match for most of the stone used in buildings in CCCP. Swanshaw sandstone has been used for paving in some parts of CCCP, and stone from Dunduff quarry may be a suitable substitute for stone used in this way.

Figure 3 Quarries in the local (Ayrshire) outcrop of Swanshaw Sandstone Formation

a and b – Typical areas of worked former sea cliff forming ‘Gas House’ quarry. c – Buff sandstone with scattered greenish grey mud flakes and several large orange (ferruginous) patches developed on a fresh bedding plane surface revealed in a recently worked boulder on the beach at Gas House quarry. d – Boulders on the beach at Gas House quarry; the boulders were probably detached from the natural cliff face (hidden in the trees) during earlier (original) workings at the quarry; fresh surfaces on the two boulders in the photograph are the result of recent trials by NTS masons to determine whether suitable stone to use in CCCP can still be obtained from this site.

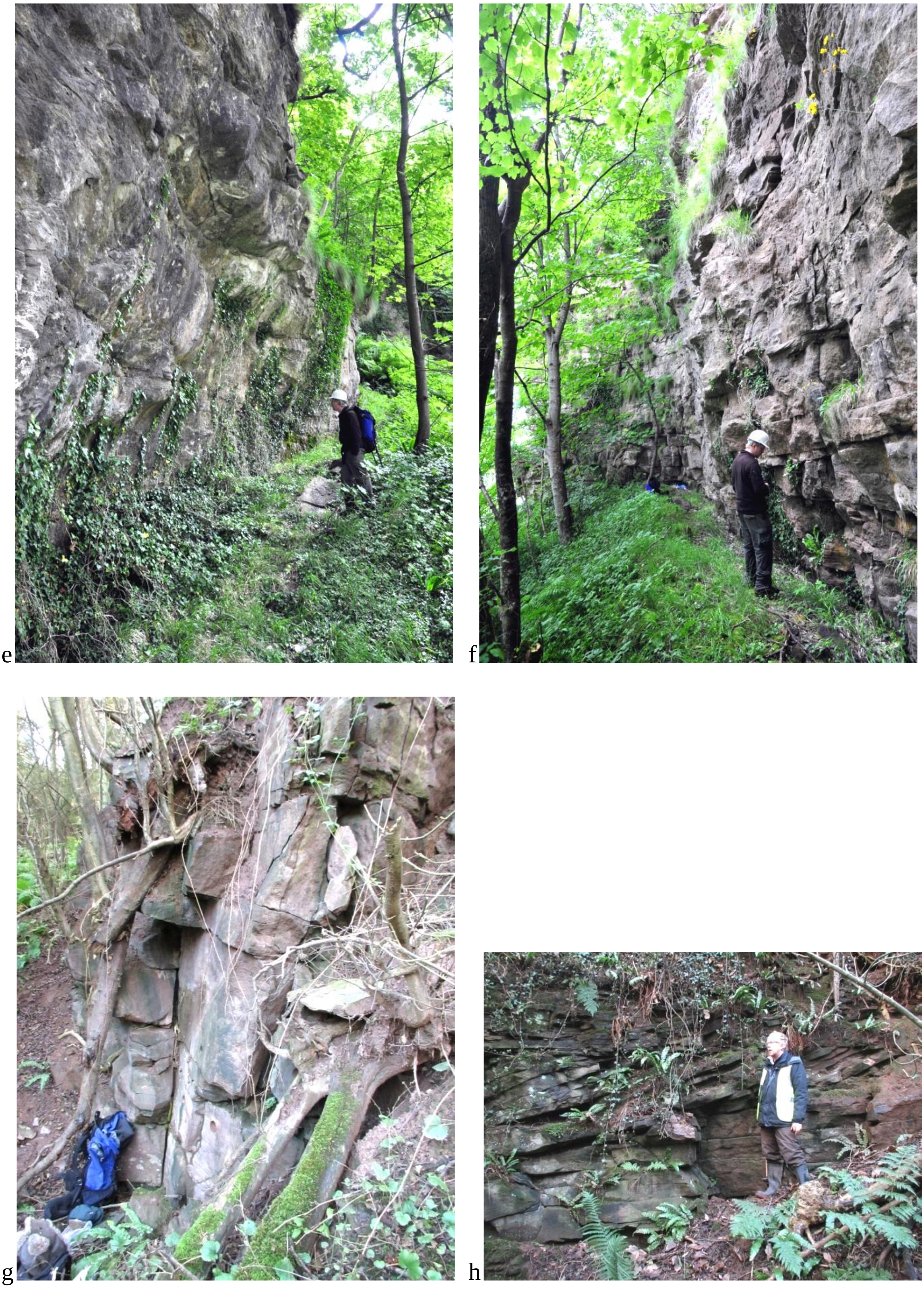

Figure 3 continued
e – Swallowcraigs quarry, lower level. f – Swallowcraigs quarry, upper level.
g – Bedrock exposed on the steep back wall of Ballochneil quarry. h – Bedrock exposed in an over-deepened part of the floor of Ballochneil quarry.

Figure 3 continued
i – Rancleugh Burn quarry; the quarry is choked with brambles, trees and other vegetation; the main remaining worked face is faintly visible in shadow, immediately to the right of the image centre. j – Cross-bedding and colour variation in Swanshaw sandstone exposed in Rancleugh Burn quarry. k – The north side of St Murray's quarry (main pit); the quarry and worked faces are readily accessible. l – Part of the exposed worked face in St Murray's quarry, showing Swanshaw sandstone with granulation seams (narrow ribs that stand proud) and scattered pebbles of quartz and granite.

3 Constraining the timing of quarry activity around Culzean Castle & Country Park

3.1 INTRODUCTION

Knowing which quarries produced the stone that has been used in CCCP buildings, and when they did so, is important for two reasons: it can inform efforts to identify potential new sources of suitable stone to use in repairs, and it can provide interesting detail about the social and economic history of CCCP and the surrounding area. This section of the report describes the outcomes of an attempt to produce a ‘timeline’ integrating building construction dates in CCCP and active periods in nearby quarries, based on historical records.

The timeline is presented in Figure 4. The list of built sites in CCCP and their construction dates were supplied by NTS; the list of sites is comprehensive and the construction dates are in most cases well constrained. Far less is known about quarrying activity, and this study has focused nearly entirely on that aspect of the timeline.

Two main types of record have been reviewed: written accounts, for example *Statistical Accounts of Scotland* and *Memoirs of the Geological Survey*; and Ordnance Survey (OS) maps. A list of all the records that have helped to constrain the timing of quarry activity is presented in Table 1. Unfortunately the OS map editions extend back only as far as 1856, but each edition provides an indication of quarry status at the time; for example, a quarry will usually only be shown on a map if it formed a significant topographic feature at the time, and the maps commonly include an annotation such as the quarry name (which, if present, usually indicates the quarry was at least locally significant and was, or had recently been, active) or ‘Old quarry’ (which would indicate the quarry was inactive at the time the map was published).

A comprehensive review of all available records (that could include, for example, the archive store at CCCP, records held centrally by NTS, and the National Records of Scotland) would be a substantial task, requiring considerably more work than has been possible here. A list of relevant reference sources, including those examined in this study and those that could be included in a more comprehensive review, is presented in Appendix 1.

3.2 CONSTRAINTS ON QUARRY ACTIVITY DATES

A range of reference sources was trawled for information relating to ‘active’ and ‘inactive’ periods in the seven quarries described in sections 2.1.1 to 2.1.7. Details of the various written reference sources and the information gleaned from them are summarised in Appendix 2. The information has been used on Figure 4 to indicate the periods in which each quarry is known to have been active or inactive.

Unfortunately, this review has identified relatively few records that help to constrain the timing of quarry activity, and very little evidence that links individual quarries directly to specific built sites in CCCP (Figure 4 and Appendix 2). Broad references to quarrying activity are more common, but still rare. Consequently, the period(s) in which each quarry was active in most cases remains poorly constrained. The review of records was not exhaustive, and more research may improve the precision of the timeline. Some of the more relevant bits of information are summarised in sections 3.2.1 to 3.2.7; additional details, and details of the source references (indicated below in parentheses) can be found in Appendix 2.

Quarry	17	C18th						C19th										C20th				
	1600s	1700-1750	1750	1760	1770	1780	1790	1800	1810	1820	1830	1840	1850	1860	1870	1880	1890	1900	1910	1920	1930	1940
Ballochneill quarry										🟧			🟧				🟧		🟧			
Blanefield quarry																			🟧			
Coralglen quarry													🟧				🟪		🟪			
Gas House quarry / Swallowcraigs quarry						🟧				🟧	🟧											
Rancleugh Burn quarry													🟧				🟧		🟪		🟪	
St. Murray's quarry											🟧	🟧	🟧				🟧		🟧		🟧	

Built site name *				Date of construction *	17	C18th						C19th										C20th				
					1600s	1700-1750	1750	1760	1770	1780	1790	1800	1810	1820	1830	1840	1850	1860	1870	1880	1890	1900	1910	1920	1930	1940
CUZ/01	Culzean (including West Wing)	CUZ/01a	Castle	1777-1792; 1879 (W wing, E porch)					🟩	🟩	🟩								🟦							
		CUZ/01b	West Wing Flanking Walls	c.1787						🟩																
		CUZ/01c	Carriage Ring Walls, De Avise La Fine	c.1787						🟩																
		CUZ/01d	Runnel	1780's -1790's					🟩	🟩	🟩															
CUZ/01	Carriage Ring	CUZ/01e	Mortar and Steps	c.1780's						🟩																
		CUZ/01f	Viewing Platform							🟩																
		CUZ/01g	Urn Garden							🟩																
CUZ/02	Fountain Court	CUZ/20	Fountain	1876															🟩							
		CUZ/02a	Orangery	1814									🟩													
		CUZ/02b	Upper Terrace Including Stair Tower	1652, c.1780 additions	🟩					🟦																
		CUZ/02c	Lower Terrace Including Stair Tower	1652, c.1780 additions	🟩					🟦																
		CUZ/02d	Ha Ha (built from c.1811 Cat Gate	1961																						
CUZ/03	Clocktower complex	CUZ/03a	The Coach House	c.1808									🟩													
		CUZ/03b	Education Room	1750s			🟩																			
		CUZ/03c	Clocktower Cottage				🟩																			
		CUZ/03d	WVS Cottage				🟩																			
		CUZ/03e	Royal Artillery Cottage				🟩			🟦																
		CUZ/03f	Clocktower				🟩			🟦																
		CUZ/03g	Lock-up Garage (5No.)	1750 with 1780's additions			🟩			🟦																
		CUZ/03h	Lower Store				🟩			🟦																
		CUZ/03i	The Garderobe	1750, 1780s alteration			🟩			🟦																
		CUZ/03j	The Gun Room and Stores	between 1792 and 1852						🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩									
CUZ/04	Dolphin House complex	CUZ/04a	Dolphin House	1840												🟩										
		CUZ/38	Plunge Pool	1816									🟩													
		CUZ/38	Round House										🟩													
		CUZ/04b	Cisterns	Age not known																						
		CUZ/05	Bath House	1816									🟩													
CUZ/06	Segganwell Cottages	CUZ/06a	Segganwell Cottages (North & South)	Pre 1856													🟩									
		CUZ/06b	Segganwell Wash House	1856													🟩									
CUZ/07	Firbank Cottages	CUZ/07	Firbank Cottages (North & South)	Mid-late 19th century																						
CUZ/08	Home Farm	CUZ/08a	Shop / Display / Audio Visual Area	c.1780, 1970s conversion						🟩																
		CUZ/08b	Restaurant							🟩																
		CUZ/08c	Public Toilets							🟩																
		CUZ/08d	Stores							🟩																
		CUZ/08e	Stone Barn Conference Room							🟩																
		CUZ/08f	Country Park Office							🟩																
		CUZ/08g	Home Farm House							🟩																
CUZ/09	Viaduct and Ruined Arch	CUZ/09a	Viaduct and Ice House	c.1787						🟩																
		CUZ/09b	Ruined Arch							🟩																
		CUZ/09c	Flanking Walls to Carriage Ring							🟩																
		CUZ/09d	Approach Walls to Ruined Arch							🟩																
CUZ/10	Gazebo Court	CUZ/10a	Old Stable	Post 1856														🟩								
		CUZ/10b	Gazebo	1790							🟩															
		CUZ/10c	Court Walls	1790							🟩															
CUZ/11	Gas Court	CUZ/11a	Gas House	c.1849													🟩									
		CUZ/11b	Gas Manager's House														🟩									
		CUZ/11c	Gas Court Walls														🟩									
		CUZ/11d	Gas Court perimeter wall														🟩									
		CUZ/11e	Gasometer Pit and Yard														🟩									
		CUZ/12	Sea Wall and Access Steps	post 1945																						🟩
CUZ/13	Main Drive Walls	CUZ/13	Main Drive Walls	Unknown																						
CUZ/14	Service Drive Walls	CUZ/14a	Stone Chute	Post 1856													🟩									
		CUZ/14b	Upper Service Drive Walls	1780-1795						🟩	🟩															
		CUZ/14c	Lower Service Drive Walls	1652, additions 1780	🟩					🟦																
CUZ/15	Hoolity Ha Lodge	CUZ/15	Hoolity Bridge	c.1818									🟩													
CUZ/16	Ardlochan Lodge	CUZ/16a	Ardlochan Lodge	1830, c.1900 extension											🟩							🟦				
		CUZ/16b	Gateway												🟩							🟦				
CUZ/17	Cat Gates	CUZ/17	Cat Gates	c.1811-1816, restored 1996									🟩													
CUZ/18	West Wall	CUZ/18	W Wall at S side of W green	pre-1814									🟩													
CUZ/19	Orangery	CUZ/19	Orangery	1814, restored 1993-4									🟩													
CUZ/22	Terrace Walls	CUZ/22	Terrace Walls	1652, c.1780 additions	🟩					🟦																
CUZ/23	Camellia House	CUZ/23	Camellia House	c.1818									🟩													

* Site names and dates of construction are from the ‘NTS Schedule of Stone Structures at Culzean Castle and Country Park’.

🟧	Historical record indicates quarry is ‘active’
🟪	Historical record indicates quarry is ‘inactive’
🟩	Date of construction of built site
🟦	Date of alteration of built site

Figure 4 'Timeline' integrating dates of built site construction in CCCP and dates of quarry activity/inactivity

Possible links between quarries and buildings are revealed by comparing dates of construction and quarry activity.

Quarry	17	C18th						C19th										C20th				
	1600s	1700-1750	1750	1760	1770	1780	1790	1800	1810	1820	1830	1840	1850	1860	1870	1880	1890	1900	1910	1920	1930	1940
Ballochneill quarry										🟧			🟧				🟧		🟧			
Blanefield quarry																			🟧			
Coralglen quarry													🟧				🟪		🟪			
Gas House quarry / Swallowcraigs quarry						🟧				🟧	🟧											
Rancleugh Burn quarry													🟧				🟧		🟪		🟪	
St. Murray's quarry											🟧	🟧	🟧				🟧		🟧		🟧	

Built site name *				Date of construction *	17	C18th						C19th										C20th				
					1600s	1700-1750	1750	1760	1770	1780	1790	1800	1810	1820	1830	1840	1850	1860	1870	1880	1890	1900	1910	1920	1930	1940
CUZ/24	Walled Garden complex	CUZ/26	Garden's House	c.1815									🟩													
		CUZ/47	Garden's Cottage										🟩													
		CUZ/24a	Vinery	1859													🟩									
		CUZ/24b	Grotto	1903																		🟩				
		CUZ/27	Stores and Potting Sheds	1815									🟩													
		CUZ/24c	North Garden	c.1815									🟩													
		CUZ/24d	South Garden										🟩													
		CUZ/24e	Herb Garden Gateway	1906																		🟩				
		CUZ/25	Slip Dyke	c.1820's										🟩												
		CUZ/24f	Spine Wall	pre-1815									🟩													
		CUZ/24g	North Garden Wall										🟩													
		CUZ/24h	South Garden Wall										🟩													
CUZ/27	Sunnyside Mill	CUZ/28	Sunnyside Mill	pre-1856													🟩									
CUZ/28	Water House	CUZ/29	Water House	c.1877 (?)															🟩							
CUZ/29	Filter House	CUZ/30	Filter House	1884																🟩						
CUZ/31	Swan Pond Buildings	CUZ/31a	Aviary and Toilets	c.1816, restored 1991									🟩													
		CUZ/31b	Swan Pond Cottage										🟩													
		CUZ/31c	Catering Area										🟩													
		CUZ/31d	Catering Stores										🟩													
CUZ/31	Swan Pond	CUZ/33	Duck House	c.1811									🟩													
		CUZ/34	Swan Pond Bridge										🟩													
		CUZ/37	Ice House										🟩													
		CUZ/31	Hogston Gate Pillars	pre-1828										🟩												
CUZ/35	Pagoda	CUZ/35	Pagoda	1814, reconstructed 1997									🟩													
CUZ/36	Powder House	CUZ/36	Powder House	1815									🟩													
CUZ/39	Morrison Bridge	CUZ/39	Morrison Bridge	c.1894																	🟩					
CUZ/40	Glenside	CUZ/53	Lower Bridge (Whitestone Bridge)	Between 1755-1775			🟩	🟩	🟩																	
		CUZ/54	Glenside Old Bridge	pre-1770				🟩																		
		CUZ/40	Glenside Railway Bridge	c.1894																	🟩					
CUZ/44	Frameyard	CUZ/44	Frameyard Walls	Unknown																						
CUZ/46	New Stables Building	CUZ/46a	Shop Area	1869, alterations1998														🟩								
		CUZ/46b	Upper North Flat															🟩								
		CUZ/46c	Lower North Flat															🟩								
		CUZ/46d	Upper South Flat															🟩								
		CUZ/46e	Lower South Flat															🟩								
CUZ/52	Caves	CUZ/52a	Stable Caves	17th century	🟩																					
		CUZ/52b	Castle Caves	Unknown																						
		CUZ/52c	Drain Outlet and Retaining Wall	c.1766				🟩																		

* Site names and dates of construction are from the 'NTS Schedule of Stone Structures at Culzean Castle and Country Park'.

🟧	Historical record indicates quarry is 'active'
🟪	Historical record indicates quarry is 'inactive'
🟩	Date of construction of built site
🟦	Date of alteration of built site

Figure 4 (continued)

3.2.1 Gas House quarry

Hayles & Bluck (1994) recorded that the "basal structure" of Culzean Castle (presumably the original 'L-plan' tower) "was built during the Twelfth Century from stone which was quarried beneath Home Farm, facing the sea, on the Culzean Estate (grid reference 234 104)". This clearly refers to the site of 'Gas House' quarry, but unfortunately the authors did not cite the source of their information.

The earliest identified records pertaining to building stone in CCCP are from the late-18th century and appear in 'The Register of Improvements on Entailed Estates, Inventory of Ayr Sheriff Court'. These records refer to 'leading stones from Cullean (sic)' (SC6/72/1, 1786), and 'quarrying stones…at Cullean (sic) Quarry' (SC6/72/1, 1788); however, the location of the quarry site (or sites) is not hinted at until 1826 with the mention of 'quarrying and dressing stones upon the shore' (SC6/72/7); this description suggests 'Cullean' quarry may refer broadly to the site termed 'Gas House quarry' in this report.

None of the OS map editions gives any hint of former quarrying operations at this site.

3.2.2 Swallowcraigs quarry

No historical records have been identified that unambiguously link Swallowcraigs quarry to CCCP. However, in describing the source of stone used in 'the castle' (i.e. Culzean Castle), Camp (see Appendix 3) stated that "It has been suggested that stone also came from Swallowcraigs"; unfortunately, the author did not cite the source of this information.

All editions of the OS map show a bowl-shaped 'scoop' on the approximate site of Swallowcraigs quarry, with the name 'Swallow Craigs' or 'Swallowcraigs' next to it. However, the site is not identified as a quarry (either by name or map ornament) on any of the OS maps.

3.2.3 Ballochneil quarry

The earliest identified reference to Ballochneil quarry is in 1829 (SC6/72/8), when it is mentioned in association with details of infrastructural elements (e.g. paving) in Cassillis estate. 500 tons of stone was being produced annually from the quarry in the mid 1850s (Hunt, 1857).

The site is named and identified as a 'freestone quarry' on the first (1856) OS map, and is named (and may therefore have been active) on both the 1897 and 1911 editions. A quarry is not shown on any of the present-day OS maps.

3.2.4 Blanefield quarry

No historical records linking Blanefield quarry to CCCP have been identified. Both Camp (1990) and Rowan (1992) indicated that the quarry may have supplied a lot of stone to 'Culzean', but unfortunately neither author cited the source of their information. Worked ground at Blanefield appeared for the first time on an OS map in the 1911 edition, where a 'gravel pit' was recorded. It seems possible therefore that a 'Blanefield quarry' supplying building stone predated and had been infilled by the time of the first OS map (1856), and a second (possibly unrelated) Blanefield quarry producing gravel opened subsequently, and was active around 1911. There is no obvious sign of any previous quarrying activity at the site today (but see section 2.1.4).

3.2.5 Rancleugh Burn quarry

No historical records linking Rancleugh Burn quarry to CCCP have been identified. The site is recorded as a 'freestone quarry' on the first (1859) OS map, was shown as a quarry ornament but not labelled on the 1897 map, and was labelled 'Old quarry' on the 1910 edition. Rancleugh Burn quarry is still shown but not labelled on the current OS map.

3.2.6 St Murray’s quarry

The earliest records that mention St Murray’s quarry link the quarry to ‘Castle farm’ (SC6/72/10, 1832) and to cope stones used on a ‘wall at bridgend’ (SC6/72/11, 1836) on the Cassillis estate. There is no record of farm buildings being under construction in CCCP at this time, so it is not clear if these sites are within present-day CCCP; however, the record may relate to a repair (see Appendix 2). 5,000 tons of stone was being produced annually from St Murray’s quarry in the mid 1850s (Hunt, 1857); this is the largest recorded tonnage of any quarry between Ayr and Girvan at this time.

