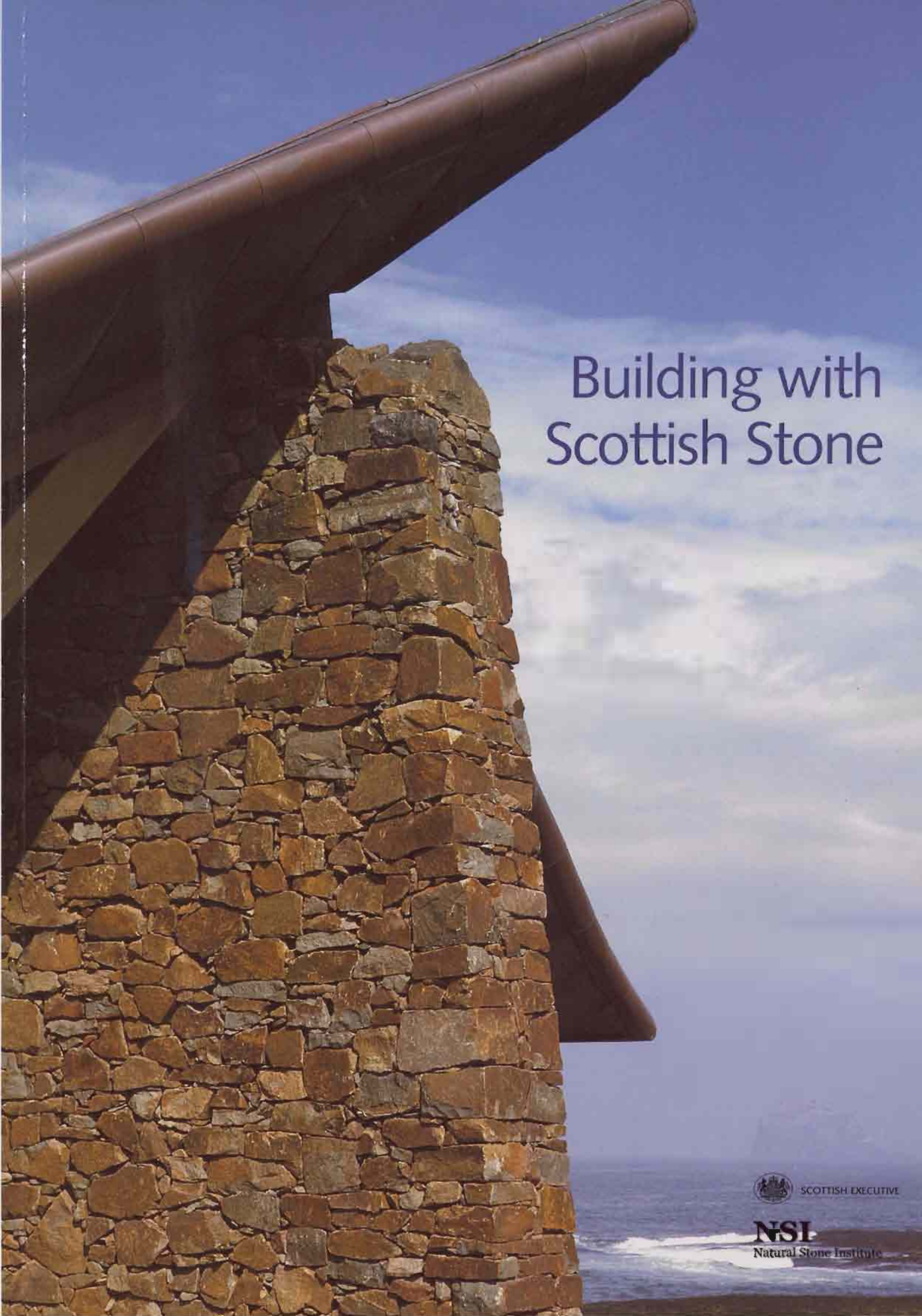
Building with Scottish Stone



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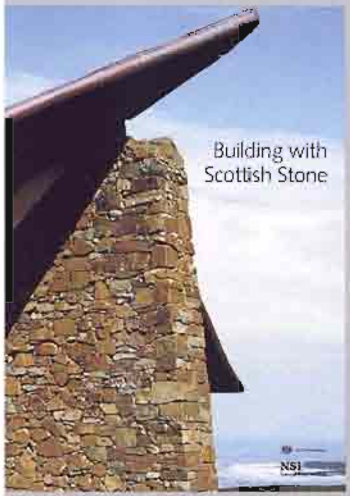

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Introducing Stone

History of Stone

Working with Stone

Building with Stone

Resources

Scotia's Stone

Peter Wilson
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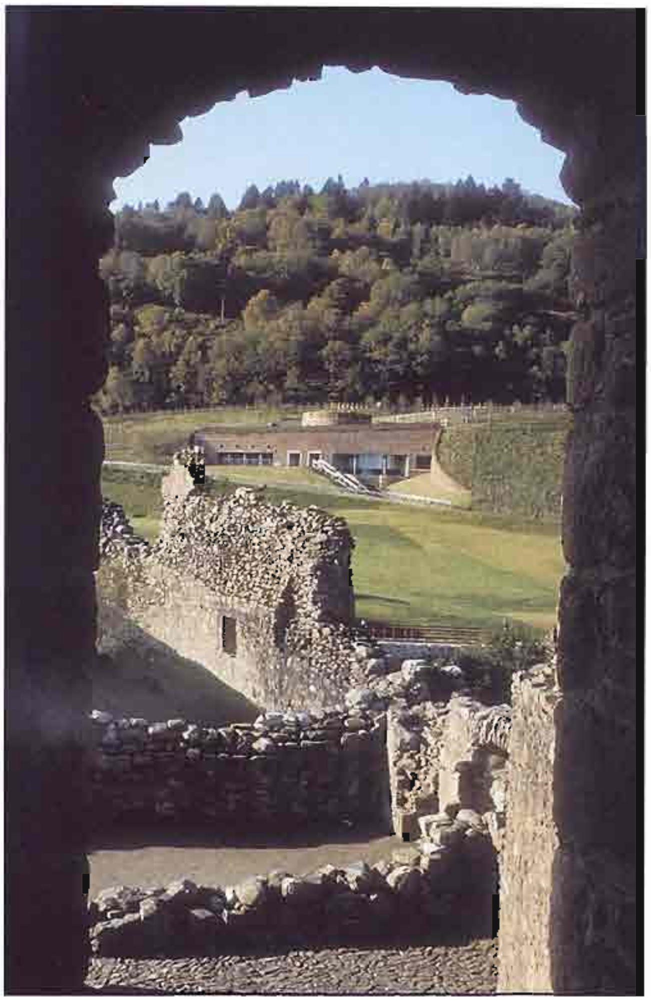
The past few years have witnessed a renaissance in the use of stone in the construction of new buildings in Scotland, and with it has come demands for more up-to-date information on the various stone types available from local sources and the properties of each. This reawakened interest has been stimulated in part by environmental concerns and the embodied energy used to transport construction materials from around the globe, but it has arguably also been a response to the re-emerging sense of nationhood that has accompanied the devolution of aspects of government to Edinburgh. Along with the latter has come a rethinking of those elements that for centuries have characterised national and regional identity, with the importance – and potential – of traditional materials undergoing a critical re-evaluation.

For most architects, this process is creative rather than nostalgic, but there is increasing recognition that there is much to learn from our past on the best ways to use the natural resource from our quarries. True, there are far fewer of these working today (around ten) than at the peak of stone construction 150 years ago (over 750), but the reopening of Cullaloe quarry in Fife in 2004 may well be regarded in the future as the turning point for an industry so umbilically linked to Scotland's built heritage. The Museum of Scotland, the Scottish Parliament and the Weston Link at the National Gallery of Scotland in Edinburgh all attest to the potential for use of indigenous stone in major architectural projects, but throughout the country many other fine examples of the use of stone on new buildings continue to emerge and their completion has put a very positive spotlight on the quality and distinctiveness of the materials available from different areas.

Of course stone is not a renewable resource, but aside from life cycle calculations which can make its use more compelling, there are several important issues to consider when specifying stone from Scotland's quarries as opposed to material imported from overseas (although the long tradition which continues to this day of using stone from England and slate from Wales should be noted). There is an appreciation here of the ways in which indigenous stone responds to local environmental conditions and long experience of working with the material; it is easier to



Above
The colour and texture of the indigenous stone structure of Castle Urquhart in Inverness-shire is echoed on the façade of the adjacent visitor centre by LDN Architects.

Opposite above
In a symbolic reference to the architectural history of Scotland, stones from around the country are set into the concrete wall of the Parliament building.

Opposite below
The arrival of devolved government focused attention on Scottish culture and traditions. The Stone Circle by artist George Wylie brings together stones from every part of Scotland on a site overlooking the Parliament building. A valuable reference source for anyone interested in the use of Scottish stone.

monitor the quality of what is quarried and delivered and it is usually possible to obtain proven replacement stone for maintenance and repairs; and the energy employed in quarrying, processing and delivery is less than with stones obtained from abroad. Scotland's quarries are also significant employers in what are usually rural areas, and – against a rising tide of imported materials – the stone produced in these locations has a positive economic value to the UK.

All of these reasons would be of no consequence were it not for the fact that Scotland produces some of the world's finest natural building stones. The purpose of this publication is to remind architects, contractors, developers, planners and politicians of this fact, and to encourage more use of locally-sourced material. As with other skills, building with stone requires knowledge of the resource, an understanding of how best to design with it and – most important of all – regular practice in directly working with it.

The increase in construction with stone is not a phenomenon exclusive to Scotland, however, and specifiers need to be aware of the plethora of new European standards covering the use of this rich and varied material. There are many challenges ahead, but the stone industry in Scotland is increasingly well positioned to respond to the new demands being placed upon it. This publication is an important step in reminding us all of the excitement and pleasure to be had from building with Scottish stone.

A Modern Material

Peter Wilson
Manifesto Centre for Architectural Research, Napier University

For thousands of years the construction of stone buildings has been characterised by the gravitational methods employed: stone laid upon stone, the weight of each bearing onto those immediately below, with arches, lintels and cills distributing the structural forces around openings. In this tradition, walls were the primary loadbearing structural element, with piers, columns and buttresses of the same material emerging over the centuries as man sought to extend the architectural possibilities of stone construction. Increasingly sophisticated methods and materials for joining stones developed and the design of building façades began to be considered separately from the construction of the loadbearing rubble walls behind. A distinction between form and function had begun to emerge.

The 19th century brought cast iron into widespread use as an industrially-produced structural material. From this, larger and taller metal-framed buildings became possible, and the scene was set for a radical rethinking of the purpose of the external wall. This came in the 20th century, perhaps most influentially with Le Corbusier's 'Domino Frame', a concrete frame solution utilising repeatable columns and slabs and which permitted the development of the open plan and the free façade. The economics and methods of construction were transformed, and the perceived role of stone in building was changed forever. No longer essential for even domestic projects, a new case was required for the use of stone.

With these changes came a transformation in the knowledge and skills required of architects, engineers and stonemasons. The connection between architectural style and material was irrevocably affected and the need to understand the physical and structural characteristics of different stones began to disappear. The use of stone decreased and with it demand for workers who had served the long apprenticeship to become stonemasons. The craft of hand-tooling stone was progressively replaced by factory processes, themselves separated from both quarry and building site and geared to industrialising as much of the material's processing as possible. The need for traditional masonry skills transferred from new buildings to the repair of old ones, and the architectural understanding of different stone types shifted to those specialising in conservation and restoration.

As a consequence, for a large part of the architectural profession today the ability to design with stone is something of a forgotten art, rarely featuring in the curriculum of schools of architecture and specified mainly by practitioners involved in the design of commercial buildings. Primarily employed in these situations as an external, non-structural cladding material, a stone's final selection is invariably based upon availability, cost, colour, texture and – fashion. Pressure from planners to match adjacent properties is sometimes a factor, but the sheer distance between quarry source and the final application as well as a diminished understanding of detailing appropriate to local environmental conditions has too often produced unsatisfactory results.

Holyrood Park House by architects CDA uses Clashach sandstone to good effect on its principle façade and demonstrates the suitability of this stone type to high quality commercial buildings.

Weston Link by John Miller & Partners uses Light Clashach Sandstone to form a battered, rusticated entrance wall.

Yet stone is the material universally associated with the constructed landscape of Scotland. From the earliest forms of habitation at Skara Brae through tower houses and castles to tenement blocks; from the first ecclesiastical buildings at Whithorn and Iona through Romanesque (Norman), Gothic and Reformation churches to the 19th century explosion of denominational construction; and from the mansions of the aristocracy to the suburban detached villas of the middle classes, stone has been synonymous with the nation's cultural development. Urban expansion brought civic and cultural institutions, banks, hotels and railway stations. Most were faced in stone with, more often than not, the material coming from quarries in the immediate vicinity. The sense of continuity and of a distinctive indigenous – and regional – architecture remains palpable, the many external influences tempered by the need to respond to the characteristics of locally available stone.

Part of the appeal of the material in the Scottish environment is the way in which its appearance responds to local weather and natural lighting conditions. From the sparkle of recently-wet granite in the traditional buildings of Aberdeen to the rich tones of the red sandstone used to construct Glasgow's commercial centre and its tenement housing, the exigencies of Scotland's climate bring out the best features of the nation's wide range of natural stones. And in response to these characteristics, a truly regional range of architectural styles progressively developed around the country. The sheer hardness of Aberdeen's granite mitigated against fine detailing on the city's buildings, while the strong Craigleith sandstone used to construct Edinburgh's New Town appears as precise today as when it was first cut by masons in the 18th century.

The best of Scotland's historic architecture demonstrates how to take advantage of each stone's specific qualities and evidence can be seen throughout the country of the many different but locally appropriate approaches taken to the manipulation of advance and recess, of light and shade, and of surface and texture in the surface of a wall. These characteristics are not purely historical, however – they are the stuff of architecture, and more use of natural stone in contemporary buildings may well stimulate architects, developers, planners and politicians to once again view one of Scotland's most important natural resources as a fundamental – and economically viable – element in the historical continuum of our towns and cities.

Table 1 Types of stone in Scotland and their variability

Sedimentary rocks	Igneous rocks	Metamorphic rocks
Sandstone Sandstone is a sedimentary rock containing visible mineral grain constituents held together by natural cement. Sandstones vary widely in terms of constituent minerals, cement types, grain size and pore structure, leading to a wide variety of colours and different performances as building stones. Many Scottish sandstones are composed of variable proportions of quartz grains, naturally cemented by silica or, in some cases by carbonate. Variable quantities of clay minerals may be present. Mica may also be present. Sandstones may be massive (without internal lamination) or bedded. Sometimes they may have sedimentary structures such as ripple bedding or cross bedding. Rarely they may contain fossils. Depending upon these factors they respond differently to tooling. Bed heights vary and dictate how stone may be used for example as traditional ashlar or as modern cladding.	Fine to coarse-grained crystalline rocks originating from the molten state. Basic or intermediate igneous rocks such as basalt, dolerite or gabbro are generally dark or grey in colour and contain little or no quartz. Pale or strongly coloured varieties such as felsite and porphyry are generally associated with volcanic areas. The colloquial term 'whinstone' is commonly used to describe igneous rocks other than granite, although this name is commonly applied to any dark hard rock, such as the sedimentary greywacke sandstone of southern Scotland.	Metamorphic rocks are the products of alteration of sedimentary and igneous rocks by temperature and pressure. Metamorphism is often referred to in relation to 'metamorphic grade', where a low grade metamorphic rock is one which has undergone a moderate degree of alteration and where original features such as bedding are still preserved. High-grade metamorphic rocks may undergo complete recrystallisation or even melting producing a hard crystalline rock with complete destruction of its original textures, containing distinct metamorphic banding such as in schist and gneiss.
Flagstone Flagstone is generally a layered (thinly bedded or laminated) sedimentary rock (sandstone or siltstone) capable of being naturally split or riven into large thin slabs suitable for paving. Some flagstone quarries are capable of producing 'stone slates' for roofing.	**Granite** Granite is a coarse-grained crystalline igneous rock composed of visible quartz, feldspar and mica, intergrown to give a uniform hard building stone. Granites can vary widely in colour, with common grey and pale red-orange varieties dependant on their feldspar composition.	**Slate** Slate is a general term used for any stone capable of being uniformly split to form a natural roofing tile. 'True slate' is the product of metamorphic alteration of very fine grained rocks such as mudstones at such high temperatures and pressures as to completely recrystallise the constituent minerals to form a series of parallel cleavage planes along which the stone will readily split into thin sheets. 'Stone slates' are sedimentary rocks (or metamorphic rocks) which do not possess true slaty cleavage, commonly splitting into thin slabs along bedding or other planes. Note that slate can also be used as building stone and for paving.
Limestone Limestone is principally composed of calcium and/or magnesium carbonate, commonly formed from the accumulation of fragments of marine organisms. It is widely variable in colour and texture and may contain fossils on a microscopic or macroscopic scale.		**Marble** Marble is a limestone that has been recrystallised by metamorphism under conditions of heat and pressure. The presence of different metamorphic minerals in marbles can result in widely different appearances, such as the green serpentinite marbles formed by the iron- and magnesium-rich minerals olivine and serpentine.

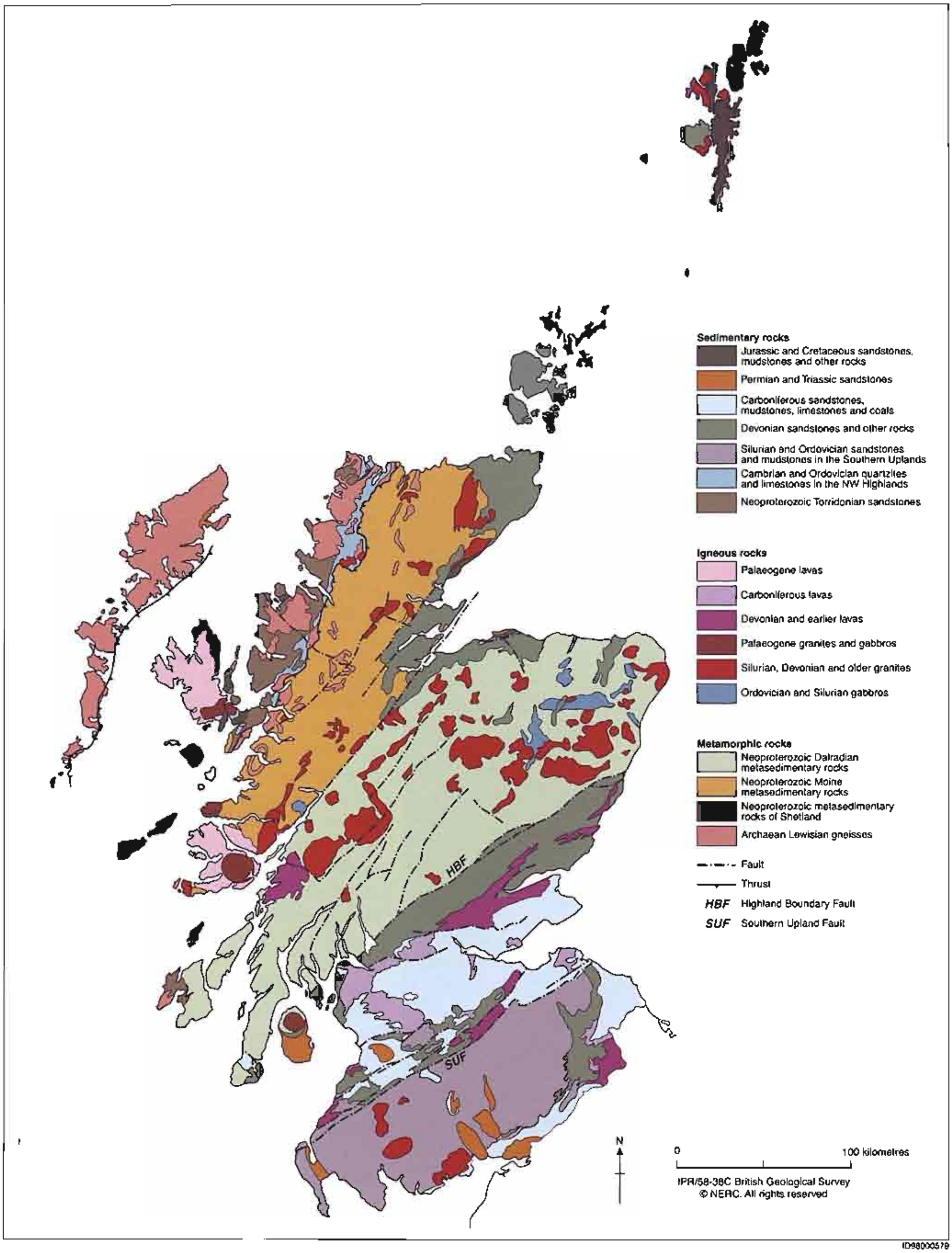
What is Stone?

Andrew A McMillan and Ewan K Hyslop,
British Geological Survey

What is stone? The Oxford English Dictionary defines stone as "A piece of rock or hard mineral substance (other than metal), of small to moderate size". One of the most commonly used terms related to geology it derives from stan (Old English) and steinn (Old Norse). In the Gaelic it is clach.

The formation of sedimentary rocks was described in 1802, by Professor John Playfair, uncle to architect William, and friend of James Hutton, founder of modern geology. The notable 19th century Scottish geologist Sir Archibald Geikie eloquently commented on the process of transition from unconsolidated sediment to sedimentary rock: "If you take a quantity of mud, and place it under a weight which will squeeze the water out of it, you will find that it gets firmer. You can thus harden it by pressure. Again, if you place some sand under water which has been saturated with lime or iron, or with some other mineral that can be dissolved in water, you will notice that as the water slowly evaporates it deposits its dissolved material round the grains of sand and binds them together. Were you to continue this process long enough, adding more of the same kind of water as evaporation went on, you would convert the loose sand into a solid stone."

This is essentially the process of lithification (derived from the Greek word lithos – a rock). Thus in a sedimentary basin through compaction by the weight of overlying strata and by cementation by mineralised fluids so **sedimentary rocks** are formed. In contrast, **igneous rocks** are usually consolidated by crystallization of minerals from molten material either within the earth's crust (e.g. granites) or at the surface (e.g. basalt lavas). As their name suggests **metamorphic rocks** have been transformed (recrystallised) from the original rock by a combination of heat and pressure. In these circumstances, new minerals sometimes form.



