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Building stone: the geological dimension

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Abstract

Although the location, planning and operation of building stone quarries is similar in many respects to other industrial minerals, the scale of the operation and the methods used for stone extraction result in significant differences. Restoration and conservation techniques have rarely taken very much account of the petrology of the material to which they were applied. This is now changing. The complex chemical, mineralogical and biological changes involved in the weathering of stone demand a contribution from a multi-disciplinary team working on our cultural property.

Introduction

Although stone has been used as a building material for at least 10 000 years, it was only after the Norman Conquest that it achieved major importance in Britain. Before that time its use had been largely restricted to megalithic burial chambers and stone circles although, at Skara Brae in the Orkneys, the lack of suitable timber resulted in the construction of walls, beds and even cupboards from stone. From the 11th century onwards, the quality of stone building in Britian was equal to that anywhere in the world. The major period of ecclesiastical building in the 12th and 13th centuries produced our finest cathedrals. The great houses built in the 16th, 17th and 18th centuries continued this tradition of fine masonry work using native stone. Although it is the cathedrals and country houses which tend to be used to illustrate the use of building stone, much was also used for vernacular buildings from medieval times onwards.

Although the first English bricks appeared in about the 13th century and were used extensively from the 17th century onwards, they were expensive. However, with the removal of the brick tax in 1850 and the introduction of mechanical methods of mass production and better transport facilities, brick became the most common building material. The development of Portland Cement at about the same time contributed to the decline in the use of stone as a building material.

Whilst still used for prestigious buildings, the relatively high cost of building stone in recent years has tended to preclude its use for housing and smaller scale commercial use. However, modern production methods, coupled with the high costs of land and other materials used for building, have now resulted in stone-faced buildings becoming an economic proposition. The cost of a new house, using different materials for the outer wall, is indicated in Table 1. The economics of building in different types of stone depend not only upon the cost of the stone itself but also upon the ease with which it can be used. Split walling is essentially stone which has been shaped using a guillotine; the high labour costs of laying this stone arise from the difficulties involved in tying the relatively irregular stone course into the inner, breeze-block or brick wall whilst maintaining the correct cavity between the two components. Dressed stone will probably have been sawn to size hence although it is then easy to lay, it is more expensive to produce. These economic facts,

TABLE 1. *Illustrative costs of building a house using different materials*

	Construction material of outer wall			
	Brick	Cast Stone	Split Walling	Dressed Stone
Cost materials / m^2	£12	£18	£32	£50
Cost building labour / m^2	£10	£10	£30	£10
Total cost / m^2	£22	£28	£62	£60
Total cost outer wall	£3300	£4200	£9300	£9000
Other building costs	£37000	£37000	£37000	£37000
Cost of land	£30000	£30000	£30000	£30000
Financial charges and profit margin	£23200	£23500	£25200	£25000
Selling price of house	£93500	£94700	£101500	£101000
Walling material as % of the sale price	3.5%	4.4%	9.2%	8.9%
% increase in sale price compared to brick built	—	1.3%	8.6%	8.0%

TABLE 2. *Typical British building stones from strata of all geological ages*

System	Building Stone	
Quaternary	Tufa.	
	Cobbles from Drift.	
Tertiary	Limestone:	Quarr, Binstead.
	Sandstone:	Sarsens.
Cretaceous	Limestone:	Beer Stone, Clunch, Kentish Ragstone, Totternhoe.
	Sandstone:	Bargate Stone, Carstone, Horsham, Hurtwood, Salcombe, Wealden.
	Flint.	
Jurassic	Limestone:	Ancaster, Barnack, Bath, Blue Lias, Chilmark, Clipsham, Collyweston, Guiting, Ham Hill, Kettton, Lincoln, Portland, Purbeck, Weldon.
	Calcareous ironstone:	Edge Hill, Hornton.
	Sandstone:	Aislaby, Boughton.
Triassic	Sandstone:	Corsehill, Grinshill, Hollington, Rosebrae.
	Alabaster.	
Permian	Limestone & Dolomite:	Cadeby, Linby, Tadcaster.
	Sandstone:	Lazonby Red, Mansfield, Penrith, St. Bees.
Carboniferous	Limestone:	Hopton Wood, Moelfre, Orton Scar, Ulverston.
	Sandstone:	Birchover, Blue Pennant, Bolton Woods, Briercliffe, Cat Castle, Darley Dale, Delph, Dunhouse, Forest of Dean, Greenmoor Rock, Kerridge, Stancliffe, Waddington, York Stone.
Devonian	Limestone:	Ashburton.
	Sandstone:	Caithness Flags, Dunmore, Red Wilderness.
	Slate:	Delabole, Mill Hill, Tredinnick.
Silurian	Limestone:	Wenlock.
	Slate:	Berwyn, Burlington.
Ordovician	Sandstone:	Hoare Edge.
	Slate:	Aberllefeni, Brandy Crag, Broughton Moor, Cumbria Green, Kentmere, Kirkstone, Portmadoc/Ffestiniog.
Cambrian	Limestone:	Ledmore Marble, Skye Marble.
	Slate:	Nantile, Penrhyn.
Precambrian	Limestone:	Iona Marble.
	Slate:	Ballachulish, Swithland.

coupled with a greatly enhanced appreciation of the environment, have resulted in a major reactivation of the building stone industry. Even so, the production is very small compared with other extractive industries, the total output for 1990 being only 850 000 tonnes. Unfortunately, a large proportion of the stone used is still imported. Although it is understandable that quantities of marble and igneous rocks should be obtained overseas, it is surprising to find that 1054 tonnes of sandstone, 3968 tonnes of limestone and 37 759 tonnes of slate were imported into the UK in 1992. Exports of building stone for the same period amounted to 2001 tonnes of sandstone, 439 tonnes of limestone and 5961 tonnes of slate (source: *Stone Industries*, **28**, (6), 1993).

Geology of building stone

A vast range of rock types has been used for construction purposes in the United Kingdom. This is not due to the fact that all the materials used are especially suitable for building purposes, but rather is a result of the high cost of transport. It is true that some material has been transported considerable distances; Purbeck marble for example is found in many of our great cathedrals and French limestones, such as Caen, were frequently used for ecclesiastical buildings. However, movement of stone was normally only undertaken for special purposes and even then only when much of the journey could be undertaken by water. An exception to this appears to have been in Roman times, when the transport of ordinary building stone over distances up to 100 km does not appear to have been uncommon; some stone may even have been brought from the Mediterranean region (Blagg 1990).

Within Britain, stone from almost the whole of the geological column has been used as building material. Table 2 lists a representative, but in no way exhaustive, list of strata used. It should be noted that those stones listed under 'slates' commonly yielded other building materials such as walling stone, flooring and lintels, while limestones such as the Collyweston and Ham Hill provided roofing tiles, as did sandstones such as the Horsham, Kerridge, Pennant and Hoare Edge.