Both pits on the St Murray’s quarry site (see section 2.1.6) are shown on all editions of the OS map of the area. The north pit was disused by the time of the first edition (1859) map. The main (south) pit is recorded as ‘disused’ on the present-day map, but on all older editions it is named and may therefore have been active (continuously or discontinuously) from at least 1859 until 1938. The change in the mapped extent of St Murray’s quarry on the 1859 and 1897 editions of the OS map show that the quarry grew significantly during this period.

3.2.7 Coralglen quarry

No historical records linking Coralglen quarry to CCCP have been identified. The site is recorded as a ‘freestone quarry’ on the first (1859) OS map but was infilled by the time of the second (1897) edition.

Table 1 Reference sources used to constrain periods of activity in quarries around CCCP

Quarry	Written record	Ordnance Survey maps			
		Edition	Sheet	Quarry shown	Map annotation
Ballochneil (Ballochneill)	1829 (SC6/72/8) 1857 (Hunt)	1856	Ayrshire 44	Yes	'Ballochneil Quarry (Freestone)'
		1897	Ayrshire 44SW	Yes	'Ballochneil Quarry'
		1911	Ayrshire 44SW	Yes	'Ballochneil Quarry'
		Current	NS20NW	No	none
Blanefield	None	1856	Ayrshire 44	No	none
		1897	Ayrshire 44SW	No	none
		1911	Ayrshire 44SW	Yes	'Gravel Pit'
		Current	NS20NW	No	none
Coralglen	None	1859	Ayrshire 44	Yes	'Coralglen Quarry (Freestone)'
		1897	Ayrshire 44NE	No	none
		1911	Ayrshire 44SW	No	none
		Current	NS20NE	No	none
Gas House	1786 (SC6/72/1)* 1788 (SC6/72/1)* 1826 (SC6/72/7)	1856	Ayrshire 44	No	none
		1897	Ayrshire 44SW	No	none
		1911	Ayrshire 44SW	No	none
		Current	NS21SW	No	none
Rancleugh Burn	None	1859	Ayrshire 44	Yes	'Freestone Quarry'
		1897	Ayrshire 44NE	Yes	none
		1910	Ayrshire 44NE	Yes	'Old Quarry'
		1938	Ayrshire 44NE	Yes	'Old Quarry'
		Current	NS21SE	Yes	none
St. Murray's	1832 (SC6/72/10) 1836 (SC6/72/11) 1845 (Gray) 1857 (Hunt) 1885 (Groome)	1859	Ayrshire 45	Yes (north pit)	'Old Quarry (Sandstone)'
		1859	Ayrshire 45	Yes (south pit)	'St Murray's
		1897	Ayrshire 45NW	Yes (north pit)	'Old Quarry'
		1897	Ayrshire 45NW	Yes (south pit)	'St Murray's Quarry'
		1911	Ayrshire 45NW	Yes (north pit)	'Old Quarry'
		1911	Ayrshire 45NW	Yes (south pit)	'St Murray's Quarry'
		1938	Ayrshire 45NW	Yes (north pit)	'Old Quarry'
		1938	Ayrshire 45NW	Yes (south pit)	'St Murray's Quarry'
		Current	NS31SW	Yes (north pit)	'Quarry (disused)'
		Current	NS31SW	Yes (south pit)	'Quarry (disused)'
Swallowcraigs	None	1856	Ayrshire 44	No	none
		1897	Ayrshire 44SW	No	none
		1911	Ayrshire 44SW	No	none
		Current	NS21SW	No	none

4 Geological character of Swanshaw sandstone

Swanshaw sandstone is moderately variable, particularly in terms of colour, and presents a wide range of responses to weathering processes. A thorough assessment of the geological character of the stone is key to understanding both the variability in its appearance and the varied response to weathering. A description of the stone based on macroscopic and microscopic assessments is presented in this section of the report. A full, detailed assessment ideally would include Scanning Electron Microscopy (SEM) analysis, but that is beyond the scope of this project.

The names of buildings referred to in this and later sections of the report are taken from the 'NTS Schedule of Stone Structures at Culzean Castle and Country Park'. The same names are used in Figure 4. A description of the location and character of the buildings in CCCP is beyond the scope of this report.

4.1 MACROSCOPIC CHARACTER OF SWANSHAW SANDSTONE

This description of the macroscopic character of Swanshaw sandstone (i.e. how the stone looks to the unaided eye) is based on observations of the stone in quarry faces, in stone structures in CCCP, and in hand samples collected from quarries and buildings. Hand samples collected by BGS for the current project and the 2012 project have been included in the assessment, together with several hand samples supplied in recent years by NTS (to support commercial BGS Building Stone Assessment studies) and several samples held in the BGS Rock Collection.

The Swanshaw Sandstone Formation consists dominantly of sandstone but includes subordinate proportions of mudstone and conglomerate. All of the stone used in CCCP is sandstone and the following description refers only to that rock type. Intact beds of mudstone and conglomerate were not observed in any of the visited quarries, though in rare localised cases a high density of mudstone flakes in the sandstone suggests a thin bed of mudstone was disaggregated *in situ* by an unusually strong current.

The sandstone is typically medium-grained (individual sand grains are mainly in the range 0.25 to 0.5 mm in diameter), but grades locally towards fine-grained (<0.25 mm) and coarse-grained (>0.5 mm). Granules and pebbles of quartz, chert, granite and other rock types occur locally, though rarely in sufficient concentration or abundance to form pebbly sandstone. Fresh stone is typically strongly cohesive and moderately permeable. Weathering tends to reduce cohesion and can increase or decrease permeability.

The primary sedimentary structure (or fabric) of the stone typically varies on a range of scales. At the scale of a masonry block the stone can be parallel-bedded, cross-bedded, laminated or uniform (Figure 5a,b).

The colour of the freshest stone ranges from orangeish buff to greenish buff and purplish grey, but the stone weathers to an even broader range of colours including reddish brown, orange and green (Figure 5c).

Orange to brown spots and patches, which range from less than 1 mm up to several 10s of centimetres across and typically occur in clusters, are a common feature of the stone (Figure 5a,b,d). These are likely to be local concentrations of iron oxide minerals left when an iron-rich carbonate mineral dissolved (see below and Appendix 3); these are referred to below as *ferruginous spots* and *patches*. Thin, straight to curved, orange to brown lines that cut the stone locally are likely to be former veins of iron-rich carbonate from which the carbonate mineral has been dissolved leaving an iron oxide residue (Figure 5d).

Thin veins of white quartz cut the sandstone locally; these were observed in some of the stonework of Home Farm and may be a feature only of stone from Gas House quarry. Sets of very thin, usually anastomosing fractures representing small geological faults are developed rarely; examples were seen in Swallowcraigs quarry and in some masonry blocks (Figure 5e).

Fragments of grey to green and purple to brown mudstone are relatively common (Figure 5f). These are typically up to several centimetres long and can be isolated but they usually are concentrated in bedding-parallel bands up to several 10s of centimetres thick. Grey to green mudstone typically occurs in buff sandstone while the purple to brown mudstone typically occurs in purplish stone.

The stone in individual quarries and outcrops, and in many individual buildings in CCCP, commonly displays some or all of the features and variability described above, which in most cases means it is not possible to conclusively relate the sandstone blocks in a building to a particular quarry without supporting historical information. The Swanshaw sandstone used in CCCP is therefore best considered to be a single building stone displaying a range of colour and other characteristics.

In general, stone from Gas House quarry, Ballochneil quarry and Rancleugh Burn quarry cannot be distinguished easily on the basis of geological character alone. Stone from St Murrays quarry, while still displaying essentially similar characteristics in most respects, may be considered to be a distinctive purplish grey to reddish brown variant of Swanshaw sandstone.

4.2 MICROSCOPIC CHARACTER OF SWANSHAW SANDSTONE

Microscope examination of stone samples allows the most detailed description of the stone in its current form, and an assessment of the processes that have occurred during its geological history.

A thin section (an ultra-thin slice of the stone that is thin enough to be transparent) for microscope analysis was prepared from each of seven samples of stone collected by BGS. Four of these are from quarry sources: Gas House quarry (sample ED11209), Ballochneil quarry (ED11211), St Murray’s quarry (ED11214) and Swallowcraigs quarry (ED11357). These four represent most of the colour range of Swanshaw sandstone, and the stone in each case is in a relatively fresh (unweathered) state. The remaining three thin sections represent samples from buildings in CCCP: one (ED11215) is from a piece of moderately weathered stone that had detached naturally from Ruined Arch. The two others (ED11359 and ED11360) are pieces of greenish, strongly weathered sandstone collected from the NTS stone yard in the park; these are from blocks of stone that have been replaced in repaired stonework, and represent the character of the most weathered stone in the park.

Sandstones consist of two main categories of material: *granular* (or *detrital*) *constituents* and *intergranular constituents*. Granular constituents are the sand grains (and, in some cases, pieces of plant matter and shell fragments) that were deposited by water or wind to form the layer of sand from which the sandstone ultimately formed. Intergranular constituents include any minerals that formed on or between the granular constituents after they were deposited, and any space between the granular constituents that is not occupied by minerals; the latter is referred to as *pore space*. Pore space is commonly considered to be ‘empty space’ but is in fact always occupied by a fluid such as water, oil, natural gas or air.

Prior to preparing the thin sections, each sample of stone was impregnated under vacuum with a blue resin; the resin fills all the accessible pore spaces in the stone, and these appear blue in thin section. The thin sections were examined using a standard optical (polarising) microscope. Simple petrographic descriptions for the seven samples, including photographs of each sample in hand specimen and thin section, are presented in Appendix 3. In the following summary descriptions all percentages assigned to individual constituents are estimates of the proportion of rock volume that they occupy, based on a simple visual assessment of the thin sections. The thin section photographs presented in Figure 6a-d should be consulted while reading the following description.

4.2.1 Granular constituents

The two main types of granular constituent in all the Swanshaw sandstone samples are *quartz* (28–36%) and *rock fragments* (14–37%). *Feldspar*, which is the third main granular constituent in many sandstones, is a minor component in the Swanshaw sandstone samples, comprising only 1–4% of rock volume. These relative proportions of the main granular constituents mean that Swanshaw sandstone can be classified as *lithic-arenite*.

Grains of quartz typically consist of fragments of single quartz crystals (i.e. they are *monocrystalline*), and the rock fragments consist almost exclusively of small pieces of volcanic igneous rock and mudstone; these characteristics are typical of many sandstones deposited in Scotland during the Devonian Period (between 419 and 359 million years ago). The quartz grains are typically angular or very angular (i.e. they have suffered little abrasion during transport, which suggests they did not travel far before deposition). Both of the common mica minerals – *muscovite* (white mica) and *biotite* (brown to black mica) – are present in small proportions (total mica = 1–5%) and form elongate flakes that are usually aligned parallel to the bedding orientation. Flakes of muscovite are usually fresh and flakes of brown biotite commonly have been replaced by green *chlorite*. Rounded fragments of the minerals *tourmaline*, *zircon*, *apatite* and, rarely, *garnet* form a tiny (<<1%) proportion of each sample.

4.2.2 Intergranular constituents

The Swanshaw sandstone samples contain evidence for a moderately complex history of mineral growth and mineral dissolution in the intergranular spaces of the stone.

Many of the detrital quartz grains have thin overgrowths of quartz that formed during burial; the quartz overgrowths comprise 1–4% of the rock volume. In the sample from St Murray’s quarry the quartz grains have a veneer of iron oxide (probably the mineral *hematite* or *goethite*). This is a feature that is commonly observed in sandstones deposited in a desert (as opposed to river- or sea-bed) environment, and is likely to be at least partly responsible for the purplish to brownish appearance of St Murray’s quarry stone compared to the generally buff sandstone from other quarries. Some grains of feldspar have thin overgrowths of feldspar, but these are much less common than the overgrowths on quartz grains.

Carbonate minerals comprise up to 12% of rock volume, though their proportion varies considerably in different samples. Two carbonate minerals are present: *calcite* ($CaCO_3$) and an iron- and manganese-rich carbonate mineral. The latter mineral is likely to be *ankerite* ($Ca[Fe,Mg,Mn][CaCO_3]_2$), though *ferroan dolomite* (which has a similar chemical formula to ankerite) or *siderite* ($FeCO_3$) may be present instead or additionally.

Carbonate minerals are susceptible to dissolution in groundwater, so the proportion that is present in the stone today depends on how much formed in the geological past and how much has survived subsequent dissolution. Ankerite is rich in iron and manganese, and it typically grows in sandstone pore spaces as clusters of well-formed rhomboidal crystals. When ankerite dissolves it commonly leaves a residue of iron-manganese oxide minerals, which appear black in thin section and commonly preserve the shape and outline of the original ankerite crystals. Even if all the ankerite has dissolved, such residues can provide good evidence that it was there previously. Calcite is more likely to form poorly shaped crystals, and typically contains little or no iron and manganese, so calcite can dissolve completely from sandstone and leave little evidence that it was there previously.

The thin section evidence indicates that ankerite and calcite were previously important intergranular constituents in all the Swanshaw sandstone samples but have typically suffered moderate to substantial dissolution. The sample from St Murray’s quarry is the only one that contains no carbonate mineral today, but iron-manganese oxide residues throughout the stone (at 24% the largest proportion in any sample) indicate that ankerite was formerly an important mineral cement that has now dissolved completely. There is no evidence in St Murray’s stone to indicate that calcite was previously present, but comparison with the samples from other quarries suggests it is likely to have been present formerly. Ankerite originally developed in all the samples but to varying degrees: in the St Murray's sample it was distributed evenly throughout the stone; in the Ballochneil sample it may have been concentrated in bands; and in all the other samples it appears to have formed mainly as scattered, isolated nodules and spots. The orange to brown spots, patches and veins described in section 4.1 are likely to be patches of altered ankerite.

Where it is preserved, calcite typically forms isolated (sometimes corroded) small crystals or larger patches that can enclose several to many sand grains.

A clay mineral, probably *kaolinite* ($Al_2Si_2O_5[OH]_4$), forms between 2 and 14% of the rock volume in all the samples. The clay typically forms clusters of very small crystals filling intergranular spaces.

Intergranular *pore space* is a significant component of all samples, forming between 6 and 13% of the rock volume.

4.3 DIAGENETIC HISTORY

Sandstone can undergo a long history of mineral and textural changes that are related to the physical and chemical processes that occur as the deposited sand is buried (sometimes to a depth of several kilometres or more), converted to rock, and uplifted back to Earth's surface; these changes are referred to collectively as *diagenesis*, and the sequence of changes is the *diagenetic history*. Diagenesis does not include processes and effects related to *weathering*, which occur when the stone is exposed to atmospheric agents and organic matter at Earth's surface and in the shallow subsurface.

Careful observation of mineral textures in thin sections allows the various changes that occur during diagenesis to be placed in order. The following *diagenetic history* for Swanshaw sandstone has been interpreted, beginning with the earliest event.

1. *The deposited sand suffered compaction as it was buried to progressively deeper levels by continuing deposition of new sand at the surface*. Compaction causes the sand grains to press into each other with the effect that softer grains (notably some of the rock fragments and the mica flakes) are squeezed between harder grains (mainly quartz) causing them to deform; mica flakes in particular become twisted and kinked by compaction deformation. A substantial proportion of the primary pore space is lost during compaction, and the sediment gains cohesion (becomes *lithified*) as the sand grains are pressed against each other.
2. *Grains of quartz and feldspar suffered pressure-solution at grain contacts, releasing silica and other ions into the pore water and allowing overgrowths of quartz to form on most quartz grains and overgrowths of feldspar to form on some feldspar grains*. The overgrowths act to bind the sand grains together more strongly, forming a strong mineral cement. The Swanshaw sandstone samples contain evidence for at least two generations of quartz overgrowth development, perhaps related to separate phases of burial. Compaction of the stone and the development of quartz overgrowths reduce the size of individual pore spaces and the overall volume of pore space.
3. *The fragments of volcanic rock began to suffer chemical alteration*. This happens as burial increases the temperature and changes the chemical composition of the groundwater. The main effect of alteration is that susceptible minerals in the volcanic rock fragments (including feldspar, amphibole, pyroxene and mica) are replaced by the minerals chlorite (an iron-magnesium-aluminium-silicate mineral) and iron oxide. This process of alteration probably continues throughout much of the subsequent geological history.

4. *Crystals of ankerite grew in some of the remaining pore space*. Clusters of small, well-formed, rhomboidal ankerite crystals locally form scattered small spots, larger patches, discrete bands, or a continuous mineral cement. Calcite may crystallise after the ankerite crystals as part of the same diagenesis event.
5. *Crystals of kaolinite (clay mineral) grew in most of the remaining pore space*. In sandstones, kaolinite typically forms through the chemical alteration of feldspar and mica; the clay particles can replace these minerals *in situ* or they can crystallise in pore spaces.
6. *Ankerite dissolved locally*. This created new pore spaces and a 'residue' of iron-manganese oxide minerals. The oxide minerals can preserve the original shape of the ankerite crystals and can also enclose patches of relict fresh ankerite.
7. *Crystals of calcite grew in some of the remaining pore space*. This happened partly in pore spaces and partly by direct replacement of other minerals (notably feldspar). The result is an intergranular calcite cement that typically forms discrete spots or patches up to several millimetres across.
8. *Crystals of calcite dissolved*. Calcite is present today in most of the examined samples, suggesting that calcite dissolution (at least as a diagenetic process) is generally limited. However, the complete absence of calcite from the St Murray's quarry sample suggests the mineral may have dissolved completely from some parts of the Swanshaw Sandstone Formation; it's not clear if this was a result of diagenesis or weathering.

Subsequent events related to weathering are described in section 6.

Figure 5 Macroscopic character of Swanshaw sandstone

a - Block of greenish Swanshaw sandstone showing cross-bedding, ferruginous spots and soft-bed erosion (Ruined Arch, south tower). b – Ashlar from St Murray’s quarry showing parallel bedding and cross-bedding with ferruginous spots and patches (Culzean Castle West Wing). c - Rubble wall showing the typical range of colour in Swanshaw sandstone; some blocks, particularly green stone, show locally significant material loss behind relatively recent repointing mortar (New Stables, west elevation). d - corner block of weathered Swanshaw sandstone showing contorted bedding, hairline veins, iron-rich spots and salt efflorescence (Ruined Arch: south limb). e – Small fault (granulation seam) showing minor offset of beds in Swanshaw sandstone (Home Farm). f – A mullion of pinkish grey sandstone from St Murray’s quarry with scattered grey to reddish brown mud flakes (Camellia House).

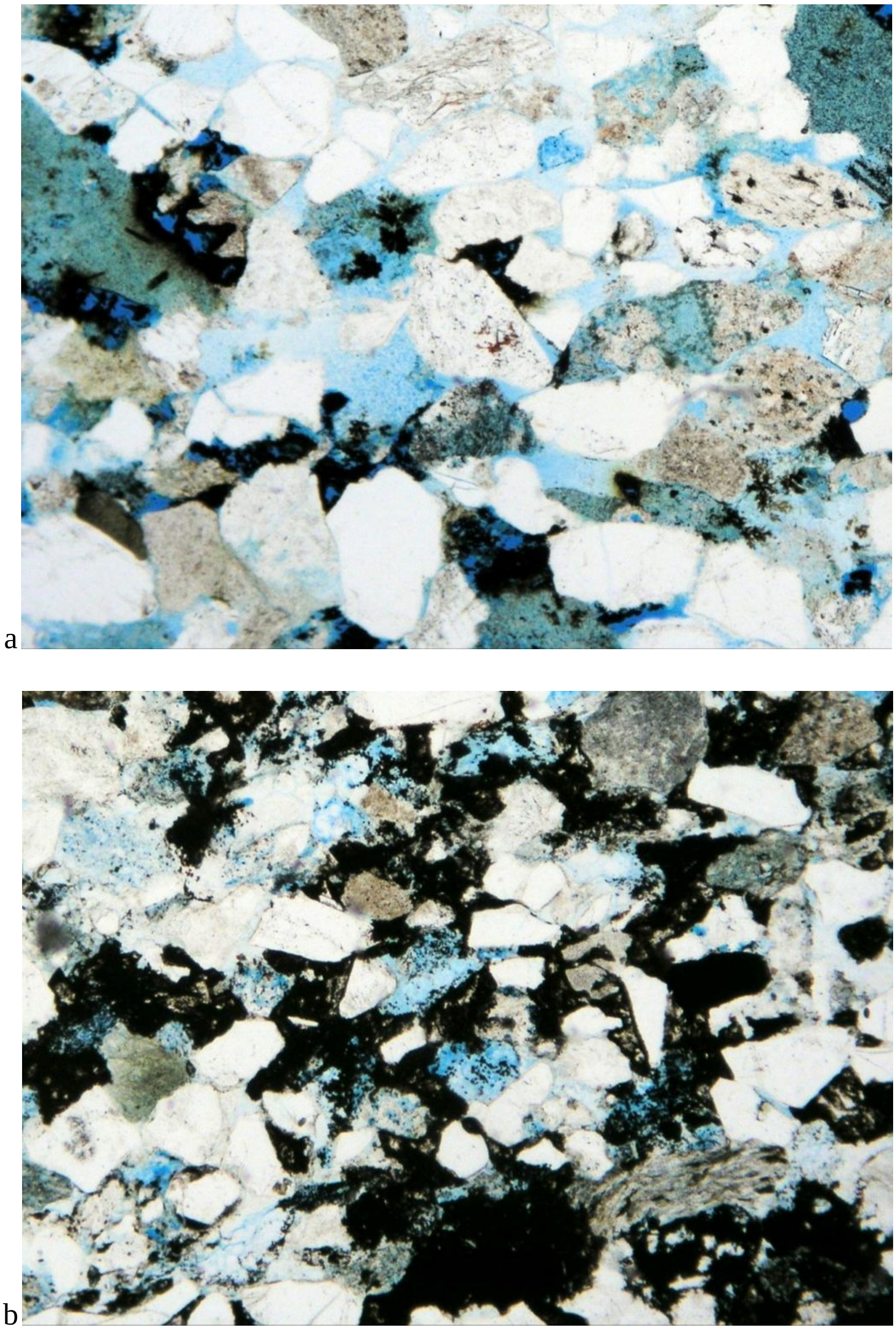

Figure 6 Microscopic (thin section) character of Swanshaw sandstone

a – Typical stone from Gas House quarry (sample ED11209). b – Typical stone from Ballochneil quarry (sample ED11211). The field of view in both images is around 2 mm wide. In both images: white grains are quartz, light brown grains are mainly feldspar and mottled green to grey grains are rock fragments (fine-grained volcanic rock); black patches are iron oxide, mottled pale blue areas are kaolinite clay and dark blue areas are pore spaces. A small proportion of fresh iron carbonate mineral is contained within the iron oxide in the sample from Ballochneil quarry. In both samples the iron oxide shows evidence that it has formed from the dissolution of iron carbonate, including preserved mouldic pore spaces.