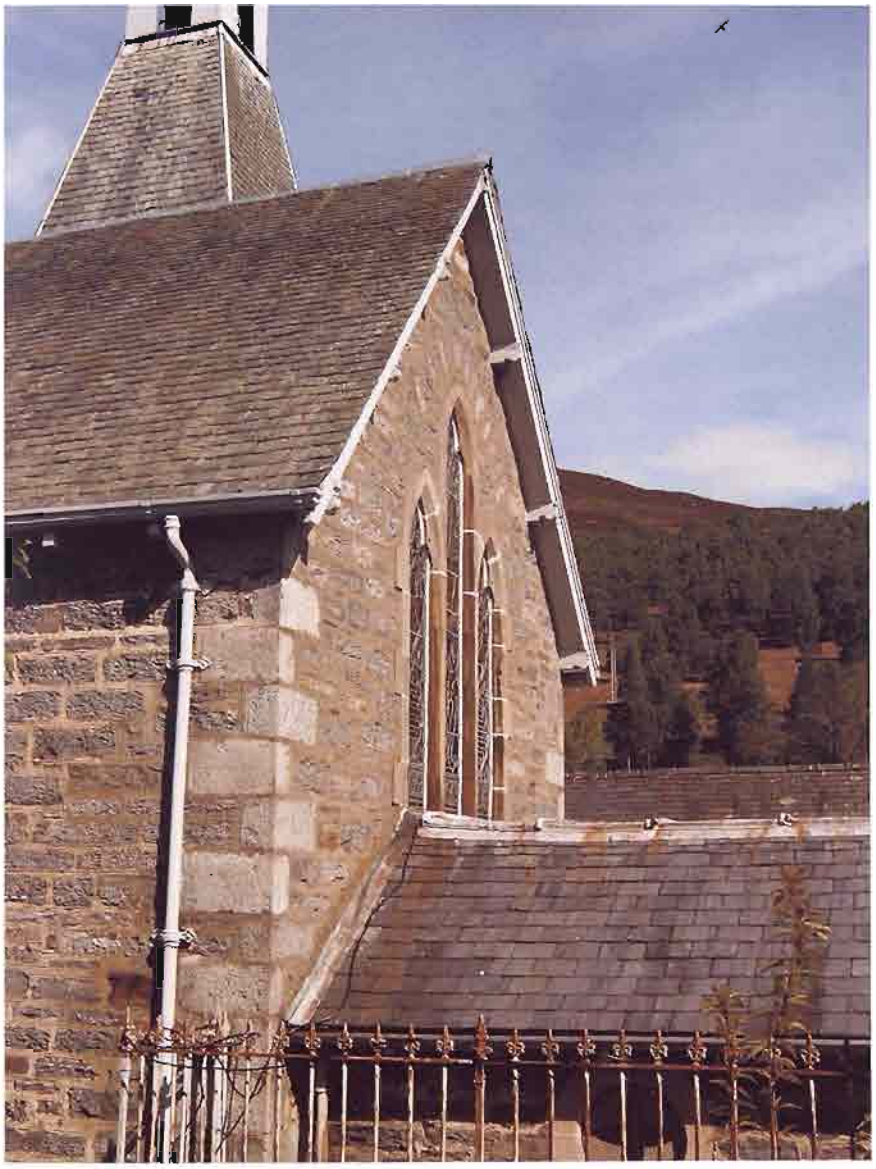
Simplified geological map of Scotland showing major stone types, illustrating the geological diversity of the country

A Land of Stone

Andrew A McMillan and Ewan K Hyslop,
British Geological Survey

Scotland is a land of stone. Its diverse landscape owes much to the complicated underlying geological foundation of sedimentary, igneous and metamorphic rocks some of which date back nearly 4000 million years (Table 2). The nature and distribution of the rocks reveal a prehistory which involved the opening and closing of oceans, intermittent volcanic activity, the formation of sedimentary basins, the development of ancient river systems and repeated glaciations. Over the last 5000 years Scotland's varied rocks have provided a major source of building materials. It is the nation's geological complexity – the geodiversity – that is responsible for the diversity in its stone-built heritage in terms of both materials and architectural style and which accounts for local distinctiveness. The fundamental geological properties of a particular rock type in an area determine how that material can be shaped and utilised as a building stone.

Structurally Scotland can be divided into three fundamental geological regions separated from each other by major faults. North of the Highland Boundary Fault, extending from Arran to Stonehaven, the Highlands and Islands are dominated by Precambrian (Dalradian, Moine and Lewisian) crystalline metamorphic rocks (Table 2) including metasandstone, quartzite, schist, gneiss, slate and, less commonly, marble. Lewisian gneiss makes up much of the Outer Hebrides and NW Scotland where it is overlain by remnants of hard, bedded, purple Torridonian metasandstone. Generally the crystalline rocks are difficult to work using traditional methods and were used only locally for building purposes. Slate (metamorphosed mudrocks) of the Grampian Highlands (e.g. Ballachulish) were exploited on a major scale for roofing.



Use of metasandstone in Episcopal Church, Kinloch Rannoch. 1864.
(A A McMillan)

Table 2 Geological timescale and distribution of Scottish rock types used as building stone

Geological System		Age of base in millions of years	General distribution	Typical Scottish building stone types
QUATERNARY		2	Throughout Scotland	Various glacially-derived materials, both of local and far travelled origin
TERTIARY (NEOGENE)		65	Inner Hebrides, Arran, Tertiary dykes in Western, Central and Southern Scotland	Basalt lavas, gabbro and other igneous rocks including basalt dyke swarms; Arran granite and dykes
CRETACEOUS		140	Remnants on Mull, Skye, Lochaline	Sandstone
JURASSIC		200	Moray Firth Coast and pockets in Inner Hebrides	Sandstone
TRIASSIC		250	Moray Firth Coast Solway Coast	Sandstone
PERMIAN		300	Dumfries and Galloway, Mauchline, Arran	Red sandstone
CARBONIFEROUS		360	Midland Valley, Solway coast, Berwickshire	Sandstone; basalts and other volcanic rocks
DEVONIAN		410	Angus and southern parts of Midland Valley; Caithness, Northern Isles; granites of Southern Uplands and Grampian Highlands	Sandstone,notably Flagstone; major granite intrusions; Andesite lavas and other igneous rocks
SILURIAN		440	Southern Uplands	Greywacke sandstone, siltstone (locally used as 'slate')
ORDOVICIAN		510	Southern Uplands	Greywacke sandstone, siltstone (locally used as 'slate')
CAMBRIAN		570	North-west Scotland	Quartzite, Durness Limestone
PRE-CAMBRIAN	DALRADIAN	850	Grampian Highlands, Argyll, Islay, Jura	Slate, quartzite, schist, metamorphosed igneous rocks
	TORRIDONIAN	1000	Skye and Applecross to Laxford; parts of Cape Wrath	Arkosic sandstone (Feldsarenite)
	MOINIAN	1200	Northern Scotland and northern part of Grampian Highlands	Schist, quartzite
	ARCHEAN	Oldest Scottish rocks c.4000	North-west Highlands and Outer Hebrides, Coll and Tiree	Gneiss, schist, quartzite, marble

Clashach stone in the Museum of Scotland, 1999. (A A McMillan)

A 19th century greywacke constructed building in Earlston. Note pink sandstone quoins and lintels. (A A McMillan)

Igneous rocks (Table 2) are widespread, with major granite intrusions of Devonian and Carboniferous age present throughout the Grampian Highlands and older Precambrian intrusions in the Northern Highlands. The famous granites of Aberdeenshire were exploited over centuries and exported around the world. Younger Tertiary intrusions underlie western coastal areas and islands, forming large granite and related igneous bodies in the islands of Skye, Mull and Arran.

Devonian sandstones, present in Caithness and Orkney, were deposited in a vast lake, producing both flaggy material and thickly bedded strata which have long been exploited respectively as pavement and building stone. The Mesozoic sandstones which occur in coastal areas on Mull and Arran were also hewn, generally for local use. Sandstones of similar age were worked around the Moray Firth and still supply quality stone (e.g. Clashach).

The fault-bounded lowlands of the Midland Valley of Scotland is underlain by mainly Devonian and Carboniferous sedimentary strata, deposited in former river systems and desert plains. Sandstones were exploited over many centuries to build villages, towns and cities. Many sandstones were relatively easily worked both for pavement and masonry. Small sedimentary basins of Permian red sandstone were exploited in the late 19th century (e.g. at Mauchline, Ayrshire), particularly for the Glasgow market. Devonian and Carboniferous intrusive igneous rocks and volcanic lavas are present in the Lothians and around Glasgow but are difficult to work and were generally used locally for rubble walling, or for roadway construction including setts.

The land of the Borders and Southern Uplands, south of the Southern Upland Fault, is mainly underlain by folded strata of Ordovician and Silurian age. The main rock types are greywacke sandstone (a hard rock made up of mineral and rock fragments, colloquially known as whinstone), siltstone and mudrocks. The greywackes are difficult to work and were generally used only locally for rubble walling or roughly dressed dimension stone. Fissile siltstones provided reasonable stone 'slates' for roofing. Stone was also supplied from the inliers of Permian and Triassic red sandstone, in Dumfries and Galloway, and the Devonian and early Carboniferous sandstones of the eastern Borders. The granite masses of Galloway were exploited for building and monumental purposes and harbour construction. Smaller bodies of Devonian and Carboniferous basic intrusive and volcanic rocks are locally present, particularly in the north and east of the Southern Uplands and were mainly used for only local construction.

Geological influences on how stone was used

The early construction of walls and dwellings commonly utilised rounded field-stones and boulders, the products of glaciation, gathered from the land or from the bed of rivers and along the coastline. Much of this material was used with little, if any, further dressing to form random rubble walls. Field clearance during the late 18th and early 19th centuries provided a ready source of boulders suitable for the building of field drains, enclosures and march dykes. The character of the dykes very much depended on the geological nature of the stones. In western Scotland weather-worn, rounded field boulders of a range of rock types were utilised to produce ill-fitting constructions. In contrast, the Devonian ('Old Red Sandstone') flagstones of Caithness and the Northern Isles were set in the ground on edge to produce a tight-fitting fence arrangements. When laid horizontally these regular shaped flagstones produce brick-like walls. Galloway dykes used mainly hard greywacke sandstones of irregular shape and size. The irregular profile of such material demanded highly skilled mason work for effective coursing. Tightly packed small face slip-stones and pinnings were commonly used to make up the course bed height.

Local stone was extracted from rock outcrops not only for domestic and farm use but also for larger buildings such as medieval castles which were mainly rubble-built constructions. The size of available stones, determined by the geological factors such as bed height and joint spacing in the original rock, affected the form of the building. The relatively small dimensions of available stones dictated that walls were mainly constructed with small openings, a feature suited for the purpose of defence. The availability of large stones determined whether wide openings could be spanned. Thus large blocks of dressed stone were often transported from further afield for use as lintels and corbels of window and door openings. Stones used for tombstones and slabs, crosses and effigies also utilised local stone of metamorphic and sedimentary origin which could be easily worked and sculpted.

Stone resources, past, present and future

In the late 18th and 19th centuries, as villages and towns grew from early settlements so the requirement for building materials increased and large numbers of local quarries were developed. Before the days of mechanised transport local sources of stone were utilised almost to the exclusion of materials from farther afield except for the most important buildings and monuments. Owing to the cost of transport this continued to be the case well into the 19th Century. Thus many of the buildings in major Scottish cities and towns were constructed of local stone with only materials for roofing and paving being sourced from further afield (e.g. slates from Argyllshire and paving stone from Angus

Above
Typical arrangement of rock-faced, rusticated and polished ashlar in pale-coloured Craigleith sandstone, the New Town of Edinburgh.
(A A McMillan)

Opposite page. Top to bottom.
Vertically emplaced flagstones in the quarry harbour at Castletown, Caithness. (A A McMillan)

Youkil Quarry, Thurso, Caithness in c. 1910, yielded excellent resources of flagstone for pavement and building stone.
(BGS ©NERC. All Rights Reserved. IPR/58-38C)

The 16th century Priory house next to Melrose Abbey constructed of local warm coloured Devonian sandstone.
(A A McMillan)

and Caithness). Stone for both ashlar and rubble work could often be supplied from the same quarry by working different beds. The Early Carboniferous Craigleith Sandstone, west of Edinburgh, for example, supplied the finest 'liver rock' (massive, non-laminated sandstone) for ashlar in the New Town. Broken residual material from dressed blocks together with more thinly bedded sandstone was used for rubble-built walls thereby ensuring fullest use of the stone resource. Hailes Quarry, Edinburgh yielded primarily thinly bedded, laminated sandstones which, although unsuitable for ashlar, was in much demand for squared rubble and also for stairs and landings. Similarly, Glasgow and Dundee had local sources of sandstone which could be used for a variety of purposes. The local theme is continued with granite: the city of Aberdeen, the "Granite City", and other towns in Aberdeenshire, and Dalbeattie in Dumfries and Galloway are built almost wholly of the locally available resource.

In the 19th century Scotland became a major producer of building stone and slate for both local use and for export. By 1860 there were in excess of 1200 working quarries. With the development of the road, canal and railway networks, it became economic to use a variety of stones from further afield for general domestic, industrial and commercial use. During the mid-19th century, the famous Stirlingshire, West Lothian and Angus sandstone quarries supplied much stone to Scottish cities both for prestigious buildings as well as houses and tenements. Permian red sandstone became popular by the end of the 19th century and stone for ashlar

Table 3. Terminology of bed thickness and typical architectural use

Bed thickness: geological definition		Architectural use	Notes
	Very thickly bedded		
1 metre	Thickly bedded	Ashlar and sculpture	Beds suitable for building may contain internal thinly bedded or laminated structure
0.3 m	Medium bedded		
0.1 m	Thinly bedded	Sculpture panels	
0.03 m	Very thinly bedded	Flagstones for pavement and roofs	Individual laminations unsuitable for building
10 mm	Thickly laminated		
3 mm	Thinly laminated		

from sources in Dumfriesshire, Ayrshire and Arran was in much demand. Stone, too, started to be imported from northern England, as local supplies of good quality building stone became scarce or more difficult to provide.

From its peak during the 19th century, the Scottish stone industry went into rapid decline in the early part of the 20th century. Man-made building materials, improved transport links, competition and a changing global economy meant that by the end of the 20th century the stone industry declined to some 20 working quarries with a similar decline in quarrying and stone masonry skills.

Geological factors which determine the use of stone

Both for repair and new build the decision to select a particular stone type is dependent upon the ability of that stone to fulfil a number of criteria. These include physical characteristics such as strength, durability, uniformity and dimensional aspects (Table 3) such as bed height and spacing of any lamination (for sedimentary rocks) and block size. The stone must also be capable of being worked, sawn, dressed and tooled in the required manner. Specific functional requirements demand particular criteria, such as that for slip resistance for natural stone paving, or the appropriate structural characteristics required for use as stone cladding panels.

Many of the requisite criteria relating to laboratory testing are given in the appropriate British and European Standard documents relating to a particular product. Testing methods are being harmonised under the European Committee for Standardization (CEN). Although laboratory tests are an important guide to the predicted performance of a stone type, lessons can be learnt from the past performance of a stone type in a structure which may have been exposed to the weathering environment for durations of hundreds of years. Geological criteria are vitally important when sourcing appropriate material for repairs. Reliance upon physical laboratory test data alone is not sufficient to identify matching stone types where subtle differences in mineral composition, microscopic texture and porosity characteristics can exist. The consequences of using inappropriate replacement stone can be serious, both in terms of changing the appearance of the built heritage and by causing accelerated damage to the original historic fabric.

Top to bottom

A ruined doocot near Selkirk built of greywacke sandstone with red sandstone pigeon roosts. (A A McMillan)

The 12th century St Margarets Chapel, Edinburgh Castle built of local sandstone and igneous rock. Thick roofing flagstones. (BGS ©NERC. All Rights Reserved. IPR/58-38C)

Smailholm Tower in the Scottish Borders constructed of black basalt with red sandstone window and door surrounds. (A A McMillan)

Warm weathering colours in trachyte, a locally quarried igneous rock, used here in a 19th century building in Haddington, East Lothian. (A A McMillan)

Devonian house, Halkirk, Caithness. A new property built entirely out of local Caithness flagstone. (A A McMillan)

Cullaloe quarry, Aberdour. Re-opened in 2004 yielding sandstone of similar character to that of Craigleith. (A A McMillan)

Finally, colour and texture are important in the selection of building stone. The aesthetics of natural stone were an important factor historically, but today it is one of the main reasons why stone is preferred to synthetic materials in new-build projects. For the purposes of conservation and repair of historic stone buildings, colour and texture are equally crucial if a like-for-like conservation philosophy is to be adopted for the selection of replacement stone. The natural weathering of stone can also add to its aesthetic characteristics.

In new build, above all, designers must sometimes expect natural colour variability when using stone even if the physical properties remain the same. Thus stone from different beds within the same quarry may exhibit pleasing colour variation which can be used to good effect in panelling. Similarly the utilisation of stone from one bed in a quarry with variegated colour patterns originating from circulating iron-rich fluids at time of formation (e.g Clashach) can be aesthetically pleasing as is demonstrated on the Museum of Scotland. Wherever possible today's architects might be well advised to not simply rely upon technical specification, but to emulate their predecessors by visiting quarries to experience at first hand the natural variability which is embodied in stone before deciding how it may be appropriately used.

Today, Scotland imports more building stone than it produces. Recently, however, increased recognition of the value of the country's stone-built heritage has produced greater demand for sources of appropriate indigenous stone types for both repair and new-build projects. Although many Scottish quarries were worked out, others still have available resources. It is crucial that these resources are assessed before other development (e.g. landfill) takes place. In recent years, the re-opening of old quarries for short periods (known as 'snatch-quarrying') has been successfully applied to supply specific orders either for stone repair or new-build. Through the efforts of the Scottish Stone Liaison Group, Cullaloe Quarry in Fife has been reopened to supply appropriate stone for the repair of buildings in Edinburgh's New Town, and the slate resources at Ballachulish are currently being assessed.

Case Study 1	
Building:	Museum of Scotland, Edinburgh
Architects:	Benson + Forsyth Architects
Stone Type:	Clashach sandstone, Elgin, Morayshire
Construction Type:	Rainscreen cladding

Intended to be a museum of the social and cultural history of the nation, the Museum of Scotland's stone cladding is undoubtedly the oldest artefact in the institution's collection. The exterior reflects the building's importance as a national institution in a stone-built city. The darkest grade of Clashach was selected for reasons of durability, varied figuring and – unusually for a sandstone – its ability to be cut in any direction from the block. At 100mm thick, each slab is far deeper than conventional stone cladding and is separated from its neighbours by a precise 6mm gap to allow air and moisture to circulate. In this rainscreen system, each stone is supported by stainless steel pins and cramps penetrating through external insulation and a rubberised membrane sealed to the building's solid concrete structure.

The dimensions of the stone banding were set out precisely on the architects' drawings (the height of each relates to floor levels and other internal features and allows the building's section to be interpreted on its exterior), with only the lengths of stone allowed to vary. No other restrictions were placed on the installing contractor as to where individual pieces of stone should be hung, resulting in an abstract composition of the material's rich and varied figuring. The freshly-cut and brightly-coloured stone of 1998 has since mellowed and has begun to attract the veneer of permanence associated with the material. Of particular interest is the precise off-site cutting of the curved stone sections installed on the building's corner tower.

