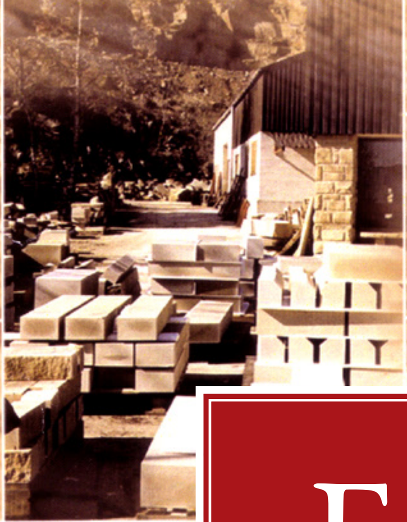
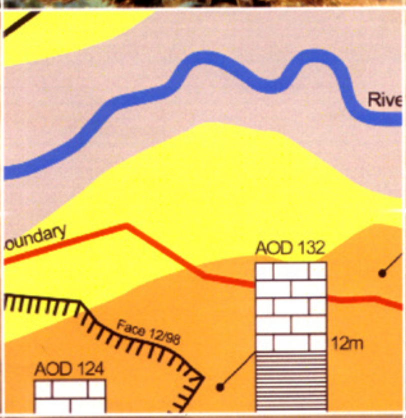


England's Heritage in Stone

Proceedings of a Conference

Tempest Anderson Hall, York
15 - 17 March, 2005

English Stone Forum



A PUBLICATION OF THE ENGLISH STONE FORUM

Limestone Petrography and durability in English Jurassic Freestones

TIM J. PALMER

Porous limestones that are used as building stones weather and decay by a variety of processes that are water-driven. These processes operate most severely where water is held tightly within the fabric of a stone, particularly in areas of high local microporosity. In contrast, connected macroporosity within a stone permits ready drying and mitigates water-related decay processes. The slogan 'macroporosity good: microporosity bad' suggests itself. Well-regarded Jurassic freestones from four localities (Bath; Portland; the Lincolnshire Limestone belt; Dundry) are compared, and their durability performances are related through their porosity characteristics to their petrography.

Durability (resistance to weathering) is arguably the most important attribute that a commercial building stone used for external work must display. Much of the reputation of a stone among masons and architects stands or falls on durability considerations such as how long it lasts in the built environment, or how well it retains sharp detailing. Stones that failed the test of time in the past, such as the Headington Limestone extensively employed in Oxford during the eighteenth century (Arkell 1947), left blighted streetscapes and huge expense to later generations. Modern fears of similar costly errors and resulting litigation may turn architects away from natural materials, because they view their non-standard variability as being a potential source of trouble. It is not surprising that, when stone started to be studied from a scientific point of view, pointers to weathering behaviour were some of the first characteristics to be sought. The subject is now quite well understood, but the communication between geologists and stone technologists on the one hand, and architects and restorers (who receive very little exposure to the properties of stone during their training) on the other, has often been poor. Greater appreciation among specifiers about exactly what can and what cannot be expected of a natural stone that is employed in a variety of exposure situations, may lead to wider use of this beautiful and versatile material. Limestones of Jurassic age have provided materials for both walling and dressings in both polite and vernacular architecture from before the Norman Conquest up to the present day. Many buildings built of Jurassic limestone over the past thousand years are still standing and much original stonework may still be examined for its lasting qualities. The best stone is hardly altered, even in the most exposed situations (Fig. 1). On

Fig. 1. *Detail of excellently preserved Barnack Stone mediaeval ashlar in Bury St. Edmunds, showing minimal weathering decay over several centuries.*

the opposing hand, other varieties of stone have performed badly, and yet other types were avoided completely in building. The petrographic differences between these different varieties clearly have a lesson to teach us. An even clearer lesson, tantamount to a controlled experiment, is provided by certain stone types that are petrologically heterogeneous within single stone blocks. Adjacent laminae or local patches of contrasting lithology may weather in different ways, pointing to criteria that tend to enhance or to compromise the durability characteristics of the material in question. The experiences and opinions of masons about which stones perform well under certain conditions are an invaluable additional source of information, although these often do not enter the written record. The many practitioners in stone who have shared their opinions over many years are gratefully acknowledged.