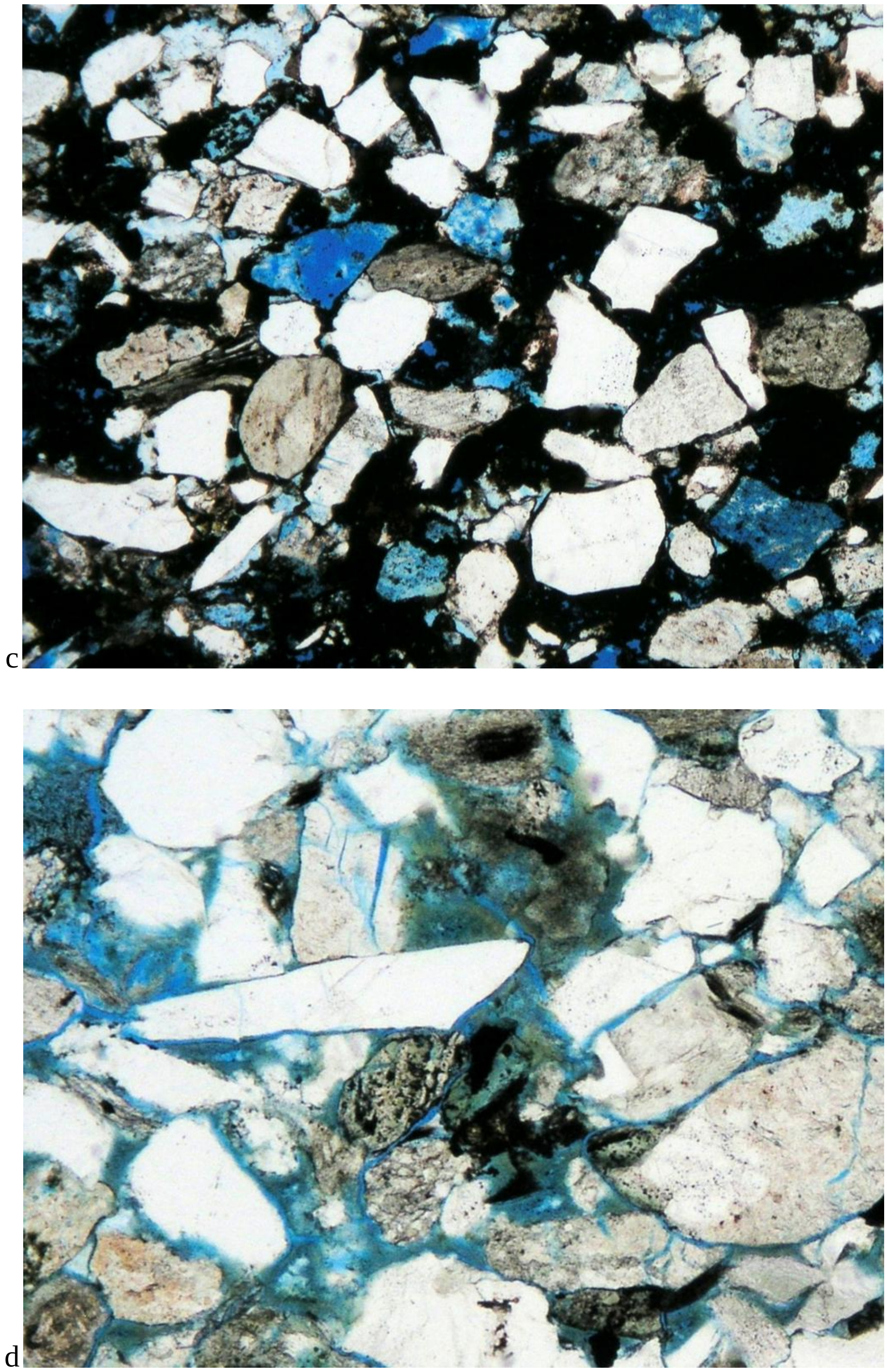

Figure 6 (continued)
c – Typical stone from St Murray’s quarry (sample ED11214). d – Strongly weathered Swanshaw sandstone recovered from a building in CCCP (sample ED11359). The field of view is around 2 mm wide in the top image and 1 mm wide in the bottom image. In both images: white grains are quartz, mottled green, brown and grey grains are mainly fragments of fine-grained volcanic rock, though a small proportion are feldspar; black patches are iron oxide, mottled pale blue areas are kaolinite clay and dark blue areas are pore spaces. The St Murray’s stone (c) has a large proportion of iron oxide and no carbonate mineral; mouldic pore spaces after dissolved rock fragments are common. The strongly weathered sample (d) shows green chlorite developing on many grain boundaries and along widened gaps between the sand grains; the green mineral is the cause of the increasingly green colour of strongly weathered stone, and the widespread gaps between sand grains are the cause of granular disintegration.

5 Causes of weathering in sandstone

Weathering refers to the processes that cause rocks and minerals to change when they are exposed to atmospheric agents and organic matter at Earth's surface and in the shallow subsurface; the colour, composition, texture, permeability, density, cohesion and strength of stone can all be affected by weathering. Weathering occurs *in situ*, and is thus distinct from *erosion*, which involves the movement of rock and mineral fragments by water, ice, wind and gravity; however, the two processes commonly work together as stonework ages and decays.

Two classes of weathering can be distinguished: *physical* (or *mechanical*) *weathering* and *chemical weathering*. Physical weathering, which involves processes like *abrasion* and *freeze-thaw action*, is commonly accentuated in cold or dry environments, whereas chemical weathering, which involves chemical reactions (in the presence of water or air), is usually most intense in warm, humid environments. The two classes of process usually work together to some degree, particularly in temperate environments.

The character and causes of weathering in sandstone are reviewed briefly below, to provide context for later sections of this report. Photographs illustrating some of the features are presented in section 6. Numerous publications provide more detail on the character and causes of weathering in sandstone; some of the more commonly referenced publications include Smith & Turkington (2004), Prikryl & Smith (2007), and ICOMOS-ISCS (2008).

5.1 NATURAL WEATHERING PROCESSES THAT CAUSE STONE DECAY

The main weathering agent to affect sandstone is usually water. Most of the sandstone exposed at Earth's surface (including nearly all building stone sandstones) is permeable to some degree, and both liquid water and water vapour are able to penetrate the stone *via* connected pore spaces between the sand grains and *via* cracks, joints and other fractures. A range of natural weathering processes can occur once water is in (or on the surface of) the stone and in contact with minerals:

- *mineral alteration* – some minerals undergo chemical reaction that leads to the formation of new minerals; for example, feldspar can be replaced by kaolinite (a clay mineral), and iron oxide can be replaced by iron oxyhydroxide
- *mineral dissolution* – some minerals are prone to dissolve in weathering environments, in which case their constituent chemical elements may be removed completely in percolating water or precipitated elsewhere in the stone as new minerals; carbonate minerals (such as calcite, dolomite and ankerite) are particularly susceptible to dissolution
- *mineral growth* – some minerals, including salt and ice, can grow in sandstone pore spaces in weathering environments.

Most of the effects of weathering in sandstone are a direct consequence of one or more of these grain-scale processes. Some of the effects that are commonly visible in stonework are described below.

5.1.1 Discolouration

Mineral alteration and mineral dissolution can lead to the precipitation of new minerals, either at the same location or at another location in the stonework where the chemical environment is suitable; the precipitation of new minerals can discolour stone. For example, the alteration or dissolution of carbonate minerals commonly results in the precipitation of iron and manganese oxide minerals; these minerals are typically orange, brown or black, and even very small proportions can cause stone to become significantly discoloured. Much of the colour variability displayed by Swanshaw sandstone is due to the varying degree to which iron oxide minerals have formed in intergranular spaces following the dissolution of an iron-rich carbonate mineral.

The growth of white salt crystals on exposed stone surfaces (*salt efflorescence*) is another cause of stone discolouration.

5.1.2 Case hardening and scaling

The contrast between the chemical environments inside and outside a masonry block can create a chemical gradient within the stone. Such gradients typically develop perpendicular to the surface of the block, and can cause chemical elements released by mineral dissolution or mineral alteration to move from interior parts of a stone block towards the surface of the block where they can precipitate as new minerals. *Case hardening* – in which the near-surface parts of a stone block harden due to mineral precipitation while the stone behind the hardened stone becomes weaker due to mineral dissolution and alteration – is a common consequence of this process in sandstone masonry. Sandstone blocks that have suffered case hardening are typically prone to *contour scaling*, whereby flakes and platy fragments of stone detach from the block along fractures that develop parallel to the block surface in the band of weakened stone.

5.1.3 Granular disintegration

The bonds between sand grains in sandstone can be weakened by weathering processes; for example, mineral alteration or mineral dissolution can weaken or remove some of the framework grains and mineral cements, and crystals of ice or salt growing in pore spaces can prise apart formerly cohesive sand grains. If the bonds become sufficiently weak, individual sand grains can become detached from the surface of a stone block and removed by erosion; this process is known as *granular disintegration*.

5.1.4 Soft-bed erosion and coving

Sandstone is deposited in layers, or *beds*, and each bed may differ slightly in character compared to those above and below it (e.g. in terms of grain-size, or the amount and type of granular constituents and intergranular constituents). This commonly leads to differences in the weathering susceptibility of each bed, with the effect that some beds become more weathered than others; this produces a weathering effect known as *soft-bed erosion*. Extreme erosion due to granular disintegration can produce large concave depressions in block surfaces, known as *coving*.

5.1.5 Delamination

Bedding surfaces and bedding planes (the surfaces that separate successive layers of deposited sediment) in sandstone can be particularly prone to weathering and parting. Parting along bedding surfaces (which typically manifests as hairline planar cracks that follow the ‘grain’ of the stone) is known as *delamination* or *splitting along bedding*.

5.2 ENVIRONMENTAL FACTORS THAT CAN ACCELERATE STONE DECAY

The following factors related to environment and setting can influence the rate at which natural stone (and stonework) suffers weathering-related decay.

5.2.1 Exposure and aspect

The degree to which stonework is exposed to rain, wind and sun can have a major impact on the dynamics of moisture ingress and egress. For example, elevated, protruding, south-facing stonework is likely to receive more sun and more wind than recessed, north-facing stonework, and hence may be less prone to chronic water saturation.

5.2.2 Salt weathering

Salt derived through evaporation of sea-water can be transported onshore in an aerosol (a suspension of fine solid or liquid particles in air), and in this form can enter the pore structure of sandstone stonework (this includes pore spaces within the stone, within the mortar, and in gaps between stone and mortar). Crystals of salt can grow in the pore structure if the host material subsequently dries out. In some cases the expansive force of growing salt crystals can prise-apart constituent components in the stonework, promoting granular disintegration in the stone and widening any gaps between stone and mortar. *Alveolisation*, also known as *honeycomb weathering*, is the most distinctive weathering style that is likely to be due mainly to salt, though other factors including case hardening may play a role in producing the distinctive alveoli. The stone buildings on a coastal site (such as those at Culzean), especially those adjacent to the sea, will be potentially more susceptible to salt weathering than inland buildings.

5.2.3 Freeze-thaw action

The transformation of liquid water to ice is accompanied by an increase in volume, so repeated freeze-thaw cycles promote granular disintegration and crack-widening in wet stonework and as such are an important cause of physical weathering. Stonework in sheltered areas and ‘frost hollows’ is likely to suffer more freeze-thaw cycles than stonework in exposed areas, but stone structures on coastal sites and low-lying sites generally will suffer fewer freeze-thaw cycles than buildings in inland and/or upland sites.

5.2.4 Biogenic growth

Stone surfaces that are moist or wet for long periods of time can provide a good environment for biogenic growth to develop. Bacteria, algae, lichen, mosses, fungi and even higher-order plants growing on stone surfaces are commonly a sign of long-term wetness. The development of biogenic growth will usually exacerbate a wetness problem because the plant matter retains moisture and prevents the stone surface from drying out.

5.2.5 Subsidence or structural instability

Fractures that develop in individual stone blocks or transect stonework (e.g. because of subsidence/structural instability) can act as conduits through which water can penetrate quickly into the fabric of the stone/stonework.

5.3 MAN-MADE FACTORS THAT CAN ACCELERATE STONE DECAY

A range of human factors can (often inadvertently) increase moisture ingress or inhibit moisture egress in stonework, thereby increasing the risk of accelerated weathering and stone decay. They include the following.

5.3.1 Using inappropriate materials to modify or repair buildings

Any material that is inserted into or placed on stonework, and is less permeable than it, will to some extent inhibit moisture transfer and the free exchange of moisture and air with the atmosphere, with the common result that the stonework is unable to dry out effectively. Such materials include: stone that is less permeable than the original stone; mortar that is less permeable than the stone or underlying mortar; paint, render and other coatings applied to exterior surfaces; and paint, plasterboard, insulating materials and any other materials used to cover interior stonework surfaces.

5.3.2 Block shape and tooling character

In general terms, weathering is likely to proceed more slowly on surfaces with a smaller surface area than on surfaces with a larger surface area, so the shape and surface texture of masonry blocks can play an important role in determining the rate of weathering. Blocks with angular corners and blocks with carved or tooled surfaces therefore would be expected to weather more rapidly than those with flat, smooth surfaces and curved or rounded edges. However, it should be borne in mind that other factors (including exposure and aspect, whether or not scaling occurs, and the extent and character of biogenic growth) usually play a contributory role in determining the rate and style of weathering on block surfaces.

5.3.3 Face bedding

Sandstone blocks are usually placed in a stone wall with the sandstone beds orientated horizontally. Blocks of sandstone in which the bedding orientation is vertical and parallel to the wall surface are said to be *face bedded*; such blocks are prone to *delamination*, which can in turn accelerate the rate of weathering and stone decay.

5.3.4 De-icing salt

De-icing salt laid on carriageway surfaces can enter adjacent permeable stonework by dissolving in rainwater that is drawn into the stone by capillary action. The stone is then susceptible to salt-weathering (whereby the expansive force of growing salt crystals can prise apart constituent components in the stonework, promoting granular disintegration in the stone and widening any gaps between stone and mortar).

5.3.5 Ineffective or poorly maintained rainwater goods

Poor maintenance of features designed to remove rainwater from roofs (copes, skews, flashings, guttering, drainpipes) and prevent water from flowing across walling surfaces (cornices, string courses) can reduce their effectiveness; in such cases rainwater can flow onto and into stonework leading to prolonged wetting in focussed areas.

5.3.6 Increasing the humidity within buildings

Increasing the humidity inside buildings without providing adequate ventilation can create condensation and lead to damp stonework. An increase in interior humidity is often associated with a change in building use (for example converting a barn to a dwelling house).

6 Causes of weathering in the stone structures of Culzean Castle and Country Park

Every example of the effect of weathering on stonework is the result of a complex interplay between material properties, weathering agents, physical and chemical (± biological) processes, environment and setting, and time.

In this section some of the factors that have produced the range of characteristic weathering styles in CCCP, and those considered likely to be causing accelerated stone decay, are described using examples from the park. This assessment of weathering features and their causes is based on a brief examination of buildings in different parts of the park over a period of three days; it should not be considered to be a comprehensive evaluation.

An assessment of the decay mechanisms operating in samples of sandstone from the 'Adam Balcony' on the sea-facing elevation of Culzean Castle is presented in Hayles (1998) and Hayles & Bluck (1994; 1995a,b). The study examined stone from a single locality using high-resolution analytical techniques not employed here; the conclusions appear to be broadly in line with those presented here.

Some of the terms used to describe weathering effects in this section are defined in section 5.

6.1 SHAPE AND SURFACE TEXTURE OF MASONRY BLOCKS

Perhaps the two most striking characteristics of weathering in CCCP are: (i) the widespread occurrence of scaling, particularly in ashlar blocks (rather than rubble blocks); and (ii) a relationship between weathering intensity and stone colour, whereby relatively weakly weathered stone surfaces typically are orange, brown or purple tones while the most intensely weathered stone typically is green. This study has shown that these features may be related, and that both may be a consequence of the original shape and surface texture of masonry blocks.

6.1.1 Scaling

Both ashlar and rubble blocks are used extensively in CCCP; some structures consist entirely (or nearly entirely) of ashlar while others have ashlar dressings (quoins, string courses, cornices, window surrounds etc) and rubble walling. As a general rule, ashlar blocks have suffered considerably more from scaling than have rubble blocks.

The ashlar blocks (in their original form) are characterised by essentially planar, usually perpendicular, smooth sawn surfaces; however, coarse to fine droving (usually in horizontal but sometimes inclined or vertical rows) is a common feature of much of the ashlar in the park. Many ashlar blocks, particularly those with exposed corners (such as quoins) have suffered substantially from scaling (Figure 7a,b). This is likely to be (at least in part) because the regular chemical gradient in the stone that is needed to create a case-hardened zone and behind it a zone of weakened stone along which fractures can readily form (see section 5.1.2) develops most easily behind a flat, planar surface.

The stonework facades of several structures in the park (e.g. the archways leading onto Home Farm courtyard; Figure 7a) have been cut back and re-dressed within the last few decades, probably because the ashlar had suffered severely from scaling. Weathering ridges (Figure 7c) and corner fractures (Figure 7d) may develop on the corners of some ashlar blocks due to contemporaneous scaling on two adjacent perpendicular surfaces.

By contrast, rubble blocks (in their original form) are characterised by rough, hand-worked surfaces, commonly with stugging. Though the exposed surfaces of such blocks may be broadly planar overall, in detail they each consist of many differently angled elements. The lack of a smooth, planar surface behind which a regular chemical gradient can form is likely to be the reason that rubble blocks appear to have suffered relatively little scaling.

Stone from St Murray’s quarry (which is readily identified in CCCP buildings by its relatively even, reddish grey colour) is much less prone to scaling than Swanshaw sandstone from other quarries. Indeed, the surfaces of all (ashlar and rubble) blocks of St Murray’s stone appear to be essentially unaffected by scaling and to have weathered instead by granular disintegration without first having suffered scaling (e.g. Figure 5b). This suggests that calcite, which is present in stone from all the examined quarries except St Murray’s (see section 4.2.2), is the key factor in determining whether or not Swanshaw sandstone is prone to case hardening and subsequent scaling. Where it is present at the time of building, the calcite may dissolve locally in the weathering environment to form zones of weakened stone and re-precipitate (as calcite and/or other calcium-bearing minerals such as gypsum) to form zones of ‘hardened’ stone.

6.1.2 Development of intensely weathered, green stone

The most strongly weathered and eroded stone in CCCP buildings is commonly green (sometimes tending to dark grey), and the intensity of this colour increases with the intensity of erosion (Figure 5a,c and Figure 7b,e,f). This can be interpreted in two ways: either green Swanshaw sandstone is more susceptible to weathering, or the stone becomes green(er) as it weathers.

First impressions of some of the buildings in CCCP suggest that stone blocks of different colour were used for different purposes during construction; specifically, it can appear that green stone has been used for ashlar dressings and differently coloured (mainly orange) stone has been used for rubble walling (Figure 7g). This was referred to as ‘colour selection’ in the BGS summary deliverable from the work done in 2012.

However, new observations suggest that ‘colour selection’ is not responsible for the apparent colour differences we see today. One line of evidence comes from the quarries: as far as can be determined, none of the quarries produced stone that was green in its fresh state (the stone samples collected from Swallowcraigs quarry are greenish buff, but the stone is somewhat weathered and likely to be buff in its fresh state). A second, more compelling, line of evidence comes from the thin section examination. Unlike the samples of fresher stone from both quarries and buildings, the two most weathered samples of stone (ED11359 and ED11360, both from buildings; see Appendix 3) contain a very-fine-grained green mineral that has formed along grain boundaries as part of the weathering process. The mineral is likely to be *chlorite* or a chlorite-like mineral such as *corrensite* (in which layers of chlorite are interstratified with layers of a clay mineral), and its development is almost certainly the reason why strongly weathered stone becomes increasingly green. The new mineral (referred to hereafter as chlorite, although it has not been identified unambiguously) appears to form through a chemical reaction between kaolinite and iron oxide. Where the chlorite is present, new pore spaces typically have developed between the chlorite and adjacent grain boundaries and the stone as a whole is typically friable and suffering granular disintegration (Figure 6f). This suggests that the chlorite undergoes volume expansion as it grows or when it is saturated with water, leading to granular disintegration. The chemical reaction also results in an increase in pore space as kaolinite is consumed.