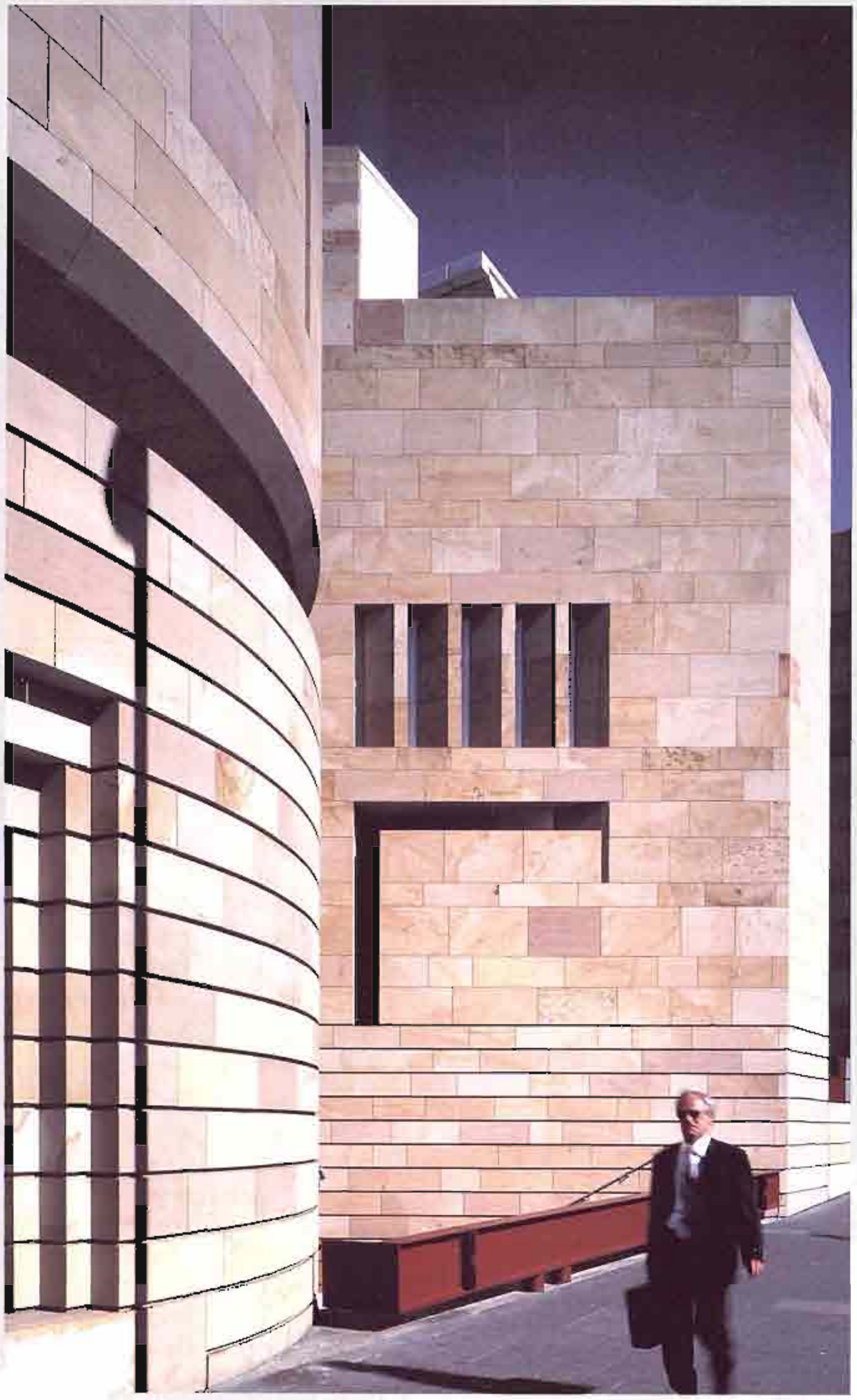
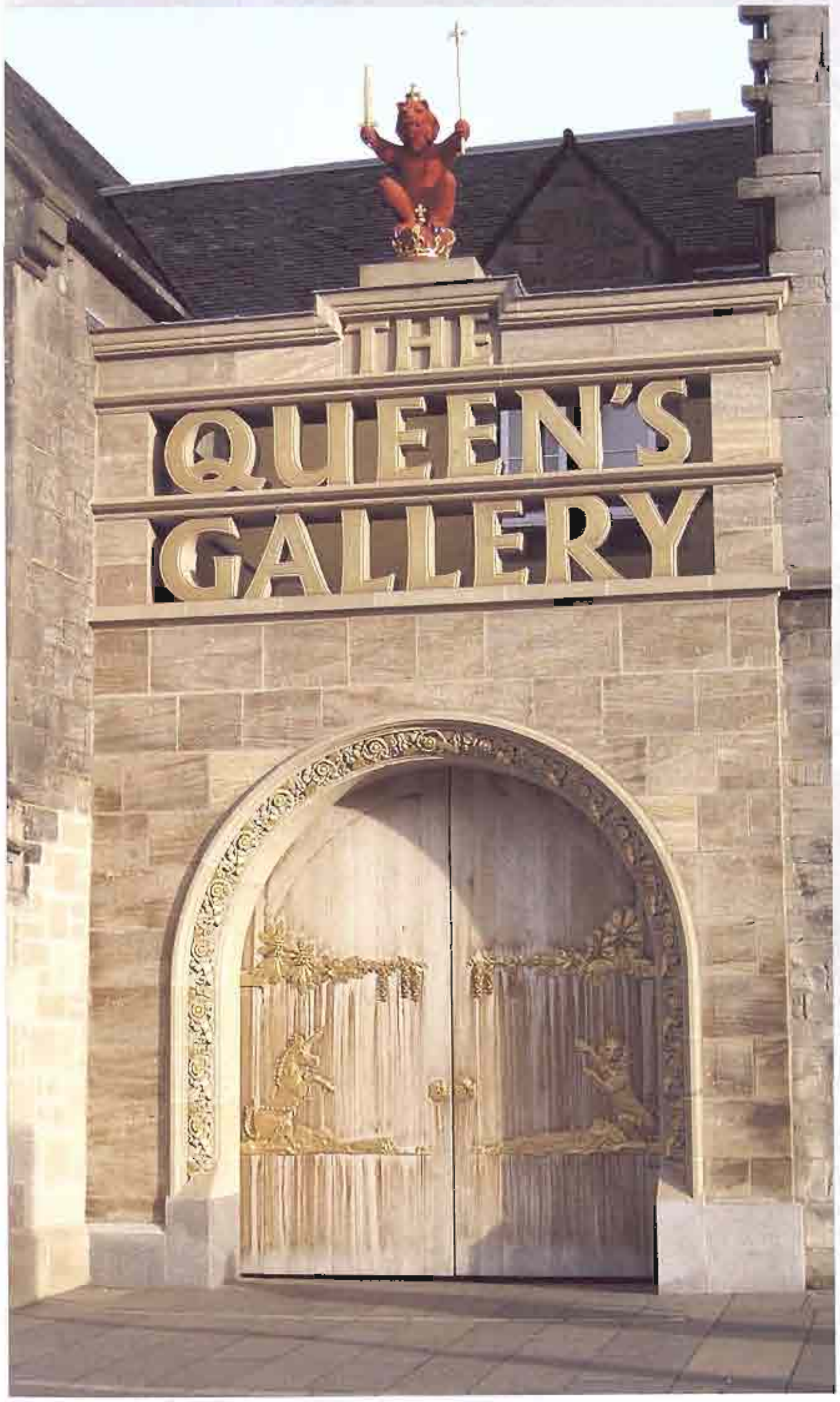


Photo: Paul Zanre

Case Study 2	
Building:	The Queens Gallery, Holyrood, Edinburgh
Architects:	Benjamin Tindall Architects
Stone Type:	Catcastle sandstone; Stainton sandstone; Caithness slab; Kemnay granite; limestone
Construction Type:	Loadbearing construction



Transformed from a former chapel at Holyrood Palace, the new gallery designed to house temporary displays from the Queen's art collection has been given a dramatic new public entrance. The architect's sound understanding of stone has led to five different types being used here – Catcastle sandstone for the walling, Stainton for the finely carved doorway and Kemnay granite for the base with a Caithness slab floor. The lion above was carved from limestone in Pietrosanto, Italy by artist Jill Watson. Quite intentionally, no 'match' was made to the materials of the original building and the new internal doorway is formed from three massive Stainton blocks, with 2.5 metre slabs of honed Caithness slab forming the floor.

Several aspects of good practice are evident here – detailing to avoid rainwater staining; granite used as a dpc (a Victorian trick used on bank buildings, the hard impermeable stone preventing moisture rising into the solid walls); excellent jointing with large stones balanced in step and platt manner; and best use made of the large sizes and proportions possible with Caithness slab. Kemnay granite was specified to echo its use on the Scottish Parliament opposite although Peterhead granite was considered in reference to the Duchess of Huntly's funding of the original building

The assembly of the masonry lettering is analogous to a house of cards. Three stones form the string courses separating the letters, with the end stones counterbalanced to support the third, middle stone via a joggled joint. The letters themselves have no supporting function.

Case Study 3	
Building:	Scottish Parliament, Edinburgh
Architects:	EMBT / RMJM Ltd
Stone Type:	Kemnay granite, Aberdeenshire; Belfast Black granite, South Africa; Caithness slab flooring
Construction Type:	Rainscreen cladding and feature panels to external walls

Begun in 1998 and completed in 2004, the Scottish Parliament is arguably the most important public building constructed in Scotland for almost 300 years and considerable public debate took place over the type of stone to be used to clad the building's exterior. The architect, Enric Miralles, selected granite in order to emphasise the complex's relationship to the landscape and for its sparkle when wet. Fyfe Glenrock quarried 14,000 tonnes of granite from Kemnay Quarry in Aberdeenshire to provide material for the grey rainscreen covering, and some 2,000 tonnes of Black Belfast granite were imported from South Africa by Scottish Natural Stones to form the overlaid mosaic of feature panels.

The profile of the panels is reputed to have its origins in the outline of the Reverend Robert Walker skating on Duddingston Loch, a popular painting in the National Gallery of Scotland. Innovative fixing methods needed to be devised to support the technically complex granite panels in locations which were often at some distance from the reinforced concrete structural wall. The variety of different fixing surfaces posed a significant technical challenge to the contractors, Watson Stonecraft, who also had to ensure that all fixings and components fabricated for the stonework had a design life in excess of 100 years. In all, 128 feature panels and 26 smaller feature panels were installed.

Set into the concrete boundary wall on the Canongate are stones from around Scotland, some containing fossils and others inscribed with Scottish proverbs and quotations for passers-by to read.

A History of Scotland's Masonry Construction

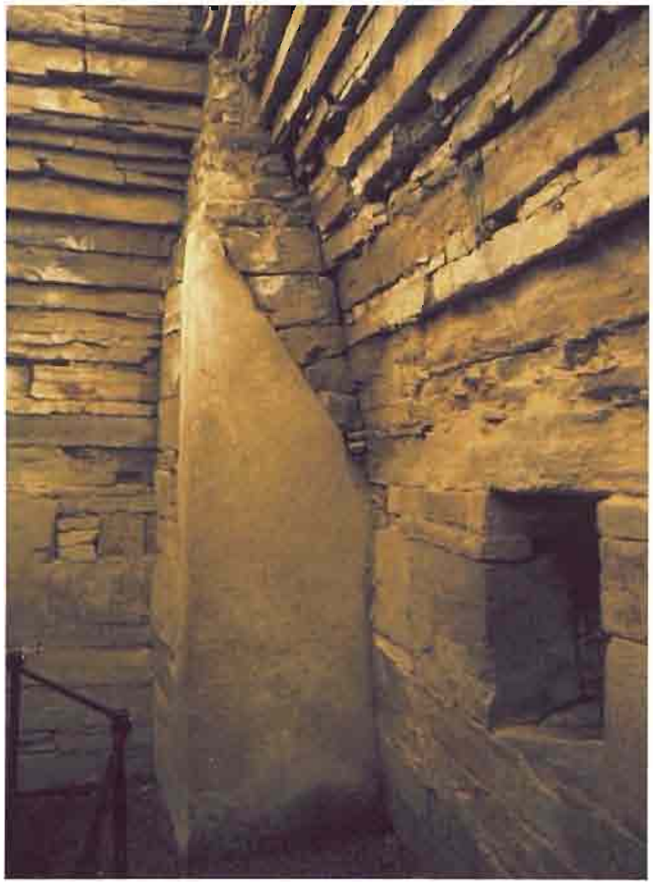
Ingval Maxwell
Director of Technical, Conservation, Research and Education, Historic Scotland.

Prehistory

The introduction of farming into Scotland during the Neolithic period created a demand for permanent structures from about 4000BC. Dating from c.3500 – 3100BC the stone building at Knap of Howar, Papa Westray, Orkney is one of the oldest surviving houses in NW Europe. Using local material gathered from the immediate vicinity, the rubble dry-stone construction illustrates the builder's remarkable understanding of the structural use of stone, and an ability to exploit its natural properties to advantage.

The strength of dry-built rubble stonework relies upon each stone physically touching its adjacent and underlying neighbour. Each successive layer of masonry has its vertical joints staggered to "break bond" so that the weight of every stone is effectively borne by those lying immediately below. This was spectacularly achieved at Knap of Howar where a further sophistication is the form of the figure-of-eight plan-shape employed in each of the two adjacent blocks. Here stones marking the neck of the eight in each apartment are neatly aligned to form a slot into which vertically set thin stone slab partitions are located. The curvilinear form of construction adds to the structural strength of the building whilst simultaneously retaining the mounded earth fill behind the wall faces.

Skara Brae, Orkney. aerial view of complex



Dating from c.3100 – 2200BC, the best preserved sequence of Neolithic building developments is at Skara Brae, Orkney. Continuing the Knap of Howar constructional techniques, the juxtaposition of curvilinear low stone-walled houses, and interconnecting streets, created an integrated village community. Exposed by a storm in 1850 the complex utilises the free flowing nature of dry-built rubble work and contains sophisticated stone furniture, stone-on-edge partitioning, with door, window and passageway openings spanned by slab lintels. The various voids between the house walls were infilled with compacted midden material to create an effective waterproofed wall core.

Readily available in Caithness and the Orkney Islands, Old Red Sandstone is an ideal material for effecting sophisticated masonry construction. This is nowhere better illustrated than inside the Neolithic Maes Howe chambered tomb of c.2700BC, where a 4.6 metres square and 3.8 metres high central roofed chamber was created by corbelling out successive courses of large parallel-sided slabs. Above a datum of 1.4 metres, the diminishing plan dimensions occurring on all 4 sides of the chamber eventually permitted the placing of a single slab to cap the central void. To help stabilise the structure, buttressing monoliths were positioned at each of the four corners and braced against the walling by a tightly bonded horizontal infilling of carefully chosen stonework. Earth cover over the entire central masonry chamber, and 11 metre long entrance passageway, create a mound 35 metres in diameter and 7 metres high. Additionally, another natural material, clay, was applied as a protective waterproof layer over the masonry work to help keep the internal chamber dry.

Top *Skara Brae, Orkney.*
Stone lined fire hearth and interior furniture

Left *Maes Howe, Orkney.*
Chambered Tomb interior

The largest and most extensive group of prehistoric cup-and-ring marked rock carvings in Scotland exists at Achnabreck in Argyll. Whist a variety of enigmatic concentric circles, alignments and other features are cut into three exposed rock outcrops the examples are representative of the first true form of stone art to be found in Scotland. Although no full understanding of what the purpose of this art form was, similarities can be identified in the overall form and plan shape of Broch sites some millennia later.

Standing 13 metres high with a 5 metre internal diameter, the double walled dry-stone Mousa Broch on Shetland represents the pinnacle of rubble-stone building construction. Erected c.200BC – 100AD, the tower is the best preserved example of Iron Age architecture in Scotland. Utilising roughly dressed stone, the concentric walls are carefully built in tightly placed horizontal courses. The cylindrical face of the internal skin rises almost vertically, whilst the external skin is slightly inclined to produce a truncated conical exterior. The two walls are linked by a series of interconnecting stair and passageways which spiral up to the wall top. Larger sized stones were carefully chosen to serve as stair treads and passageway lintels and, like the rubble work, are roughly dressed. Similar forms of Broch construction are found throughout the northern Isles and mainland of Scotland, extending as far south as the central belt.

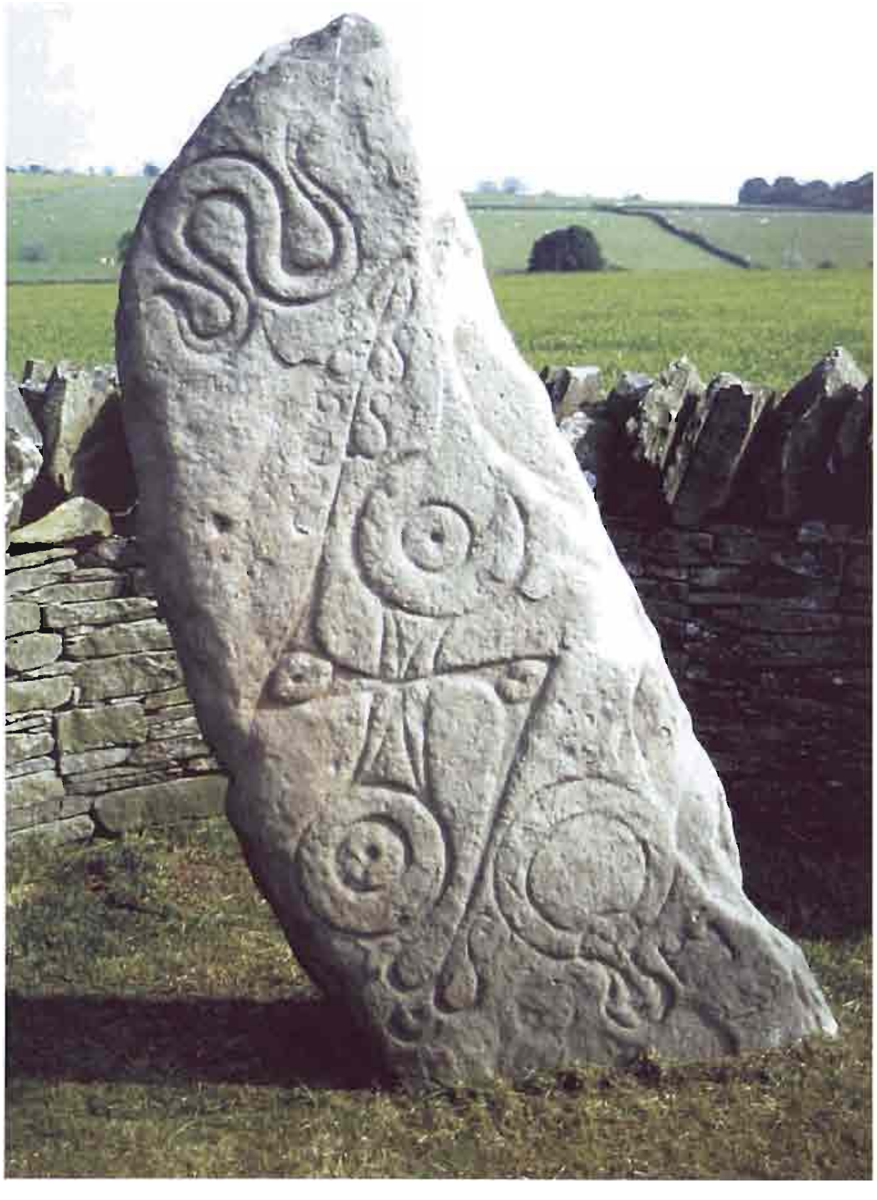
Achnabreck, Argyll. Cup and ring marked bedrock.

Discovered in 1929, the Broch of Gurness in Orkney is of similar construction to Mousa, and at c.20 metres in diameter, might originally have stood 8-10 metres high. Set within a series of concentric outer defensive ditches and walls, a free flowing, irregularly planned village of interconnected houses surrounds the broch. Continuous runs of thin stone slabs on edge were used to create subdividing partitioning within each house. Constructed between 500 – 200BC the site remained in use until c.100AD.

Gurness Broch, Orkney. aerial view

Continuing the pattern of building in rubble masonry, the multi-period site at Jarlshof, Shetland spans from c.2000BC – 17th century AD. The earliest buildings on the site consist of small oval shaped houses, followed by a Bronze Age smithy, and an Iron Age broch and village of round houses with two small souterains or earthhouses. These were overlaid with the remains of four first millennium AD wheelhouses, a Norse settlement, a medieval farm, a 16th century Laird's house and, finally, a 20th century visitors office – all constructed in stone. Spanning this range, the site provides a unique snapshot of how horizontally coursed dry stone rubble construction first seen at Knap of Howar continued across the ages. In emphasis of the relevance of this technique, the same process of building two concentric sets of walls infilled with loose material was still in use almost 4000 years later in the construction of traditional Hebridean Black Houses on Lewis during the 1860's.

Aberlemno, Angus. 6th Century Pictish Stone



Roman

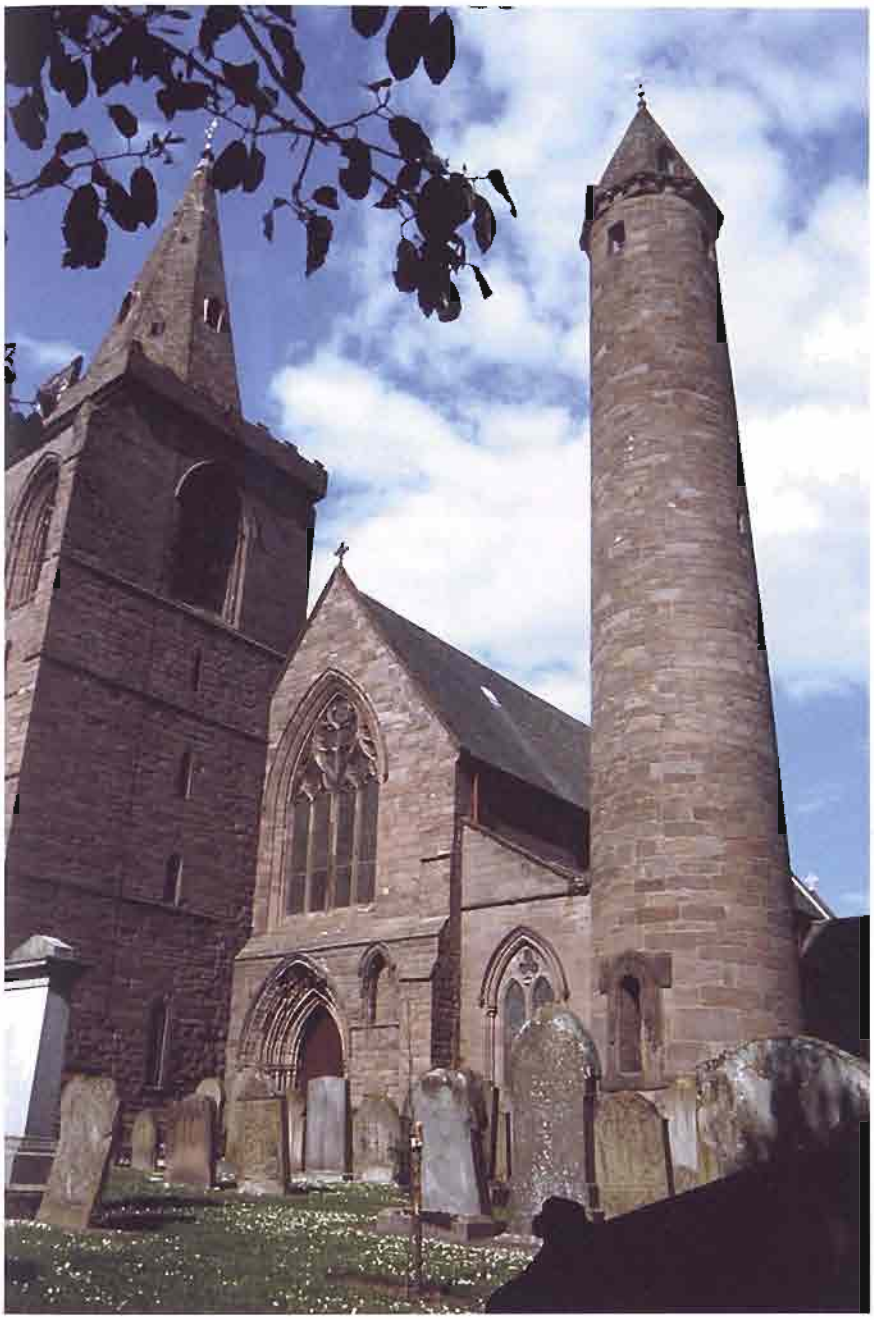
The Romans occupied Scotland on three separate occasions between the 1st and 3rd century AD, and brought their own particular building styles, town-planning and engineering skills. They introduced something new to the Scottish building portfolio – the use of ashlar masonry comprising square-dressed stones of uniform course height coupled with lime mortar and plastering techniques. This use of locally sourced material, stone quarrying and hewing, and lime burning, slaking and mixing, continued more or less unchanged until the early 1900's.