SCOPE OF STUDY

This account considers some attributes of limestones that have been found in earlier studies and in historical experience to relate to weathering behaviour. It then discusses the geological features that determine the character and influence the weathering behaviour in four widely-used and well-regarded Jurassic limestones, three of which are still in production today. All are freestones used widely for ashlar and dressings; some are (or were) also used locally for vernacular walling. Petrologically they are rather different in character, indicating that there is no single petrographic criterion that can be used to predict a good building stone. However, an understanding of the range of characters that lead to good or poor durability performance can be gained from these four stone types, and the inferences can be applied to other comparable stones, leading to reasonable predictions about their performance in use.

The first type is Bath Stone (Bathonian, Middle Jurassic; Great Oolite Group) from the city of Bath itself and from the vicinity of nearby towns such as Corsham, Wiltshire. The character and weathering style of these widely-used stones are shown more generally by the range of other honey-coloured limestones of Bathonian age that extend north and north-eastwards along the eastern Cotswold Hills towards the East Midlands. Second is the Upper Jurassic (Portlandian) Portland Stone, exemplified by Portland Whit Bed, which, although it outcrops over a very localised area on the Isle of Portland (Dorset), has developed through its successful use in London and many other major cities, often in polluted environments, a reputation as Britain's premier dimension limestone. Third are the Upper Lincolnshire Limestone stones of Middle Jurassic (Bajocian) age, best exemplified today by Clipsham and Ancaster Stones, but including Weldon, Barnack, Ketton and a number of lesser-known limestones. The fourth, also Bajocian (Upper Inferior Oolite) is Dundry Stone from south of Bristol, extensively used in mediaeval times in southwest England, and also shipped as dressings in some quantity to Wales and Ireland (Waterman 1970). Dundry Stone was produced again from the mid-nineteenth to the early twentieth centuries.

POROSITY CONSIDERATIONS

Distribution of porosity in Jurassic building limestones

Most Jurassic limestones, particularly those used as building stones, are geologically sub-mature. That is, they show moderately high levels of porosity, and have not reached the same diagenetic grades (by addition of diagenetic cement or by calcite recrystallisation) as older rocks, such as the Car-