The fact that intensely weathered, green stone has in most cases developed in ashlar blocks suggests there is a relationship with scaling. In other words, the reaction that produces chlorite in the stone may be triggered only (or particularly) when scaling occurs, perhaps due to the suddenness with which pre-weathered stone is exposed to the elements.

The following sequence of events is proposed.

- Ashlar blocks suffer case hardening and scaling.

- The scaling reveals weakened, pre-weathered stone that is susceptible to water ingress and granular disintegration.
- Under these conditions, chlorite forms along grain boundaries through a reaction involving kaolinite and iron oxide.
- The chlorite expands as it grows (or when it comes into contact with water), leading to the widening of grain boundary fractures and rapid granular disintegration.
- The pore spaces created by expansion, granular disintegration and consumption of kaolinite increase the permeability of the stone, making more of the stone subject to weathering and chlorite growth.

Once underway, the process may be self-perpetuating and the rate at which it spreads through a stone block may increase over time. The process may explain why some stone blocks appear to suffer dramatically increased rates of granular disintegration associated with the development of an increasingly intense green colour (Figure 7e,f).

Corner blocks of ashlar are in general more susceptible to scaling and subsequent intense weathering than blocks enclosed by other blocks, presumably because of their larger surface area relative to volume (Figure 7h).

By contrast, the roughness of the surfaces of rubble walling stone may largely preclude the development of case hardening and the associated development of weaker stone within blocks and scaling. Instead, rubble blocks have in general weathered more slowly; material loss has occurred mainly through granular disintegration at exposed surfaces and (generally orange) discolouration of surfaces is due mainly to oxidation of iron (Figure 7g).

6.2 SHAPE AND STYLE OF BUILDING ELEMENTS

The connected network of pore spaces in Swanshaw sandstone means that fluids like water, water vapour (‘moisture’) and air can migrate through the stone in response to changes in temperature, humidity and air-pressure, and by capillary action. If the mortar joints in sandstone stonework are also permeable, these fluids will also be able to migrate across masonry joints (i.e. from block to block) as well as along joints. In this way, fluid that enters stonework at one location can migrate through it *via* many blocks and joints before escaping at an entirely different location. The shape and style of buildings and building elements will be amongst the range of factors that control the three-dimensional shape of fluid-migration gradients in permeable stonework. Some examples are described below.

- In many structures in CCCP the most strongly weathered and eroded stone occurs in a crudely horizontal band within the body (rather than at the top or bottom) of the structure. This is mainly (or perhaps just more obviously) a feature of free-standing or largely detached structures like arches (Figure 7i), gate posts (Figure 7j) and stair towers (Figure 7k). The strongly weathered and eroded band is usually between c. 1 and 4 metres above the ground surface, but this is not always the case. The reason for this arrangement is not obvious, but one possibility is that the strongly weathered bands are at the meeting point between moisture migrating down from the top of the structure and moisture migrating up from the base; moisture accumulates at the meeting point (causing weathering and stone decay) and can only be removed by transferring laterally and evaporating from the side of the structure.
- Vertical zones of accelerated decay associated with moisture egress commonly develop on one of the two surfaces of ashlar corner blocks. The zones typically develop 10-20 cm from the corner and typically manifest as rougher, slightly concave surfaces sometimes with a white band of salt efflorescence along one edge (e.g. Figure 7l,m,n). The reason why these features form, and the conditions that determine which surface of the stonework they form on, are not clear, though aspect and exposure are likely to play an

important role. The zones extend vertically across the horizontal joints separating blocks, suggesting that moisture and air migrate pervasively through the stonework.

- Weathering and erosion may proceed more slowly in round structures (e.g. the round tower in Figure 7i) than in angular structures.

6.3 BED ATTITUDE

The bedding in sandstone typically gives it a near-planar fabric (though stone displaying cross-bedding or convoluted bedding has a more complex fabric). Stone blocks are usually placed in stonework with the bedding fabric aligned horizontally. Blocks in which the bedding fabric is tilted away from horizontal are in general more susceptible to weathering. This is probably because the varying susceptibility to weathering of different beds leads to soft-bed erosion, which in turn causes water to become channelled in eroded beds leading to more intense weathering of those beds. Blocks placed in stonework such that the bedding fabric is steep to vertical, for example in archways (Figure 7o) and face-bedded blocks (Figure 7d), commonly display well-developed examples of soft-bed erosion.

6.4 REPAIRS OR ADDITIONS USING INCOMPATIBLE STONE

Placing blocks of sandstone with contrasting permeability next to each other in stonework can impede the transfer of moisture and air through the stonework, and can lead some blocks (usually the more permeable ones) to suffer accelerated decay. Evidence of inhibited moisture transfer and accelerated decay in blocks of Swanshaw sandstone that are adjacent to repairs or additions made using different stone suggest the new stone and original stone are incompatible.

This study has identified a number of examples in CCCP where apparently incompatible stones have been placed against Swanshaw sandstone. Perhaps the best example is on the east-facing elevation of Dolphin House, where a large area of damp stonework and rapidly eroding blocks of Swanshaw sandstone occur in the lower part of a wall in which large areas of original stonework have been replaced relatively recently by new blocks of Stanton Moor (Derbyshire) sandstone (Figure 7p,q,r). The spatial association of these features suggests the blocks of new stone are preventing adjacent blocks of Swanshaw sandstone, in particular those that are partially surrounded by the new stone, from ‘breathing’ adequately; however, the new stonework was inserted at around the same time as the building use was changed, and the situation may have been exacerbated by increased humidity inside the building associated with the change of use.

Blocks of Swanshaw sandstone apparently suffering accelerated decay adjacent to new blocks of different sandstone were also observed in a wall adjacent to a section of Culzean Castle that has been substantially replaced by Springwell sandstone (Figure 7s) and in the east limb of the south arch at Home Farm courtyard (Figure 7t).

Swanshaw sandstone sourced from different quarries (or different parts of the same quarry) is likely in most cases to be broadly compatible. However, if weathering affects one block to a significantly greater degree than adjacent blocks (for example, if a block of ashlar suffers scaling and subsequent intense weathering and adjacent blocks do not) the changes in the affected block over time may mean that it effectively becomes incompatible with adjacent blocks and starts to affect them adversely. There are many examples in CCCP of stone decay apparently ‘spreading’ from block to block through stonework, presumably as a result of weathering-induced incompatibility (Figure 7u,v,w,x).

Powder House is an example of a structure that is in a relatively exposed setting beside the coast but in which the stone throughout the structure has survived in a relatively weakly weathered state. The absence of strongly weathered stone in this case is probably due in part to the geological and geometrical uniformity of the stone blocks (ashlar has been used throughout), but will also reflect other factors such as the absence of large windows openings and the good condition of the roof and cornice.

6.5 INCOMPATIBLE MORTAR IN POINTING AND PATCHING

Incompatible mortar (usually caused by very low permeability) can have the same effect on stonework as incompatible stone. Damp stone and/or accelerated stone decay adjacent to repointing mortar is a widespread problem in CCCP (Figure 7y,z,aa,ab,ac,ad).

Stonework affected by weathering commonly suffers from loose or lost mortar, and very often the response simply is to re-point the stonework without addressing the root cause of the weathering. In some cases, the area of weathering-affected stonework may be the egress point for moisture that entered the stonework elsewhere. If the mortar used for re-pointing is incompatible, it will exacerbate the problem, and within a short time may need to be replaced again. In other cases, the original mortar may have decayed through age and re-pointing with an incompatible mortar may be the prime cause of stone decay. A history of multiple attempts at re-pointing can make it difficult to judge the extent to which the current mortar is the cause of dampness and weathering in stonework; however, a gap between the mortar and adjacent stone is usually a sign that the mortar and stone are incompatible (e.g. Figure 7ab).

'Plastic repair' using a (presumably cement-based) mortar has been used to conceal badly weathered stonework in some buildings, and there is evidence that this material is incompatible (probably very low permeability) and locally causing damage to adjacent stone (Figure 7p).

6.6 ASPECT

Several structures in CCCP display good examples of the effect of aspect on stone weathering rate. For example, the N-facing elevation of a boundary wall adjacent to Culzean Castle is significantly more weathered than the S-facing elevation, probably reflecting differing exposure over many years to wind, salt aerosol, and sunlight (Figure 7ae,af). Other similar examples include: the NW-facing and SE-facing elevations of Cat Gates; the N-facing and S-facing elevations of the Walled Garden main entrance arch; and the NW-facing and SE-facing elevations of Ruined Arch. In each case the elevation with a dominantly northern aspect is in general weathered more strongly.

6.7 SALT

The coastal location of CCCP means that many (possibly all) of the buildings are exposed to significant quantities of salt-bearing aerosol. Honeycomb weathering (alveolisation), which presents the most obvious example of the effect of salt, is developed in a number of CCCP buildings that are situated close to the sea, including Dolphin House (Figure 7ag), parts of Culzean Castle, and parts of the Clock Tower. Many of the stone blocks in Dolphin House also display well developed coving (Figure 7ah), and this may also be a consequence of salt weathering. Stone blocks forming the Round House, which sits within the intertidal zone, are coated with small crystals of salt (Figure 7ai). Previous repairs to the Round House include sneck-and-mortar pockets that have been inserted into large gaps created by substantial material loss (probably greatly enhanced by salt weathering) in what was formerly probably ashlar with tight joints (Figure 7aj).

6.8 FAILING RAINWATER GOODS

The condition of rainwater goods was not a priority of this assessment, but some examples of defective features were observed, including the following selection: green biogenic growth with associated mortar loss and incipient stone decay are developing on an area of wettened stone beneath a defective gutter on the Powder House (Figure 7ak); large areas of damp, decaying stonework have developed beneath what appear to be defective skews on large stone sheds in the Walled Garden (Figures 7ac,7ad); and stone discolouration, biogenic growth, mortar loss, salt efflorescence and incipient stone decay are developing on replacement Springwell sandstone at several locations on the south-east elevation of Culzean Castle, as a result of inadequate rainwater management (Figure 7al,am).

Camellia House presents a good example of some of the effects of water ingress to stonework at roof level. The structure, which is built entirely of stone from St Murray's quarry, has suffered in the past from defective pointing and possibly other issues at roof level, as evidenced by streaks of discoloured stone and bands of weathered stone developed on both exterior and interior walling surfaces directly below vertical masonry joints at roof level (Figure 7an,ao). Some repair work to the building was carried out in 2012 and it is not clear if the causes of water ingress were addressed at that time. As described in section 6.1.1, the St Murray's stone shows little sign of case hardening and scaling; instead, most of the weathering seems to involve localised granular disintegration. Inside the building, some of the most weathered stone is on and adjacent to the surfaces of carved columns and recurved arches that are well below the roof line (Figure ap). These intricately carved stonework features present a large surface area over which evaporation can occur, and it is inferred that moisture has migrated through the stonework in response to a humidity gradient between the moisture access point at roof level and the egress area around the carved features.

6.9 BIOGENIC GROWTH

Biogenic growth on stonework in general appears to be a minor problem in CCCP and seems (currently at least) to have little impact on weathering. Lichens are the most common and most visible manifestation of biogenic growth, and they can play a significant role in the visual appearance of stonework at a range of distances (Figure 7aq,ar).

In most cases, lichens appear to cause little or no significant damage to the underlying stone, but one species of light grey lichen clearly plays a role in causing local stone decay. In most cases these lichens sit flat on the stone surface and appear to be essentially inert. However, in some examples the central part of the lichen has swelled out from the stone to form a blister, and in many cases the surface of the blister has split open or spalled off revealing underlying stone that has suffered granular disintegration and in some cases has eroded to form a pit up to one centimetre or so deep. Good examples of this phenomenon are displayed on the south-facing elevation of the main gate into the Walled Garden (Figure 7as,at) and in de Avise La Fine arch. The cause of the blistering and stone decay is not obvious, but lichens can secrete acid compounds and this may be a factor.

Different species of lichen are tolerant of different environments (and microenvironments), so the distribution of lichen species on a stonework surface will in some cases reflect the condition of the underlying stone. Perhaps the most striking example of this in CCCP is the commonly observed transition from black lichen to light grey lichen to yellow lichen and then to no lichen, which follows the transition from weakly to strongly weathered stonework (Figure 7ac,ad,au). Typically, the black lichen sits on stonework that is in relatively good (weakly weathered) condition, and the light grey lichen sits on slightly more weathered stone. Strongly weathered stone has no lichen (presumably because the stone surface is suffering granular disintegration and is therefore too unstable a substrate for lichen), and yellow lichen sits in a (usually narrow) band between the light grey lichen and the stone with no lichen. It may be possible to use the distribution of lichen species as an indicator of stonework health; for example, black lichen seems generally to form on healthy stone, but a clear transition from black to light grey lichen may point to stonework that is suffering incipient weathering and decay.

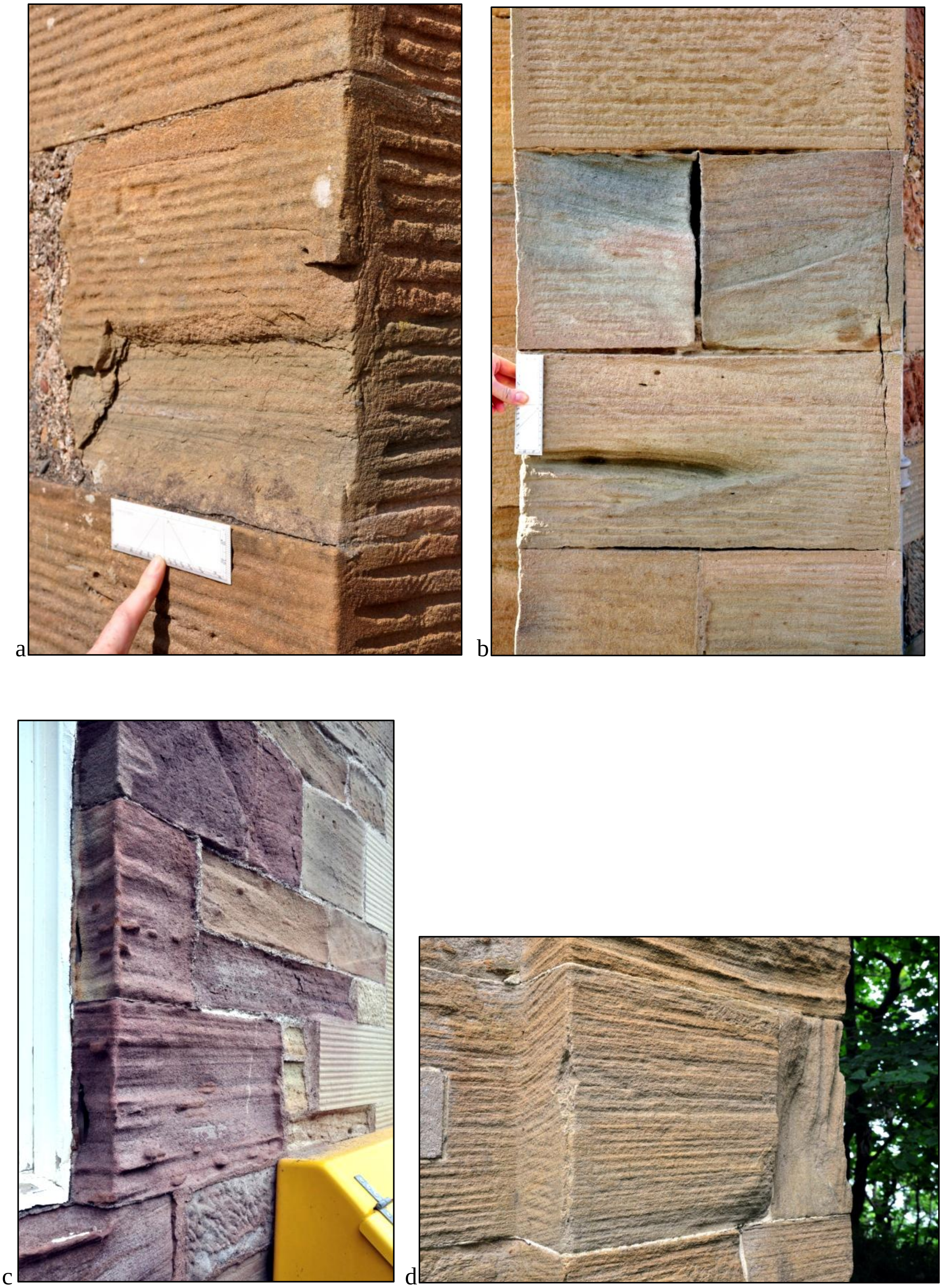

Figure 7 Character and causes of weathering in the stone structures of CCCP

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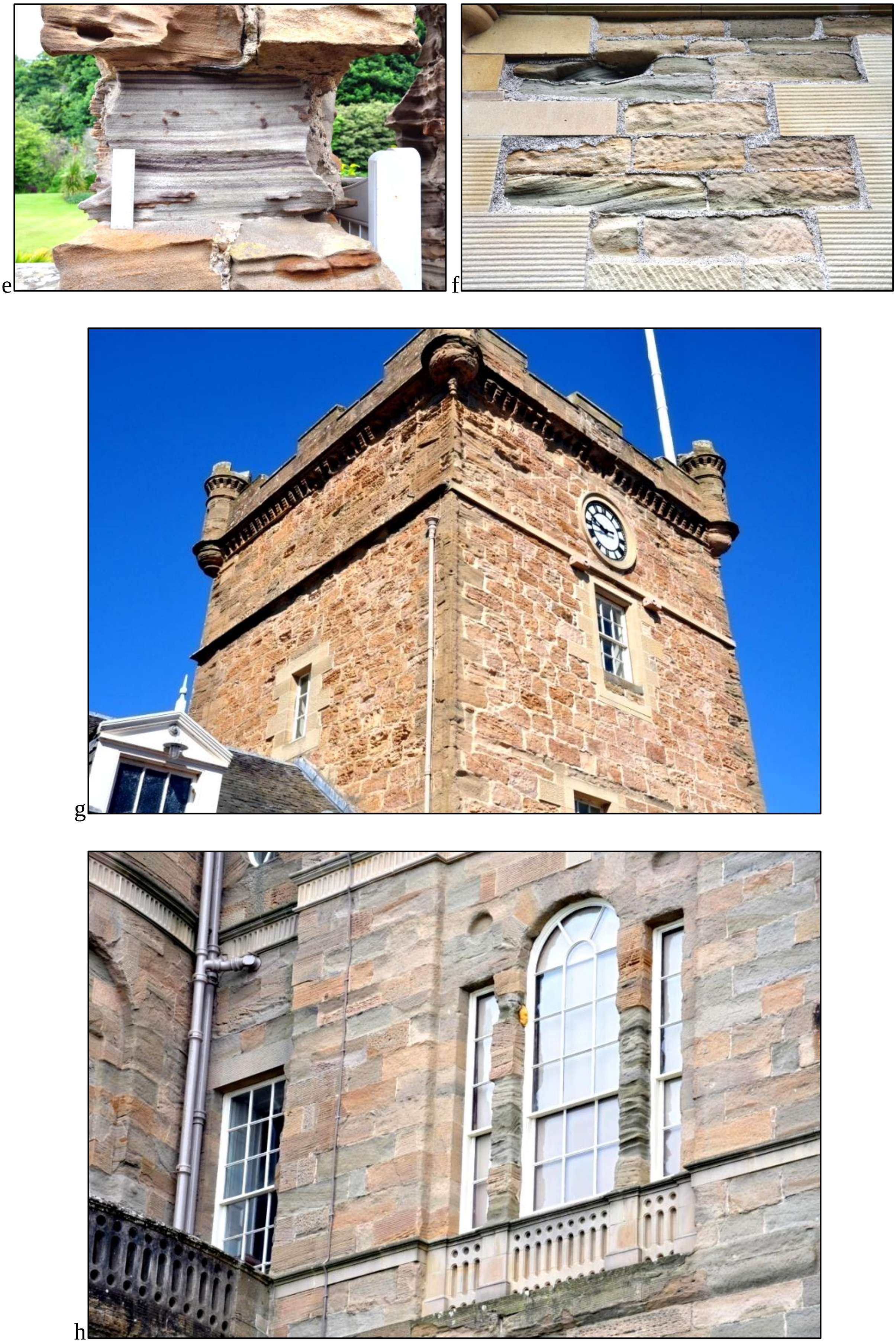