Pictish and Early Christian Stones

Whilst cup and ring marked designs and incised prehistoric linear alignments offer the first examples of indigenous Scottish art, the imagery carved onto the face of free-standing stones during the 6th – 9th centuries AD presented another sophisticated competence in the artistic use of stone in Scotland. Although easier-to-work sandstones were preferred, intricate pagan and Christian symbols were also carved into monoliths of granite, schist and other stone types. The size and quality of the chosen slabs clearly reveal that, in addition to understanding the geological properties of the various stones, a full awareness of quarrying, handling and transportation techniques was implicit at the time.

Ecclesiastical Influences

Following the introduction of Christianity by St Columba to Iona in 563AD, basic masonry-built churches started to emerge on the peripheral West Coast islands and South West mainland from the 8th century onwards, with more mature buildings emerging as it took hold. Continuing the original Roman influence, ashlar masonry of the early Romanesque period was characteristically blocky in appearance



Brechin Round Tower, Angus.

with structures such as the 11th century Brechin Round Tower and the square towers of Dunblane Cathedral and St Rules, St Andrews, emanating from this time.

Ashlar blocks became more rectilinear from the 11th century onwards. Whilst this required advances in quarrying and hewing techniques, the resulting stones produced a more structurally stable wall and were capable of incorporating more refined architectural moulding and detailing in the devices of corbelling, buttressing, lintels and arching.

At the same time Scotland's ecclesiastical masonry buildings were increasingly influenced by wider European and English designs. The Romanesque chevron pattern detailing on the nave piers of Dunfermline Abbey (1130 – 40AD) were, for example, modelled on details from Durham Cathedral, while Elgin Cathedral's 13th century East-end incorporated more typical European Gothic mouldings and tracery.

Although their overall proportions were predetermined by the geological characteristics of the rock, the size of individual stones allowed them to be worked, managed and lifted into place by 1 or 2 men. The key individual was the Master Mason, who used not much more than compasses, a square, and ropes to lay out complex building plans full size. From this, the geometric details of elevations and vaults could be projected, templates taken, and individual stones precisely hewn and built to fit within the overall concept. The craft of stone carving emerged with increasing refinement, perhaps reaching its zenith with the construction of the Apprentice Pillar at Roslin Collegiate Chapel in 1440 – 60.

Quarry material for the construction of the medieval cathedrals, abbeys and churches was generally sourced locally. The stone supply route at Arbroath can still be followed on the nearby foreshore where grooved and worn parallel runs of cart tracks are exposed at low tide. These lead across the rocks to the broken angular remains of the flat bed outcrops from which the Abbey building stones were prised.

Medieval Secular Developments

In consequence of civil unrest, plague and a diminishing influence in the way the church maintained its hold over the country, protection and defence needs increasingly dictated the adoption of mass-masonry building from the 1300s onwards.

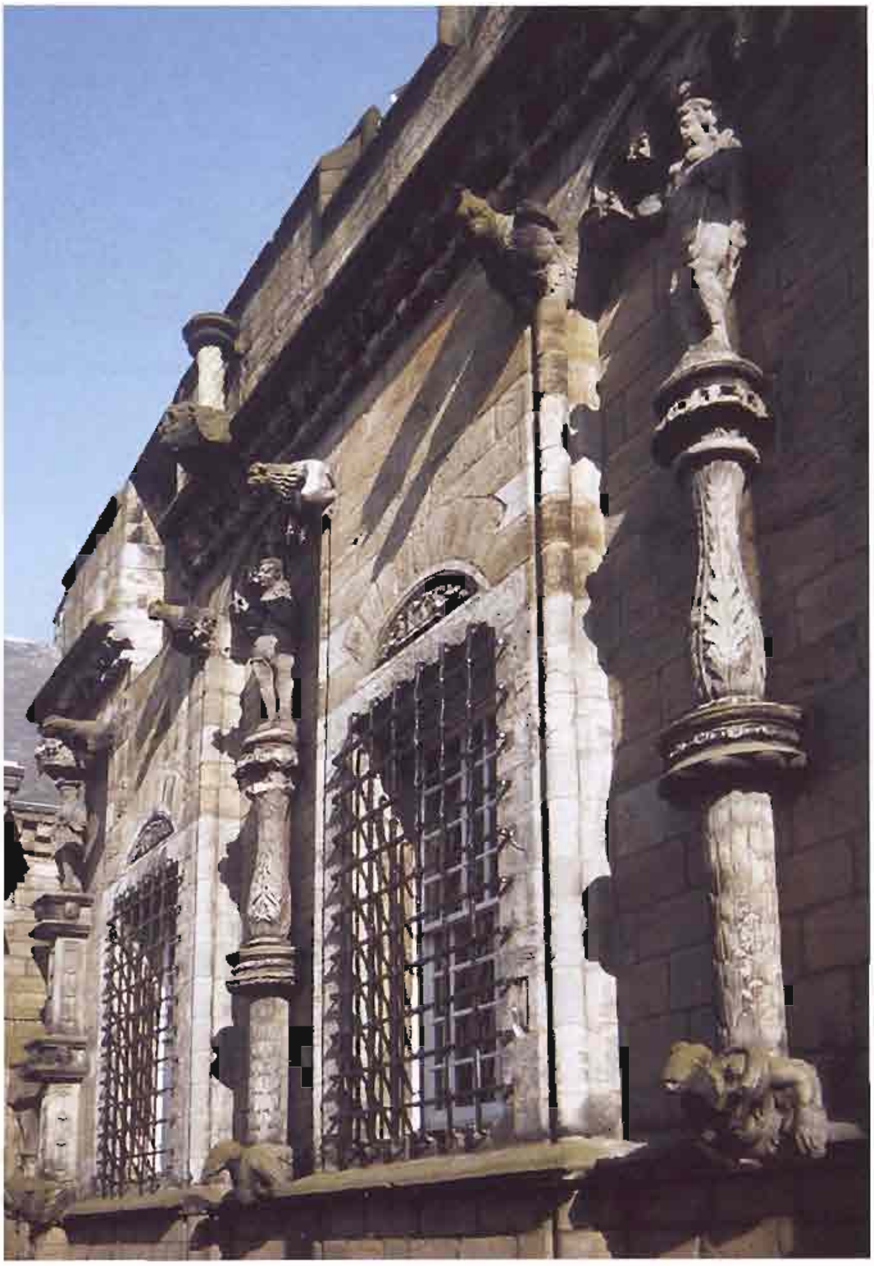
During the early 12th century, castles were simply sculpted from the ground to create defensive mounds, or motes, of earth topped with timber palisades. Whilst foreign influences determined new approaches to their design and layout, Scottish castle building had its constructional pedigree firmly combined in prehistoric dry-stone and Roman lime-mortar building technologies. Being built of high quality (and costly) dressed and moulded work, medieval ecclesiastical architecture was characterised by a light and airiness where the use of stone was pushed to its structural extremes. Secular masonry castle-building had to answer a completely different functional requirement. Defence dictated the need for solid, massive, impenetrable walls. To create the necessary mass the builders also had to adopt more economic forms of construction. Depending upon the local geology, this created distinctive forms of rubble building. Like dry-stone, the build stones were laid and bedded to distinctly horizontal courses but the need for volume often revealed "day-work" joints of successive construction periods. To provide added weatherproofing, the castles exterior were often lime render, or harled.

Above *Arbroath, Angus. Foreshore quarry cart tracks.*

Below *Tantallon Castle. Defensive curtain forewall viewed across outer ditch*

One of the earliest secular masonry constructions emerged at Castle Sween, Argyll during the late 12th century, and set the trend for future castle building. Constructed of coursed rubble-stone set with pinnings in lime mortar, walls of considerable height, thickness and strength were erected on a naturally defensive rock outcrop above a coastal cliff face on the east side of Loch Sween. The integration of design intention and natural features met the defence requirements.

Compared to religious buildings, openings in the outer walls of castles were greatly reduced in size and number, serving, where they existed at all, as thin functional defensive slits. Entrance gateways were heavily engineered for security, with surrounding projecting parapet walls supported on corbelled courses to provide both protection and defence mechanisms at the wall tops. Building economy also prevailed. Hewn stonework was reserved for corbels, door and window dressings. Structural strengthening was created by alternating in-band and out-band coursing at external corners. Virtually everything that was extracted from the quarry was used since by employing the greatest volume of stone the amount of manufactured mortar needed to bond the structure together was greatly reduced. Lime was not always used in the construction and examples of clay mortar, or a mixture of both materials, can also be found. Walls relied upon the compressive strength of their stone for stability and the principles of dry-stone rubble construction prevailed.



Above *Lochmaben Castle. Section through collapsed wall revealing alignments of "day-work joints"*

Right *Stirling Castle Palace Block.*

Kirkwall. Air view showing the radial pattern of the medieval town plan lying to the west of St Magnus Cathedral and the adjacent Bishops and Earl's Palace.

Renaissance and Georgian

Architectural styles began changing by the mid-15th century and, informed by Italian developments as well as the emergence of new thought processes and descriptive pattern books, Scotland's stone architecture became increasingly more domestic, decorative and sophisticated. A new classicism emerged and defensive castle construction was replaced by a substantial phase of "palace" building. In the increasingly refined appearance of masonry work, European-influenced Renaissance detailing became more commonplace.

As the pace of change quickened, the role of the pragmatic Master Mason was replaced by that of Master of Works, followed rapidly by the emergence of the architectural and surveying professions. By the mid-17th century numerous great domestic stone houses were being built around the country. Predominantly using well-cut ashlar masonry on the façades, rubble stonework was relegated to the construction of internal walls and the role of a backing skin to the dressed work. In a trend that continued for another century and a half, all reference to defensive detailing in the stonework was abandoned as its functional purpose evaporated. Those that remained were purely decorative and aesthetic.

By contrast and commensurate with advances in the manufacture of artillery and theories of warfare, when the Government saw the need to create outposts to deal with civil unrest in 18th century Scotland, military structures became more scientifically influenced in their design and layout. To function effectively, this relied upon the strength of inclined and angled engineered masonry work combined with the softness of earth toppings to deflect and absorb missiles. This pattern of building was continued for a further century, culminating in the construction of Fort George, near Inverness, in 1748 – 69.

Essentially a rural country, the established urban centres of early 18th century Scotland were still fundamentally medieval in function and layout, with timber-framed and rendered infill-panel buildings. From late 1600s, however, an increasing number of domestic dwellings built from rubble masonry began to appear on the urban footprint.

Linking human activity to environmental ideals, 18th century developments during the period of the Enlightenment inevitably impacted upon Scotland's architecture. From 1767 onwards, the use of locally produced stone was preferred for the development of Edinburgh's spacious New Town. Already endorsed as the nation's favoured structural and decorative building material, what had also been learnt in the construction of the large country palaces was translated into the design and detailing of entire street façades. The Edinburgh model was set to influence the rest of the country, with many smaller towns copying the gridiron plan, the building forms, and the architectural detailing, whilst using locally quarried material to emulate it. This increasing demand for stone soon outstripped available supplies.

With significant 18th century advances by improving landowners also occurring in agriculture, the pattern of change was equally profound across rural Scotland. The early enclosure of farmland fields is well illustrated in the Military Map of Scotland made by General Roy during the national survey that he began in 1747. Clearing the ground of glacially deposited rounded boulders created more workable parcels of land for agricultural needs and saw the gathered stone consumed in the making of field drains, surrounding boundary dykes, and in the construction of the earliest "Improved" farm building ranges. Typically, the basic rubble construction of the farm steadings from this period reflects the appearance of mainland masonry structures from prehistoric times. What was different, however, was that walls were built as regularly dimensioned structural elements, in the region of 450 – 600 mm thick, using clay or lime mortar.

Flowing from the emerging Industrial Revolution and the period of greater stability that emerged after the Napoleonic Wars, the Scottish population exploded from 1815. The resulting increase in demand for accommodation, employment and food had an overwhelming effect on both urban and rural building programmes.

With better methods of husbandry increasingly being adopted, agricultural and financial returns from the land also increased. So too did the demand for superior quality masonry farm buildings with integrated layouts and more workable detailing. Functionalism predominated. Based on experience, research through trial and error, and pragmatism, comprehensive guidance covering a wide ranging of topics were written, printed and promoted to landowners. Commensurate with the different types of farming, various pattern books emerged on all aspects of steading design, many of which were built and remain today. With a view to building economics, landowners who were fortunate to own the right material often opened up supplying stone quarries and built the necessary lime kilns on their estate.

Milton Bank, Fife. Horse Engine House

Victorian

Demand for more functional farm buildings ran hand-in-hand with the great building programmes in the cities and towns. Here, differing domestic needs were satisfied by the construction of stone built terraced rows of integrated tenements, individual town houses and villas.

As the demand for building stone escalated, the increasing needs could only be satisfied by opening up new sources of supply from outwith the urban boundaries. Quarrying activity and masonry skills flourished. As demand grew, suppliers for Edinburgh, Glasgow and the other Scottish cities were increasingly sourcing their stone from further afield. Initially it was possible to source from quarries along the (limited) Scottish canal network. Then, as the rail communication network developed from the mid 19th century onwards, building stone and slate supply were brought into the central belt from all over Scotland. Probably the pinnacle of Scottish masonry construction, around 1200 building stone quarries were in production at this time.

As the rail network continued to grow and new markets opened up, supplies were often delivered from as far south as the English Midlands and Wales. Ship-borne trade in stone also flourished where the movement of stone was a two-way process. Caithness slabs were shipped to Europe; Galloway granite found its way into the construction of Liverpool's docks and London's embankment, and Dumfries' red sandstone was often transported to the eastern seaboard of the USA and Canada. As the British Empire grew, high class and exotic stones used for finishing work were also brought into the country through the Clyde ports.

Coates Gardens, Edinburgh.

20th Century

With the passing of Victorian times, the significant consequences of two World Wars, and the depression of the 1920s, a decline in the general use of stone occurred during most of the 20th century. It became less and less economic to use as manufactured materials, such as Portland cement, concrete, and mass-production brick, gained a greater foothold on the country's architecture. A brief revival in its specialist use occurred during the late 19th century Arts and Crafts Movement. Some limited use was also made of it during the 1930s and 1950's by local authorities such as Edinburgh, Aberdeen and Dumfries, who favoured the use of locally produced material in small parts of their domestic housing stock.

Stone only began to make a limited reappearance during the mid-1960s, although compared to the widespread scale and understanding of its earlier usage, confidence in its structural capabilities had by this time been lost. The stone industry had refocused to supply the "dimensional" market, and stone was predominantly specified by practitioners as a high-class cladding material, held onto the face of buildings with metal clamps and other hidden fixing devices.

The intended demolition of Edinburgh's 18th Century George Square during the 1960s created a wake-up call to the nation as to the amount of traditional stone building that had been lost, and the extent of the remaining still under threat. This particular case led to the inauguration of the Edinburgh New Town Conservation Committee. Other heritage orientated pressure groups were to follow and the emerging collective voice began to articulate the value and quality of Scotland's remaining masonry-built inheritance.

By the end of the 20th Century this awareness had developed further and recognition of how much of the intuitive understanding of how to specify, work and build with stone had been lost was also dawning. Consequently, during the late 1990s much was recognised as having to be relearnt – where stone could be obtained, how it should be worked and detailed, and how it actually performed in use. In this process, Historic Scotland has led the way in determining the extent of knowledge that has been lost, the location of traditional supplies, and, in working with industry and other lead body interests, how to resurrect the skills required to work the material.

Argyll House, Edinburgh.

Case Study 4	
Building:	Arbroath Abbey Visitor Reception Building
Architects:	Simpson & Brown
Stone Type:	St Bees: reclaimed Carmyllie slabs for internal flooring
Construction Type:	Cavity wall construction

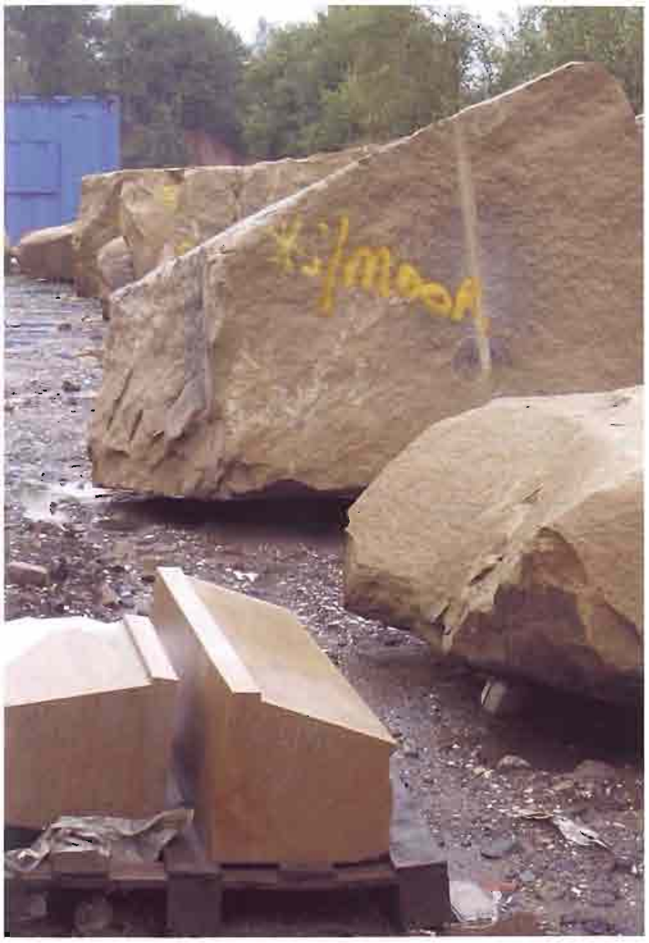
As one of the most significant buildings in Scotland's rich history, Arbroath Abbey had long suffered from inadequate visitor facilities and an architectural competition in 1999 set out to find an answer to the many challenges presented by the highly sensitive site. The winning solution for the new visitor reception building eschewed a mock-historical response, and instead offered a design intended to have minimal impact on its environment.

Maximum use is made of natural materials such as stone and timber, and a green planted sedum roof emphasises the building's horizontality while setting it firmly within its immediate landscape. Additionally, the solid appearance of the new walls avoids any styling that might date the construction, yet the stonework draws on the deep wall details of Scotland's traditional castle architecture as well as making reference to 20th century European modernism.

Sensibly, the architects recognised the impossibility of precisely matching the stone used on the Abbey itself (originally sourced from the nearby shore area) and have instead chosen St. Bees red sandstone to complement the rich hues of the towering historic structure. The new stone forms the outer leaf of a cavity wall construction, the individual blocks jointed with lime mortar. Internally the same stone is used to face those areas of wall which are visible, with notable details such as the beautifully-cut handrail to the stair emphasising not only that stone can be used as a modern building material but that the knowledge and craftsmanship exists to create elegant and timeless features.

Quarrying and Processing of Natural Stone

Alex Stark, Watson Stonecraft



The Resource

Few now recall the heady days of Scotland's stone industry when literally hundreds of often very small and individually-owned quarries were in daily use throughout the length and breadth of the country. These quarries provided the enormous range of stones used to build the nation's cities, towns and villages and which gave a distinct character to each. Many of these sources became either worked out of useable stone or simply fell into disuse with the decline in the industry which resulted from changes in construction materials and methods. Nevertheless there are still a good number of working quarries in Scotland able to provide stone for new projects as well as previously redundant quarries such as Cullaloe in Fife that are being brought back to life to produce replacement material for existing buildings. Contrary to broad perceptions therefore, the industry is in a stronger position now than it has been for many years and is once again looking to increase the use of stone. Architects and specifiers should look to Historic Scotland's TAN12 on 'The Quarries of Scotland' for background to those sources still operational, as well as 'The Stone Specifier's Guide' (available from the Stone Federation) for information on suppliers.

Unlike timber, stone cannot be described as a renewable resource. Its use can, however, be justified over the life-cycle of a building, and the decision to specify it is made easier when the material is sourced locally. This is not only because less transport is involved – resulting in lower embodied energy costs – but also because locally-sourced stone invariably responds better to the regional climatic and environmental conditions. Local sourcing also supports employment and the skill base available in what are often rural areas. Tradition too plays a part, as does experience of how to use specific stone types in different applications.

The Quarry

Few architects and specifiers today have a background training in the use of stone or indeed a working knowledge of the stones available and the different uses to which they can be put. Even for experienced practitioners, there is no doubt that a visit to the quarry can help avoid unrealistic specification demands and possibly contribute to a more creative use of the stone in the design process. Not only can the different sizes of quarry operations be better understood, but also the quality and extent of the resource available.

English quarries also supply stone to the Scottish market. Stanton Moor is a popular choice because of its similar colouring to that of many existing buildings in Scotland's main cities.

Stone is not a consistent material and even across a single quarry there can be considerable variation in bed heights, block size, strength, colour, texture and veining (figuring). Clashach, for example, is an unusually hard sandstone from the Moray coast area, and is available in different grades. Dark, medium and light Clashach each have very different colouring and veining, as can be seen on the Museum of Scotland where the darker grade provides the building's rich exterior texture. By contrast, light Clashach's more even colour can be seen to advantage on the exterior of the Weston Link connecting the Royal Scottish Academy and the National Gallery of Scotland in Edinburgh.

Kemnay Quarry was the source of the grey granite cladding for the Scottish Parliament building.

Extraction

Different quarries produce blocks with quite different characteristics, and the extraction process may vary according to the scale of quarry operation, the relative hardness of the stone, and the ease or otherwise with which it can be separated from its natural bed. The objective of the process for extracting dimensional stone is to ensure that the largest possible blocks are obtained within the quarry's natural restrictions (e.g. bed heights) and other logistical issues. It is important also to avoid undue force in the stone's extraction as this can cause cracks that only become apparent during later stages of production.