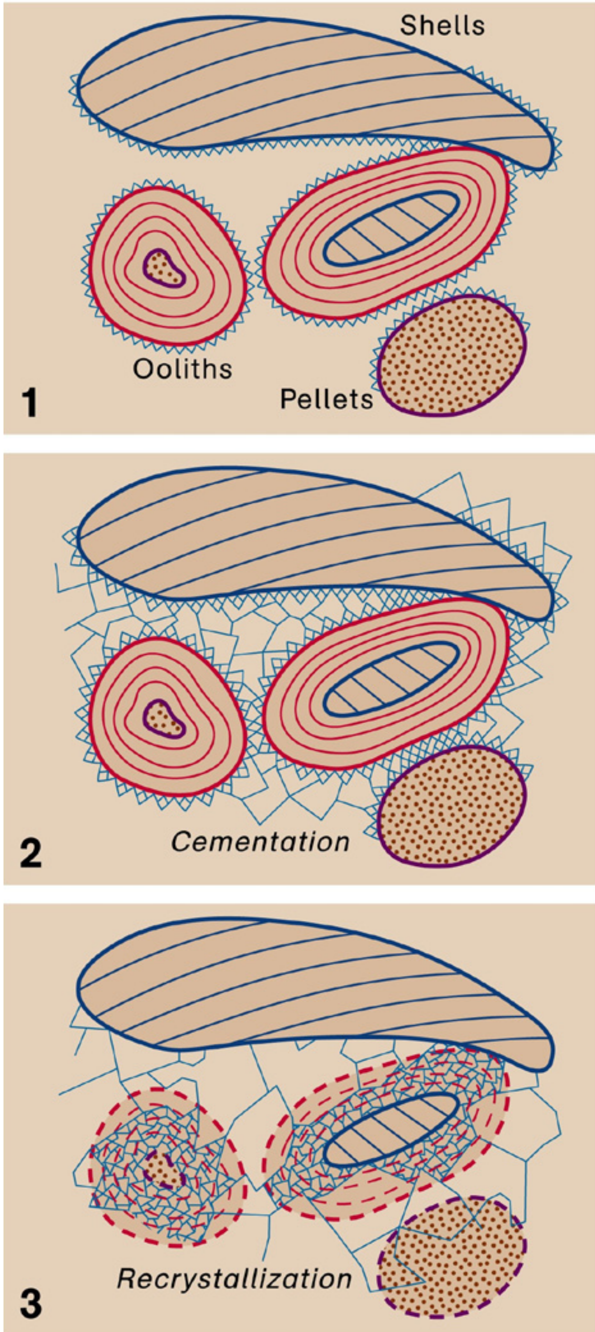


Fig. 2. *Changing character of calcite cement in primary porosity between original grains as a limestone progresses from sub-mature to mature. 1, 2, cement growth starts as small crystals growing out from grain surfaces, gradually infilling the primary porosity; a zone of weakness runs around the edge of each grain where the cement coat is composed of small crystals. 3, in mature limestones, cement crystals may recrystallise to form a denser fabric of fewer, larger crystals that cut across grain boundaries and result in a stronger fabric.*

boniferous Limestone, that have had a longer and deeper burial history. This is particularly true of the freestones, some of which (e.g., Ketton Stone from the Lincolnshire Limestone) have virtually no calcite cement within their primary pore space. These stones tend to break around the constituent grains, showing that, even where a natural calcite cement is present, the bond with the underlying grain is weak. Limestones older than the Jurassic, from the Lower Carboniferous for example, characteristically have larger cement crystals which often permeate the grains and cross their boundaries, thus reducing lines of weakness along grain boundaries and causing fracture surfaces to cut across grains and surrounding crystalline matrix alike (Fig. 2).

Durability and microporosity in limestones; general remarks Within and between different types of sub-mature limestones, pore-spaces vary in size from less than 1µm to several mm across. Pore-space of less than 5µm is conventionally referred to as microporosity, and is the single factor that best correlates with poor durability in limestone freestones. This relationship was first appreciated in continental Europe (e.g. Hirschwald 1908) but did not receive much attention in Britain until the studies of the Building Research Group in the inter-war years (e.g., Schaffer 1932; Edmonds & Schaffer 1932). Today, on the other hand, the standard tests that are performed on building stones across Europe in order to classify them into suitability for different uses (based on harshness of the weathering environment), are either direct weathering simulations (freeze-thaw; salt crystallisation test) or tests that measure, directly or indirectly, the sizes and interconnectedness of pores (Porosity; Saturation Coefficient; Critical Moisture Content; Mercury penetration; various capillarity coefficients); see discussions and references in Leary (1983) and Honeybourne (1982). However, the approach that led to recognition of the importance of microporosity in stone durability was largely empirical, and, except within the oil industry, little consideration has been given to the geological origins of pore distributions in deposition and diagenesis. Using techniques such as resin impregnation, combined with staining, acid etching, light and SEM microscopy, pore characteristics can be adduced and a picture can be built up of a finite number of different styles of porosity distribution in limestone building stones. Correlations between certain pore styles (together with other petrographic features) and known weathering behaviour of familiar limestones can be recognised. This leads to recognition of 'good' and 'bad' types of pore space in limestones, and hence to the possibility of some predictability of a stone's expected performance from careful petrographic study.

Distribution of types of pore-space within limestones Several distinct pore-space habits, with different locations within the stone, sizes, degrees of interconnectedness, and geological origins are recognised. The most significant in the British Jurassic stones are given below.

1. Macropores between grains, representing the original spaces between the individual particles of carbonate sediment. Most Jurassic building stones are grainstones, in which the grains are typically between 0.1mm and 2mm in diameter. They accumulated in shallow seas where the winnowing by currents kept them free of mud-sized particles, so the intergranular pores are large and open (typically up to several hundred µm in diameter). When these survive later diagenesis, open or partially occluded by diagenetic cement (Fig. 3a, Fig. 9), they form the principal interconnected pathways through which water can travel in and out of the stone.
2. Pores within original calcite biological skeletons. Some animal and plant groups had a skeleton that shows a primary porous microstructure where the living soft tissue was located, e.g., bryozoans, echinoderms, some brachiopods, coralline algae, and foraminiferans. Sizes typically range from µm to tens of µm; they are often filled by the later calcite cement.
3. Pores formed within the original carbonate grains by excavating microborers, particularly concentrated just below grain surfaces (the micrite envelope; e.g.