As well as sedimentary and metamorphic rocks, igneous rocks have also traditionally been used as building materials. Granites such as Bosahan, De Lank and Trevone from Cornwall are well known, as are the Mountsorrel Granite from Leicestershire and the Shap Granite from Cumbria; to the west of the Lake District the granodiorite at Waberthwaite has been used under the name Broad Oak Granite. The dolerite of the Whin Sill has been worked as a building stone using the local name of 'whinstone'.

Suitability and use of stone for building

Stone has been used on its own or in combination with other materials for walling, flooring and roofing, for door and window frames, for seats and tables, while other uses range from statuary to coffins. The style of many early stone buildings, especially the older cathedrals, indicates how the craftsmen were influenced by the traditional methods of building and carving in wood. As with wood, different stones are best suited to different purposes. The most obvious example of this is the use of relatively hard limestone, such as the Weldon, for the quoins, lintels, architraves or copings while the walls may have been constructed of a softer material such as Jurassic ironstone. Some stones can be sawn to produce ashlar, others are suitable for use in both sawn and split form. Unlike other industrial minerals, such as aggregates, there are no British Standards dealing with the testing of most building stone, the exceptions being slate for roofing, sills, copings and damp-proof courses. The Standards relating to the use of stone in building tend to be codes of practice and as such do not specify a testing programme. Moreover, despite the efforts of a number of workers, notably at the Building Research Establishment, to develop tests which will assist in determining the durability of stone (Ross & Butlin 1989), these tests leave much to be desired and should be used with caution. In fact so little is known about the chemical and physical processes which determine whether or not a particular stone will be durable, it is unlikely that standard tests could actually be developed at the present time. A good stonemason can normally distinguish between good and bad stone considerably more quickly and successfully than any of the tests currently available.

There are a number of American (ASTM) Specifications relating to natural building materials. However, most of the specification requirements relate to engineering properties, the limit on water absorption being the only factor in the American Standards which may be considered as relating to durability. Testing procedures in Europe suffer from similar failings, although an actual freeze–thaw test is available in France. New European Community Standards are in preparation and their publication is awaited with interest.

Practical aspects of building stone extraction

Although some building stones are produced in relatively large quantities, for example Portland, Bath, Guiting and Welsh slate, the majority of traditional materials are worked on a completely different scale to most industrial minerals. Outputs of between 2000 and 6000 tonnes per annum would be typical for quarries producing only building stone. Another noticeable difference, when compared with the extraction of aggregate, lime, cement or brick raw materials, is that the stripping ratio can be apparently higher in building stone quarries than would normally be acceptable for these bulk minerals. A major difference between building stone and other quarries, is the extraction cost per tonne of stone. The producer of crushed rock aggregate may be looking for a production cost of £2–3 per tonne or even less, although this figure is very much dependent upon how the quarry costings are performed, whereas the production cost of building stone, before dressing, could be as high as £35 per tonne. These high production figures are offset by the fact that building stone can sell for £150 per tonne or more. A small amount of processing, for example trimming to standard sizes for roofing tiles, can increase the value to £1,000 per tonne, or even more if it is cut into high added-value products such as fireplaces. Table 3 is a comparison of the quarrying costs of crushed stone aggregate and building stone. The large amount contributed by items related to plant is a reflection of the inefficient use of mobile plant in low-capacity operations. The table also illustrates the labour intensive nature of building stone extraction. An output of 1000 tonnes of stone per man per year would be typical of a quarry which was producing only building stone; a crushed stone aggregate quarry may well expect 25 times this output for each employee.

As different parts of the geological succession may provide different products, quarry development must provide continuous access to all the various strata, resulting in quarries with very many low benches. Small and cheap, but versatile, mobile plant is therefore often required.

The geologist's role in building stone extraction

Introduction

Building stones, whether dimension stone or rubble walling, are as much natural resources as aggregates, cement raw materials or gypsum. The methods used to find and develop building stone resources are therefore identical to those used for other industrial minerals. The only difference between the exploration, reserves

TABLE 3. *Comparison of quarrying costs for crushed and building stone*

	Crushed stone quarry 500,000 t.p.a.		Building stone quarry 3,000 t.p.a.	
	Cost/tonne £	% of total cost	Cost/tonne £	% of total cost
Variable costs				
Materials incl. fuel	0.20	6	3.50	11
Explosives	0.20	6		
Royalties	0.40	13	2.30	7
Overburden	0.04	1		
Plant hire	0.02	1	0.50	2
Fixed costs				
Labour	0.50	16	12.70	40
Repair and maintenance	0.60	19	3.40	11
Power	0.18	6	0.85	3
Overheads	0.20	6	4.00	13
Depreciation	0.60	19	3.40	11
Sales and administration	0.18	6	0.70	2
Total	3.12		31.35	

The figures do not represent any particular quarrying operations and are intended to illustrate the differences between the two types of quarry. Blasting is not normally undertaken in building stone extraction, and overburden removal is frequently an integral part of winning the building material.

proving and quarry planning for building stone is the scale of the work.

Exploration

A literature search will precede any search for mineral resources in order to reduce the size of the target area. In the case of building stone this includes not only searching geological sources for stratigraphic and lithological data, but also studying historical and archaeological information. Maps are searched for names such as 'Quarr Lane' and aerial photographs for signs of ancient workings as well as geological features.

The historical and archaeological theme is continued into the reconnaissance stage. As stone was generally transported for only short distances, buildings and walls provide considerable 'outcrop' information. For example, stone houses which have been constructed with walls consisting of alternations of two thick courses followed by a thin one, are not the result of some architectural whim, but are a reflection of the local stratigraphy. Furthermore, there is no point in searching for beds of stone 300 mm thick, if the maximum course height in any of the existing buildings is only 150 mm; the early stonemasons made best use of what was available and if thicker beds had been present, they would have used them.

During the reconnaissance stage it is also important to remember that due to the low output from building stone quarries only a small area may be required, e.g. 1.5 hectares of land could easily supply stone for 25 years if the relevant strata was of the order of 5 metres thick. Moreover, due to the low key nature of the stone extraction, it may be possible to site a quarry in a location which would not be acceptable for bulk mineral production.