At its simplest, the quarrying process begins when the 'overburden' is removed. This is the earth and broken rock that is above the consolidated quarry block that is needed to produce dimensional stone. Once a suitable "face" has been established, the extraction of useable dimensional stone can begin. Since it is important to avoid fracturing the block in any way, no blasting takes place at this stage and where possible the blocks are picked out mechanically using a claw tool or a bucket to bring them down from the quarry face and onto the quarry floor. Blasting – if required – only takes place under the careful supervision of an experienced quarry manager.

In some cases the larger blocks – whether on the quarry face or the quarry floor – need to be split into manageable sizes. This is achieved by drilling a series of holes and using traditional plug and feather techniques or small quantities of explosive powder to separate the blocks from the face or into two pieces (it should be noted that quarrying Caithness Flagstone requires a different process). They are then lifted by crane, forklifts or mechanical diggers onto lorries or dumper trucks for delivery to the processing unit or stoneyard.

Primary sawing process:
circular diamond-tipped blade (above) and monoblade (below) saws in use

Processing

It goes without saying that the closer the stoneyard is to the quarry, the less transportation and energy use is involved. This is not always achievable, however, and modern processing operations may handle a number of different stone types at any one time. The rough blocks arriving at the stone yard from the quarry are irregular in size and shape and are inspected to identify the most efficient way to cut them into slab form while minimising wastage. This also depends on the stone type and the intended final application since, for example, bedded stones such as sandstone can only be used in certain ways without de-laminating.

Once the initial inspection is complete, the block is primary sawn into slab form by means of large circular diamond-tipped blades, wire or monoblade saws which cut one slab at a time, or by a frame saw with multiple blades that cut each block – depending upon its size – in a single operation into a number of slabs. With this operation the thickness of the block can be varied to suit the finished stone it is being cut for, and it is only when the block is opened in this way that any internal defects can be discovered. It is important to remember that stone is a natural product and that colour and veining (figuring) may also vary throughout a block or from block to block and result in some slabs being rejected.

The next phase – secondary sawing – consists of cutting the slabs into dimensioned ashlar. The machines used are usually computerised bridge saws with circular diamond blades ranging in diameter from 600-1200mm and can also have tilting heads to provide angled cuts.

The resulting ashlar is coded ready for palleting or sent to the mason workshop for other masonry work such as broaching, droving or stugging to take place. In the second of these options slabs can also be cut to sizes and shapes that can be moulded by hand or, equally common today, by means of lathes profiling and water jetting machines (these machines are mostly controlled by computers). The stone that passes through the lathes, profiling and water jetting machines can either be returned to the secondary saws to be jointed or moved to the banker area for the masons to carry out further work such as returning moulding, sunk mouldings or to cut out moulded brackets in a cornice course. Following the completion of work to each stone it is checked for quality and any defects before being polished, palleted and 'shrink-wrapped' ready for delivery to site.

The banker area is where time-served masons and apprentices using traditional tools such as mells (mallets), teeth tools, chisels, etc. carry out work that cannot be undertaken by machines. Nowadays most of their chisels have tungsten instead of steel tips and – instead of employing the blacksmith of former years – are sharpened by use of grinding wheels. The masons may now also use compressed air tools and angle grinders along with drilling and coring machines.

Surface Dressing / Finishing of Natural Stone

A building's architectural expression can be greatly enhanced by the choice of surface finish and in the case of natural stone a variety of considerations apply, including the function, type, and hardness of the material as well as the aesthetic effect desired. Greater awareness of the range of light and shade effects possible on different stone types and of the techniques available to draw out the unique qualities of each has increased demand for manually dressed stone, and this traditional process has become easier and quicker with new types of compressed air tools and machines. Depending upon a stone's intended application, material strength and the minimum thickness needed to withstand differing processing pressures, it is now possible to apply all kinds of finishing techniques (see table 4).

Final surface character is determined by the fineness of the applied finish used and can bring out a stone's mineral content, colour, texture and structure. Not all the listed finishes can be applied to every stone type, e.g. only sufficiently hard and dense stones such as granite can have a polished finish (the finest), but honed and fine-rubbed finishes are achievable on Scottish sandstones. Rougher finishes gather dirt more quickly and need more maintenance.

Compressed air tool being used to fine-rub stone to a polished finish.

Sequence of stone processing

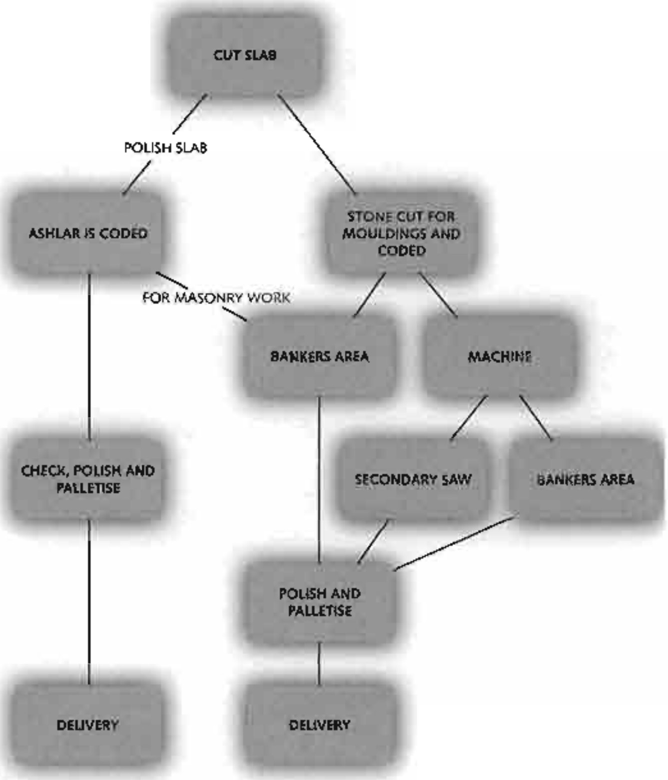


Table 4. Types of Stone Finishes

1	Polished
2	Fine-rubbed
3	Honed
4	Riven
5	Stugged / punched / picked
6	Broached / furrowed
7	Droved / boasted
8	Vermiculated
9	Reticulated
10	Rock and bull faced
11	Split and crop faced
12	Bush-hammered
13	Fine bush-hammered
14	Diamond-sawn
15	Shot sawn
16	Sandblasted
17	Flamed

2

5

6

Finished Clashach palletised for delivery.

Table 5. Things to Remember When Selecting Stone

1	**Accurate identification**
	Confirm the traditional name of the stone and the location of the quarry location (see BS EN12440 Natural Stone – denomination criteria).
2	**Is it an active quarry producing block of the sizes required?**
	Some quarries are no longer in production and it is not possible to match stone from the original source; others have parts of the quarry worked out and the areas still active may produce blocks unsuited in size and quality to the design.
3	**Is the stone you want available in the quantities required?**
	Some stone is available in limited quantities only, due to the size of the operation quarrying the stone, planning restrictions or just the scarcity of the particular stone desired.
4	**Is the stone available in the sizes required?**
	It is important to design to the best strengths of the material chosen, for example by using repetitive elements co-ordinated with the size of typical blocks from the quarry. There is no point in specifying 1m square slabs if the stone in question is only available in blocks of no more than 0.5m square. This limitation does not always arise because of the size and sophistication of the plant being used to extract and process it – bed heights can also restrict the sizes available.
5	**Does the quality of the available stone meet the specific needs of the project?**
	Establishing the specification criteria applicable to a particular project or stone use at an early stage is vital. Aside from aesthetic considerations, new EN test requirements (see 9 below) can highlight the suitability or otherwise of a particular stone against the criteria set.
6	**Is the stone required to have a continuous colour or texture?**
	Does the appearance and finishes meet those of the contract samples? Stone is a natural material formed over many millions of years and as such has many variations within it. A single sample cannot show this and a range of samples can better indicate the level of variation acceptable for a particular project. There is no substitute for visiting the quarry however.
7	**Will the stone be used 'on bed'?**
	As a rule of thumb, limestones and sandstones should be used 'on bed' – i.e. they should be used in construction with the plane that was horizontal in the quarry also being horizontal on the building. Failure to do so can lead to accelerated weathering. This of course represents a constraint to the thickness of course height that can be achieved.
8	**Can the stone be supplied within the timescale required by the project?**
	Can block production from the quarry meet the project programme? This is not necessarily a criticism of the supply chain, but can be a result of a particular stone's popularity or ongoing demands on particular parts of the quarry.
9	**Does relevant test data meet new EN methods (cladding)?**
	Changing regulations require greater scrutiny to ensure the selected stone meets the latest standards for: • Petrographic examination • Flexural strength • Breaking load at dowel hole • Water absorption an atmospheric pressure • Apparent density & open porosity • Frost resistance In cases where stone is being specified for flooring, test data is also required for: • Slip resistance • Abrasion resistance
10	**Will additional matching stone be available at economic cost at a later stage for maintenance or repair purposes?**
	Stone obtained from quarries overseas may appear to be available at low cost, but obtaining replacement material at a later stage may prove to be difficult and/or expensive.

Best Practice in the Use of Stone

Andy Davey, Simpson & Brown Architects

Architects have always been drawn to using stone; for its cultural and historical value, its physical and symbolic strength, its durability, and its aesthetic quality. Important buildings were once designed and put together by master masons who knew how to work with stone, and understood the advantages and limitations of the material. They were skilled at producing enduring masonry buildings that combined structural *firmness*, technical *commodity* and aesthetic *delight*. The beauty of a good stone building is determined not just by its finely balanced proportions or architectural composition; it relies also on sound detailing and robust specifications which help to protect the structure from decay and maintain the appearance of the building throughout its expected life.

Selecting Stone

Many architects today specify a stone type purely on the basis of its texture and colour, without proper regard to its physical and chemical properties or its "fitness for purpose". The choice of a particular stone should not only be influenced by aesthetic considerations, but should also take account of its intended architectural or structural function, its exposure to the elements and its expected performance over the anticipated life of the building.

It is important at the design stage to understand the nature and characteristics of individual types of stone – where they can be used to their best advantage and how the worst effects of decay can be avoided. The strength, weathering characteristics, durability, porosity, appearance and "workability" are all material considerations when deciding which stone type to use in a particular circumstance. Sound knowledge of the effects of salt contamination, erosion, chemical attack, frost-action, vegetation growth, etc on different stones informs the selection process and is the first stage in "designing out" predictable risks.

The choice of stone for vulnerable areas – ie those subject to hard wear, severe exposure, atmospheric pollution and repeated wetting, as well as for areas of carved or moulded work – is especially important as it is here that failures or disfiguration are most likely to occur. Steps and paving, plinths and base courses, cills, copes and cornices as well as decorative elements are all prone to attack and decay at a far greater rate than simple vertical cladding. Harder-wearing and more impervious stones are generally better suited to such vulnerable areas.

In response to the colour and texture of existing adjacent buildings, stone from Stanton Moor quarry was selected to form the outer leaf of the cavity wall construction of a new house by Arcade Architects in Edinburgh's Merchiston area.

Construction Methods

Emphasis has generally shifted from self-supporting, load-bearing "primary" masonry to the "secondary" construction techniques of applied cladding and rainscreens. This shift has partly occurred as a consequence of cost constraints and partly because of the accelerated building processes of the modern era in which lead-in and ordering times are truncated and where structural shells protected by roofs can be built well in advance of the completion of the exterior walls. Because of this, stone has increasingly come to be regarded more as a decorative veneer than as an integral structural element. Nevertheless, the principles of sound traditional masonry construction should not be forgotten in the design of new work, a rule that applies not only to correct detailing but also to the implementation of basic building techniques in, for example, the construction of a rubble wall that does not end up looking like vertical crazy paving.

Design and Best Practice

At its simplest, stone likes to sit in a neat vertical stack, as it is found naturally, and protected from the harsh Scottish climate. As soon as it is removed from this state and become exposed, it is necessary to take "corrective" action. In traditional buildings this meant introducing "drips", "throats", "weatherings" and "stoolings", as well as providing the "good hat and good shoes" of protective copes and impervious plinths. Many architects seem to deliberately and wilfully eschew such traditional detailing, but careful study of the construction of older stone buildings can lead to an understanding of how they weather, how rainwater is "managed" and disposed of, the places where dirt is likely to accumulate, the various ways it can be washed off, and the soiling patterns that are likely to be created as a result. All of these time-served conventions apply to contemporary projects and to ignore them is to dice with potential failure – not only of the masonry itself, but of the entire architectural or aesthetic concept. The design challenge is to avoid the emergence of green slime on "battered" plinths, the ugly encrustations of salts and grime on base courses, the staining of wallheads and the run-off streaks of dirt beneath each and every cill and copestone.

The complex design of the exterior stonework to the National Library of Scotland on Edinburgh's Causewayside manifests many of the technical issues highlighted here and in the following section.

Joints are filled between the carefully proportioned courses of Blaxter's stone cladding on Evolution House by Reiach and Hall Architects in Edinburgh's Westport.

Some "Best Practice" Considerations

- It is important to consider the specific characteristics of any chosen stone, and how its performance will influence its use in the design. Bedding planes and porosity are good examples. There are dangers in using face-bedded stones, especially in cladding, or naturally-bedded stones for elements with exposed horizontal surfaces, such as cills and copes. Impervious stones shed water more quickly, concentrating its effects on the joints; porous stones on the other hand act like sponges.

- Orientation, exposure, and local environmental or climatic conditions will all influence the choice of stone. Polluted or marine environments need special consideration. Elevations exposed to the prevailing winds and rains will be more vulnerable than those which are protected. Areas subjected to repeated or prolonged dampness will support unwanted vegetation growth which may accelerate stone decay. Plinths and base courses will attract dirt and be prone to mechanical damage and disfigurement by splashback.

- The principal causes and mechanisms of stone decay through salt contamination, acid attack and frost action need to be properly understood and evaluated so that appropriate avoiding action can be taken in order to minimise their destructive effects.

- Water and moisture are the most potent agents of decay and disfigurement. The designer needs to assess where moisture will rise or move, where rainwater will run and accumulate, where it will be driven by wind, where it will seep and percolate and how it can be effectively dispersed. Vulnerable areas can be protected from damage by good detailing and effective "water management".

- DPCs can play an important role in preventing moisture movement, but they can also concentrate dampness in a particular area and thereby accelerate decay, for example on copes and balustrades. The tracking of moisture should be predicted, and trapped water allowed to escape, for instance via weepholes or open joints. Remember that some modern DPCs can be incompatible with traditional lime mortars.

- Eaves, wallheads, openings and base courses, all need careful detailing, especially at junctions with other materials or elements such as windows, doors, roofs and abutments. Particular attention needs to be given to flashings or other protective measures.

- Mortars and jointing are as important as the stones themselves. The use of traditional lime mortars should be encouraged, and due care should be given to ensuring that the strength and mix of the mortar is suited to the stone. There is a danger of less porous stones channeling water into the joints; bedding stones in the traditional manner helps to shed water outwards.

- Some tooled finishes can effectively double the surface area and consequently also the absorption capability of certain stones. Careful consideration should be given to the varying characteristics of rubble and ashlar work, as well as to different toolings. Rubble, for example, is more "forgiving" than polished ashlar.

- The different requirements of traditional masonry construction, stone cladding and modern rainscreens need to be taken into account. Traditional masonry is usually self-supporting and load-bearing, with little need for mechanical fixings, and relies on sheer thickness and good detailing to resist the weather. Stone cladding is applied to a structural backing of a different material and is usually separated from it by a cavity, insulation and membranes. The cladding is close-jointed, pointed or sealed, and generally supported at each storey level. A rainscreen is open-jointed, with every stone individually supported by mechanical fixings off a backing structure, so that rainwater is allowed to migrate into and ultimately escape from the cavity in a controlled manner.

- Differential movement caused by thermal expansion/ contraction can occur between the structural frame or wall backing and the stone cladding, and due attention needs to be given to the methods of fixing in order to avoid failures or stone falling from the building. Mechanical fixings, particularly in modern cladding and rainscreen applications, need to be carefully coordinated with the masonry design. The site installation of fixings should be properly evaluated, and realistic tolerances allowed. The type and material of fixings should also be considered. Remember, for instance, that expansion anchors may split sedimentary stones (just as they are intended to do in the quarrying process), and that some metal fixings may be prone to bi-metallic corrosion if fixed direct to steel support frames.

- Building stone production necessarily involves a relatively high proportion of 'waste', but this can be reduced in the quarrying process by intelligent design, for example by using smaller stones; using already extracted material; using repetitive elements co-ordinated with the size of typical blocks from the quarry; and accepting variations in colour and figuring.

- Designers should be familiar with the stone quarrying industry, so that they understand the variations of the material itself and the limitations of the production process. "Range" samples should always be sought and approved, and stone size tolerances established. Remember that the industry standard for tolerances is ± 2mm, which may result in a 4mm discrepancy between supposedly identically-sized stones. This may cause serious problems in finely-jointed ashlar work, unless the specification is enhanced accordingly.

- Transport distances from the originating quarry can add considerably to the 'embodied energy' costs of a particular stone. Similarly, stone sourced from overseas may not respond well to the local climate and can be difficult to repair or replace later. Try to source stone locally if at all possible.

- Maintaining Health & Safety standards during the design and construction process is an important consideration, as well as for future maintenance. Careful attention needs to be given to the sequence of installation, the weights involved and the complexity of the fixing process.

- Pigeons and other birds have a nasty habit of perching on the ledges of buildings, resulting in despoliation of the stone. This type of problem can be anticipated and avoided by careful attention to the detailed design.

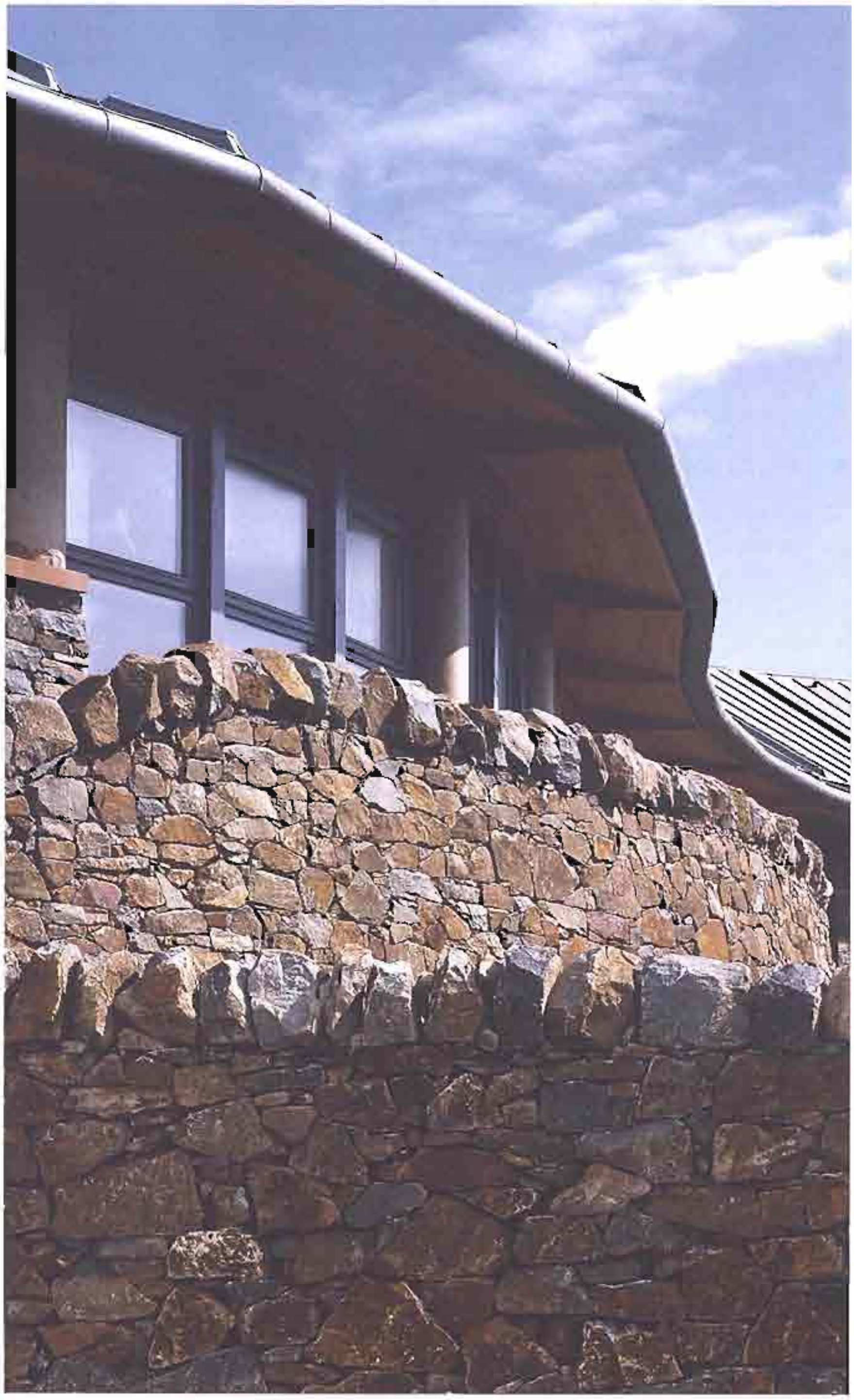
- However hard the particular stone type selected, vulnerable areas need to be protected against mechanical damage or defacement from, for example, graffiti and skateboarders.

- Compliance with current Codes of Practice, British Standards and European Regulations is important, notably BS 5628 Part 3 (Code of Practice for use of masonry) and BS 8298 (Code of Practice for design and installation of natural stone cladding and lining)

- Ultimately the success or failure of the stone selected will depend on the attention to detail shown on the production drawings, the level of quality control exercised within the architect's office to ensure that potential problems are eliminated at the design stage, and the effectiveness of site supervision during the construction process.

Case Study 5	
Building:	Scottish Seabird Centre, North Berwick
Architects:	Simpson & Brown Architects
Stone Type:	Reddish-brown whinstone from Bangley Quarry near Haddington, East Lothian
Construction Type:	Back-bedded drystone walling used as rainscreen

With the Bass Rock as its backdrop, the Millennium Commission-funded Scottish Seabird Centre stands beside the old harbour at North Berwick on a rocky promontory exposed to wind, rain and saltwater. The building houses large screens and computers linked to cameras positioned among the colonies of puffins on Fidra and gannets on the Bass, enabling visitors to watch the birds in real time all year round without the need for boat trips to the islands.