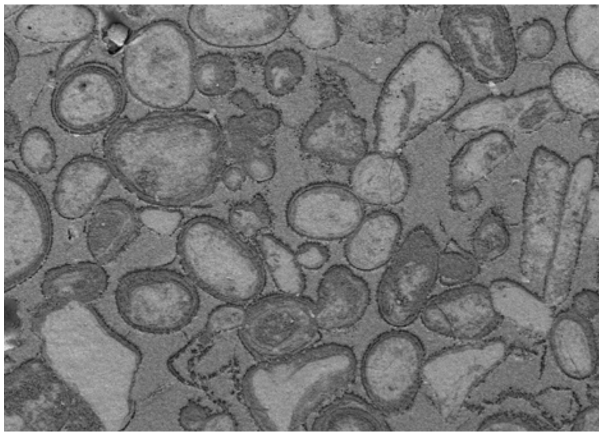


Fig. 3 *Macroporosity (>5µm) (a, b) and, microporosity (<5µm) (c, d) in Jurassic limestone freestones shown in Scanning Electron Micrographs.* **Fig. 3a** *Weldon Stone with thin layer of calcite cement coating surface of grains, and large volumes of well-connected pore-space (filled with resin in this sample) remaining.*

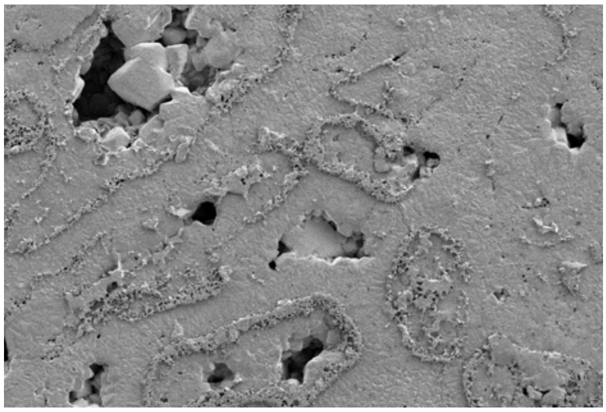


Fig. 3b *Primary pore-space and secondary pore-space (after dissolution of aragonite shell-fragments) nearly filled by calcite cement crystals, but a small amount of pore-space in the centre of the voids remaining unfilled.*

Bathurst, 1976). Typically such pores are tunnels from 1-50 µm in diameter, though often they are partly occluded by micrite (microcrystalline calcite) or diagenetic iron compounds. Porosity types 1-3 together represent the primary macroporosity of the rock.

4. Dissolution macropores (= secondary porosity), usually representing sites that were occupied by shells or skeletal fragments that have dissolved away. In Jurassic limestones, the dissolved shells were nearly always aragonite molluscs and corals (Fig. 3b), though in some stones biogenic silica and high magnesium calcite have also been dissolved out to provide secondary porosity of this sort.
5. Sheet pores or larger areas of pore space between cement crystals, representing incomplete filling of type 1-4 macropores by diagenetic calcite cement. Primary macropores or dissolution macropores are commonly infilled by calcite cement crystals, which nucleated on the surfaces of the grains that formed the pore walls, and grew outwards to fill the pores. Fillings may be incomplete, more so in the case of secondary pores that dissolved relatively late in the rock's diagenetic history, leaving a limited amount of time for cement growth.

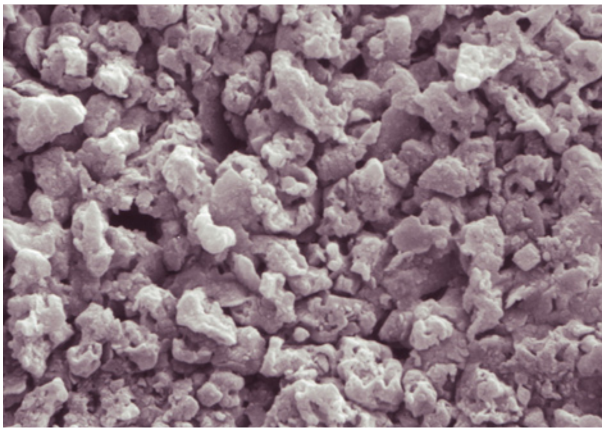


Fig. 3c *Microporosity within lime-mud matrix that fills intergranular pore-space in a bed of Bath Stone that is rejected for building purposes (see Fig. 8 for thin section).*

Even in cases where complete infilling appears to have occurred, thin sheet-like pores less than a µm across lie between adjacent cement crystals. At the surfaces of stones that have been tooled or cut, there is a tendency for such pores to open up slightly in response to the physical disturbance.