As with any natural resource, it is vital to determine the three-dimensional nature of the deposit by borehole drilling and pitting. However, the cost of a borehole exercise is considered an extremely expensive option for building stone quarries. Moreover, although providing good lithostratigraphic information with cores of up to 100 mm diameter giving samples for chemical and physical testing, the information obtained is very limited in the context of extracting large blocks. For instance, if a bed of stone one metre thick is extractable in two metre square blocks, it could be extremely valuable. On the other hand, if it can only be broken from a quarry face in irregular one metre blocks, its value will be reduced. Should the joint pattern be so close and irregular that only small pieces of the bed can be extracted, the stone may be virtually worthless for building purposes. Exploration and sampling using relatively large pits can therefore yield much more information, as the joint pattern and lateral variation in the stone can often be ascertained.

In view of the rate and method of working in a building stone quarry, it will not be necessary to identify every variation in the sub-surface at the exploration and planning stages. As long as adequate reserves have been identified and a flexible quarry is designed the occasional unexpected feature of the deposit, such as a patch of de-calcified limestone, can be accommodated during normal quarrying operations. However, care must be taken to ensure that sufficient is known about the variation in the quarry to enable continuous output of all the products to be maintained at all times. Modern building methods require that a building stone producer supplies not only the required quantity of stone of the correct quality, but also that he provides it at the right time to fit in with the construction schedule; the similarity with aggregates or other natural raw material based building materials is obvious here.

Calculation of quantities of building stone

As only stone which can be removed from the ground in 'lump' form is of value as a building material, very great care must be exercised when translating apparent volumes of stone in the ground into quantities of products suitable for sale. In addition to allowing for cavities, deduction must be made for the volume of material which will not be acceptable as building material due to its soft or broken nature. Careful measurement of borehole core and/or quarry faces is required for this calculation. Great care must be taken in assessing the waste factor, as this may not only affect the viability of the scheme, but also the quarry development plan. In particular, the rate of backfilling, which is likely to be dependent upon the quantity of waste generated, must not interrupt progress of the working faces. Some waste factors are quite remarkable, for example in quarries working Welsh slate or Norwegian larvikite the wastage can be in excess of 95%. A further factor in the economics of building stone production is dressing loss. For example, if due to the irregular nature of the ex-quarry stone, a block one metre thick and one metre square has to have 20 mm removed from all sides in order to produce a six-sided sawn block, the loss of stone will be 11%. If the block is very irregular and requires the removal of 80 mm from each side, the loss will be in excess of 40%. Although, in common with other industries, every effort is made to use any 'waste' material which is generated once the stone has left the quarry, as 'sawn paving' for example, this is not always possible. It is therefore necessary to work closely with the stonemasons and management when assessing the size of the reserve correctly.

The testing of building stones

Introduction

Appearance, strength and durability are the three attributes of a building stone which may require testing. It may also be necessary to investigate other properties of stone such as its chemistry and mineralogy if it is to be used in conjunction with other materials. Reactions between different building stones, limestone and sandstone or limestone and dolomite for example, are not uncommon (Schaffer 1932). The potential for reaction with mortars, particularly those which are based on Portland Cement, is great. Even the thermal properties and the stresses inherent in the constituent crystals may have to be investigated in certain materials. The 43 000 panels of Carrara Marble on the Amoco building in Chicago had to be replaced with granite when, due to bowing and/or dishing, they started falling off the 82-storey high building. The cause of the distortion is a matter of debate, although thermal effects resulting in permanent dislocations in the calcite crystals has been suggested.

The testing of slates is well established and is covered by two British Standards, BS 5642 for sills and copings while BS 680 is appropriate for roofing slates. Roofing slates are subjected to tests for water absorption, wetting and drying, and a sulphuric acid immersion test. Slates for sills and copings are only required to pass the wetting and drying test and the sulphuric acid immersion test.

Appearance

This is clearly an aesthetic matter which is not amenable to scientific testing. However, the geologist can play an important role in determining the amount of variation which may be encountered in the colour and texture of stone. Being a natural material, many building stones will vary in colour, even when obtained from a single bed. This variation must be quantified to avoid complaints. It must also be borne in mind that the type of finish applied to a building stone can radically alter its appearance. The ability of the stone to be sawn and possibly polished would also be valuable information when an assessment is made.

Strength

The strength of the stone is not quite as important as it may at first appear. In most modern buildings, although built with natural stone, the outer stone wall is in fact only a cladding consisting of thin sheets of stone, normally between 40 and 100 mm in thickness fixed to the concrete shell of the building with corrosion resistant metal fittings. Even where stone is used for the outer part of a cavity wall, as in house building, the load is essentially only that of the wall itself. If load-bearing properties are required, the majority of building stones have compressive strengths at least as great as bricks or concrete (Table 4). It should be noted that the compressive strength of many rocks, in particular sedimentary rocks, is dependent upon the direction in which the force is applied. Bedded or foliated rocks should be tested and laid in such a manner that the forces are normal to the lamination (see, for example, Leary 1983, 1986). Compressive strengths also tend to be reduced when the material is saturated with moisture. The American Standard Test Method for the compressive strength of natural building stone (ASTM C170) recognizes these variations and specifies both wet and dry tests, as well as testing the material both parallel and normal to the bedding.

TABLE 4. *Compressive strengths of building materials. (Rock strengths based on Knill 1978)*

Material	Compressive strength (MN/m^2)
Basalt, dolerite, some quartzites.	250
Fine-grained granite, diorite, basalt, well-cemented sandstone, quartzite, limestone.	160–250
Sandstone, limestone, medium and coarse-grained granite, granodiorite.	60–160
Porous sandstone, limestone, mudstone.	30–60
Tuff, chalk, very porous sandstone/siltstone.	<30
Fired clay bricks.	10–60
Concrete	typically 48

Durability

The Standard Definition of durability given in ASTM C119 is 'the measure of the ability of natural building stone to endure and to maintain its essential and distinctive characteristics of strength, resistance to decay and appearance, with relation to a specific manner, purpose and environment of use'. As the Standard notes, the concept of durability depends upon both the intended purpose and the conditions of use, including the length of time over which the stone will be expected to perform. These are variables which will clearly create difficulties in developing Standard Tests. At the present time British Standards do not contain any tests for the durability of building stones. However, the Building Research Establishment has developed a series of tests, related to crystallization, the saturation coefficient and the porosity, that is claimed to provide an indication of durability. In addition sandstones can be tested using the acid immersion test (Ross & Butlin 1989). Unfortunately the tests are open to criticism from geological, petrological and geochemical standpoints. On the basis of the crystallization test for limestone, a building stone can be classified as having a degree of durability, ranging from very good (Class A) to poor (Class F). The durability class will determine the suitability of the stone for use in different exposure zones in a building, for example whether it is suitable for paving, chimneys, copings or string courses (Leary 1983). However, most stonemasons and many geologists can provide examples of building stones which have been located for many hundreds of years in positions that, on the basis of the tests, should be completely unsuitable for that particular material.