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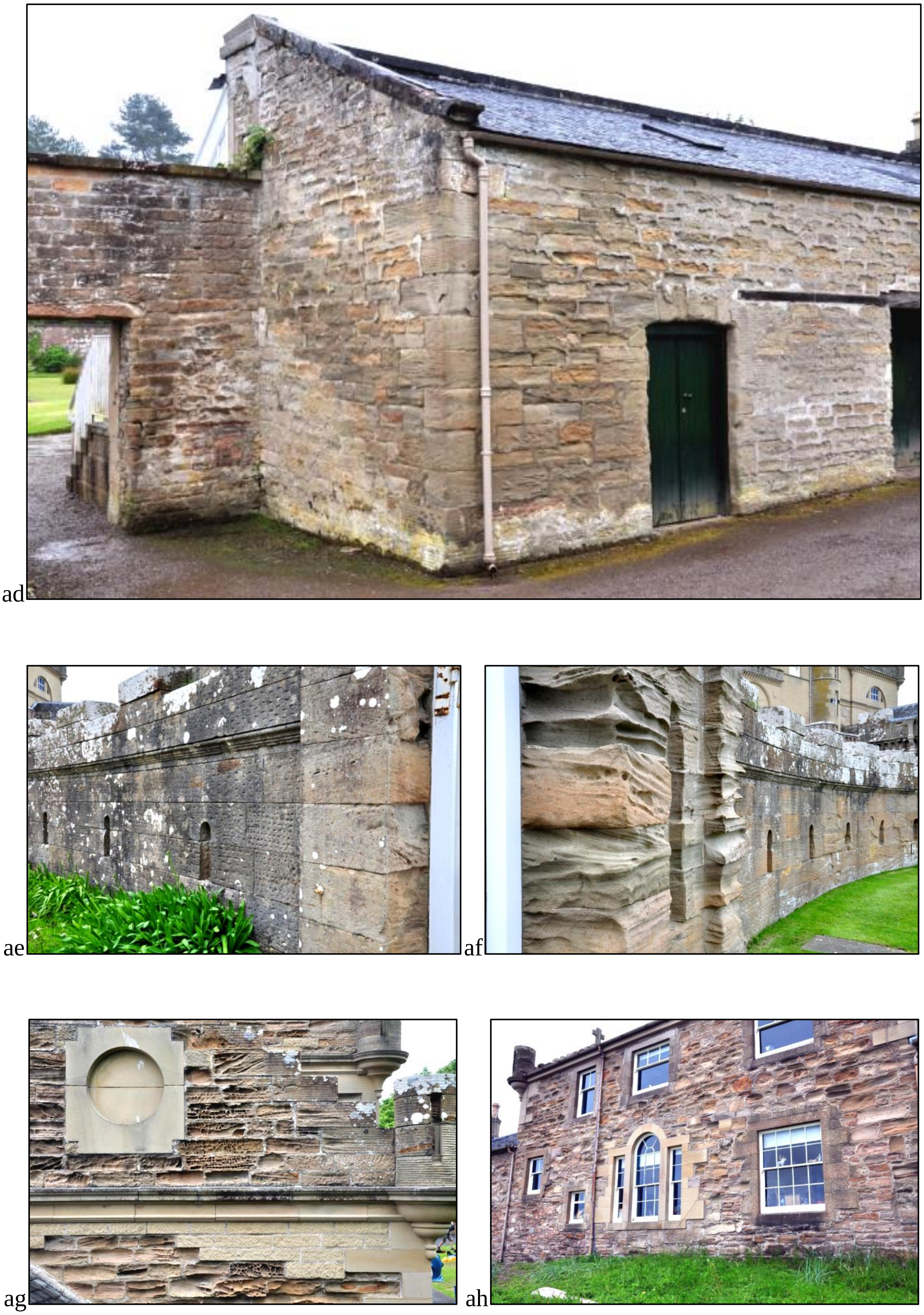

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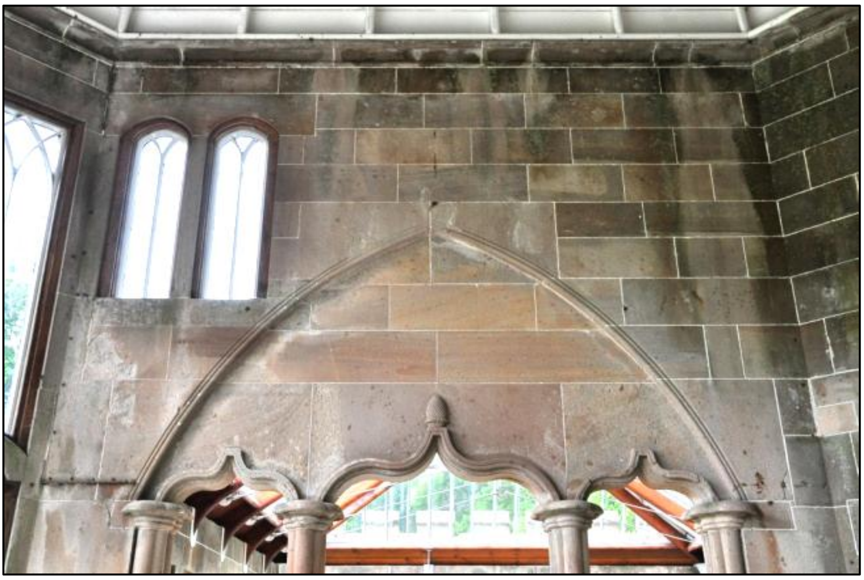

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Figure 7 captions

a – Droved ashlar block that has suffered contour scaling on the south limb of the east arch (courtyard-facing wall), Home Farm courtyard. The stone exposed by the scaling has a greenish tinge in contrast to the orange surface elsewhere on the block.

b – Dressed-back and re-droved ashlar blocks on the north limb of the west arch of Home Farm courtyard. The surfaces have suffered rapid weathering since being dressed-back, including the development of vertical fractures (as a precursor to scaling; right side), substantial mortar loss, granular disintegration, loss of droving detail, and selective accelerated (soft bed) erosion. The most intensely weathered stone is green.

c – Blocks of reddish brown sandstone (left) and indents of buff sandstone (far right) in a wall at the NE end of the SE elevation of Dolphin House. Most of the stonework is damp and the reddish brown sandstone is weathering rapidly (the small pile of loose sand on the yellow grit box is due to granular disintegration in the blocks above), suggesting the new stone and the older stone are incompatible. Local repointing with a relatively impermeable mortar may be exacerbating the problem. Good examples of vertical 'weathering ridges' have developed in the corner blocks at the left side of the photo; these may form where scaling occurs contemporaneously on two perpendicular surfaces.

d – Brushed ashlar stonework on the east elevation of Powder House. The sandstone bedding orientation is nominally horizontal in all blocks except the block right of centre, which is ‘face-bedded’ (i.e. the sandstone bedding orientation is vertical and parallel to a walling surface). The face-bedded block is notably more strongly weathered than the other blocks. Note also the vertical fracture that has developed along the exposed corner of the main block in this view; such ‘corner fractures’ are inferred to form as a result of incipient scaling on two adjacent perpendicular surfaces.

e – A severely weathered and eroded ashlar block on the NW elevation of the southern-most stair tower, midway along Fountain Court. The eroding block is green-grey and a pile of loose sand grains (the product of rapid granular disintegration) is developing below it. By contrast, the blocks immediately above and below are orange and much less eroded.

f – Blocks of rapidly weathering older stone surrounded by pristine blocks of replacement stone on the SE elevation of Dolphin House. The older stonework looks to have been re-pointed at the same time as the new stone blocks were inserted, but gaps between the new mortar and the older stone indicate the stone has subsequently suffered significant material loss (due to granular disintegration and erosion). This, and the damp appearance of many of the new and older stone blocks, suggests the new stone and the older stone are incompatible. The most intensely weathered and eroded stone is green.

g – Corner of the NE and SE elevations of the Clock Tower, showing apparent ‘colour selection’ of stone: original ashlar dressings (especially the quoins) have a generally greenish tone whereas the rubble walling blocks are mainly orange.

h – Part of the NW elevation of Culzean Castle, viewed from the SW. Stone blocks that have suffered extensive scaling (as evidenced by loss of all droving detail) are typically green, whereas blocks that have not suffered from scaling (droving detail usually still visible) are typically orange. The most intensely weathered and eroded stone has developed around the window openings, especially in the mullions, because the blocks there have the largest exposed surface area relative to their volume. The stonework forming the mullions demonstrates well the relationship between stone colour and intensity of weathering/erosion (the most intensely weathered/eroded stone is the greenest). Note the local indent repairs using light buff sandstone.

i – The east-facing elevation of Ruined Arch. The most intensely weathered and eroded stone is developed in a band at mid-height (between ~1 and 3 metres elevation) and notably in corner blocks. The image also shows the relationship between lichen species and weathered stone: black lichen/soiling on the least weathered stone at the top of the structure gives way downwards to white lichen on more weathered stone. Lichen has not grown on the most intensely weathered and eroded stone. The stonework of the round tower at left has suffered less weathering and erosion than the arch and square tower, probably because each block has a much smaller area of exposed stone, there are fewer openings in the stonework, and few exposed corners.

j – North elevation of the west gatepost in the boundary wall between the NE end of Culzean Castle and Fountain Court. The top course (above the cornice) was probably added some time after the rest of the structure was built. Elsewhere, the stone is least weathered at the top and base of the structure and in general becomes more intensely weathered towards the middle.

k - NW elevation of the southern-most stair tower, midway along Fountain Court. The top three courses (above the cornice) were probably added some time after the rest of the structure was built. Elsewhere, the stone is least weathered at the top and base of the structure and in general becomes more intensely weathered towards the middle.

l – Stone quoins forming the west corner of the Aviary (by Swan Pond). A vertical band of weathered and weakly eroded (and possibly damp) stone has developed in the left-facing blocks in this image, whereas the perpendicular (right-facing) surfaces of the same blocks are relatively unweathered. The weathering process here seems to be the same as in Figure 7m, though in a more advanced state.

m – Replacement stone quoins forming the SW corner of the SE elevation of Dolphin House. A vertical dark orange band on the ashlar blocks facing the camera marks the position of moisture egress from the stone. The left side of the orange band is bounded by a narrow white band of salt efflorescence. The stone shows signs of incipient weathering along the orange band. Moisture egress bands and/or associated weathering are commonly observed in the blocks forming one side of a corner. The vertical continuity of the band across at least three stone blocks suggests the block margins and mortar in this case do not significantly influence the moisture migration geometry within the stonework. The weathering process here seems to be the same as in Figure 7l, though in a less advanced state.

n – Corner of the NW and SW elevations in the northern-most stair tower, midway along Fountain Court. The stone is strongly weathered and eroded on one elevation but not the other. The weathering process here seems to be the same as in Figures 7l and 7m, though in a more advanced state.

o – North side of the north arch, Home Farm courtyard, showing variably intense weathering and alveolisation in orange and green stone. Stone blocks lining the arch in general become more strongly weathered and eroded towards the top of the arch, as the angle of bedding increases. In general, green stone is more intensely weathered and has suffered more material loss than orange stone, and stone exposed on the underside of the arch (presenting a large surface area to the elements) has suffered more weathering and material loss than stone in the rubble wall above. Many of the blocks lining the arch display weathering ridges at exposed corners, efflorescence bands ~10-20 cm behind the corners, and enhanced erosion beyond the efflorescence bands.

p – Part of the wall at the NE end of the SE elevation of Dolphin House. At the extreme left a plastic repair in pinkish mortar has been used to re-shape weathered window dressings. However, subsequent substantial scaling and loss of detail in the stone blocks adjacent to the plastic repair suggest the stone and the material used in the plastic repair are incompatible.

q – Blocks of older stone (mid-centre and top-centre) surrounded by blocks of pristine replacement stone (left, right and bottom) in the SE elevation of Dolphin House. Much of the stone (older stone and replacement blocks) is damp and the older blocks in the centre of the image are suffering rapid weathering, granular disintegration and erosion. The most eroded stone is the greenest. The evidence suggests the new stone and the older stone are incompatible, with the result that moisture has accumulated locally in the stone causing accelerated decay.

r – General view of the SE elevation of Dolphin House. Large areas of damp (slightly darker) stonework are visible in the lowest 2-3 metres of the walling, in association with extensive indents of replacement stone.

s – Junction of the NE corner of Culzean Castle (left, formed of Springwell sandstone) and a boundary wall (right, formed of Swanshaw sandstone). The blocks of Swanshaw sandstone adjacent to the junction lack the black soiling / biogenic growth that is typical elsewhere on the boundary wall, and have suffered significant weathering and erosion (mainly scaling). The stone in the boundary wall is elsewhere generally in excellent condition. The weathering and erosion probably occurred after the original Swanshaw sandstone in Culzean Castle was replaced by (incompatible) Springwell sandstone.

t – Loss of mortar and accelerated decay of older blocks of Swanshaw sandstone (left) adjacent to relatively recent indents of a different (incompatible) stone (right), in the east limb of south arch (arch-facing wall), Home Farm courtyard. The older blocks have been dressed-back and re-droved, and were presumably flush with the new indents at the time they were inserted; the mortar loss, loss of droving detail and material loss in the older blocks therefore presumably post-date (and result from) the indents.

u – Junction of the NW elevation of the northern-most stair tower midway along Fountain Court (right) and a boundary wall (left). Stone blocks in the boundary wall are suffering significant decay and lack black soiling / biogenic growth where they abut the other structure. The stone in the boundary wall is elsewhere generally in excellent condition. The top three courses of the boundary wall were probably added later than the rest of the structure. The stone blocks at mid-height have suffered most from weathering and erosion.

v – Gate post on the boundary wall separating Culzean Castle courtyard and the Clocktower complex. Substantially eroded blocks have developed on just one (north-facing) side of this structure.

w – SW elevation of the SW wing (Wardrop & Read extension) of Culzean Castle, showing incipient weathering in sandstone from St Murray's quarry. Some blocks are pristine while others are suffering material loss (through granular disintegration; there is no scaling). The most strongly weathered blocks tend to be adjacent, suggesting the process of stone ‘decay’ starts in one block and spreads to adjacent blocks. A crack suggesting structural instability has propagated through several of the blocks and joints in this image.

x – West elevation of the north limb of De Avise La Fine Arch, showing significant local variation in the degree of weathering and erosion. The column at the right of the image is relatively pristine (retaining its original smooth surface) and covered extensively in white lichen. By contrast, the column just left of centre has suffered substantial scaling and granular disintegration, particularly between 0.5 and 2.5 metres elevation, and has no lichen. Stone blocks in the boundary wall to the left of the eroded column have also suffered significant erosion, whereas the stone elsewhere in the boundary wall is generally in excellent condition. All the stone is Swanshaw sandstone, and the stone ‘decay’ appears to have spread from the column into the boundary wall as individual blocks of sandstone in the column became weathered and incompatible with adjacent blocks.

y – The NW elevation of Old Stable, with a large area of damp (slightly darker) stonework visible at the north (lower left) corner of the building. The damp area lacks lichen and coincides with an area of stonework in which aggregate-rich mortar has been used to re-point the stone.

z – The SW elevation of the Gazebo, with a large area of damp (slightly darker) stonework forming the lower part of the wall. The damp area lacks lichen and coincides with an area of stonework in which aggregate-rich mortar has been used to re-point the stone. The exposed parts of the window dressings are indents of replacement stone or plastic repair.

aa – The west elevation of Swan Pond Cottages. The stonework at mid-height in the wall is damp and suffering accelerated decay (granular disintegration and coving) behind pointing; see Figure 7ab.

ab – Detail of re-pointed, damp stonework that is suffering rapid granular disintegration and coving on the west elevation of Swan Pond Cottages. The sizeable gaps that have developed between the mortar and the decaying stone suggest the mortar and stone are incompatible and the mortar is at least partly responsible for accelerated weathering.

ac – NW elevation of the main (central) building in the Garden Sheds complex, showing severe erosion and 'greening' of formerly orange to brown stone due, at least in part, to use of inappropriate mortar for repointing and patching. Mortar appears to have been applied in extensive patches before much of it fell off in the most affected area. Note that the top boundaries of the worst affected areas to left and right of the window are sloping and are essentially parallel to the skews forming the edge of the roof; this may indicate that water is entering the stonework via defective skews (see also Figure 7ad).

ad – North corner of the NE-most building in the Garden Sheds complex showing advanced stone decay behind extensive cement pointing and patching, associated with a large area of wet stone and mortar. White and yellow lichen associated with dry courses at base of wall. Note that the top and bottom boundaries of the worst affected areas have a parallel slope that is broadly parallel to the skews forming the edge of the roof; this may indicate that water is entering the stonework via defective skews (see also Figure 7ac).

ae – South side of the boundary wall between the NE end of Culzean Castle and Fountain Court. Stone on this side of the wall is in relatively good condition compared to that exposed on the north side (Figure 7af).

af – North side of the boundary wall between the NE end of Culzean Castle and Fountain Court. Stone on this side of the wall is in relatively poor condition compared to that exposed on the south side (Figure 7ae).

ag – The SW elevation of Dolphin House, showing extreme alveolisation in many older blocks. Many blocks on this elevation have been replaced.

ah – The NW (sea-facing) elevation of Dolphin House showing strongly eroded walling (with good examples of coving), numerous indents of replacement stone, and plastic repairs to window surrounds.

ai –A block of eroded sandstone on the land-facing side of the Round House. The surface of the block is covered with tiny crystals of salt.

aj – The Round House, viewed from the north-east. The lower courses are formed of generally strongly weathered buff to green stone; this may be the original walling stone. The upper courses are of less strongly weathered orange to brown stone, which probably replaced strongly weathered blocks of the original stone. The lowest course, which is partly protected by the outcrop of igneous rock on which the Round House is built, contains the least weathered original walling stone.

ak – The north elevation of Powder House, showing biogenic growth forming on wet stone associated with a poorly functioning rainwater runoff hole.

al – Base of the SE elevation of Culzean Castle, showing early signs of weathering (incipient development of biogenic growth and mortar loss) on replacement Springwell sandstone due to inadequate rainwater management.

am – of the SE elevation of Culzean Castle, showing early signs of weathering (vertical white bands of salt efflorescence, bands of slightly darker [damp?] stone, and localised mortar loss) loss on replacement Springwell sandstone due to inadequate rainwater management.

an – An interior wall of Camellia House, looking south. Vertical bands of stained stone and biogenic growth have developed on the interior wall due mainly to water ingress through vertical joints at the roof line. Note also the slightly 'roughened' appearance of block surfaces at lower levels (immediately above the arches), presumably marking the position of moisture egress from the stonework.

ao – The rear (west-facing) wall of Camellia House, showing locally substantial erosion and localised biogenic growth (green and russet colours) on this dark, dank elevation. The most decayed stone is in vertical bands below leaking (or formerly leaking) vertical joints in the cornice.

ap – Interior of Camellia House, looking north from the south wing. A band of dark soiling above and left of the left-most arch separates stone with smooth surfaces and scattered white lichen (indicating dry stone) above from stone with rough surfaces and no lichen (indicating the stone has suffered moisture-related decay) below.

aq – Northern-most stair tower on Fountain Court, showing an extensive covering of light grey lichen on the top courses and cope stones, black lichen / soiling on lower (unbrushed?) courses, and the typical overall effect of lichen on the visual appearance of stonework in CCCP.

ar – Part of the castellated wall bounding Fountain Court, showing the extensive covering of light grey lichen on the top courses and cope stones.

as – S-facing elevation, east limb of the main gate into Walled Garden, showing detail of a blister in the centre of a light grey lichen. The blister has burst, revealing weathered stone beneath.

at – S-facing elevation, east limb of the main gate into Walled Garden, showing detail of a blister in the centre of a light grey lichen. The blister has burst, revealing weathered stone beneath.

au – The NE side of the south tower on Ruined Arch. Black lichen/soiling on the least weathered stone at the top of the structure gives way downwards to light grey lichen on more weathered stone. Lichen has not grown on the most intensely weathered and eroded stone.

7 Best-practice procedures for long-term repair and maintenance of stonework in Culzean Castle and Country Park

Nearly all weathering processes in sandstone stonework are associated in some way with water. The prime objective of a long-term repair and maintenance programme therefore should be to minimise water ingress to stonework and ensure that wettened stonework can dry quickly through the natural transfer and evaporation of moisture.

Even in ideal conditions all stone and mortar will decay eventually, and periodic sensitive intervention should be seen as a necessary and ongoing process in the management of built sites. However, it should also be recognised that any change to the fabric of stonework and/or its local environment can upset the delicate natural balance that regulates moisture content and moisture transfer, and interventions commonly cause unintended adverse consequences. Changes, especially interventions to the stonework fabric, therefore should be kept to a minimum.

A best-practice approach to the repair and maintenance of stonework in CCCP needs to take into account many factors, including the condition of existing stonework, the environment and setting of individual structures and even individual building elements, the heritage significance of the structure, and financial constraints. The following points should be considered when designing best-practice procedures for long-term repair and maintenance of stonework in CCCP.

7.1 REGULAR SURVEY OF STONEWORK CONDITION

All stonework should be subjected to a regular ‘stonework condition survey’. This could involve park-wide surveys spaced at regular intervals or a ‘rolling programme’ of continuous survey involving a subset of buildings every year. Each structure ideally should be surveyed at intervals of no more than five years.

The main objective of a stonework condition survey should be to identify and grade areas of concern. What might constitute an ‘area of concern’ is somewhat subjective. However, it is important to recognise that some degree of weathering is inevitable, and stonework that weathers at a slow, steady ‘background’ rate can remain strong and healthy for many decades. Areas of concern could include situations where: the current stonework condition threatens structural stability; the rate of weathering significantly exceeds the ‘background’ rate; stone decay is spreading rapidly into adjacent stonework; and there are signs of incipient weathering that may develop rapidly if not controlled. A ‘traffic-light’ system (e.g. green = no problem, amber = requires monitoring, red = requires immediate attention) can be a simple, useful device in surveys of this sort.

The survey should include an assessment of the underlying cause of weathering at each area of concern, and could include an assessment of whether intervention is appropriate and what it should/could consist of.

Stone in an advanced state of weathering is relatively easy to identify, but it is important to identify signs of incipient weathering. These include permanently damp stone or mortar, evidence of material loss (detached grains and fragments of stone or mortar) and loss of surface texture (e.g. roughening of smooth surfaces), the development of cracks, the appearance or spread of biogenic growth, changing lichen species (either spatially or over a period of time), and progressive discolouration of stone surfaces (particularly the ‘greening’ of stone described in section 6.1.2).

Comparing results from surveys made at different times should help to identify situations where either the intensity/effect of weathering or the area of stonework affected by weathering has increased measurably between surveys. Maintaining a photographic record of stonework surfaces can be an effective way of monitoring weathering-related changes in the medium- to long-term.

The results of each survey should be used to design and inform a programme of effective long-term maintenance and repair.

7.2 PREVENTATIVE MEASURES

The best way to ensure the long-term health of stone structures is to prevent weathering developing at a rate above the ‘background’ rate. Wherever possible, steps should be taken to remove anything that is preventing stonework from ‘breathing’ naturally (e.g. paint, biogenic matter, incompatible stone or mortar, soil banked up against stonework) and anything that channels water onto or into stonework (e.g. defective rainwater goods, leaking pipes, inadequate ground drainage).