The Scottish Seabird Centre is designed to relate to the rugged shoreline, and it's unusual form is intended to reflect the panoramic views of the Firth of Forth and to draw visitor's into the landmark structure. Robustly built, its drystone rainscreen wall not only responds to the irregularly shaped plan but its loose construction also avoids the use of expansion joints and other external junctions likely to be adversely affected by the local weather conditions.

The Centre is an essay in the use of natural materials, its copper roof supported on solid larch trusses with rough-sawn larch cladding and local reddish-brown whinstone forming the distinctive exterior walls. While appearing as a traditional drystone assembly, the whinstone is employed instead as a rainscreen cladding and is back-bedded to the main structure of the building. This allows the walls to be taller than might otherwise be the case with this type of construction, and has the additional advantage of drying out quickly and thereby reducing the likelihood of mould growth and damage from salts in the atmosphere.

The Four D's of Stone
(or how to avoid dirt, deterioration, decay and destruction)

Dr. Maureen Young,
Scott Sutherland School, The Robert Gordon University

Figure 1. Typical soiling on a limestone façade. Rainwashed areas on limestone buildings remain clean due to the slight solubility of the minerals in the stone.

Nowadays, stone is used more for cladding purposes than for its loadbearing virtues, and with this change the traditional ways of detailing stone are often eschewed in favour of clean lines and simple surface finishes. But there is far more to the specification and detailing of stone than making simplistic choices about colour and texture; and long-established approaches to the prevention or reduction of biological growth, soiling and physical decay of stone have come from practical experience and are as relevant to the design of contemporary projects as they are to the repair and restoration of historic buildings. A sound understanding of what causes these conditions is critical when choosing a particular stone as well as to the development of details appropriate to a new building's design.

Water Damage

It is an obvious but often neglected fact that newly constructed building façades do not retain their initial pristine appearance for very long. Soiling can have a deleterious effect on façades where clean lines and surfaces are unable to accommodate the inevitable effects of weathering. This type of damage can be reduced or avoided at the earliest stages of design by incorporating strategies which ensure that the façade works with its natural soiling and weathering patterns rather than against them. The single most important consideration in this regard is rainwater. Most soiling and decay processes involve water: stone which remains dry has an almost indefinite life. Traditional stone façades incorporated design elements to deal with water shedding thereby minimising the exposure of the façade to rainwater and facilitating rapid water shedding which reduced the moisture loading of exposed elements.

Soiling and Patina

In different contexts changes to building surfaces are perceived as soiling or as patination, but these are quite separate conditions. Soiling is an accumulation of externally derived material on a substrate. On a stone building façade this is likely to include soot, oils, salts, dust particles and organic remains from biological growths. Most façade soiling nowadays is derived from vehicle pollution, and soiling rates can be remarkably rapid on busy city streets. In the past some building façades were deliberately stained to allow them to blend in more easily with existing heavily soiled elevations. This generally involved the application of lamp black in linseed oil to the stone surface and it is clear in these cases that the soiled appearance was anticipated.

Soiling, especially in urban areas, is inevitable but with imaginative consideration of design elements it need not impact negatively on a façade's appearance, especially when the level of soiling is only moderate. It is most visible when it affects large, flat areas of light colour. The visual impact of soiling is reduced in situations where the surface is rougher or where there are colour or height variations across elements of the façade.

Stone types respond very differently to soiling. On sandstone and granite structures, soiling typically adheres to stone on and adjacent to rain washed areas. Soiling adheres most readily to damp areas. Limestone and calcareous sandstone behave very differently – soiling is removed from rain-washed areas due to the slight solubility of the mineral calcite (calcium carbonate), which is abundant in these stone types. Black gypsum crusts are most commonly recognised on limestone buildings where they accumulate in sheltered areas and are known to cause severe damage, but gypsum deposits can be found on all stone types. On granite they are most usually found in sheltered areas of façades, adjacent to rain water run-of zones and joints, deriving calcium salts from lime in the pointing. Gypsum is also damaging to sandstone – but sandstone is more porous than granite and less chemically reactive to the acids in rain water and air pollution than limestone, so gypsum accumulates below the surface, damaging the stone internally, eventually causing contour scaling and other forms of decay.

Patina, on the other hand, is a mineralogical change on the stone surface which results from weathering. Minerals near the stone surface are altered by weathering and may be removed from or deposited at the stone surface causing the development of a colour change. While patina can often be seen as imparting the positive attributes of age, permanence and authority to a structure, soiling, by contrast, is negatively perceived and gives the impression of neglect and lack of maintenance.

The stone around this window has been deliberately stained, probably at the time of construction, to achieve the 'expected' soiled appearance. This 'soiling' has since been partially washed off by rainwater

Patination can enhance aesthetically pleasing natural varitions in stone

The black gypsum crust on this granite is causing blistering and disintegration of the stone surface.

Biological Growth

Biological growths on stone can be disfiguring. Their effects are mainly aesthetic, but in a minority of cases they can cause stone decay. The main forms of biological growth encountered on building stone are algae, lichens, fungi, bacteria, moss and higher plants.

Green algal growth is particularly dangerous on walking surfaces, forming a slippery layer when wet

Green algal growth on stone may be considered aesthetically disfiguring but it seldom causes physical damage

Lichens can occasionally cause stone decay. Here, growth in the central part of the lichen has caused pitting of the stone surface

Cyanobacterial growth occurs on damp stone in low light areas and can cause localised stone decay

Algae

Algae are mainly green, although other colours, including orange, may be encountered. Algae require a lot of moisture and will not normally grow on sunlit areas of stone. They are mostly harmless, but heavy growth can cause superficial spalling. Many algae (and some other organisms) produce a sticky film which helps them to adhere to surfaces and gives the organism protection from environmental stress. This sticky film attracts soiling so that surfaces affected by algae will eventually blacken, especially in urban and high air pollution areas.

Lichens

There are many varieties and colours of lichens and they are often considered to improve the aesthetic appearance of façades, especially on older buildings, as they give an impression of age and maturity. They are slow growing organisms which extract some of their nutrition from the substrate and can therefore cause stone decay, albeit very slowly. Lichens are generally sensitive to atmospheric pollution and are rarely encountered in cities. They require less moisture than algae and can easily colonise the sunlit sides of buildings.

Fungi

Fungi are barely visible to the naked eye although the colour changes they produce can be highly visible. They are often the cause of black stains on marble and limestone surfaces. Fungi produce acids to help them penetrate substrates and this can damage vulnerable surfaces such as polished marble.

Bacteria

Bacteria are ubiquitous in the environment. One type of bacteria – cyanobacteria – produce patches of intense blue-green coloration similar in appearance to green algae. Often found in sheltered areas, cyanobacteria prefer low light levels and are especially common adjacent to artificial lights in damp stone interiors. They can cause superficial stone decay where growth is abundant.

Mosses and Higher Plants

Mosses require high moisture levels and some soil in which to take root. Most commonly they colonise roofs and horizontal ledges. Higher plants can take root where building maintenance has been neglected. Root penetration can cause damage, with woody plants being the most dangerous as the penetration of their roots can dislodge stones and lead to structural instability.

Stone Decay

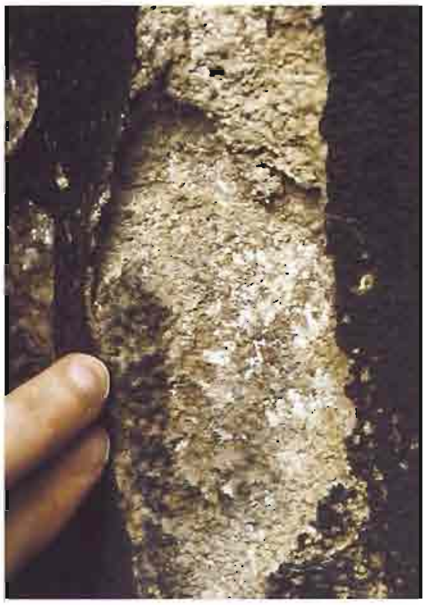
Building stone decay is influenced by the qualities of the stone (mineralogy, porosity, etc), local climate, adjacent materials (mortar, other stone types, etc), soiling and applied treatments (stone cleaning, water repellents, etc).

For sandstones, the mineral cements which bind the grains together are very important with respect to durability. Siliceous sandstones which have abundant silica (quartz) cement are relatively durable and resistant to stone decay, but sandstones which are lacking in cement or which have weak binders (e.g. calcareous sandstones) are more vulnerable to agents of decay. Weakly cemented and calcareous sandstones may, for instance, be affected by case hardening. This is caused by mineral dissolution and re-deposition near the stone surface – a hardened crust develops over a weakened interior. The stone may appear sound until the crust is breached, but when the weakened interior is exposed there will be rapid decay.

Granite is generally more durable than sandstone, however it too is subject to stone decay. Because granite lacks the porosity of sandstone, decay is generally superficial, involving flaking and spalling of the surface.

Climate is also a strong influence on stone decay. Stone which is robust in an inland environment may, for instance, decay rapidly when exposed to sea salts in a coastal location. And in the future, climate change is likely to affect the behaviour of building stone. The wetter climate predicted for the northern UK will increase the amount of biological growth on buildings. It is also likely to increase many forms of stone decay – most of which are accelerated by increased moisture levels.

Mortar makes up a large proportion of most stone walls, and decay can be induced in stone by use of inappropriate mortar mixes, such as pointing mortars which are too hard and impermeable. Such mixes force moisture movement (and consequent decay) to take place in the stone rather than the pointing. Granite can also be damaged by hard mortars; not all granites have low porosity and in some older buildings constructed with relatively weathered, porous granite moisture and decay can penetrate the stone. Differential porosity between adjacent stone types can cause problems on building façades. Where porous stone (e.g. sandstone) overlies less porous stone (e.g. granite), moisture movement is restricted and, depending on the vulnerability of the stone, decay can occur in the porous stone adjacent to the contact. Chemical incompatibilities between adjacent stones can also cause problems. Calcareous stones can leach damaging calcium salts into adjacent stones. Where different stone types are adjacent to each other on a façade, care should be taken to ensure that they are compatible. This is



Case hardening of sandstone – a hardened crust develops over a weakened interior. The stone may appear sound until the crust is breached, but when the weakened interior is exposed there will be rapid decay

Hard pointing mortar can induce decay of adjacent stone if the mortar is more impermeable than the stone. Moisture movement, and associated decay, occurs within the stone rather than the pointing

Salt concentrated in sandstone above impermeable granite. The salts are derived from residues of cleaning chemicals which reacted with pollutants in the stone. Salts of this type can cause rapid stone decay

Different stone types can be successfully combined where there are no incompatabilities in their composition with respect to stone performance

Damage to this string course on a limestone building has accelerated decay on lower stonework. Black gypsum crusts are deposited on sheltered areas away from the rainwater run-off

Where indented stone is a poor match for the original, decay may be induced by changes in moisture movement through the stone

Here, indenting with a new stone which was too impermeable has accelerated decay in the remaining original stone

similar to care which must be taken when indenting stone during façade repair (see below).

Atmospheric pollution causes stone decay as it introduces harmful salts into stone – especially sulphate salts. Crystallisation of salts below the surface breaks down the bonding between grains. Pollution induced decay is most rapid in streets with high traffic levels and it affects granite as well as sandstone and limestone buildings.

Stone decay is particularly harmful when it affects functional features such as string courses or mouldings. The loss, or partial loss, of function in a detail can detrimentally affect rain water run-off control on a façade. This will result in increased wetting of stonework at lower levels and is likely to accelerate decay. Unless appropriate intervention is taken, decay may progress to affect structural elements and lead to dangerous instability of the façade.

Stone Cleaning

Soiling can be harmful to stone surfaces, causing flaking, granulation, blistering and other forms of decay. Surface cleaning is beneficial in situations where soiling is damaging the stone, but many cleaning methods also affect the stone's condition: choosing an inappropriate method can exacerbate stone decay. A building may be cleaned several times and the damage caused is cumulative. It is essential, therefore, to seek expert advice before undertaking stone cleaning. There is often pressure to adopt the quickest and cheapest solution that will 'restore' the façade to a condition approximately similar in appearance to the original. Such an approach is unlikely to be the best long-term solution.

Stone Repair

Damage by weathering and pollution has in many cases been compounded by the effects of inappropriate stone cleaning methods – and increased decay leads to increased repair. There is a danger that cost, rather than recognition of good conservation practice, dictates the quality of many repairs.

Repairs to stone buildings must be carried out by skilled practitioners with appropriate materials. The ideal is to replace or indent damaged stone with new stone of the same type, but this is not always possible as the original quarry may no longer be operating. If the source can be established then it may be possible to obtain permission to extract a small amount of stone from closed quarries. Where the original stone is unavailable it will be necessary to take expert advice in order to locate a replacement stone compatible with the original in its mineralogy, permeability and appearance. Stone matching based on appearance alone is extremely inadvisable as differences in chemical and physical characteristics between the old and new stone can result in rapid stone decay. A replacement stone which has a permeability significantly lower than the original stone will cause moisture movement in the wall to become concentrated through the remaining original stones, accelerating their decay. Should the replacement stone have calcareous cement and the original not, damaging calcium salts can be transferred from the new stone into the old stone, again accelerating its decay.

In terms of appearance, it is important to choose a stone which will weather to match the existing stone. It is not necessary to clean remaining stone as the new stone will eventually weather in. Replacement stone should match the original profile of the stone it replaces, not the existing weathered profile as this will lead to a progressive loss of stone volume over time.

Plastic repairs are not recommended for stone repair unless the area affected is small, or where it is desirable to retain as much of the original surface as possible, e.g. valuable carved historic detail. The life span of a plastic repair is short compared to that of a stone façade. It is very difficult to achieve matching of chemical and physical characteristics of the substrate with plastic repair. Unless great care has been taken, accelerated decay of surrounding stone is common adjacent to such repairs, possibly causing further injury to fragile stone surfaces. If plastic repair is used on stone then the mix must be chemically compatible and more permeable than the stone, so that moisture movement is concentrated in the repair rather than in the stone, making the repair decay sacrificially to the stone. The repair should reproduce pre-existing joints in the stone: scratching lines across large areas of repair is not acceptable practice. Problems that can be caused by plastic repair include: accelerated decay of surrounding stone, differences in soiling with respect to the original stone, loss or slumping of thin repairs due to poor bonding with the underlying stone and poor colour matching.

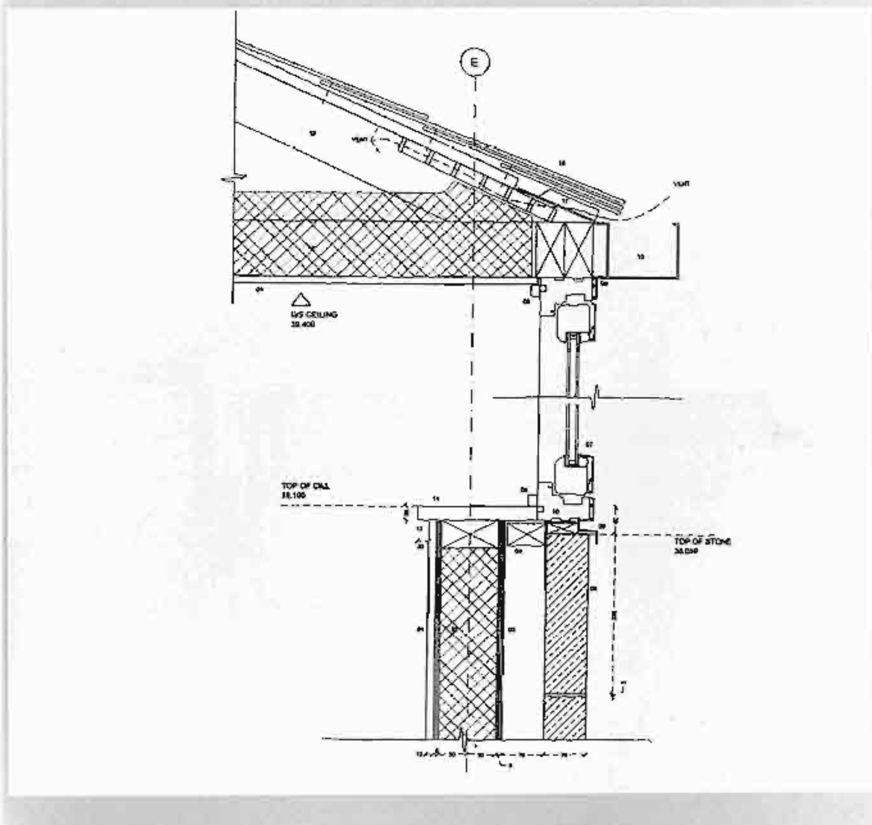
This thin layer of plastic repair has failed to bond with the underlying stone, forming the 'slumped' surface

This plastic repair was coloured to match the soiled stone. When the building was cleaned, the colour no longer matched. The pigment used to achieve a soiled appearance is now running off onto underlying stone

Moisture trapped by a plastic repair of low permeability can induce decay in the adjacent stone

The life span of a plastic repair is short compared to that of a stone façade

Case Study 6	
Building:	27 Whittinghame Drive, Glasgow
Architects:	Davis Duncan Architects
Stone Type:	75mm stack-bonded Copp Crag sandstone
Construction Type:	Loadbearing outer leaf. Timber frame inner leaf



Built as a speculative development, 27 Whittinghame Drive aims to marry the construction techniques of commercial architecture with the building systems of the residential sector. The new building sits lengthwise on a narrow plot of land between existing houses in the West End of Glasgow, its gable walls necessarily devoid of windows. To take best advantage of what might otherwise be considered a problem, the entrance is set to one side of the new property to allow its front and rear elevations to be almost fully glazed, thereby providing as much light as possible into the depth of the largely open plan ground floor.

Planning policy for the area did not stipulate the use of stone on the building, but the architects chose the high quality material to provide an apron panel to the first floor bedrooms. The crisply detailed external appearance of the house is enhanced by the way that the Copp Crag sandstone has been used – equally-sized stack-bonded blocks span the full width of the elevation in a panel that is designed to be loadbearing, entirely belying the existence of the insulated timber frame kit which forms the principal structure of the property. A 5mm mortar bed coloured to match the finely grained yellow-pink stone is used to join the blocks horizontally, with open perps and joints between the stones to 75mm above the galvanised steel lintel. While not a construction technique common to domestic property, the use of stone here unquestionably gives the house a contemporary presence.

Case Study 7	
Building:	Castle Extension, Couston, near Aberdour, Fife
Architects:	Morris & Steedman Architects
Stone Type:	Clashach columns and flooring; hand-cut roofing slates from Easdale in Argyll
Construction Type:	Loadbearing columns

A common approach when extending a historic structure is to replicate the form and construction of the original, but at Couston Castle, the architects Morris and Steedman opted instead to make a clear distinction between the previously-restored tower house dating from the 15th century and its 21st century addition. The design of the new extension draws on historical sources for its inspiration, most notably the loggia built in the early part of the 20th century at Dunderave Castle on Loch Fyne by Sir Robert Lorimer.

The owners of Couston Castle desired additional ground floor accommodation which would provide better views across the loch than those available from the small windows in the tower, and the new extension is constructed on the site of a former walled garden to be only 10 metres from the water's edge. The modern, light-filled garden room is accessed from the tower's kitchen and uses stone and slate to echo the wall and roofing materials of Scotland's traditional architecture.

The horizontal emphasis of the extension's design contrasts strongly with the verticality of the tower and in this wholly contemporary structure the design of the glazing capitalises on the views to the landscape beyond whilst the glass itself is effectively rendered invisible. The new extension appears simple but its unframed glass panels are detailed to check into the stone columns in order to maintain clarity between solid and void. The round columns are fitted around steel rods and are formed from 60 semi-circles of oxide-veined Clashach sandstone.

Sustainability and Whole Life Costs for Building Stone

Tim Yates and Kathryn Bourke, BRE

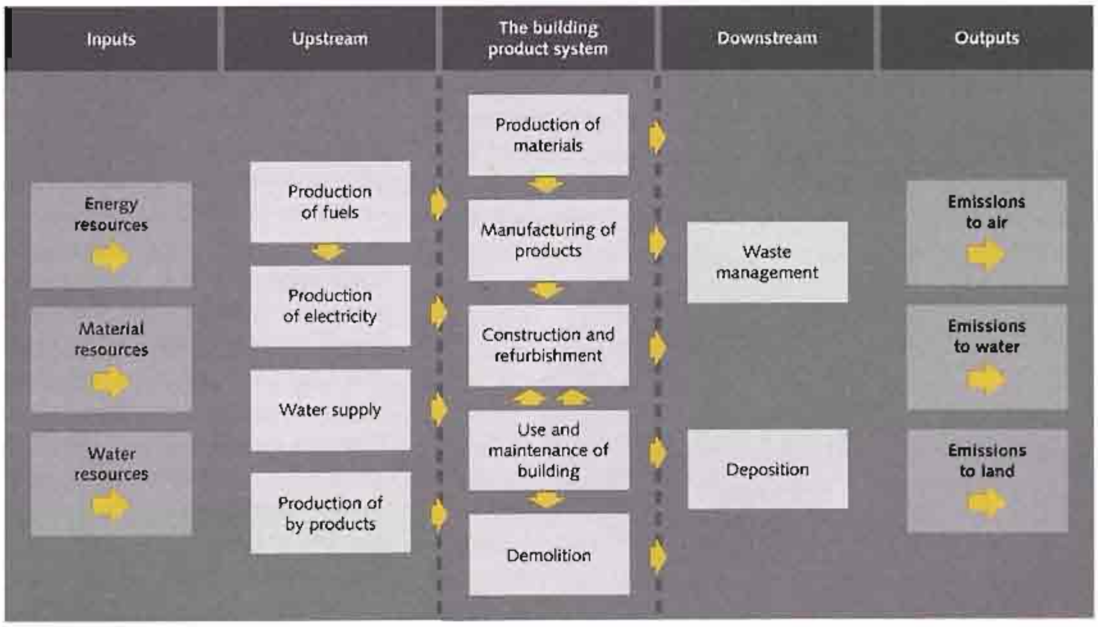
Whole Life Cost and Performance Assessments for Stone

Stone selection nowadays is made almost exclusively on an aesthetic basis, but the medium-to-long term durability of the stone is also important. Often a stone is chosen because the architect has used it before and is comfortable with it. Indeed, in the past, stone was selected on the basis of local availability and a knowledge of what performed well in the immediate environment. Current approaches to the design of façades (including elements such as cornices, sills, overhangs, plinths etc.) and detailing (the presence of lips, drips, bed orientation etc.) tend to be based on the architect's aesthetic decision and the strictures of British Standards such as BS5390, BS8298 and BS6093. Too little consideration is given to the effect design and detailing have upon the stonework's future durability and façade maintenance and hence upon the Whole Life Costing and Performance. In order to demonstrate stone's value for money, therefore, it is usually necessary to undertake a Whole Life Cost and Performance Assessment. This looks at the material's (initial and long term) physical, functional, environmental and economic performance and assesses whether competing alternatives provide satisfactory performance at similar cost. The performance criteria set by a client's brief may include:

- Service life requirements (e.g. design life of not less than 60 years)
- Aesthetic requirements (e.g. no significant discoloration during the first 10 years of use)
- Maintenance frequency requirements (e.g. scaffolding to be erected at intervals not exceeding 10 years)
- Maintenance expenditure requirements (e.g. no excessive maintenance requirements within 25 years)

A detailed comparison is required to appraise these requirements and to consider alternative specifications (and associated costs). Where this is done in association with a Whole Life Costing and Life Cycle Assessment it should also include the aspects shown in figure 1.