Crystallization test

Used for limestones and some sandstones, this is based upon 19th century tests for frost susceptibility. It involves the determination of the loss of weight of a sample after it has undergone 15 cycles of alternately being soaked in a solution of sodium sulphate and then dried in a humid oven. The test samples are compared to known internal standards. The test is clearly designed as an accelerated test for the crystallization stress caused both by minerals such as gypsum, which may develop due to weathering, and the growth of ice during a period of frost. Whether or not the stresses caused by the growth of sodium sulphate crystals, or any other salt, can be used to emulate the growth of ice crystals does not appear to have been proved. The use of the test to simulate growth of gypsum or other mineral in the stone is even more questionable as it involves the addition of a mineral to the system, whereas in normal weathering any mineral growth is the result of chemical reaction between contaminants and the stone itself. As with any accelerated test, great care should be taken in interpreting the results of the crystallization test.

Saturation coefficient and porosity

Also originally designed as a test for frost susceptibility, the saturation coefficient is defined as the ratio of the volume of water which can be absorbed by a sample, to the total volume of pore space in that sample. High saturation coefficients are said to indicate poor durability. However, due to the relationship between capillarity and pore size, a highly porous and fragile stone can have the same coefficient as a strong solid stone with only one or two small pores. It is important therefore to consider the saturation coefficient and porosity together. Ross & Butlin (1989) advise that, even when comparing stones of similar porosities, the results of the saturation coefficient will not be totally reliable.

Richardson (1991) has suggested that by combining the saturation coefficient and porosity into a single value, termed Factor 'D', it is possible to determine the durability of all porous rocks, both limestones and sandstones. If this were true, it would indicate that the durability of a stone was entirely dependent upon the nature of the porosity. This is not the case as other factors, in particular the chemistry of the rock, play a major role in the breakdown of building stone (Jefferson 1992a). In the case of a potential limestone building stone of unknown durability, it is therefore recommended that the specialist uses the results of all the tests: crystallization, saturation coefficient and porosity, as a guide to the durability of the stone. It is not considered that the tests are appropriate for the development of a classification system.

In cases where an investigation involves a stone which has been used in the past for building purposes, much information on durability can be gained from a detailed study of existing buildings. Where the stone has not been used, it is possible to study the weathering of natural exposures. Finally in the author's experience the opinion of a good stonemason is often a better guide to the durability of a stone than any of the tests so far devised.

Acid immersion test

This is a pass/fail test used on sandstones to identify those stones likely to decay in an acidic atmosphere. The acid normally used is 20% (w/w) sulphuric acid. However, if a long life is required for the stone, 40% sulphuric acid may be used. Clearly the smallest quantity of carbonate will react violently in such a test. Many silicates which would be relatively stable under normal atmospheric conditions will also react with sulphuric acid. Whether or not such a destructive method of 'accelerated weathering' really indicates the durability of a stone under natural conditions is open to debate. The results of such tests should only be used in conjunction with a petrographic study, in order to interpret the results in a sensible manner.

Sampling

The classification of the building limestones in Leary (1983) appears to have been undertaken on the basis of four 40 mm cubes from each bed. Ross & Butlin (1989) suggest that, unless the stone is particularly variable, between four and six 40 mm cubes should be adequate. Sedman & Stanley (1990a,b,c), working with Doulting Stone, reviewed the crystallization test and suggested that eleven samples were required to provide a confidence level of 90% with a potential error of 5%. Ross & Massey (1990) dispute this result and suggest that the correct number of samples should have been seven. To those involved in bulk industrial minerals, a reproducible representative sample of 40 mm size material would be at least 4 tonnes in weight (Gy 1979). There is, however, a major difference between bulk mineral testing and stone durability testing. In the latter it is only the surface of the sample which is being assessed. All the tests involve the rock being impregnated by soaking, the fluid penetrating only a small distance into the stone. For example, tests on a sample of Ham Hill stone indicated that water penetrated the stone only to a depth of between 0.25 mm and 1 mm; less than 10% of the actual sample was therefore involved in the test.

Whereas the sampling of bulk minerals tests the bulk properties of the material, the durability of a stone is dependent upon the nature of what may be termed the individual 'units' which make up the bulk material. In the case of a sedimentary rock these would be the individual layers of relatively uniform sediment, or 'laminae', which are frequently visible on weathered surfaces. Each block tested may be considered to be a bulk sample made up of pieces of these laminae. It is suggested that sampling should initially be based on the thickness of the thinnest common laminar feature. Building stone beds are often selectively worked, the selection being made on the basis of appearance. Individual horizons, for example the Ancaster Weather Bed, tend to be geological units composed of a set of homogeneous features with the occasional anomalous lamination. The latter are easy to identify and should not be used in assessing the sampling procedure.

In Ham Hill stone, thin sandy laminae about 4 mm thick are the commonest thin horizon in blocks of the stone. If therefore the 9600 mm^2 of surface area of a 40 mm cube are considered to be composed of rectangular samples 4 mm by 4 mm, each cube would represent 600 samples. Using Gy's 'low-cost' version of his 'safety rule', that is $M_s = 60\,000\ d^3$ (Gy 1979), where M_s is the sample weight expressed in grams and d the maximum particle diameter in cm, the total number of particles required in the sample would be about 25 000. If, therefore, each cube represented 600 particles, the total number of test cubes required would be about 40. In the context of the Ham Hill stone, this would appear to be a reasonable sample size.

In the case of apparently uniform material, such as Ketton Stone, the laminae used for the calculation could be taken as the thinnest layer of oöids in point contact with each other, or if the oöids were 'floating' in the matrix, the typical diameter of one oöid plus their average distance apart. This figure could be as low as 1 mm, thereby suggesting that the choice of four to six cubes for a completely uniform material, as suggested by the Building Research Station, would be adequate.

It should be stressed that these suggestions as to sample size, are only intended as an initial guide and once test results are obtained, a more rigorous method, such as geostatistics, should be used to determine the correct sample size and sampling pattern.

Planning building stone extraction

Although a building stone quarry may be only a fraction of the size of an aggregate extraction operation, or any other bulk industrial mineral quarry, it is still necessary to produce detailed quarry development plans. These are not only required for planning purposes, but are essential for a quarry to develop in a manner that enables it to respond to changes in demand. To a large extent the market variations in bulk industrial minerals relate to quantity rather than quality. In many building stone operations a period of producing split walling stone could be followed by a large order for sawn block, which in turn might be followed by a mixture of rough block and dressed building stone. In common with all quarrying operations, these variations must be handled in such a manner that overlying stone does not have to be discarded in order to obtain material from lower beds and all the quarry faces must progress at more or less the same rate, if backfilling is not to sterilize unworked lower strata.