The performance and condition of rainwater goods (e.g. gutters, drainpipes) and rain-shedding features (e.g. copes, skews, cornices, string courses) should be assessed on a regular basis (ideally more frequently than the stonework condition survey), and any faults should be addressed quickly.

Removing the weathered rind on stone blocks by brushing or ‘dressing back’ the stone to reveal the healthy stone beneath can slow down the weathering process; however, it will be important to identify and address any underlying cause of accelerated weathering. Stone that shows any sign of ‘greening’ and/or rapid granular disintegration should at the very least be monitored carefully and ideally should be treated rapidly. Treatment could include removing all the affected stone (e.g. by chiselling it out or re-dressing the block surface) to reveal a fresh surface, but in some cases it may be necessary or safer to replace the entire block.

Stone that shows any sign of ‘greening’ and/or rapid granular disintegration should not be recycled into stonework.

Chronically damp stonework close to ground level may point to rising damp. Where this is suspected, a careful evaluation should be conducted to determine if this is indeed the problem and to identify the contributory factors. Measures to tackle rising damp include improving ground drainage, inserting an effective stone base course, and/or inserting a damp-proof course (if the latter option is selected, steps may need to be taken to ensure the damp-proof course itself does not become the cause of accelerated decay in the stone beneath it).

Exposed stonework should be lime-washed, harled or painted (e.g. to take it back to its original state on conservation grounds) only if it is dry and in good condition.

7.3 INTERVENTIONS

Any planned repair to weathered stonework should be preceded by a careful evaluation of the nature and root cause of the weathering and a consideration of the possible adverse consequences of making the intervention.

Mortar used for repointing and patching old stonework, for pointing new stonework, and for making ‘plastic’ repairs, must be compatible with the stone it is placed in contact with; in other words, it must not prevent or significantly impede the transfer of moisture and air through the stonework. The degree to which mortar is likely to be compatible with stone can be difficult to predict; it may be worth conducting a long-term trial to test and monitor the performance of different mortars in Swanshaw sandstone stonework.

Only stone that is compatible with the original stone should be used in stonework repairs. Stone compatibility is usually considered in terms of three main criteria.

- *Appearance* – to what extent will the new stone look similar to the original? This depends on the colour and macroscopic fabric of the two stones, but even if they are closely similar in these respects the clean, fresh surfaces of new stone blocks will often contrast markedly with the weathered surfaces of the original stone (though the contrast is likely to diminish over time).

- *Grain-scale properties that determine weathering behaviour* – many of the grain-scale properties of sandstone will play a role in determining its weathering behaviour over a range of time scales, but perhaps the most important properties in this respect are permeability, cohesion, and mineral components. Stone permeability is arguably the most important compatibility criterion, because the new stone or the original stone can suffer accelerated weathering if the two stones are incompatible in this respect.
- *Functional and performance requirements* – if the original stone performed a functional (e.g. load-bearing) role, or demonstrated a particular performance requirement (e.g. an ability to incorporate finely carved detailing), the new stone should be able to match it in these respects.

The degree to which one stone might be ‘compatible’ with another can be difficult to predict. In nearly all cases, the most compatible stone (and certainly the safest choice) will be stone from the same quarry (or failing that the same geological formation) as the original stone – in this case Swanshaw sandstone. A supply of new Swanshaw sandstone will need to be secured in order to implement a best-practice approach to the long-term repair and maintenance of CCCP buildings. This would ideally involve opening or re-opening one or more quarries (more than one source may be necessary to replicate the natural range of character displayed by Swanshaw sandstone), but recycled Swanshaw sandstone might provide a partial solution.

Using any stone other than Swanshaw sandstone increases the risk of causing accelerated weathering and decay in adjacent stonework. However, if Swanshaw sandstone is not available the closest-matching currently available alternative stone should be used in cases where repair is deemed essential (e.g. to inhibit the rapid spread of decayed stone or because weathering-affected stonework is a threat to structural stability).

The observations presented in section 6.1 of this report suggest that leaving the exposed surface(s) of new blocks of Swanshaw sandstone with a rough, ‘rock-faced’ texture might inhibit the development of case-hardening and scaling, and thereby reduce the rate and intensity of future weathering (in particular, it might prevent the rapid, intense weathering and erosion associated with scaling and growth of chlorite in the stone). Preparing new blocks of dressing stone with rounded rather than square corners might also inhibit the development of case-hardening and scaling, thereby reducing the rate of weathering. However, adopting measures like these would in some cases involve a departure from some of the traditional detailing styles in CCCP.

7.4 MONITORING PAST INTERVENTIONS

Records should be kept of all additions and interventions to stonework; the records should include details of the location, date and nature of the work, and details of the materials (e.g. type of stone and mortar ‘recipe’).

The performance of each intervention should be assessed periodically. Further intervention may be required if there is evidence of an adverse consequence (e.g. the appearance of permanent damp or accelerated stone decay). The information should be used to inform and improve future interventions.

8 Conclusions

The key conclusions arising from this study of the source, character and weathering style of building stone in Culzean Castle & Country Park are presented below.

Arguably the two most obvious effects of weathering in CCCP are contour scaling and rapid granular disintegration associated with progressive 'greening' of the stone. The conclusion of this study is that these effects are related to each other and to the shape and surface character of stone blocks: scaling is far more common in ashlar than in rubble walling, because the chemical gradients and surface-parallel zones of weakened stone that lead to contour scaling develop more readily and more extensively behind the smooth, planar surfaces of ashlar blocks; and the rapid, intense weathering associated with 'greening' happens only (or mainly) in blocks that have suffered scaling. Further detailed analysis would be needed to determine the precise nature of the grain-scale processes involved; however, our observations suggest that stone affected by scaling is susceptible to a chemical reaction (involving iron oxide and the clay mineral kaolinite) that produces small quantities of the mineral chlorite (or a chlorite-like mineral) along grain boundary fractures. The chlorite is green and capable of swelling (either as it grows or as it becomes water-saturated); the chlorite is therefore likely to be responsible both for the change in colour ('greening') and the rapid granular disintegration of affected stone.

Past interventions are another significant cause of ongoing stone decay in CCCP. Swanshaw sandstone has not been available in recent decades and stones from other parts of the UK have been used to effect repairs; there are now many examples in CCCP of Swanshaw sandstone suffering accelerated weathering and erosion where it is adjacent to indents of a different (incompatible) stone and where stonework has been re-pointed or re-shaped using an incompatible mortar. Identifying and sourcing a compatible stone and compatible mortar to use in future repairs should be considered a priority. Fresh Swanshaw sandstone would almost certainly be the most compatible stone, and should provide the best solution in the long term.

Few historical records indicate which quarries supplied the stone that was used in CCCP, and even fewer relate the stone used in specific buildings to individual quarries. However, there are sufficient records to indicate that most, if not all, of the stone used in the park was sourced from a handful of quarries within a radius of c. 7 km of Culzean Castle. All of these quarries – 'Gas House', Swallowcraigs, Ballochneil, Blanefield and St Murray's – sit on the local outcrop of the Swanshaw Sandstone Formation. In general, stone from all of these quarries is closely similar and cannot be distinguished easily on the basis of macroscopic character alone. Stone from St Murrays quarry is an exception; while still displaying essentially similar characteristics in most respects, St Murray's stone can be considered to be a distinctive purplish grey to reddish brown variant of Swanshaw sandstone. St Murray's stone also lacks calcite, and this may explain why it appears to be much less prone to scaling than stone from the other quarries.

St Murray's quarry is still readily accessible, and it may be possible to obtain new stone relatively easily from this source. Blanefield quarry no longer exists, and the other quarries are without exception thoroughly overgrown and difficult to access; the stone exposed in them is also typically moderately weathered. Obtaining a significant supply of fresh stone from any of these quarries would require a substantial effort. A brief assessment of other outcrops of the Swanshaw Sandstone Formation in central Scotland has shown that two former building stone quarries (Penning Hill and Wellshields) are still potentially accessible, and one (Dunduff) is still active (producing stone for aggregate); however, the Swanshaw sandstone produced by these quarries is in general darker, finer-grained, and probably less permeable than the stone used in CCCP, and may prove to be no more compatible than sandstone from other geological units. Gas House quarry and Swallowcraigs quarry are probably still the most accessible of the original quarries, and geographically they are the closest; they probably present the best potential amongst the existing quarries for providing a supply of new, generally buff, Swanshaw sandstone. However, most of CCCP is underlain by the Swanshaw Sandstone Formation, and consideration should be given to opening a new quarry (or quarries) in a discreet location on the estate. Managed properly, such a source could provide fresh Swanshaw sandstone on demand for an indefinite period. A suitable site should only be selected following careful geological assessment and, ideally, drilling of one or more exploratory boreholes.

Best-practice procedures for the long-term maintenance and repair of stone structures in CCCP should include the following:

- All stonework should be subjected to a regular 'stonework condition survey'. The main objectives should be to identify and grade areas of concern, assess the underlying cause of weathering at each area of concern, and assess whether and what intervention is appropriate. Each structure ideally should be surveyed at intervals of no more than five years.
- A range of measures should be implemented to prevent weathering from taking hold or to slow the rate at which it spreads. Anything that is preventing stonework from 'breathing' naturally (e.g. paint, mortar) ideally should be removed. The performance and condition of rainwater goods and rain-shedding features should be assessed on a regular basis, and any faults should be addressed quickly. The cause of suspected rising damp should be assessed carefully and appropriate remedial action should be taken. Stone that shows any sign of 'greening' and/or rapid granular disintegration should at the very least be monitored carefully and ideally should be treated rapidly. Treatment could include removing all the affected stone to reveal a fresh surface, but in some cases it may be necessary or safer to replace the entire block. Stone blocks that show any sign of 'greening' and/or rapid granular disintegration should not be recycled into stonework. Where older stone is showing signs of accelerated weathering due to past intervention involving incompatible stone or mortar, consideration should be given to replacing the incompatible material with a (more) compatible one.
- Any planned repair to weathered stonework should be preceded by a careful evaluation of the nature and root cause of the weathering and a consideration of the possible adverse consequences of making the intervention. Only compatible mortar (established through a programme of tests?) and compatible stone (ideally fresh or recycled Swanshaw sandstone) should be used. If Swanshaw sandstone is not available the closest-matching currently available alternative stone should be used in cases where repair is deemed essential (e.g. to inhibit the rapid spread of decayed stone or because weathering-affected stonework is a threat to structural stability).
- Records should be kept of all additions and interventions to stonework, and the performance of each intervention should be assessed periodically. Further intervention may be required if there is evidence of an adverse consequence (e.g. the appearance of permanent damp or accelerated stone decay). The information should be used to inform and improve future interventions.

Appendix 1 Historical records that may contain information relevant to CCCP

The tables below contain lists of historical records that may contain information relevant to CCCP, and indicate which were included in the brief review conducted for this project.

Literature review

Checked	Item
Yes	Ordnance Gazetteer of Scotland, 1885
Yes	Ordnance Gazetteer of Scotland, 1901
	Pevsner Architectural Guides
Yes	Statistical Accounts of Scotland
Yes	Mineral Statistics of the United Kingdom 1853-1881
	Synopsis of the mineral resources of Scotland 1940
	The Special Reports on the mineral resources of Great Britain
Yes	Memoirs of the Geological Survey, late 19th c to present day
	District Memoirs of the Geological Survey
Yes	Economic Geology Memoirs
	Wartime Pamphlets, 1940-1945
	The Industries of Scotland, David Bremnar, 1869

Desktop review

Checked	Item	Source
Yes	Canmore	http://www.rcahms.gov.uk/
	Historic Scotland Data Services	http://hsewsf.sedsh.gov.uk/
Yes	Nat'l Library of Scotland (Maps)	http://maps.nls.uk/
	Capital Collections	http://www.capitalcollections.org.uk/index.php
	Scottish Cities	http://www.scotcities.com/
	British History Online	http://www.british-history.ac.uk/Default.aspx
	CBA guide to UK archaeology	http://www.britarch.ac.uk/info/curate.asp
	BBC Scottish History	http://www.bbc.co.uk/history/scottishhistory/
	The Scotland Guide	http://www.scotland-guide.co.uk/
	Looking at Buildings (Glossary)	http://www.lookingatbuildings.org.uk/glossary/
	History of Britain's Railways	http://www.railbrit.co.uk/index.php
	Dictionary of Scottish Architects	http://www.scottisharchitects.org.uk/
	Scotland Places	http://www.scotlandsplaces.gov.uk/
	SCRAN	http://www.scran.ac.uk/
	Glasgow Architecture	http://www.glasgowarchitecture.co.uk/
	Mitchell Library	http://www.mitchelllibrary.org/virtualmitchell/
	Clyde Waterfront Heritage	http://www.clydewaterfrontheritage.com/
	Charles Rennie Mackintosh Soc.	http://www.crmsociety.com/
	Glasgow Story	http://www.theglasgowstory.com/index.php
	Aberdeen Sites & Monum. Record	http://www.aberdeenshire.gov.uk/smrpub/shire/default.aspx
	West Scotland Archaeol. Service	http://www.wosas.net/
	Europe's Cultural Collections	http://www.europeana.eu/portal/
	World Digital Library	http://www.wdl.org/en/

Other resources

Checked	Item
Yes	Local Historical Societies, Trusts, etc. (e.g. National Trust for Scotland)
Yes	Newspaper (e.g. Google News Archive search)

Appendix 2 Summary notes from a review of historical records on quarry activity around CCCP

REFERENCE SOURCE	**REFERENCE** (bold) and **NOTES** Direct quotations extracted from references are presented in *italics*.	**RESEARCH STATUS**
Statistical Accounts of Scotland	**Dalrymple and McGill. 1791.** ***The Statistical Accounts of Scotland.*** **Parish of Air** (sic)**, Vol. 1. (Edinburgh: William Creech.)** [In the Parish of Air] *there is a considerable amount of moor-stone lying on the ground. The free-stone lies rather deep.*(p95)	Complete
	Wright, James. 1792. ***The Statistical Accounts of Scotland.*** **Parish of Maybole, Vol. 3. (Edinburgh: William Creech.)** No mention of building stone.	
	Wright, James. 1792. ***The Statistical Accounts of Scotland.*** **Parish of Kirkoswald, Vol. 10. (Edinburgh: William Creech.)** Description of Culzean Castle and grounds (incl. caves), no mention of building stone. (494-495)	
	Gray, George. 1845. ***The Statistical Accounts of Scotland: Ayr, Bute.*** **Parish of Maybole, Vol. 5. (Edinburgh: William Blackwood and Sons.)** *The sandstone at the quarry of St Murrays often affords beautiful specimens of arborescence, from the presence of the black oxide of manganese, and it is traversed by veins of lead-ore, which have been noticed at Knockdon and the manse.* (p352)	
	Inglis, James. 1845. ***The Statistical Accounts of Scotland, Ayr, Bute.*** **Parish of Kirkoswald, Vol. 5. (Edinburgh: William Blackwood and Sons.)** Description of Culzean Castle and grounds (incl. caves), no mention of building stone. (p783)	
Hunt's Mineral Statistics	**Hunt, Robert. 1857. Mineral Statistics of the United Kingdom of Great Britain and Ireland for the year 1856. (London: Longman, Brown, Green, and Longmans.)** *Name of quarry: St Murray; Nearest Post Town: Ayr; Description of Stone: Brown Freestone; Price per Cubic Foot: 6d. to 2s.; Annual Produce (Tons): 5,000.* (p141) *Name of quarry: Ballochneill; Nearest Post Town: Kirkoswald; Description of Stone: Brown Freestone; Price per Cubic Foot: 6d. to 1s.; Annual Produce (Tons): 500.* (p141) *Name of quarry: Girvan Mains; Nearest Post Town: Girvan; Description of Stone: Red Freestone; Price per Cubic Foot: 10d.; Annual Produce (Tons): 600.* (p141)	Complete
Memoirs of the Geological Survey	**Geological Survey of Scotland. 1869.** ***Memoirs of the Geological Survey, Scotland, Explanation of Sheet 7: Ayrshire: South-Western District.*** **(Edinburgh: Her Majesty's Stationery Office.)** *ECONOMIC MINERALS.* *36. Building Stones.--Red Sandstone of good quality occurs at Dykeneuk, to the north of Girvan...*(p16) No other mention of building stone relevant to this report.	Complete
	Geological Survey of Scotland. 1949. ***Memoirs of the Geological Survey, Scotland, Explanation of one-inch Sheet 14: Geology of Central Ayrshire.*** **(Edinburgh: His Majesty's Stationery Office.)** *ECONOMIC PRODUCTS.* *Freestone.--…There are numerous quarries which were formerly a source of building stones, but which are now abandoned.* (p18-19) Geological descriptions of Maybole and Culzean Bay, no mention of building stone relevant to this report (with one exception, see below). Description of two drifts as recorded visible at Ballochneil Quarry, no mention of building stone. (p132)	
	Smith, R.A. and A.A. Monaghan. 2013. Geology of the Ayr district, Sheet Description of the British Geological Survey 1:50 000, Series Sheet 14W and part of 13 Ayr (Scotland). (Keyworth, Nottingham: British Geological Survey.) *Freestone and sandstone:-* *Culzean Castle is said (Smith, 1895) to be built of local fine-grained sandstone (Swanshaw Sandstone Formation) but its exact source is unknown.* (p80)	

REFERENCE SOURCE	**REFERENCE** (bold) and **NOTES** Direct quotations extracted from references are presented in *italics*.	**RESEARCH STATUS**
Ordnance Gazetteer of Scotland	**Groome, Francis H. 1885. Ordnance Gazetteer of Scotland. Vol. II. (Edinburgh: Thomas C. Jack Grange Publishing Works.)** Description of Colzean Castle (sic) under Parish of Kirkoswald, no mention of building stone. (p434)	Complete
	Groome, Francis H. 1885. Ordnance Gazetteer of Scotland. Vol. III. (Edinburgh: Thomas C. Jack Grange Publishing Works.) *The sandstone, in a quarry at St Murray's, often affords beautiful specimens of arborescence, from the presence of the black oxide of manganese, and it is traversed by veins of lead-ore, which have been noticed at Knockdon and the manse.* (p16)	
	Groome, F.H. 1901. Ordnance Gazetteer of Scotland. (Edinburgh: T.C. and E.C. Clark) Description of Colzean Castle (sic), no mention of building stone. (p281-282) Description of Colzean Castle (sic) under Parish of Kirkoswald, no mention of building stone. (p994) *The sandstone, in a quarry at St Murray's, often affords beautiful specimens of arborescence, from the presence of the black oxide of manganese, and it is traversed by veins of lead-ore, which have been noticed at Knockdon and the manse.* (p1144)	
Geological Society Transactions	**Smith, John. 1895. *Transactions of the Geological Society of Glasgow,* vol. 10. From the Doon to the Girvan Water, along the Carrick Shore. 1-12.** *In passing along the shore from near Drumshange to Culzean Castle we find the outline of this Old Red Sandstone district much softer, the cliffs being so much cut away that the rocks seldom reach the shore … The sandstone cliffs are at first seen weathering to a yellowish colour ...* (9) *The Castle itself is built of a fine-grained yellowish stone, obtained from the Old Red Sandstone formation of the neighbourhood.* (p10) *In the Girvan Mains quarry, which is quite close to the shore, this rock has been to some extent worked for building-stone, but the excavations are at the present time partly filled with water.* (p12)	Complete
Economic Memoirs of the Geological Survey	**Eyles, V.A., et al. 1930. *Geological Survey, Scotland, The Economic Geology of the Ayrshire Coalfields, Area III, Ayr, Prestwick, Mauchline, Cumnock, and Muirkirk* .(Edinburgh: His Majesty's Stationery Office.)** *BUILDING AND MONUMENTAL STONES.* No mention of building stone relevant to this report.	Complete

REFERENCE SOURCE	**REFERENCE** (bold) and **NOTES** Direct quotations extracted from references are presented in *italics*.	**RESEARCH STATUS**
National Archives of Scotland	**The Register of Improvements on Entailed Estates, Inventory of Ayr Sheriff Court (SC6/72)** SC6/72/1, no page number, 4 March 1786 *General accounts of the expenses laid out for the new house at Dalquirharan (sic) from Martinmas 1784 to Martinmas 1785* *A/C for labourers employed at quarries serving masons and horses and carts leading stones, sand, etc.*	Complete
	SC6/72/1, no numbered pages in this volume, no date *General accounts of the expenses laid out for the new house at Dalquharran (sic) mansion house from* [Nov?] *1785 to* [Oct?] *1786* *A/C for leading stones from Cullean (sic) for the stairs*	
	SC6/72/1, no page number, 23 January 1788 *General accounts of the expenses laid out for the new house at Dalquirharan from March 1786 to March 1787* *A/C for gunpowder for quarrying stones for stair cases for new house at Dalquirharan (sic) at Cullean (sic) Quarry*	
	SC6/72/2-4 No mention of building stone relevant to this report.	
	SC6/72/5, page 206, 4 March 1823 *Abstract of Accounts of Improvements on the entailed estates of Cassillis and Cullean for the year 1822 at and prior to the term of Martinmas of that year* *A/C 33 for quarrying stones and draining on Morrieston*	
	SC6/72/6 No mention of building stone relevant to this report.	
	SC6/72/7, page 53, 4 March 1825 *Abstract of Accounts of Improvements on the entailed estates of Cassillis and Cullean for Martinmas 1823 to Martinmas 1824* *A/C 29 for quarrying and leading stones and building March dyke* [behind] *the farms of Upper Bar and Craigmulloch*	
	SC6/72/7, page 134, 8 March 1826 *Abstract of Accounts of Improvements on the entailed estates of Cassillis and Cullean for Martinmas 1824 to Martinmas 1825* *A/C 9 quarrying and dressing stones upon the shore* *A/C 35 for quarrying and laying pavement of M--land (?) House*	