Figure 1: Scope of Whole Life Assessment (Cost and Environment)



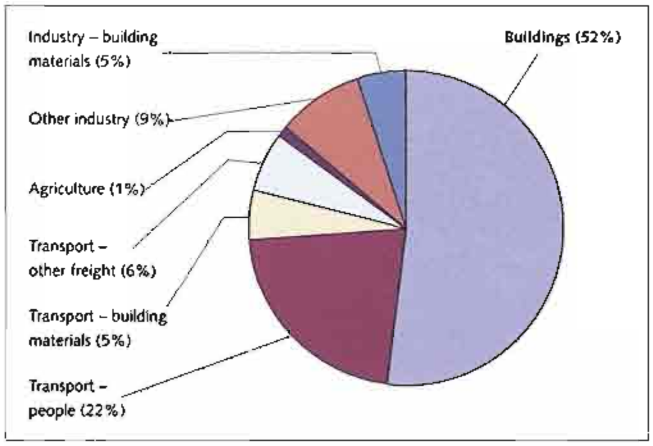
Factors to be taken into consideration when selecting stone
■ visual appearance
■ cost
■ availability
■ quality
■ ease of working the stone
■ previous experience of the stone
■ perceived durability

It is important to remember that cost and environmental impacts are measured over the service life of the product, and that maintenance or replacements accrue new impacts that make a long low-maintenance service life extremely desirable. Where a client has set high targets for service life, appearance, low maintenance, repair costs and low risk of unexpected failures, the performance of stone is likely to be highly competitive. Equally, where the assessment covers the full service life period, stone is likely to show competitive environmental impacts.

Cost Impacts of Use of Stone

Because stone is characterised by having high capital costs, low running costs and a long life, it is highly relevant to demonstrate the relative cost of ownership (Whole Life Cost) compared to competing alternatives. When Whole Life Costs are considered over different periods of time, however, a short period of assessment (e.g. 25 years) or a low discount rate are likely to make stone appear relatively expensive when compared to low capital cost, high maintenance alternatives.

Figure 2: Energy consumption of UK industries (1995)



Environmental Impacts of Stone Extraction and Use

Stone has the potential to have a significant impact in the following areas:

Extraction, Processing and Transportation – Energy

- Global Warming
- Fossil Fuel Depletion

Of all UK industries, construction is the heaviest consumer of energy (often an indicator of environmental impact) and stone extraction, production and transportation (including aggregates) forms a significant part. Figure 2 indicates this:

Extraction and Processing – Materials

- Water extraction
- Water pollution
- Mineral extraction
- Waste Generation

Air Pollution

- From the burning of fossil fuel used in transportation and production
- Dust from processing – but this is usually well controlled
- Acid rain
- Impact of stone production and transportation

Transport Congestion

- Impact of stone production and transportation

Both air pollution and transport congestion can result from stone extraction/processing and also impact on stone.

Transportation and associated congestion are potentially high cost impacts – in terms of both environment and society – and consequently tend to dominate initial assessments of sustainability. These impacts are almost entirely associated with the extraction and installation phase, however, and costs are potentially very low once the stone is in place. Assessment of Whole Life Cost is extremely important, therefore, particularly given the long potential service life of stone paving, masonry and roofing. Stone's 'end of life' stage should also be considered since there is a significant market in the re-use – rather than recycling – of stone roofing and paving materials.

Social Impacts of Stone Extraction and Use

Once in use, stone has little negative social impact and in most cases is regarded positively. In the extraction and transportation phase, however, potential problems are often perceived by nearby communities. Problems highlighted during the planning stage usually relate to the environment, e.g. landscape destruction, dust and waste, and the need for large vehicles to transport stone blocks. Planning controls and lobbying can be especially difficult in National Parks or Areas of Outstanding Natural Beauty (AONB), although there are examples where impacts have been minimised and long-term environmental effects have been reduced. It should also be remembered that stone extraction and processing (along with their associated industries) are among the few profitable primary industries remaining in rural areas and as such can have positive social benefits.

Balancing Impacts

One reaction to the potential social and environmental impacts in the UK has been to source stone from outwith the UK, usually from countries such as China and India where labour costs are lower, but questions are increasingly being raised about the environmental destruction in these places, as well as the social effects of using child workers and the exploitation of workers who do not receive a 'fair' wage. In addition, the energy used in transportation and the wider impacts of this transport need to be considered, and it is important, therefore, that an holistic approach is taken when balancing the positive and negative impacts of stone production in the UK or abroad.

Environmental Impact, Life Cycle Assessment and Whole Life Costing – UK Examples

It would seem natural to close this section with a 'case study' highlighting all the aspects of Life Cycle Assessment and Whole Life Performance, but the newness of these subjects to many parts of the construction industry means that no 'complete' single example can be easily identified. It is possible, however, to discern some key points in the whole process:

a Extraction and Transportation

This area has attracted the most attention since any new application for extraction needs to address environmental and social impacts (see above). On the basis of information available from a number of recent applications (e.g. Johnson Wellfield's application to extend the Crosland Hill Quarry), the following points are readily apparent:

- It can take 10 years or more from an initial approach to land owners to the extraction of the first blocks;
- If the land is not already designated for mineral extraction (for example under a Unitary Development Plan) the process can become more complicated with less likelihood of success;
- The existence of an old quarry, with or without a lapsed planning consent, appears to be of limited importance in a new application and so the argument that it is a traditional source of building stone can also be of limited benefit. By way of example, the application to extract natural stone from Blairingone, Kinross & Perth was refused even though there was a long tradition of quarrying in the area;
- All environmental impacts during and after extraction need to be addressed in the application, and engagement with the local community is essential (e.g. by holding public consultations and seeking input to re-instatement plans);
- Social and economic impacts can be as important as environmental ones and it may be necessary to purchase additional housing and land in order to avoid a real or perceived devaluation of living standards and house prices.

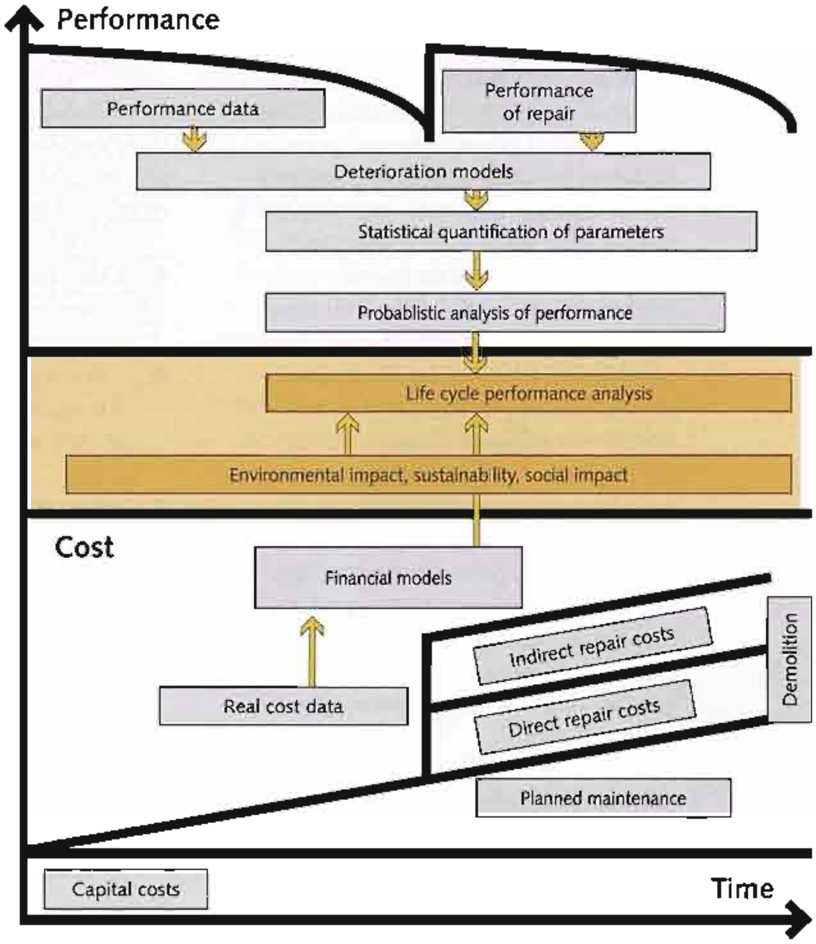
b Embodied Energy and Processing Waste

BRE's Green Guide to Housing Specification takes a wide-ranging approach to energy consumption and the production of waste to produce an overall 'Eco-Rating'. It includes examples of stone but the data used is based on general values and experience with other materials shows that there can be considerable variation between different producers. Interestingly, stone is "marked down" for 'water extraction', 'waste disposal', 'mineral extraction' and 'recycled input', but the latest extraction methods can impact significantly on the first two, while 'recycled input' is probably underestimated due to the substantial demand existing for salvaged stones such as Aberdeen granite and York paving.

c Whole Life Performance and Costing

Stone performance during its required service life is frequently examined under the heading of 'durability' and the relative cost of stone against other materials at the time of installation is often used to partly justify the selection of particular materials as well as the costing of a project. However, there can be a reluctance to combine the two elements of performance and cost to produce a reliable 'Whole Life Cost'.

Figure 3:
The scope of Whole Life Performance



Tools for Assessing Sustainability

Various tools and techniques are available to measure sustainability in its various aspects. The two most relevant to stone producers are Whole Life Costing (WLC) and Life Cycle Assessment (LCA), these being used to assess the long term costs of ownership and the environmental impacts of using particular building materials.

Whole Life Costing (WLC) is "a technique which enables comparative cost assessments to be made "over a specified period of time, taking into account all relevant economic factors "both in terms of initial capital costs and future operational costs."* WLC therefore equates to cost and benefit impacts for the customer (and potentially beyond).

Life Cycle Assessment (LCA) is "a method to measure and evaluate the environmental burdens associated with a product system or activity, by describing and assessing the energy and materials used and emissions released to the environment over the life cycle."* Figure 3 shows the broad scope of LCA assessments –

The terms can be used interchangeably, for example, 'life cycle costing' or LCC is often used, but tends to only include costs (not benefits) and to cover a shorter period. When used together, Whole Life Costing and Life Cycle Assessment permit an appropriate balance to be struck between capital and maintenance costs, and between the impacts on the environment of using natural resources and the benefits created by the building itself. Other positive benefits can be social and economic (e.g. employment and trade) while negative impacts are the costs and the damage caused to the natural environment. There are many shared issues and assumptions in the two techniques – each deals with the majority of the life cycle of the building (LCA tends to be "cradle to grave", while WLC tends to be from "factory gate to breakers' yard") and each also measures impacts in relation to the amount of materials used at various stages. The common assumptions underlying each are therefore specification, maintenance regime and service lives.

*(source of definitions – BS/ISO 15686: Service Life Planning)

Case Study 8	
Building:	Nethermill House, Auchterless, Aberdeenshire
Architects:	Kirk Natural Stone Ltd
Stone Type:	Balmoral grey granite laid randomly; pink granite cassie detailing; Caithness flag window cills and kitchen worktops; natural slate roof
Construction Type:	Cavity wall

A traditional-style house, Nethermill nevertheless demonstrates what can be achieved by builders and developers willing to use locally-available natural materials. In this instance, constructing a new property from locally-sourced grey granite, Caithness flag cills and natural slate might be seen as a bold move for a relatively small company but the use of these materials provides a solid and timeless feel to the house and adds significantly to its value. This is an unusually large family home comprising some 500 square metres of accommodation (including a kitchen, dining room, galleried hallway, utility room, shower room with hot tub, lounge, 4 bedrooms and guest room, en-suites and additional bathrooms, games room, conservatory and integral double garage and store) which, despite the granite being randomly laid, was constructed relatively quickly.

Conventional cavity wall construction was used at Nethermill House but, based upon this experience and working in conjunction with Angus Homes Ltd on a project for a site in Turriff, Kirk Natural Stone Ltd are now developing a more economical timber frame kit package which can be used with either random or dressed stone. In this system, an internal lining of plasterboard is separated from a structural timber frame by a vapour check. A thick, CFC-free insulating quilt is sandwiched between the timber uprights and is backed with a sheathing board. A waterproof breathing membrane separates this from the cavity framing, and is itself fronted with sheathing board and a further waterproof membrane. The natural stone outer skin completes the external envelope.

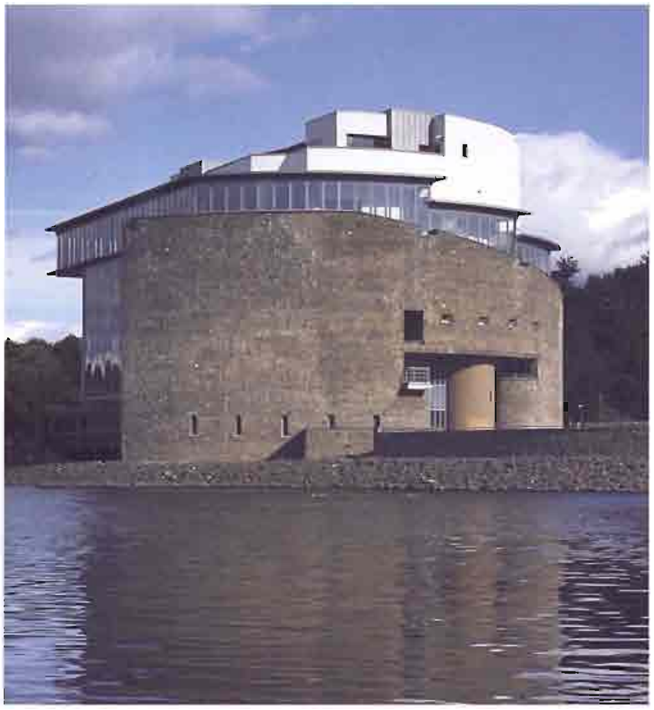
Stone as a Cladding Material

Peter Wilson
Manifesto Centre for Architectural Research, Napier University

Nowadays the word cladding is applied ubiquitously to all manner of building facade systems, but as applied to natural stone its etymology stems from the development of steel and concrete frames and the consequent potential to clothe these structures with non-loadbearing exterior walls. The particular systems now used depend as much on the building type and structural solution employed as they do on the intended aesthetics of the architecture, but in each case the skin is designed to carry no weight other than its own.

Initially, the design of stone cladding systems was founded upon time-honoured principles of loadbearing masonry construction, but the many incarnations available today have evolved in parallel with the development of mechanical fixing systems in which metal corbels, cramps and dowels transfer the loads to the structural frame. With its loadbearing function thus removed, natural stone has become only one of many material choices available for use in cladding systems. Despite this, however, stone is often preferred for its appearance, durability, longevity, quality and symbolic associations.

As the technology of fixing systems for cladding has become increasingly sophisticated, so too has the thickness of stones used been progressively reduced. Whilst this has resulted in weight and cost savings, it has also generated new technical challenges for the designer since the ways in which stone performs when its thickness is reduced can be highly variable. Depending on the building type and the particular environment it is being constructed in, the rates of thermal expansion and contraction as well as differential movement between the cladding and the substrate or frame can, for example, vary substantially from those expected with greater material thicknesses. Similarly, moisture and drying cycles can fluctuate with the absorption and porosity of the thinner stone and the particular surface finish employed, whilst structural issues such as the effects of traffic vibration on fixings as well as wind load pressure on the panels can have considerable implications for the final design solution.



The circular concrete structure of Drumkinnon Tower by Page and Park Architects was clad in stone to evoke memories of Scotland's castle architecture tradition and to form a striking visual reference point at the entrance to the Loch Lomond and Trossachs National Park.

Hand-set cladding on a luxury apartment building in Edinburgh's Murrayfield area. Reiach and Hall Architects used Peakmoor ashlar on the exterior of Succoth Heights.

Natural stone from Scottish quarries is suited to three common cladding methods -

Hand-set Cladding

Because of their geological composition and the potential to delaminate if not laid 'on bed', most limestones and sandstones have limitations in terms of the types of cladding systems they can be used with. For these types of stone, hand-set cladding systems have many advantages and can be seen to good effect on buildings such as Evolution House on Edinburgh's Westport. Loadbearing fixings are used at each floor level to support the weight of the stone and transfer the structural load back to the frame, whilst cramps and ties are employed between floors to secure each ashlar panel to an inner leaf of brick or block. The stones themselves are normally bedded in mortar, with 10mm wide vertical expansion joints required at approximately 6m intervals. Similarly, differential movement between the stone cladding and the internal skin and frame necessitates horizontal compression joints at each floor level.

Rainscreen Cladding

James Stirling and Michael Wilford's use of natural stone rainscreen cladding on the Staatsgalerie in Stuttgart in the early 1980's stimulated an interest in such systems among architects that has continued to this day. In part, this has been a response to problems associated with traditional hand-set cladding (degradation of seals in adverse climates, consequent water penetration ineffective drainage and inferior construction quality), but there has also been an aesthetic motivation since these systems permit more abstract designs free of movement joints and the traditional parapets and copings. In back-ventilated rainscreen cladding systems the weight of each stone is transferred individually to the structure, with 4-6mm open joints between stones to allow the system to dry out quickly and minimise mould growth. In projects such as the Museum of Scotland and the Scottish Parliament a ventilated cavity separates the stone from the structural concrete wall which has a waterproof membrane applied to its surface and insulation fixed between it and the stone.

Stone-faced Precast Cladding

Pre-assembled stone-faced precast panels are of benefit in situations where speed of erection is a factor, as they can be manufactured to relatively high tolerances in a factory-controlled process before delivery to site. The system is particularly useful when a large number of repetitive elements are involved, such as on the Scottish Widows head office in Edinburgh by BDP Architects or at the new headquarters for the Royal Bank of Scotland

The Clashach rainscreen cladding to the Museum of Scotland by Benson + Forsyth Architects was precision cut to form a perfect curve when fixed to the circular entrance tower.

at Gogarburn by Michael Laird Architects. Installation of complete units can be quick and precise. Relatively thin (30-50mm) sections of natural stone can be used (although this will always depend on the particular stone type selected). In manufacturing, the finished stone is laid face down in a shuttering box and s Steel reinforcement laid over it. In order to avoid differential movement between the materials, a bond breaker is used to prevent the poured concrete adhering to the stone.

The Design of Fixings and Fixing Systems

Because stone has a relatively low tensile strength, it needs to be supported and held in place when used as part of a cladding system in order to deal with the dead and applied loads involved. Essentially there are two kinds of fixings - load-bearing and restraint - with each type usually made up of three elements - the part attached to the stone; the section that spans the cavity; and the piece that is fixed to the backing structure. While the principal of fixing stone is simple to understand, the type of fixings to be used will be specific to the particular cladding system employed and the specific circumstances of each project. It should be recognised that the selection or design of fixings has now become a highly specialised area of engineering consultancy, with considerable expertise available not only on the structural issues but on the functional characteristics of different stone types.

Testing of Stone

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Unlike most other construction products, natural stones – even ones selected from a single quarry – can vary considerably in strength, breaking load, density, porosity, water absorption and frost resistance and, as well as colour, texture and veining. While these latter qualities relate to visual appearance, the former characteristics are crucial to the stone's ability to perform successfully, particularly in non-loadbearing situations. Before selecting a stone type for use in cladding system, therefore, the architect or designer should give due consideration to the following points:

- *Is the stone safe to use in the intended environment?*

It is important to establish where the material is to be used and what it is to be used for. Only a few sandstones are suited to use as cladding, for example.

- *How thinly can it be used?*

It should always be remembered that stone is a natural material and may vary considerably from slab to slab. If used too thinly it can also bow and may be subject to fairly rapid deterioration.

- *What is the largest size of panel or tile possible?*

There is a clear relationship between the length of a stone panel and its flexural strength and it is important to establish the minimum breaking load for the slab thickness intended.

The answers to these, and the many other points highlighted in Table 5 'things to remember when selecting stone' (see page 36) can only properly be discovered through testing, an essential process previously covered by an extensive list of British Standards and now – with an ever-expanding range of imported stones of uncertain provenance available – subject to rigorous European regulation. These European standards provide a valuable framework for assessing a stone type's suitability, and place the responsibility for obtaining a CE marking – and the performance of the stone (although not its installation, which is still covered by British Standards) – firmly on the company converting the block into the final stone product. The supplier has a legal obligation to provide information on the lowest expected values that have been achieved by the stone type in question.

Testing should begin as early as possible in the design process and the testing of natural stone products to be used as cladding should always be supported with the results of initial type testing carried out by the quarry/factory/supplier. The quarries should also provide test data sheets which include historical information. All of the test requirements are set out in the new series of British Standard test methods which are common to CEN members. All other test methods traditionally used – and still submitted by some stone suppliers – have now been superceded.

It is important to carry out tests relevant to the particular project, however, since not all tests are appropriate in every case. Equally, although a CE marking is of immense value in ensuring that minimum standards have been met, it should not be regarded as a panacea since it will only refer to that part of the quarry that the certified stone comes from. The Stone Federation Great Britain and BRE can provide guidance on the interpretation of test results.