The advantages which building stone quarries have over other types of mineral extraction are as follows.

- They have low output and are often worked intermittently.
- In contrast to other industrial minerals, the aim is to extract the stone in pieces as large as possible. There is therefore no blasting or crushing, resulting in very low noise and dust levels.
- Stone transport does not normally involve the use of dump trucks, again minimizing noise and dust levels.
- It is normal for the primary dressing, sawing and guillotining, to be undertaken at the quarry so that only high added-value stone leaves the quarry. This again reduces vehicle movement to and from the quarry site, thereby minimizing the impact of the site on surrounding properties.

Lincoln Cathedral Stone

Building stone quarries can be located in areas where it would be impossible to site other extractive industries. Lincoln Cathedral quarry, for example, is situated only 1.5 km north of the cathedral, well within the city limits and in the middle of a residential area. Although available to the Dean and Chapter for well over 100 years, it was only worked on a small scale throughout this period. A survey carried out in 1984 had suggested that the Lincoln Stone reserves in the quarry were almost exhausted and for a time much of the cathedral restoration work was undertaken using imported French limestone. This material is not only expensive but is also more difficult to work and has the disadvantage of not weathering to the same colour and texture as Lincoln Stone. A project was therefore undertaken to determine whether or not reserves of Lincoln Stone were available at the quarry and, if the material did exist, its quantity and quality. A field survey and short drilling programme proved that a total of 9000 m^3 of dressed Lincoln Stone is available in the reserve (Jefferson 1992b). In order to work the dimension stone it will be necessary to remove 56 800 m^3 of topsoil, limestone and shale, but about 12 300 m^3 of this could be used for walling stone, the effective overall stripping ratio is about 2.1:1, but could be as high as 6.8:1 if no walling stone is produced.

Cathedral Quarry, Lincoln

In common with all quarries, the Cathedral Quarry has to fulfil the requirements of the Mineral Planning Authority and once the reserves had been proved it was necessary to obtain the relevant planning permission. Consent to work the quarry had been originally granted in 1948 by means of an Interim Development Order. However, this did not cover the whole of the site and the permission was a combination of a new Consent and a validated IDO. The final quarrying scheme is illustrated in Fig. 1, which also indicates the proximity of the quarry to the housing. In order to obtain the planning permission, it had been necessary to prove 'need'. As with many building stone quarries this is not too difficult, as in the present 'green' climate, the use of original materials in existing buildings and 'sympathetic' stone in new construction is encouraged. Although there was little environmental concern expressed in the original IDO, it has always been accepted that the quarry development should be carried out to the highest modern standards. To this end a scheme had been prepared which involved the construction of landscape bunds down both sides of the extraction area, tree planting and on-going backfilling and restoration of worked-out areas. Access to Cathedral Quarry is by means of a track from the main road and a small amount of landscaping was proposed to help improve the visual aspect of the approach.

Apart from the existing hydraulic loader, much of the plant to be used in the quarry will be hired as and when required. An hydraulic excavator would be the preferred machine for the removal of the overburden and overlying strata but it is conceivable that the harder limestone bands may need to be broken using a bulldozer equipped with ripper. In order to minimize wastage, the Lincoln Stone itself will be worked using plugs and feathers, hydraulic rock splitters or possibly

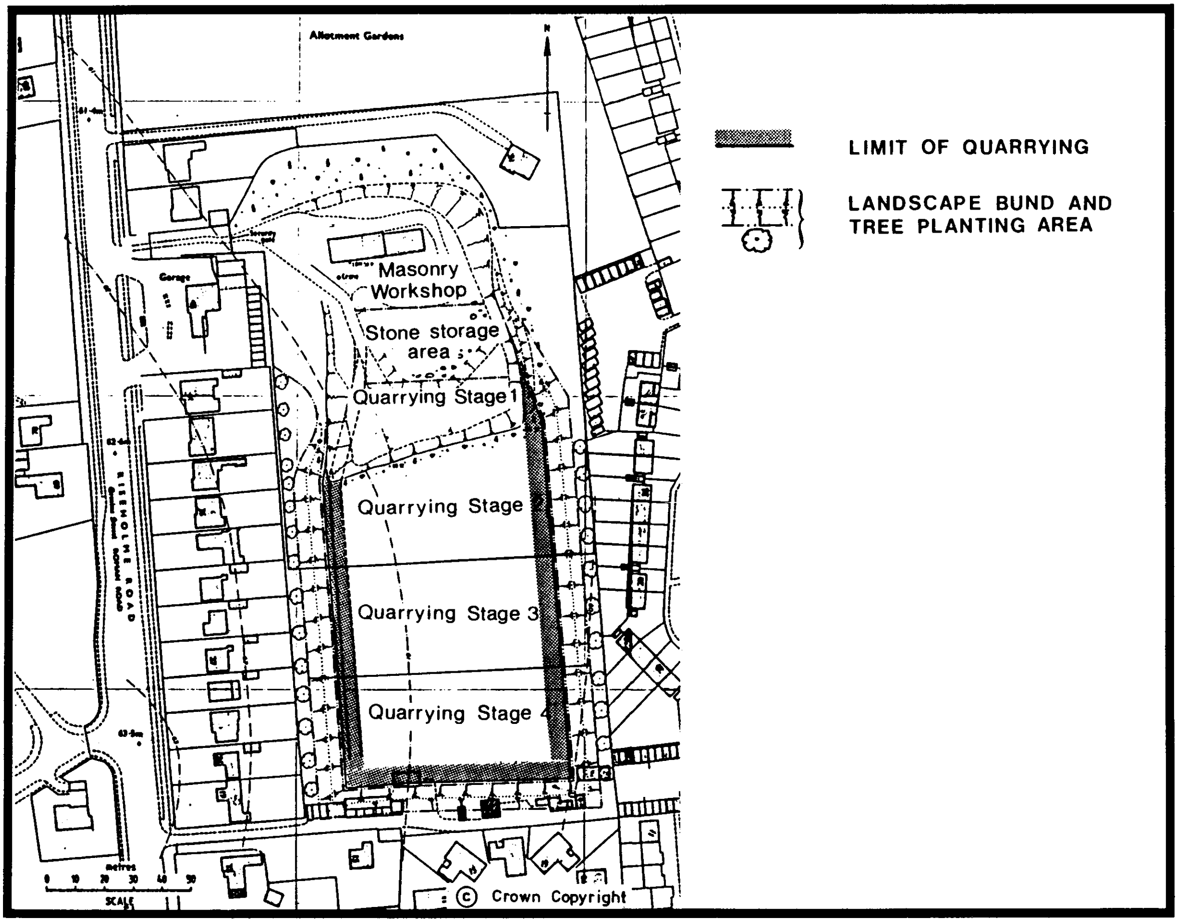

FIG. 1. Although situated in a residential area, the low-key nature of building stone extraction enables Lincoln Cathedral quarry to be worked on a continuous basis. Only during the four stages of overburden removal will mobile plant be operating close to the houses.