REFERENCE SOURCE	**REFERENCE** (bold) and **NOTES** Direct quotations extracted from references are presented in *italics*.	**RESEARCH STATUS**
National Archives of Scotland (cont.)	SC6/72/8, page 368, 16 February 1829 *A/C 62 Hammer dressing stones in Ballochneil Quarry for: laying at stone walk in garden; lifting platform in the tide way; hewing and laying the washing house well*	Complete
	SC6/72/9 No mention of building stone relevant to this report.	
	SC6/72/10, page 163, 10 February 1832 *A/C 30 Mason work at Castle farm of St Murray* [stone?] *and plasterwork*	
	SC6/72/11, page 410, 9 -- 1836 *A/C 5 Leading stones from shore and cope stones from St Murray quarry for wall at bridgend*	
	SC6/72/12-31, encompassing records from 1837-1886 (when the register stops) Not reviewed as part of this report.	Incomplete
	Ailsa Muniments: collection of Kennedy papers dating 1290-1940 bequeathed to National Archives of Scotland (GD25) GD25/1-7, encompassing records from the years 1290-1699 Not reviewed as part of this report; all records pre-date the construction of built sites under review.	Complete
	GD25/8, Former Series, Part 2, 1600-1861 Not reviewed as part of this report due to time constraints	Incomplete
	GD25/9/1-79, only those deemed relevant according to record description in the NAS catalogue have been mentioned here GD25/9/8 Financial papers, 1766-1773 GD25/9/9 Financial papers, 1774-1783 GD25/9/10 Financial papers, 1777-1813 GD25/9/11 Financial papers, 1800-1898 GD25/9/12 Financial papers, 1615-1818 GD25/9/14 Financial papers, 1693-1794 (incl. 1770-1776 Culzean accounts of wages, estate and domestic) GD25/9/15 Financial papers, 1793-1807 GD25/9/22 Financial papers, 1681-1810	Incomplete

REFERENCE SOURCE	**REFERENCE** (bold) and **NOTES** Direct quotations extracted from references are presented in *italics*.	**RESEARCH STATUS**
National Archives of Scotland (cont.)	GD25/9/31 Inventories no mention of stone or construction on Culzean Castle estate	Complete
	GD25/9/44/3 Estate surveys c.1666-1785	Incomplete
	GD25/9/46/1 Minerals (incl. 1635-1687 contracts with quarriers at Red brae, near Maybole; Corsmull; Murestoun; Dinrihill; Drummoran)	Incomplete
	GD25/9/59 Accounts, Ayrshire, etc., 1745-1770 (incl. Culzean Estate, 1745-1757)	Incomplete
	GD25/9/60 Accounts, Ayrshire, etc., 1777-1784	Incomplete
	GD25/9/70 Miscellaneous papers, Ayrshire and Galloway (incl. Culzean, 1772 and 1775)	Incomplete
	GD25/9/71 Roads and bridges	Incomplete
	GD25/9/77 Houses, lands and mills no mention of stone or construction on Culzean Castle estate	Complete
	A large collection of drawings for Culzean Castle Deposited by the National Trust for Scotland 1990 and currently located at the Royal Commission on the Ancient and Historical Monuments of Scotland. This collection was photocopied for the 1997 Quinquennial Survey by Bob Heath (incl. designs for a villa for James Kennedy by James Adam 1755; designs for Culzean Castle by Robert Adam 1777-1779 and 1787; design for a ruined bridge by Robert Adam 1787; designs for estate buildings by James Gillespie Graham 1815 and Robert Lugar, etc.). Those that were photocopied were reviewed as part of this report, and included no mention of building stone.	Complete
Culzean archive store at CCCP	A full review of the records at the Culzean archive store did not take place as part of this report.	Incomplete
National Trust for Scotland Quinquennial Surveys	**National Trust for Scotland. 2005. Landscape Gazetteer: Culzean Conservation Framework & Management Plan. Unpublished PDF.** Some stone elements mentioned, no mention of building stone sources.	Complete
	National Trust for Scotland. 2005. Building Gazetteer: Culzean Conservation Framework & Management Plan. Unpublished PDF. *Beach Quarry (disused) [NS 2366 1051]* *Description: quarried stone cliffs, picturesque and of historical significance.* (p79)	Complete

REFERENCE SOURCE	**REFERENCE** (bold) and **NOTES** Direct quotations extracted from references are presented in *italics*.	RESEARCH STATUS
National Trust for Scotland Quinquennial Surveys (cont.)	**Marta McGlynn Associates. 2005. Draft Culzean Castle and Country Park Framework Conservation Management Plan. Unpublished.** Some description of stone built structures, stonework repairs to Castle and of reclaimed stone being used on the estate for infrastructural use (i.e. walls, roads, copes); no mention of building stone sources.	Complete
	Tindall, Benjamin. 2005. Architecture & Buildings. Unpublished draft report. *1.5.05* *Due to severe erosion, the exterior masonry* [to the exterior of the central block of the Castle] *has been extensively rebuilt, in a stone* that matched the original as closely as could be done at the time without opening up local or historical quarries; which due to the micro-structure and colour differences might not be an approach that would be taken today.* (p4) **Footnote 8: Springwell* Some identification of stonework repairs on the estate, no mention of building stone sources other than as mentioned above.	Complete
	Heath, R. 1997. Quinquennial Survey Culzean Castle Ancillary Buildings. Unpublished box files. Only the historical development section relevant to each built site in CCCP was reviewed; no mention of building stone. A full review of this survey was not done as part of this report.	Incomplete
	Heath, R. 1994. Culzean Castle Quinquennial Survey. Unpublished PDF. Mention of Springwell stone repairs made in the 1990s to exterior stonework of Castle elevations. (p54-57) Identification of sandstone features of the Castle, no mention of building stone sources.	Complete
	Jarvis, Geoffrey. 1987. Culzean Castle and Country Park Quinquennial Survey. Unpublished. A full review of this survey was not done as part of this report.	Incomplete
Royal Commission on the Ancient and Historical Monuments of Scotland	**Grose, F. 1789-91. The antiquities of Scotland, 2v London. Vol. 2. Pages: 209-10** D.20.GRO.R No mention of stone or construction on Culzean Castle estate.	Complete
	Forsyth, R. O. 1805-8. The beauties of Scotland: containing a clear and full account of the agriculture, commerce. mines and manufactures of the population, cities, towns, villages, etc. of each county, 5v, 2 sets Edinburgh C.20.FOR.R Minerals of Air (sic)' and Culzean Castle; no mention of building stone on Culzean Castle estate.	Complete
	Lugar, R. 1836. Plans and views of ornamental domestic buildings executed in the castellated and other styles, London. Page: 31 D.6.L RCAHMS was unable to locate this record.	Incomplete

REFERENCE SOURCE	**REFERENCE** (bold) and **NOTES** Direct quotations extracted from references are presented in *italics*.	RESEARCH STATUS
Royal Commission on the Ancient and Historical Monuments of Scotland (cont.)	**Paterson, J. 1863-6. History of the counties of Ayr and Wigton, 3v in 5 Edinburgh. Vol. 2. Pages: 294-5** D.11.2.PAT No mention of stone or construction on Culzean Castle estate.	Complete
	Macfarlane, W. 1906-8. Geographical collections relating to Scotland, in Mitchell, A and Clark, J T 3v Edinburgh. Page(s): Vol.2. Pages: 9, 21 D.20.MAC.R Building stone at Drummochrin; Culzean Castle is mentioned, no building stone. *… the house of Drummochrin … it hath all manner of stone for building, free stone and lyme stone.*(p11-12)	Complete
	Rowan, A. 1990. The men who made Culzean. *Heritage Scotland*, Vol.7, No. 1. (Edinburgh: The National Trust for Scotland). D11.23 CUL(P) *The building accounts for Culzean introduce us to … the almost illiterate John Dick, the carter who regularly brought the stone for the house and outbuildings from Blanefield Quarry.* (p11)	Complete
	Camp, D. 1992. List of the plans of Culzean by Robert Adam and other designers held at the National Monuments Record of Scotland, Typescript. Unpublished. B.4.2.NMR.P *The main building materials used at Culzean were obtained locally. The sandstone, for example, came from Blanefield Quarry by Kirkoswald, about 7 miles away.* (p19)	Complete
	No records exist at RCAHMS in the online CANMORE database for: Ballochneill, Blanefield, Coralglen, Gas House, Rancleugh Burn, St. Murray's, or Swallowglen quarries.	Complete
Theses	**Hayles, Carolyn. S. and Bluck, Brian. J. 1994. Sandstone decay mechanisms under examination on the balcony of Culzean Castle, South West Scotland.** *In*: Fassina, V., Ott, H. and Zezza, F., eds. *Proceedings of the 3rd International Symposium, Venice, 22-25 June 1994.* Venice, italy: Soprintendenza ai Beni Artistici e Storici di Venezia. Mentions three quarries: beneath Home Farm; Ballochneil; St. Murray's quarry. No references.	Complete
	Hayles, Carolyn S. 'The weathering of sandstone on historic buildings: Culzean Castle, a case study.' PhD Thesis. Glasgow University Library Special Collections declined to send thesis to British Library for scanning due to supplementary material on 16 November 2012 (when first accessed).	Incomplete
People	**Kennedy Family, owners of Cassillis Estate.** Family contacted by Kinlay Laidlaw, no conscious knowledge of quarrying activity on the Culzean and Cassillis estates.	Complete
	Savage, Chris. Factor of Cassillis Estate. Archival records in estate offices; not reviewed as part of this report.	Incomplete

REFERENCE SOURCE	**REFERENCE** (bold) and **NOTES** Direct quotations extracted from references are presented in *italics*.	RESEARCH STATUS
People (cont.)	**Camp, Deborah. 1989. Extracts from Kennedy History, Typescript. Unpublished.** National Trust for Scotland Learning Resources (married name Debbie Jackson) *The stone for the castle could have come from more than one source. In the Ailsa Muniments there are receipts for stone from Blanefield Quarry. It has been suggested that stone also came from Swallowcraigs, further down the coast.* (p14) *In 1767, an experienced miner called William Brown was asked to look at some "mineral appearances" somewhere on the estate. The miner reported back that there was ore on the land, bringing some pieces of ore with him to prove it. It was in "small flowers lodged in ... Sparr."* (p5) *In 1772, the 9th Earl of Cassillis set up the Cassillis Mining Company with his brother David and six other men. Each man contributed £300 making a sum total of £2,400 to be used for "finding and encouraging the searching of working mines and minerals" and for the purpose of working mines and minerals of all kinds within the lands and estates of ... Thomas, Earl of Cassillis ..." (5)* No references.	Complete
	Moss, Michael. 2002. The Magnificent Castle of Culzean and the Kennedy Family. (Edinburgh: Edinburgh University Press). MM contacted by Kinlay Laidlaw, no direct information on historic quarries, but noted references in Ailsa Muniments in the National Archives of Scotland.	Complete
	Addyman, Tom. 1999-2000. Correspondence with Nigel Ruckley regarding findings from archaeological survey at Dunure Castle. Typescript. Letter to Thomas Addyman from Nigel Ruckley on the sandstones from Dunure Castle, dated 1 April 1999 *… I spent an hour scrambling up … the rock face of a former quarry at Balchriston Bay, just north of Culzean Castle. Your hunch was correct about the brownish coloured sandstones with iron patches coming from that locality.* *One can say that the green sandstones* [at Dunure Castle] *are local to Dunure. The brownish yellow sandstones, often with rich iron patches, clay galls etc are from around Balchriston Bay …* Reply to Nigel Ruckley from Thomas Addyman on the sandstones from Dunure Castle, dated 12 April 1999 *I have learnt since your visit that there are two or three sandstone quarries at Culzean. The NTS staff there could let you know their locations … I'm sure that at least one of these relates to Robert Adam's work at the castle in the late C18th …* Reply to Thomas Addyman from Nigel Ruckley on the sandstones from Dunure Castle, dated 29 April 1999 *I have contacted Gordon Riddle* [NTS staff at time of correspondence] *and he knew of only one quarry, on the beach below the Gas house, to the north side of the castle.*	Complete
Newspaper	**The Glasgow Herald, 14 October 1985** *Robert Adam's building used reddish sandstone from the local quarry of Swallowcraig…*(p15) http://news.google.com/newspapers?nid=2507&dat=19851014&id=v8JAAAAAIBAJ&sjid=36UMAAAAIBAJ&pg=2610,3543632	Complete
Historic Scotland	**Historic Scotland. 1971-2011. Culzean Castle Estate Listed Building Descriptions.** Mention of stonework repairs to the estate undertaken during the 1990s, no mention of building stone sources.	Complete

Appendix 3 Petrographic descriptions of Swanshaw sandstone samples

Petrographic descriptions (based on microscope analysis of thin sections) for seven samples of Swanshaw sandstone are presented on standard BGS description forms for sandstone. Notes describing each of the numbered items on the form are presented at the end of this appendix.

The samples were sourced from the following locations.

BGS sample no.	Sampled location	Grid reference	Representing
ED11209	Gas House quarry		Relatively fresh stone from Gas House quarry
ED11211	Ballochneil quarry		Relatively fresh stone from Ballochneil quarry
ED11214	St Murray’s quarry		Relatively fresh stone from St Murray’s quarry
ED11357	Swallowcraigs quarry		Relatively fresh stone from Swallowcraigs quarry
ED11215	Ruined Arch		Moderately weathered stone from stonework
ED11359	NTS mason’s yard, CCCP		Strongly weathered stone from stonework
ED11360	NTS mason’s yard, CCCP		Strongly weathered stone from stonework

Petrographic description of sample ED11209 (Gas House quarry)

Hand specimen observations

Stone type [1] (general classification):	sandstone
Stone colour [2] **–** fresh stone:	light buff
Stone colour [2] **–** weathered stone:	dark orangeish buff
Stone colour [2] **–** exterior surface:	dark orangeish buff
Stone cohesion [3] – fresh stone:	strongly cohesive
Stone cohesion [3] – weathered stone:	strongly cohesive
Stone fabric [4]:	uniform (some orientated grains)
Distinctive features:	coloured spots; mud flakes

Thin section observations

Stone constituents [5]:

Granular (detrital) constituents		*Intergranular constituents*	
Quartz	31%	Silica (overgrowth)	2%
Feldspar	2%	Feldspar (overgrowth)	0%
Rock fragments	37%	Carbonate	2%
Mica	5%	Iron/manganese oxide	8%
Opaque material	<1%	Clay	2%
Other	0%	Hydrocarbon	0%
Intragranular pores	1%	Intergranular pores	10%

Stone type [1] (detailed classification):	lithic-arenite
Grain-size [6]:	medium-sand-grade
Grain sorting [7]:	moderately well sorted
Grain roundness [8]:	angular
Stone permeability [9]:	moderate
Cement distribution [10]:	silica cement discontinuous
Supergene changes [11]:	weak dissolution of rock fragments; strong dissolution of carbonate; strongly remobilised iron

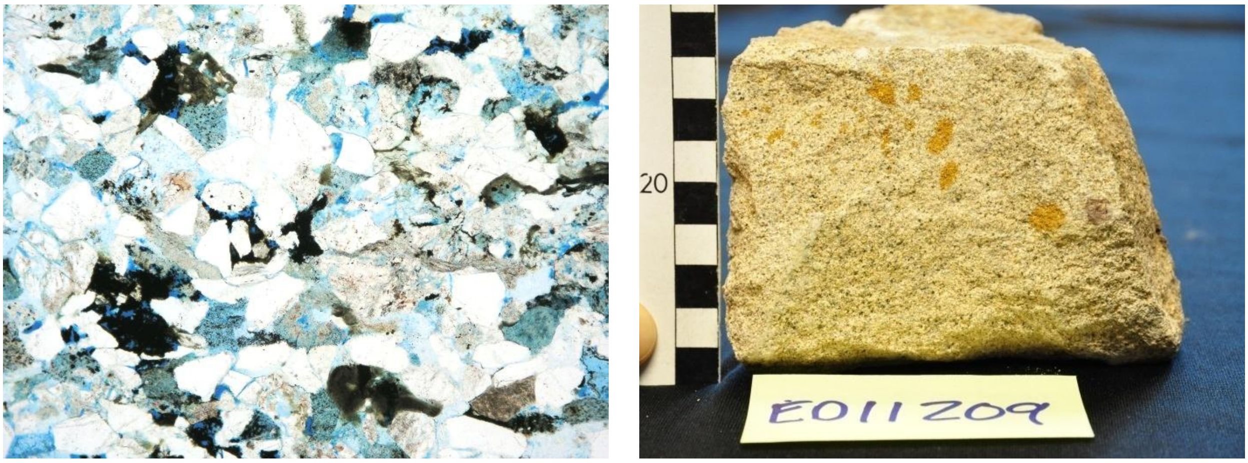
Comments

1) Local concentrations of iron oxide form orange spots 5-10 mm wide in the hand sample.

2) Most of the opaque material in the thin section is iron oxide which forms patches in intergranular spaces; moldic pores developed locally suggest the iron oxide has formed as the result of an iron-rich carbonate mineral dissolving. Most of this carbonate has now dissolved.

3) Elongate flakes of mica are aligned and indicate the bedding direction. Most of the mica present is biotite that has altered to green chlorite. Rock fragments also display a "greenish" tinge, due to the alteration of mafic minerals to green chlorite.

4) The hand sample contains several small (<5 mm), grey and purplish brown mud flakes.



At left: thin section photograph of sample ED11209. The image was taken in plane-polarised light and the field of view is c.3.3 mm wide. Pore space appears blue. At right: photograph of hand sample ED11209.

Petrographic description of sample ED11211 (Ballochneil quarry)

Hand specimen observations

Stone type [1] (general classification):	sandstone
Stone colour [2] **–** fresh stone:	purplish grey
Stone colour [2] **–** weathered stone:	purplish brown
Stone colour [2] **–** exterior surface:	purplish brown
Stone cohesion [3] – fresh stone:	strongly cohesive
Stone cohesion [3] – weathered stone:	strongly cohesive
Stone fabric [4]:	faint bedding
Distinctive features:	none

Thin section observations

Stone constituents [5]:

Granular (detrital) constituents		*Intergranular constituents*	
Quartz	28%	Silica (overgrowth)	3%
Feldspar	2%	Feldspar (overgrowth)	<1%
Rock fragments	30%	Carbonate	10%
Mica	2%	Iron/manganese oxide	13%
Opaque material	<1%	Clay	5%
Other	<1%	Hydrocarbon	0%
Intragranular pores	<1%	Intergranular pores	7%

Stone type [1] (detailed classification):	lithic-arenite
Grain-size [6]:	fine-sand-grade to medium-sand-grade
Grain sorting [7]:	moderately sorted
Grain roundness [8]:	sub-angular
Stone permeability [9]:	low
Cement distribution [10]:	silica cement discontinuous; carbonate cement isolated
Supergene changes [11]:	strongly remobilised iron; moderate dissolution of rock fragments; moderate dissolution of carbonate

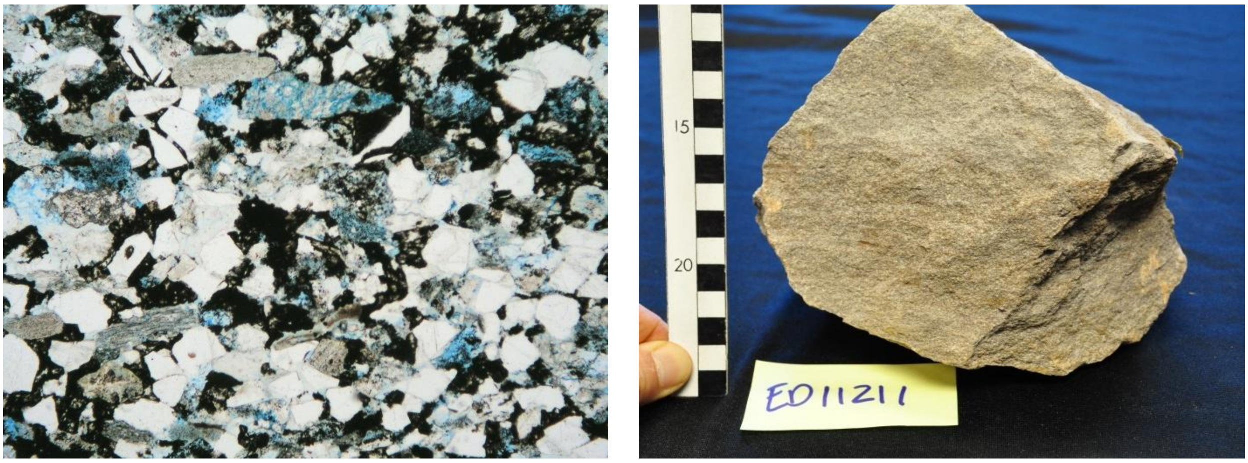
Comments

1) Alternating slightly darker and slightly lighter layers define a faint bedding fabric in the hand sample.

2) The mineral tourmaline is present in trace proportions (<1%).

3) The sample reacts strongly to 10% HCl solution; indicating the presence of calcite. Two carbonate minerals are observed in thin section; calcite and an iron-rich carbonate mineral (possibly ankerite, dolomite or siderite). The calcite appears fresh but the iron-rich carbonate has experienced significant dissolution.

4) Most of the opaque material in the thin section is iron oxide which forms patches in intergranular spaces and probably formed through alteration of dolomite. Fresh calcite has crystallised in intergranular spaces, enclosing (and therefore post-dating) the iron oxide.



At left: thin section photograph of sample ED11211. The image was taken in plane-polarised light and the field of view is c.3.3 mm wide. Pore space appears blue. At right: photograph of hand sample ED11211.