Fig. 1: Natural stone test methods for the determination of –	
BS EN 1925:1999	water absorption by capillary
BS EN 1926:1999	compressive strength
BS EN 1936:1999	real and apparent density; and total and open porosity
BS EN 12370:1999	resistance to salt crystallisation
BS EN 12371:2001	frost resistance
BS EN 12372:1999	flexural strength under concentrated load
BS EN 12407:2000	petrographic examination
BS EN 13364:2002	the breaking load at dowel hole
BS EN 13373	geometric characteristics of units
BS EN 13755:2002	water absorption at atmospheric pressure
BS EN 13919	resistance to ageing by SO_2 action in the presence of humidity
also	
BS EN 12440:2001	denomination criteria
BS EN 12670:2002	terminology
Draft Standards	
The following have also been formally approved and await publication as BS EN's:	
prEN 1469	natural stone – slabs for cladding
pr EN 13161	determination of flexural strength under constant movement

Fig. 2: Frequency of testing for factory production control	
Flexural strength	at least every 2 years
Water absorption	
Apparent density and open porosity	
Petrographic examination	at least every 10 years
Breaking load at dowel hole	
Frost resistance	
Resistance to ageing	

European Standards

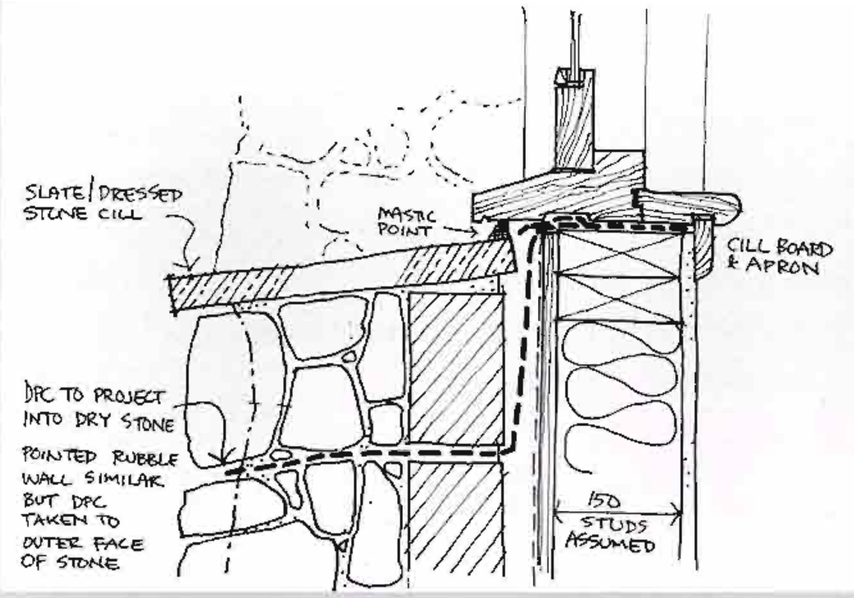
The list of key standards now approved at European level and published with BS EN numbers is shown below. Standards that set out test methods form part of the approvals procedure for products and have to be adopted in place of the various test methods currently used. Standards for products which have been harmonised will soon require those products to be CE marked before they can be placed on the market.

Stone supplied for use as cladding should be tested in accordance with the methods set out above. Slabs for cladding will eventually be covered by the new product standard (EN 1469 Natural stone – Slabs for cladding), the basis of CE marking. Companies supplying slabs for cladding will be required to carry out the testing and/or declare the results. For factory production control the frequency of the tests should be as fig. 2.

Comprehensive testing of a desired stone type at the earliest possible stage in the design process will not only help to prevent expensive mistakes being made, but will provide both designers and building owners with a reasonable degree of confidence on the future performance of the stone selected. It cannot emphasise too highly however, that visiting the quarry is an important part of the process, and that the use of proven indigenous material can provide an additional element of quality reassurance.

Case Study 9	
Building:	Auchnaguie, by Dunkeld, Perthshire
Architects:	Simpson & Brown Architects
Stone Type:	Local field stone quarried from decayed enclosure walls
Construction Type:	Timber frame cavity wall – dry stone back-bedded to blockwork basewall, behind which is an insulated timber frame

The dry stone wall has a pedigree in the domestic architecture of Scotland dating back to the Neolithic structures of Skara Brae and Maes Howe on Orkney, its durability in extreme weather conditions proven over time and its high sustainability quotient still unmatched by other methods of construction. Increased awareness of environmental issues has reinvigorated interest in the use of dry stone and, coupled with the efficiency of modern timber frame systems, presents an opportunity to create new buildings suited to the rural landscape.



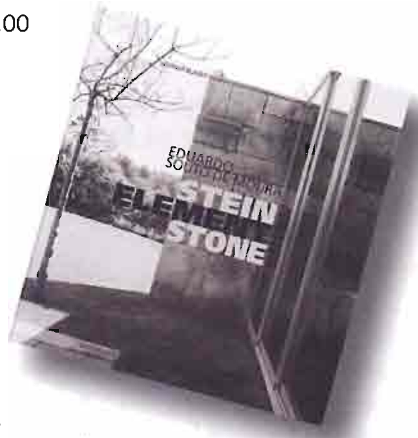
Aside from the lower fuel levels required to transport locally sourced material, there are many practical benefits to be had from using dry stone for new buildings – aesthetics, durability, low maintenance costs, re-use of existing materials, and retention of valuable craft skills. Dry stone is not the quickest form of construction, but it can be carried out in all but the worst of Winter weather. The method is not necessarily suited to large-scale housing developments, but its potential for rural housing is considerable, especially in areas where local dry stone walls have fallen out of use and – along with redundant buildings – can be a ready source of material.

At Auchnaguie, a traditional farmstead and steading range have been converted to new use as housing. As fine examples of the local vernacular, care was taken to retain original features, with two new timber frame houses built alongside to complement the grouping. The new dry stone walls function as rainscreens and are back-bedded to the timber frame construction. *www.dswa.org.uk*

Book Reviews

Eduardo Souto de Moro
Stein – Element – Stone

Werner Blaser
Birkhäuser 2003, £20.00
96pp
ISBN 3-7643-0087-6

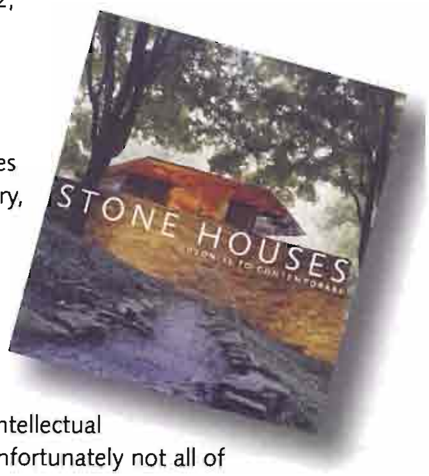


A material with the richest of colour ranges, stone's enduring qualities nevertheless seem to be best encapsulated in black and white photography. Surface, mass, texture and detail are all somehow more clearly delineated by this medium, and Werner Blaser's book uses this fact to compelling advantage in his examination of Eduardo Souta de Moro's fascination with granite. The book visually explores nine of the architect's built projects – from the domestic scale of single family houses to the extraordinary new soccer stadium set into the bowl of a granite quarry at Braga for the 2004 European championships – as well as communicating something of Portugal's rich tradition of stone construction. The text unfortunately aspires to a matching level of poetics but is thankfully limited, leaving the reader to concentrate on a thorough examination of the images.

Souta de Moro's architecture is deceptively simple, but is based on a profound understanding of the importance of stone in Portuguese culture. His work seeks to combine his nation's rich masonry tradition with the simplified and abstracted forms of contemporary architecture. This is a man who understands the significance of the construction joint, and each detail is refined and developed in response to modern sensibilities. The projects on display here have a sensitivity that only comes from an acceptance of the physical nature of the material. Deceptive it may be, but there is much to learn here: for anyone seriously interested in designing with stone, Souta de Moro's granite architecture is 'critical regionalism' at its best.

Stone Houses – Colonial to Contemporary

Lee Goff
Harry N. Abrams 2002,
Hardback, 232pp
ISBN 0-8109-3287-3



From prehistoric dwellings to the houses of the early 21st century, this book sets out to record the use of stone in the domestic architecture of the United States. The introduction seeks to establish an intellectual raison d'être, which unfortunately not all of the subsequent chapters manage to deliver. Not that the content is poor – the rich and exuberant photography almost encourages the reader to stretch out and feel the texture of the stones forming the houses on display – but the book's title could lead the unsuspecting to presume that more detail will be provided on the range of stones utilised.

Some of the examples included are particularly striking – Henry Hobson Richardson's Ames' Gate House (1880-1) demonstrates the expressive possibilities inherent in construction with large, rough stone boulders, while the delicate simplicity of Franklin D. Roosevelt's Top Cottage belies its importance as possibly the first building designed by a disabled person for himself and one of only two houses designed by a sitting US president.

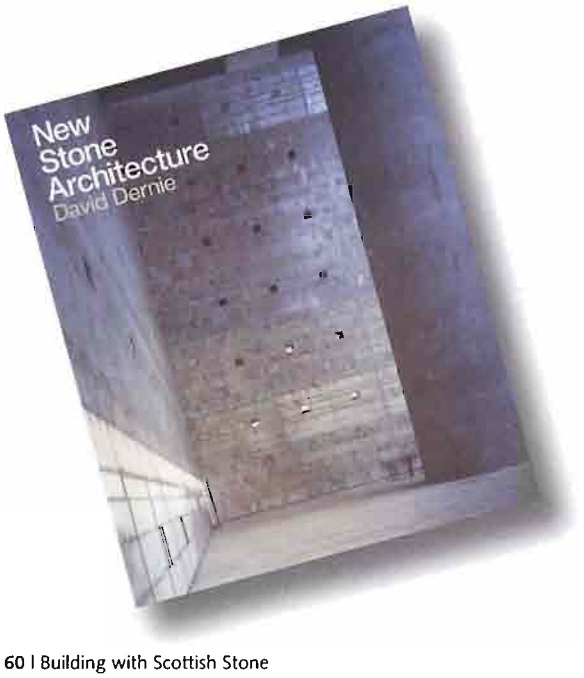
Inevitably, with a shorter timescale to work with, the 21st century examples offered are less intriguing than those of the three previous centuries. The book's value extends beyond its intended coffee table market, however, by providing technical nuggets such as "...mortar enhanced with coal dust to darken it and echo the flecks of mica in the schist..." which could only otherwise be obtained by practical experiment. For the contemporary architect seeking to design well with stone, this is the equivalent of discovering alchemical success.

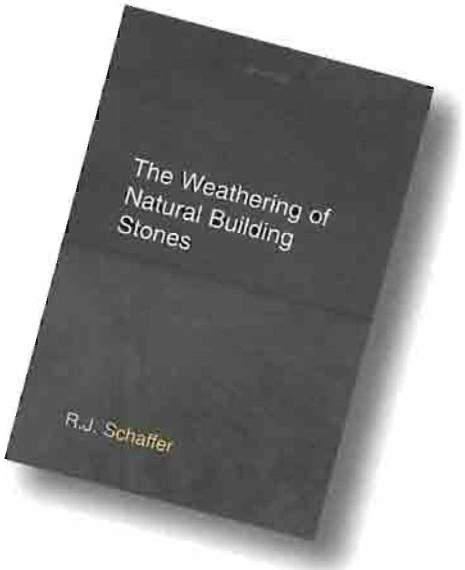
New Stone Architecture

David Dernie
Laurence King Publishing 2003
hardback 240pp, £40-00
ISBN 1 85669 312 0

For anyone seriously interested in the use of stone in contemporary building projects, this book is not only a visual delight but an essential reference source to have on the shelf. The author persuasively argues that the current creative use of stone represents a backlash against the 'formal tyranny' of digital simulation and see-through space that dominates so much of contemporary architecture. This premise is developed in four sections – 'the Power of Stone', 'Building in Stone', 'Petrified Landscapes' and 'Urban Stones' – and via thirty three case study projects from around the globe. The examples are well chosen and include stunning work by architects more usually associated with the high-tech end of the design spectrum such as Michael Hopkins, Renzo Piano and Ian Ritchie, as well as other luminaries such as Eduardo Souto de Mouro, Alvaro Siza and Rafael Moneo who have formed their reputations on the materiality and contextual responsiveness of their buildings.

In addition, the book provides useful background to current quarrying and processing methods as well as cladding techniques, with detailed analyses of the constructional challenges associated with the use of stone in differing climatic and cultural conditions. *New Stone Architecture* is far from being a technical manual, however, and the intelligent essays that preface each section set the historical and philosophical context for a material that, more than any other, delivers regional identity. In this respect, and for other environmental reasons, the author makes a compelling case for more local stone to be used in contemporary architecture.





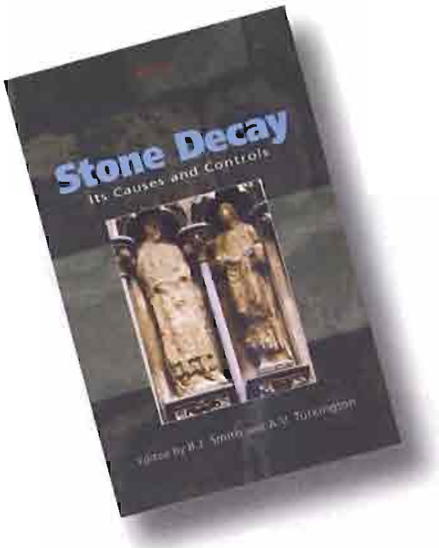
The Weathering of Natural Building Stones

RJ Schaffer
Donhead Publishing 2004, £33.00
208pp
ISBN 1 873394 69 1

Some books never go out of date even if they go out of print, and Schaffer's research into the weathering of natural stone is rightly considered a "classic". First published in 1932, this is still one of the most useful reference works available and should be in the office of every building professional whose job includes the specification or repair of stone.

Originally produced in response to concerns from the Imperial War Graves Commission and the authorities of Westminster Abbey on the effects of airborne pollution, Schaffer spent six years trawling through over 250 books and papers on the subject of weathering as well as visiting quarries throughout the UK, and his archive of site notes, photographs, samples and analyses is held – and still regularly used – by BRE. This is unsurprising because, although stone is used in quite different ways today and the nature of our environmental pollution is no longer the acidic fug of the 1920's, the chapters on the causes of weathering are still fundamentally accurate.

For a publication whose raison d'être necessarily embraces questions of chemical composition and reaction, the writing reassuringly avoids being overly scientific and concentrates instead on ensuring the issues involved are fully understood. Importantly, Schaffer identifies many weathering problems caused by poor specification, design errors and faulty craftsmanship, and the lessons to be learned from the examples given still apply today. In the area of stone cleaning, however, practice has moved on to less aggressive treatments than those recommended in these pages.



Stone Decay – Its Causes and Controls

Edited by BJ Smith and AV Turkington
Donhead Publishing 2004, £37-50
320pp
ISBN 1 873394 57 8

An immensely complex area of study, stone decay and conservation is nowadays a multidisciplinary field requiring interdisciplinary solutions, and the dynamically-styled 'SWAPNET' (or, more prosaically, the 'Stone Weathering and Atmospheric Pollution Network') has met every year since 1995 to bring together two broad groups of researchers and practitioners who have common interests in the ways that stones decay. The first group – those interested in the weathering of rocks under natural environmental conditions – comprises geomorphologists and geologists, while the second – those concerned with the decay and conservation of building stones – includes architects, engineers and conservators. The former looks for theoretical explanations of why stone decays; the latter searches for practical solutions through appropriate treatments and management strategies.

Inevitably each group uses different terminology, but there is increasing recognition of the need to understand the processes responsible for decay in order to develop sound strategies for the conservation of stone buildings. Certainly, there are nuggets of useful information to be found in these selected proceedings from an international symposium on weathering held at Queen's University Belfast in 2000, but other sections may prove a tad indigestible to architects and others at the metaphorical rockface of contemporary building design. For scientists researching into the causes of stone decay, however, there is some good bedtime reading to be had here on the impacts of pollution and the effectiveness of stone treatments. That said; this is not a book intended either for the coffee table or for those seeking an elementary primer on stone construction.

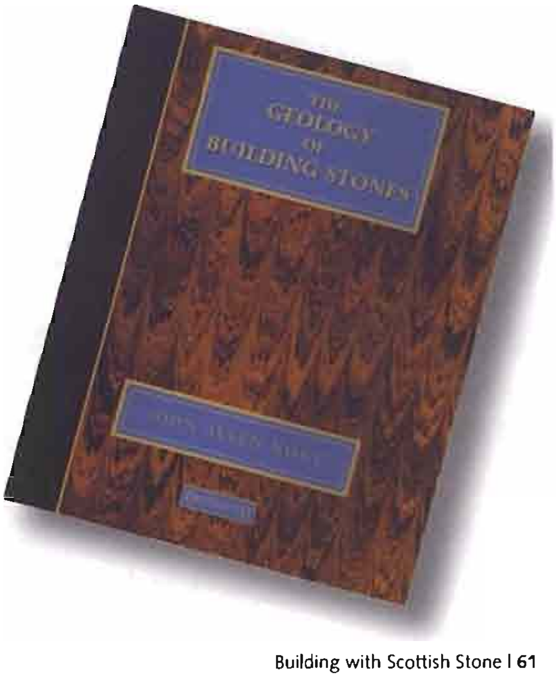
The Geology of Building Stones

John Allen Howe
Donhead Publishing 2001, £35.00
Hardback, 455pp
ISBN 1 873394 52 7

Originally published in 1910 when stone was still a major building material for prestigious and smaller domestic projects, Howe's book provided the first major study of the considerable range of building stones in use in the UK at that time. Its appendices list the larger limestone and sandstone quarries operating and give some idea of the scale of the industry at the beginning of the 20th century.

As curator and librarian of the Geological Survey, Howe was in a position to pull together all of the information then available into a valuable reference source on the qualities of granite, sandstones, limestones and less well known building stones specific to certain geographical locations. Recently republished, the wealth of geological and other scientific and technical data it contains is still valuable to anyone seeking to identify stone types used in old or historic buildings. Howe helpfully relates the various stones to completed projects, and shows the major differences between just-quarried material and the same stone after a period of time in use on a building.

Aside from an excellent introduction to stone decay caused by frost, pollution and organic growth, the chapter on testing can be seen to be far ahead of its time since it is only now that standard tests for building stones are becoming mandatory aspects of new European Standards. Howe's book may not contain all the answers to contemporary questions on the use of stone, but it has enough easily readable information to ensure appropriate decisions are reached.



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No 223	Wall cladding: designing to minimise defects due to inaccuracies and movements
No 227	Estimation of thermal and moisture movements and stresses: part 1
No 228	Estimation of thermal and moisture movements and stresses: part 2
No 229	Estimation of thermal and moisture movements and stresses: part 3
No 280	Cleaning external surfaces of buildings
No 370	Control of lichens, moulds and similar growths
No 418	Bird, bee and plant damage to buildings
No 420	Selecting natural building stone
Stone Federation Great Britain Leaflets	
TI 1 91	Fixings for stone cladding
TI 3 93	Care and maintenance of stone in buildings for building owners
TD 2 96	Mortar and pointing
TD 3 91	Damp proof courses in stonework
TD 4 91	Considerations to reduce staining on natural stone facades
TD 7 95	Sealing joints in natural stone
TD 9 93	Guide to external stone masonry and cladding tolerances
TD 11 95	Movement joints in natural stonework
also	Indigenous Stone Quarries
	Natural Stone Glossary
	Stone Specifiers Guide

Historic Scotland	
TAN 1	Preparations and use of lime mortars
TAN 9	Stone cleaning of granite buildings
TAN 10	Biological growths on sandstone buildings - control and treatment
TAN 12	Quarries of Scotland
TAN 21	Scottish slate quarries
TAN 25	Maintenance and repair of cleaned stone buildings
also	A Future for Stone in Scotland
	Stone Cleaning - A Guide for Practitioners
	Chemical consolidants and water repellants for sandstones in Scotland
	Performance of replacement sandstone in Edinburgh's New Town
	Dictionary of Scottish Building
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	Building and repairing dry stone walls
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	A brief guide to the inspection of dry stone walling work
	Specification for simple retaining walls
	Technical specification for dry stone walls
	Building special features in dry stone
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	Stone in Construction Materials Reference Book
British Geological Survey	
	Building Stone Resources of United Kingdom map
Edinburgh Geological Society	
	Building Stones of Edinburgh (1999)
QMJ Publishing Ltd	
	Natural Stone Directory

Organisations

BRE Scotland	
Kelvin Road, East Kilbride, Glasgow G75 0RZ	
Telephone	01355 576200
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Telephone	0131 448 0313
Fax	0131 440 4032
Website	www.ssig.co.uk
Stone Federation Great Britain	
Channel Business Centre, Ingles Manor, Castle Hill Avenue, Folkestone, Kent CT20 2RD	
Telephone	01303 856123
Fax	01303 221095
Website	www.stone-federationgb.org.uk

In recent years, natural stone has again figured in the design of new buildings in Scotland, and interest has been renewed in the range and characteristics of the resources available from Scottish quarries. Prominent public projects such as the Museum of Scotland and the Scottish Parliament have established themselves as contemporary architectural showpieces for the enduring and distinctive qualities of indigenous stone, and throughout the country many other examples can be found of architects, contractors and developers re-exploring the potential of locally-sourced materials. Along with this new interest has come a demand for better information on the different types of Scottish stones available and for guidance on how to use these materials well.

Building with Scottish Stone aims to encourage more use of stone sourced from Scotland's working quarries and to provide a better understanding of those mineralogical properties which give each stone its distinctive quality. The nation's architectural history is synonymous with the use of natural stone, and the principles of construction developed over generations in response to Scotland's particular climatic conditions still find relevance today in the design and detailing of new buildings. Equally, an understanding of the ways in which stone is extracted and processed is as fundamental to its contemporary use as having up-to-date knowledge of the continuously changing legislation that affects its specification and procurement.

Building with Scottish Stone is a stimulating introduction to these and many other factors to be considered when using this richly-varied and timeless resource in the design of new buildings.

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