a non-explosive demolition agent. The joint pattern in the rock allows blocks of up to two metres to be extracted from the building stone horizon. As there will be no crushing, conveyor or vehicle transport on site, no dust will be generated. The equipment used for the extraction of the building stone, compressor, hand drill, plugs and feathers and tractor/loader, have sound power levels of between about 85 dB(A) and 115 dB(A). It is calculated that, due to distance, the depth of the quarry and the landscaping bunds, the sound at the nearest property will have been attenuated to a level well below the 55 dB $L_{\mathrm{Aeq,1h}}$ recommended in MPG11 for daytime working. Obviously there will be short periods of time when the overburden is being removed, perhaps for a period of up to two weeks every three years, when there will be a certain amount of noise generated by the excavator and lorries required for this work. For very short periods of time some of this plant will be working at ground level, building the landscape bunds. However, such noise will be of very limited duration and, in common with all the quarry working, will be restricted to normal daytime working hours.

Even at a maximum theoretical output from the quarry of two cubic metres of Lincoln Stone and 6 tonnes of walling stone each day, no more than four return lorry movements per day are envisaged.

Waste stone is tipped along a broad front parallel to the working face, so that the quarry is progressively backfilled to the level of the existing workshop and stock-yard, which are well below the level of the surrounding properties. This will not only ensure that cranes or other equipment will not extend above the top of the quarry, but will also assist in confining any

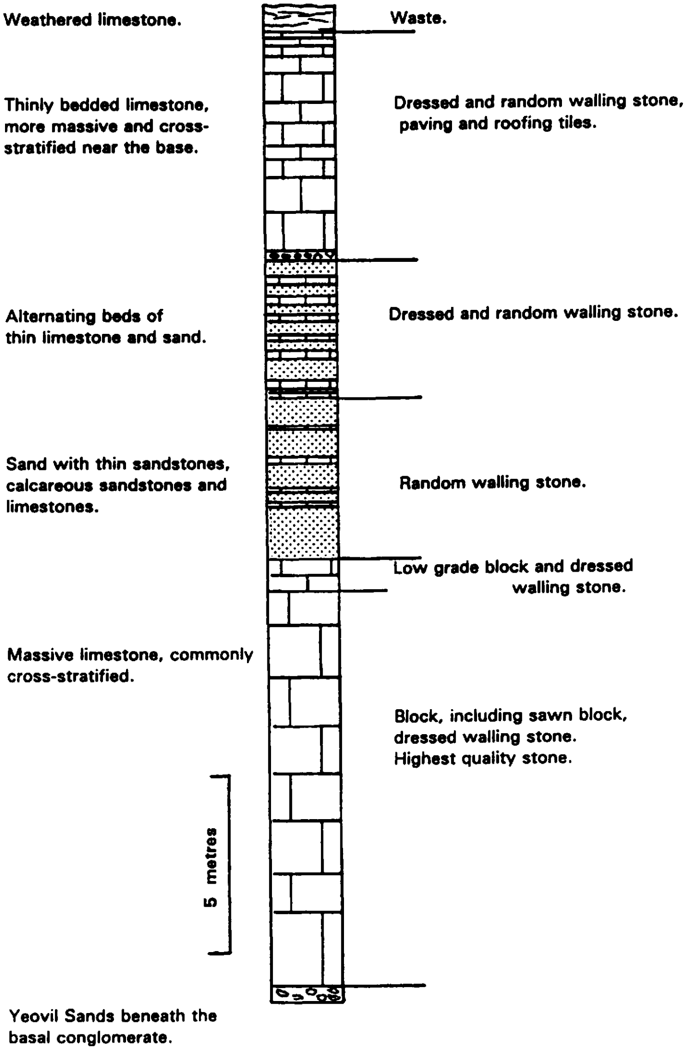

FIG. 2. The geological sequence in Ham Hill quarry, together with the products obtained from the different horizons. The dimension stone horizon is at the base of the sequence, all the strata above the massive limestone being classified as overburden. However, carefully planned overburden stripping enables a large number of products to be obtained from the material which would normally be considered as waste.

noise generated by plant to within the quarry area. The backfilled area will be restored to an acceptable surface and level of cultivation using the topsoil removed during overburden stripping.

As the final restored ground surface will be lower than the surrounding area, the shallow quarry faces round the edge of the restored ground will be backfilled to produce slopes of about 1 in 4. However, as geological exposure is limited in this area, it may be possible to retain part of the face as a Regionally Important Geological Site. Discussions with English Nature and local geological groups towards the end of the life of the reserve will indicate whether or not such exposures should be left and the best way of achieving this. As the stone extraction will continue into the next century, the final after-use of the site has not had to be determined.

In common with all planning applications, that for the Lincoln Cathedral quarry involved consultation with the various statutory bodies such as the electricity, water, gas and sewerage authorities, as well as with archaeologists and English Nature. Although discussions with the archaeologists indicated that it was not considered necessary to investigate the site before quarry development took place, the City of Lincoln Archaeological unit requested that they should be notified prior to any overburden removal, in order to arrange that representatives could be on site when this is undertaken. Discussion with English Nature indicated that they considered that the site has no national conservation value. However, the Lincolnshire Trust for Nature Conservation have classified part of the site as being of local interest on the basis of the limestone grassland and geological exposures; this was taken into account when planning the development of the site.

Ham Hill, Yeovil

Although at Lincoln, the archaeological and conservation aspects of quarrying were of minor importance, this was not the case at Ham Hill stone quarry, situated 7 km west of Yeovil in Somerset. This stone has been worked as a building stone since Roman times, its use being continuous from about the fourteenth century and of particular importance in the nineteenth century. It has not only been used for building purposes in Somerset and Dorset but also in other parts of the country including Belfast and London. The quarry, which currently produces a range of building products from ashlar to walling stone, is working a large lenticular mass of detrital shelly limestone up to about 28 metres thick, which is located at the top of the Upper Lias Yeovil Sands. The geological succession is given in Fig. 2 together with the details of the type of building stone obtained from the different horizons.

The quarry has a number of special problems. Firstly Hamdon Hill upon which the quarry and all the remaining reserves are situated is an important Iron Age hillfort and is a Scheduled Monument. Secondly most of the quarry is part of a geological Site of Special Scientific Interest and finally, the area is classified by Somerset County Council as a Special Landscape Area. The land immediately adjacent to the quarry on the western side, although in the same ownership as the quarry, is a Country Park administered by South Somerset District Council.