Petrographic description of sample ED11214 (St Murray's quarry)

Hand specimen observations

Stone type [1] (general classification):	sandstone
Stone colour [2] **–** fresh stone:	reddish brown
Stone colour [2] **–** weathered stone:	purplish brown
Stone colour [2] **–** exterior surface:	purplish brown
Stone cohesion [3] – fresh stone:	strongly cohesive
Stone cohesion [3] – weathered stone:	strongly cohesive
Stone fabric [4]:	faint bedding
Distinctive features:	none

Thin section observations

Stone constituents [5]:

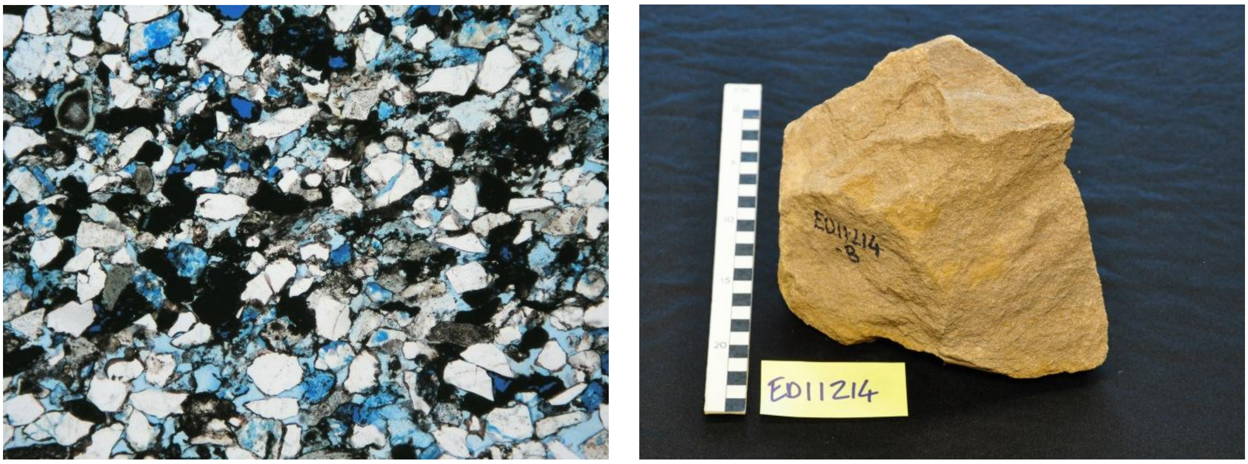
Granular (detrital) constituents		*Intergranular constituents*	
Quartz	32%	Silica (overgrowth)	3%
Feldspar	3%	Feldspar (overgrowth)	0%
Rock fragments	14%	Carbonate	0%
Mica	1%	Iron/manganese oxide	24%
Opaque material	<1%	Clay	8%
Other	0%	Hydrocarbon	0%
Intragranular pores	2%	Intergranular pores	13%

Stone type [1] (detailed classification):	lithic-arenite
Grain-size [6]:	fine-sand-grade to medium-sand-grade
Grain sorting [7]:	moderately sorted
Grain roundness [8]:	angular
Stone permeability [9]:	moderate
Cement distribution [10]:	silica cement discontinuous; iron oxide veneers on detrital grains
Supergene changes [11]:	strong dissolution of rock fragments; moderate dissolution of feldspar; strong dissolution of carbonate; strongly re-mobilised iron

Comments

1) Alternating slightly darker and slightly lighter layers define a faint bedding fabric in the hand sample.

2) Most of the opaque material in the thin section is iron oxide which forms patches in intergranular spaces; moldic pores developed locally suggest the iron oxide has formed as the result of an iron-rich carbonate mineral dissolving. The thin section contains no carbonate mineral indicating that this component has dissolved entirely.



At left: thin section photograph of sample ED11214. The image was taken in plane-polarised light and the field of view is c.3.3 mm wide. Pore space appears blue. At right: photograph of hand sample ED11214.

Petrographic description of sample ED11215 (Ruined Arch)

Hand specimen observations

Stone type [1] (general classification): sandstone
Stone colour [2] **–** fresh stone: not available
Stone colour [2] **–** weathered stone: light greenish buff
Stone colour [2] **–** exterior surface: light greenish buff
Stone cohesion [3] – fresh stone: not available
Stone cohesion [3] – weathered stone: moderately cohesive
Stone fabric [4]: uniform (some orientated grains)
Distinctive features: colour mottling due to alteration; mud flakes

Thin section observations

Stone constituents [5]:

Granular (detrital) constituents		*Intergranular constituents*	
Quartz	36%	Silica (overgrowth)	2%
Feldspar	1%	Feldspar (overgrowth)	0%
Rock fragments	14%	Carbonate	10%
Mica	2%	Iron/manganese oxide	14%
Opaque material	<1%	Clay	14%
Other	<1%	Hydrocarbon	0%
Intragranular pores	1%	Intergranular pores	6%

Stone type [1] (detailed classification): lithic-arenite
Grain-size [6]: medium-sand-grade
Grain sorting [7]: moderately well sorted
Grain roundness [8]: angular
Stone permeability [9]: moderate
Cement distribution [10]: silica cement discontinuous; carbonate cement isolated
Supergene changes [11]: strong dissolution of rock fragments; strong dissolution of feldspar; strongly re-mobilised iron; strong dissolution of carbonate

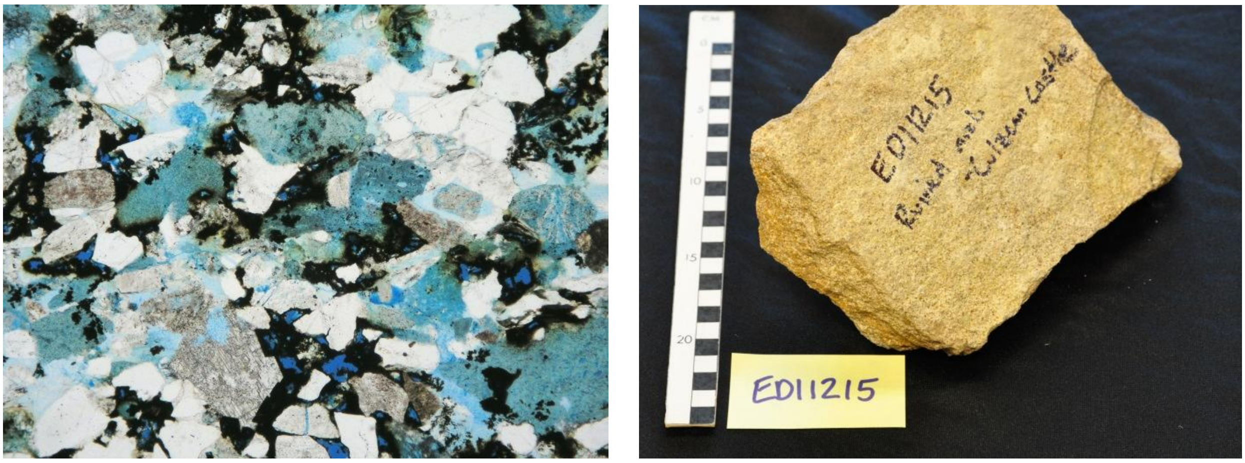
Comments

1) Patches of white salt efflorescence and dendritic crystals of black manganese oxide are developed locally on the exterior surface of the sample. In thin section, the manganese dendrites are observed growing into patches of clay.

2) Most opaque material is iron oxide and manganese oxide. Iron oxide is often associated spatially with crystals of iron-rich carbonate, and has probably formed through dissolution of the carbonate (which in places has left moldic pores after carbonate crystals). The iron is largely responsible for the orange mottling in the hand sample.

3) The sample contains two carbonate minerals - calcite and iron-rich carbonate (dolomite, ankerite or siderite) - both of which have experienced dissolution. Calcite crystals enclose (and therefore post-date) iron oxide crystals.

4) Some of the biotite mica biotite has altered to green chlorite. Some rock fragments also display a greenish tinge, due to the alteration of mafic minerals to green chlorite. Most rock fragments and feldspar grains have been replaced by clay; this has been taken into account in the detailed classification.



At left: thin section photograph of sample ED11215. The image was taken in plane-polarised light and the field of view is c.3.3 mm wide. Pore space appears blue. At right: photograph of hand sample ED11215.

Petrographic description of sample ED11357 (Swallowcraigs quarry)

Hand specimen observations

Stone type [1] (general classification):	sandstone
Stone colour [2] **–** fresh stone:	greenish buff
Stone colour [2] **–** weathered stone:	dark orangeish buff
Stone colour [2] **–** exterior surface:	dark orangeish buff
Stone cohesion [3] – fresh stone:	moderately cohesive
Stone cohesion [3] – weathered stone:	moderately cohesive
Stone fabric [4]:	faint bedding
Distinctive features:	none

Thin section observations

Stone constituents [5]:

Granular (detrital) constituents		*Intergranular constituents*	
Quartz	30%	Silica (overgrowth)	1%
Feldspar	4%	Feldspar (overgrowth)	0%
Rock fragments	24%	Carbonate	10%
Mica	2%	Iron/manganese oxide	6%
Opaque material	0%	Clay	10%
Other	0%	Hydrocarbon	0%
Intragranular pores	2%	Intergranular pores	11%

Stone type [1] (detailed classification):	lithic-arenite
Grain-size [6]:	medium-sand-grade
Grain sorting [7]:	well sorted
Grain roundness [8]:	sub-rounded
Stone permeability [9]:	moderate
Cement distribution [10]:	silica cement discontinuous; carbonate cement continuous
Supergene changes [11]:	weak dissolution of rock fragments; weak dissolution of feldspar; weak dissolution of carbonate; moderately remobilised iron

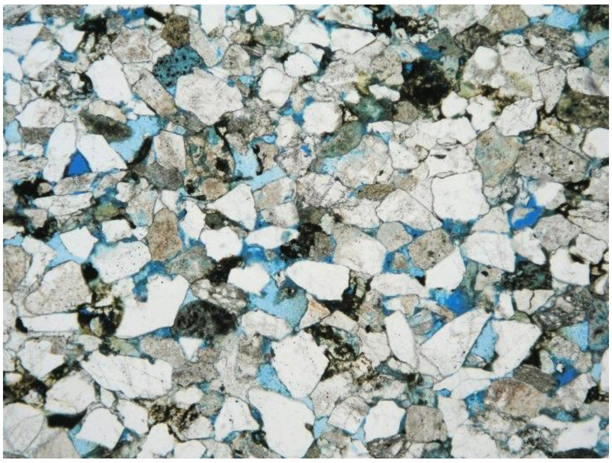
Comments

1) Alternating slightly darker and slightly lighter layers define a faint bedding fabric in the hand sample.

2) Most of the carbonate is calcite, and the remainder (c. 2% of the thin section volume) is iron-rich carbonate (ankerite, siderite or dolomite). The calcite appears fresh.

3) Rock fragments display a greenish tinge due to the alteration of mafic minerals to green chlorite.

4) Most of the opaque material in the thin section is iron oxide which forms patches in intergranular spaces and developed through dissolution of iron-rich carbonate.



At left: thin section photograph of sample ED11357. The image was taken in plane-polarised light and the field of view is c.3.3 mm wide. Pore space appears blue. At right: photograph of hand sample ED11357.

Petrographic description of sample ED11359 (NTS mason's yard)

Hand specimen observations

Stone type [1] (general classification): sandstone
Stone colour [2] **–** fresh stone: not available
Stone colour [2] **–** weathered stone: greenish grey
Stone colour [2] **–** exterior surface: greenish grey
Stone cohesion [3] – fresh stone: not available
Stone cohesion [3] – weathered stone: friable
Stone fabric [4]: uniform (some orientated grains)
Distinctive features: none

Thin section observations

Stone constituents [5]:

Granular (detrital) constituents		*Intergranular constituents*	
Quartz	35%	Silica (overgrowth)	1%
Feldspar	3%	Feldspar (overgrowth)	0%
Rock fragments	25%	Carbonate	7%
Mica	3%	Iron/manganese oxide	2%
Opaque material	3%	Clay	12%
Other	<<1%	Hydrocarbon	0%
Intragranular pores	0%	Intergranular pores	9%

Stone type [1] (detailed classification): lithic-arenite
Grain-size [6]: medium-sand-grade
Grain sorting [7]: moderately well sorted
Grain roundness [8]: sub-angular
Stone permeability [9]: high
Cement distribution [10]: silica cement isolated; carbonate cement isolated
Supergene changes [11]: strong dissolution of feldspar; moderate dissolution of rock fragments

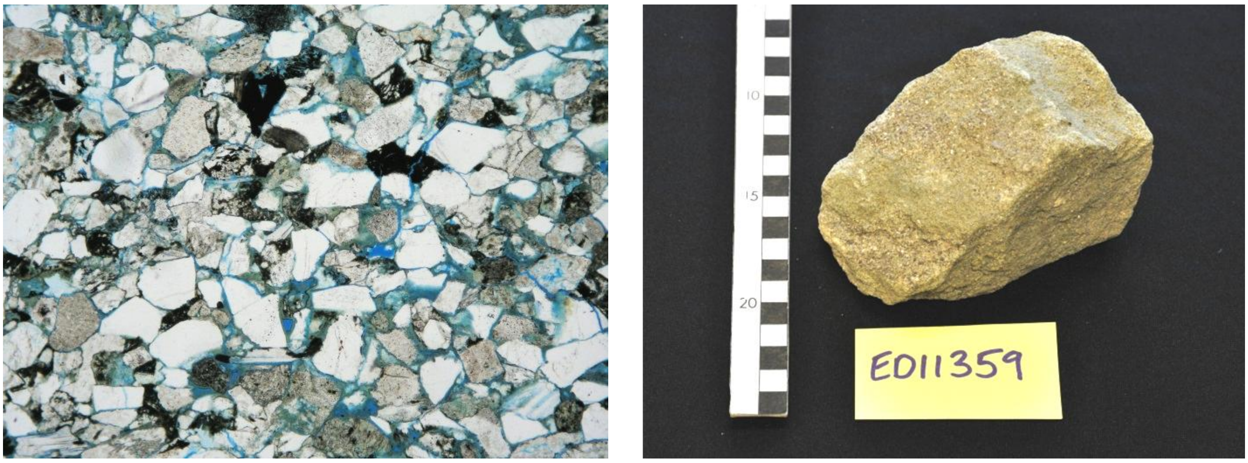
Comments

1) The entire sample consists of strongly weathered stone.

2) Most detrital grains appear to be "floating", i.e. they are not in contact with other grains in the plane of the thin section and are separated from each other by narrow gaps (filled by blue resin in the thin section). Despite the relatively low pore volume, the high connectivity of these gaps contributes to high permeability in the stone. In places the gaps are infilled with a green mineral, possibly chlorite or corrensite. This mineral comprises c. 9% of the thin section area and is classified as 'clay'.

3) The mineral zircon is present in trace proportions (<<1%).

4) The sample reacts vigorously to 10% HCl solution, indicating that the carbonate mineral is dominantly or entirely calcite. The calcite is relatively fresh and has not suffered significant dissolution.



At left: thin section photograph of sample ED11359. The image was taken in plane-polarised light and the field of view is c.3.3 mm wide. Pore space appears blue. At right: photograph of hand sample ED11359.

Petrographic description of sample ED11360 (NTS mason's yard)

Hand specimen observations

Stone type[1] (general classification):	sandstone
Stone colour[2] **–** fresh stone:	not available
Stone colour[2] **–** weathered stone:	greenish buff
Stone colour[2] **–** exterior surface:	greenish buff
Stone cohesion[3] – fresh stone:	not available
Stone cohesion[3] – weathered stone:	moderately friable
Stone fabric[4]:	uniform (some orientated grains)
Distinctive features:	none

Thin section observations

Stone constituents[5]:

Granular (detrital) constituents		*Intergranular constituents*	
Quartz	34%	Silica (overgrowth)	1%
Feldspar	2%	Feldspar (overgrowth)	0%
Rock fragments	23%	Carbonate	12%
Mica	2%	Iron/manganese oxide	2%
Opaque material	1%	Clay	8%
Other	<1%	Hydrocarbon	0%
Intragranular pores	3%	Intergranular pores	12%

Stone type[1] (detailed classification):	lithic-arenite
Grain-size[6]:	medium-sand-grade
Grain sorting[7]:	moderately well sorted
Grain roundness[8]:	angular
Stone permeability[9]:	moderate
Cement distribution[10]:	silica cement discontinuous; carbonate cement discontinuous
Supergene changes[11]:	strong dissolution of rock fragments; moderate dissolution of feldspar

Comments

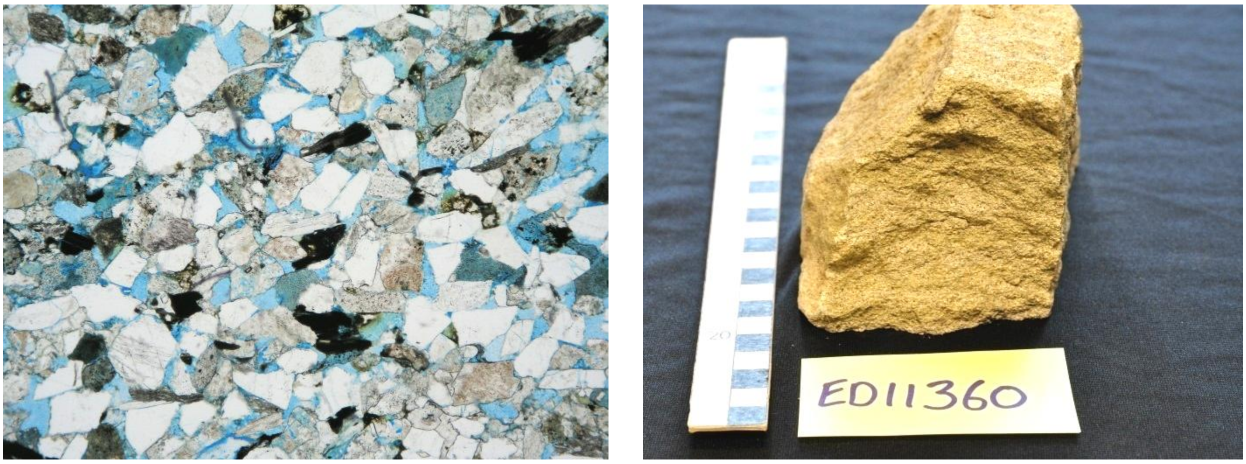
1) The entire sample consists of weathered stone.

2) Some of the material classified as clay is a green mineral (possibly chlorite or corrensite) which forms c. 1% of the thin section area and has grown in gaps between the detrital grains and patches of clay.

3) The sample reacts strongly to 10% HCl solution; indicating that the carbonate mineral is dominantly or entirely calcite. The calcite is relatively fresh, and occurs in scattered patches up to several millimetres across.

4) The minerals tourmaline and zircon are present in trace proportions (<1%).

5) Most of the rock fragments and feldspar grains have been replaced by clay; this has been taken into account in the detailed classification.



At left: thin section photograph of sample ED11360. The image was taken in plane-polarised light and the field of view is c.3.3 mm wide. Pore space appears blue. At right: photograph of hand sample ED11360.

Supporting notes for the petrographic descriptions

Each numbered note below relates to a superscript number in the preceding petrographic description forms.

1 The determination of stone type follows the classification and nomenclature of the BGS Rock Classification Scheme.

2 The 'visual' determination of stone colour is based on a simple assessment with the unaided eye in natural light. The 'Munsell' determination is obtained by matching the stone colour to one of the coloured patches in a Munsell Rock Colour Chart; each patch has a unique colour and a unique code (the 'Munsell code'), which incorporates values for hue and chroma. In stones displaying variable colour, both the 'visual' and 'Munsell' determinations record the colour deemed by the geologist to be most representative. The determination of stone colour is made on a broken (not sawn), dry surface.

3 A simple, non-quantitative assessment of the degree to which the stone is cohesive. This property is recorded in terms of four conditions, each representing one segment of a continuum: *strongly cohesive*, *moderately cohesive*, *moderately friable*, and *very friable*. The grains in a *strongly cohesive* stone cannot be disaggregated by hand, whereas the grains in a *very friable* stone can be readily disaggregated by hand.

4 A record of whether the distribution of granular (detrital) constituents in the sample is essentially isotropic (uniform) or anisotropic (non-uniform). The type of anisotropic fabric is recorded.

5 A record of the identity and relative proportions of all granular (detrital) and intergranular (authigenic materials and pore space) constituents currently in the stone. The proportions are estimates, expressed in %, which are based on a visual assessment of the whole thin section area.

6 The terms are those used for grain-size divisions in the BGS Rock Classification Scheme.

7 A simple, non-quantitative assessment of the degree to which detrital constituents display similarity in terms of physical characteristics (in particular the size and shape of grains).

8 A simple, non-quantitative assessment of the degree to which detrital constituents are abraded.

9 A simple, non-quantitative assessment of stone permeability, presented as one of five conditions (*very low*, *low*, *moderate*, *high*, *very high*) expressed relative to a nominal 'average' permeability in building stone sandstones. The assessment is based on: (i) a water bead test; (ii) the proportion of pore space in the stone; (iii) a visual assessment of the degree to which pore spaces appear connected in the thin section.

10 A record of the type and extent of authigenic mineral cement that acts to bind detrital grains, as observed in thin section. *Isolated* means the cement occurs in discrete locations (e.g. as overgrowths on individual detrital grains) that are typically not connected in the plane of the thin section. *Discontinuous* means the cement is formed in patches, each of which typically encloses several to many detrital grains. *Continuous* means the cement is more-or-less connected across the thin section.

11 A record of the evidence observed in thin section for mineral alteration that occurs in the stone when it is near the ground surface. Such alteration processes typically begin before stone is quarried, but some may continue, or be initiated, after stone is extracted from the ground.

References

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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