There had originally been no medium or long-term plan for quarry development and restoration. As a result stone extraction almost ceased due to a lack of space into which to tip the unusable overburden. This short-term problem was alleviated by obtaining planning consent for a new access road into the quarry which would utilize a quantity of waste stone as it passed through an old abandoned quarry. This has provided sufficient space for the disposal of the waste rock, thereby allowing continued working of the existing consented faces. This initial stage in the planning of the quarry was not intended merely as a short-term measure to solve the immediate problems of waste disposal, but constituted the first part of long-term development plan for the site.

In order to develop the quarry in a manner which would enable the best use to be made of the unique resource of Ham Hill stone, it was necessry to prepare a detailed development plan and obtain planning permission for a major extension to the site. As with any other quarry, the planning application had to satisfy certain requirements for such a development. Need, planning policy considerations, access and transport, control of pollution, removal of good quality farmland and so on, were dealt with in the same manner as any other application. Clearly being a unique stone, it is not particularly difficult to prove need. The Site of Special Scientific Interest has actually been improved by planning an access to some of the old quarry faces as part of the access road development. Although the existing geological sections upon which the SSSI is based will eventually be quarried away, the restoration has been designed so as to create new equivalent exposures before the present ones are physically removed. In order to remove the visual impact of the quarry from the Country Park, a landscaped area between the boundary of the Park and the quarry has been provided. In addition, all the access roads in the quarry area will be re-sited below the rim of the quarry. This will involve the use of the large amount of quarry waste which is generated in the extraction process, to re-shape the interior of the worked-out part of the quarry in order to accommodate the roads to each of the benches.

One potentially major problem was the fact that the whole area is a Scheduled Monument. Outline development plans were originally prepared which involved working stone to the west of the present quarry before the main eastward extension was started. After discussions with English Heritage, a scheme for an archaeological survey of the site was agreed and independent consultants commissioned to undertake the work. Unfortunately Iron Age pits were located to the west of the quarry. This resulted in a re-design of the development, the western part of the reserve being abandoned and additional land to the east being incorporated into the scheme in order to retain a 25 year life for the reserve. It has also been agreed that archaeological consultants will be present when overburden is removed, in order to undertake archaeological recording and collection should this be necessary. Building stone quarries have a considerable advantage over bulk mineral workings when in areas of archaeological interest. The quarry faces move relatively slowly, only small areas of overburden removal are undertaken at any time and the stripping can be carried out well in advance of the stone extraction. In the case of Ham Hill quarry, the face has been designed in such a way that it would be possible to split it into two sections, should it be necessary to leave part of it unworked for a period of time whilst archaeological work was carried out on the surface.

The geologist's role in stone restoration and conservation

Restoration of stone buildings

The most obvious task undertaken by the geologist in the fields of restoration and conservation, is the identification of stone which has been used for construction or for ornamental work. This is often relatively simple, for example Shap granite and larvikite are easily identifiable. An oöidal limestone can be a much greater problem. For example the Lincolnshire Limestone extends from the Humber to Kettering, and although a number of depositional facies can be recognized along the 150 km of the outcrop, similar facies occur at a number of different locations. This results in beds of very similar limestone occurring at various places along the outcrop. Although fairly distinctive beds do sometimes occur, Ketton Stone for example is one which can normally be recognized, the search for a probable source of a stone often involves factors other than geology.

A stone tracing exercise was recently undertaken in connection with the conservation studies being undertaken on the Romanesque frieze at Lincoln Cathedral. Information on the source of the stone from which it was carved would not only assist the conservationists in carrying out tests on a similar material, rather than on the frieze itself, but would also provide information to those historians and archaeologists interested in the carvings. In order to determine the most likely source of the Jurassic limestone from which the frieze was carved, a survey of the whole of the Lincolnshire Limestone outcrop was undertaken. The most likely source was eventually located near Ancaster, 28 km south of Lincoln down the old Roman road known as Ermine Street. Identification of the actual quarry from which particular stones were obtained is considered to be almost impossible on purely geological grounds, although it may be feasible if documentary evidence is available.

Having identified the source of a particular building stone, care must be taken not to assume that the use of such stone indicates that quarrying was actually taking place concurrently with the construction or restoration work. The winning and dressing of stone has never been an easy task, especially before the introduction of mechanical aids. The use of secondhand stone, although not universal, was extremely common in the past (Parsons 1990). Even in some of our greatest cathedrals it is not unusual to find that some of the stone used in the fabric has been taken from older buildings; stone from Roman buildings is not uncommon.

Since all stone has its own particular colour, texture and response to weathering, it is always preferable to undertake restoration work with the same material as that which is being replaced. Having identified the source of the original stone, the geologist may be asked to locate a new source of the same material. This is often difficult. For example, almost all the exposures of the Craigleith Sandstone, which was extensively used as a building stone in Edinburgh, have been lost due to the growth of the city. An alternative source must therefore be sought. A stone having similar appearance, workability and response to weathering as the Craigleith Stone would probably have been formed in similar sedimentary conditions. The Craigleith Sandstone occurs in the Dinantian Calciferous Sandstone Measures, and was probably laid down in a marginal marine-fluviatile environment. A similar type of environment appears to have existed in the lower part of the Westphalian A of the Lancashire coalfield. It is not surprising therefore that the Milnrow Sandstone from the lower part of Westphalian, which is worked on Kerridge Hill north of Macclesfield, has been used in Edinburgh as a replacement for the local stone.

The use of an alternative stone to match one already in a building is not a modern concept. It was only recently realized that the shafts in the wall arcade of the north choir aisle at Lincoln Cathedral, were made of Alwalton 'Marble' from Peterborough, rather than Purbeck 'Marble' from Dorset, the material from which all the other shafts in the building are made. Whether the choice of the alternative stone was made for economic reasons, or whether it was due to the unavailability of the Purbeck stone, is not known.

Conservation of stone

Many methods have been used in an attempt to conserve stone. These range from lime washes or the application of inorganic materials such as silicates and metal hydroxides, to complex organic compounds such as ethyl silicate, perfluoropolyethers and epoxy resins. Unfortunately the majority of the work which has been undertaken appears to treat stone as some form of homogeneous material, often porous, which may react with acid rain. The petrology of the stone is frequently ignored, as are the mechanisms involved in the breakdown of the rock. Zádor (1985), for example, considers that the requirements for a material which will protect a weathered stone from further decay are that:

- it will seal the stone against moisture,
- there should be no reaction with the stone,
- there should be 'petrophysical' similarity with the

stone, for example the vapour diffusion and thermal properties should be similar to those in the stone,
- the material should not alter the colour of the stone.

There appears to be an assumption that if undue moisture is kept out of the rock, weathering will cease. The fact that self-sustaining reactions may be occurring within the fabric of the stone does not appear to have been given much attention.

TABLE 5. *Causes of stone decay*

Chemical	Atmospheric gases and liquids, both natural and man-made. Soluble salts, both those occurring naturally in the rock and those created by human activity such as spreading salt on roads.
Physical	Frost action. Thermal strsses. Attrition by pedestrians and vehicles, together with wind-blown solid particles.
Biological	Bacteria, Algae, Fungi, Lichens. Disruption by higher plants such as ivy.

The causes of decay in stone are summarized in Table 5. Although this list refers to the destruction of man-made objects, it is identical to the causes of natural weathering, resulting in clay and soil formation. With or without acid rain, the gradual erosion of all buildings built of natural stone or man-made materials is a completely natural process. In attempting to stop, or even slow down the weathering, the conservator is actually attempting to combat the forces which shaped the planet. It would appear logical therefore to suggest that geologists should be major contributors to the multi-disciplinary teams researching methods of conserving the world's cultural heritage. Such input has already started. Work in Glasgow (Bluck & Porter 1991a) has not only identified some of the mineralogical changes which take place when sandstone weathers, but has also shown how current cleaning methods can actually contribute to these changes. As a result of the studies it has been possible to provide practical advice on preferred methods of cleaning sandstone buildings (Bluck & Porter 1991b).

Unfortunately very little is known about mineralogical, geochemical and biogeochemical changes which take place when stone weathers. For example, it is accepted that the formation of calcium sulphate is a major contributor to the disruption of many building stones. It is commonly assumed that the reaction of acid rain with carbonate in the rock is the source of this sulphate. It is possible that some of the sulphur is intrinsic to the stone (Jefferson 1993); stable isotope geochemical analysis ($^{34}S/^{32}S$) is required to investigate this possibility. If some of the sulphur is released from the rock itself, is the release purely chemical or are sulphur bacteria involved in the oxidation of sulphides? An interesting insight into the reactions which may be occurring within natural building materials was recently provided by Burrows (1990). Working on samples of stone from Lincoln Cathedral he discovered that sulphate-rich areas were found in the micritic cortices of the oöids near to the weathered surfaces (Fig. 3a). Deeper into the stone, this feature was not observed.

Burrows interpreted this phenomenon as a result of the precipitation of sulphates, derived from the weathering of the stone, due to the evaporation of moisture from the surface. However, samples of Jurassic oöidal limestone from a British Petroleum borehole near Lincoln contain oöids, the cortices of which are packed with crystals of iron sulphide (Fig. 3b). An alternative interpretation of Burrows' data therefore presents itself, that of extremely small particles of sulphide, possibly related to original algal matter in the cortex, being oxidized, either chemically or bacteriologically, in the weathering zone of the stone. The presence of sulphides in the limestone would not be an unexpected feature. It has been suspected for some time that the 'blue-hearted' limestone, normally found beneath the zone of weathering in the Lincolnshire Limestone, contained pyrite. Burrows' work on 'blue' stone from the Cathedral Quarry has confirmed the presence of this sulphide, although he could not detect the mineral in the buff coloured Lincoln Stone.

Clearly a considerable amount of work is required in order to understand the nature of reactions which are damaging our buildings, statuary and other works of art. Although much valuable work has already been undertaken, and continues to be carried out, by conservators and others involved in the protection and restoration of stone, the geological community has a considerable amount of information and expertise which has yet to be brought to bear on the problem.

Conclusions

For 10 000 years, stone for building has been an important industrial mineral. In Britain, most competent rocks have been used for construction purposes. Present-day stone extraction differs from other industrial minerals in two major aspects: firstly, the scale of the quarries; secondly, the fact that the aim is to remove stone from the ground in large pieces. As a result, building stone quarries can often be located in areas where mineral extraction would normally be completely unacceptable. As in any extractive industry, if the geologist is to assess the reserves and value of a building stone deposit, he must be knowledgable not only about the raw materials, but also the methods and economics of extraction and processing, as well as the markets for the final product.

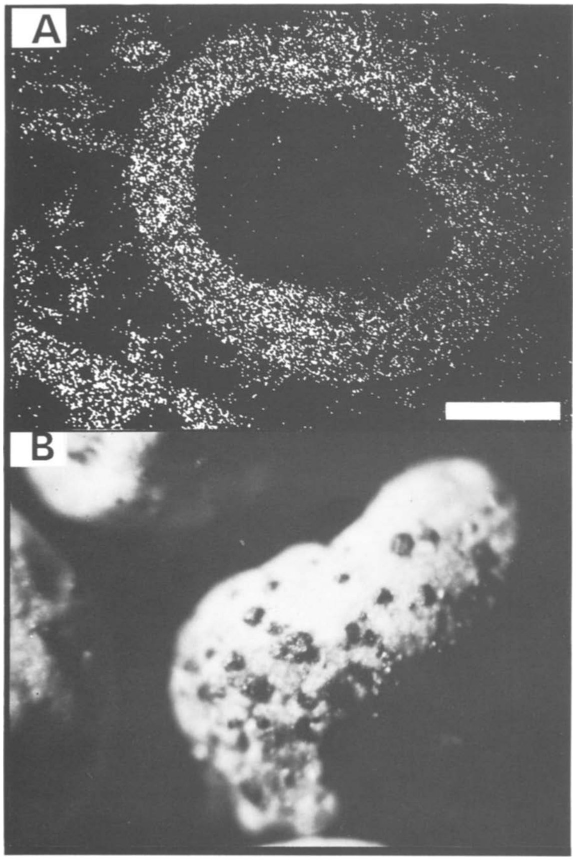

FIG. 3 (A) Sulphur dot map of an oöid near the surface of a block of weathered Jurassic limestone from Lincoln Cathedral. The dots mark the sites of sulphate concentrations. The scale bar is 100 µm in length. From Burrows 1990. (B). Sulphide crystals in the cortex of a Jurassic oöid. Sample from about 60 metres below ground surface. The oöid is about 1 mm long and 0.5 mm wide.

In contrast to most industrial minerals, the existing methods of testing building stone are not very satisfactory and the geologist must be aware of their limitations. However, until the processes which affect the durability of stone are more fully understood, there is little likelihood of reliable testing methods being developed. Not only is information on the weathering of stone required for the development of adequate assessment procedures for new building stone resources, but it is also important for a full understanding of the deterioration of existing stone buildings and sculpture. If this research into stone degradation is to be carried out in such a manner that successful conservation strategies can be developed, the geological sciences must play an important role in the work, whether it is in the fields of geochemistry, biogeochemistry or mineralogy.

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