6. Micropores within the micrite matrix that occupies the space between the larger grains (Fig. 3c). Lime sediments that accumulated on quieter sea-floors that were not subject to a lot of current winnowing have a high proportion of mud-sized particles, both of calcium carbonate (micrite) and clay mineral composition. In micrographs of limestones, this appears as a dense material that surrounds or fills the space between the larger grains. The small particle sizes of this predominantly micritic material means that its own internal pore sizes are also small, typically 1-5 µm or less. Limestones of this general structure are very common

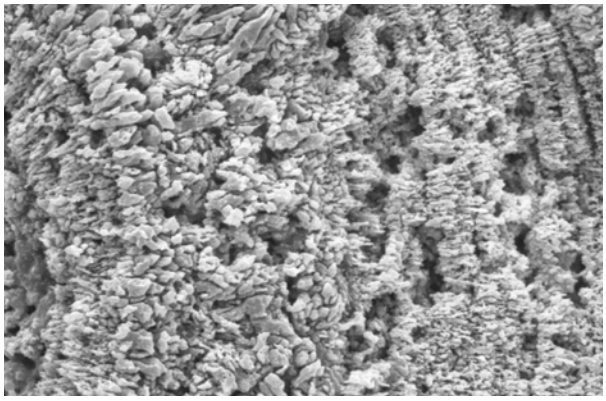


Fig. 3d *Microporosity within the cortex of a single oolith, Coombe Down Stone, Bath.*

in the Jurassic, but they tend to have poor weathering characteristics and are therefore not of great architectural value. Many early accounts refer to their having a 'mealy' texture (e.g., Howe 1910), generally considered a warning sign. They are more usually met as walling stone or rubble fill.

7. Micropores in mud laminations. Thin microporous seams rich in clay particles or micrite, parallel to the natural bed of the rock, may represent brief quiet intervals with little winnowing activity on the sea floor as the sediments were accumulating. They may also, particularly in older rocks, represent horizons along which carbonate particles have dissolved out as a result of pressure solution after the rock pile was buried, thus concentrating the insoluble clays (Bathurst 1987). Thin micropore-rich laminations typically weather back in exposed situations and exaggerate the millimetre to centimetre scale of sedimentary lamination in many limestones.
8. Micropores within pellets. Many limestones contain abundant faecal pellets of invertebrates that swallowed the mud of the sea-floor in order to extract fine food particles. These pellets are effectively made of the same micrite as in 6 above, and have similar internal microporosity.
9. Micropores within ooliths. Most Jurassic limestone freestones are oolitic, particularly those of Bath, Portland, and some of the Lincs Limestone stones. Individual ooliths can be highly microporous (Fig. 3d), containing up to 50% pore space or more (Sellwood & Beckett 1991).
10. Zones of minute pores along cleavages or isolated minute pores at dislocations within individual calcite cement crystals. Cleavage planes in spar crystals tend to open slightly where they have been mechanically disturbed adjacent to cut or tooled surfaces, thus producing a thin skin of bruised stone at the surface where water penetration may take place more readily.

Thus the pore spaces in limestones vary in size, shape, and location. They also vary in their connectivity, though the whole pore system may be regarded as open and interconnected over a geological, as opposed to an historical, time period.

Measurement of porosity characteristics

Two features of pore systems are readily measured and have been the subject of close study from stone technologists who first appreciated back in the nineteenth century their involvement in the weathering of stone. These are the total porosity (usually referred to as just the porosity) and the microporosity.

1. **Porosity.** In effect, this is the total percentage volume of a stone that is unfilled with mineral components. In the dry state, the porosity is air-filled. In the ground or under wet conditions of use, water may occupy the pore spaces. In weathered stone, minerals that result from weathering processes grow there. Porosity is measured in stone-testing laboratories by comparing the weights of samples of known volume in a saturated and a dry condition, so the efficiency with which the stone can be experimentally completely wetted (all the pores water filled) or dried (all water extracted from the pores) has a bearing on the calculated figure. Whilst drying can be achieved readily, using a combination of evacuation and heat, complete wetting (once a stone sample has been allowed to lose its natural ground water) is much more difficult because of the problems of displacing all the air from tortuous minute pore spaces deep within a sample. In particular, simple immersion of a dry sample under water is a most ineffective way of filling the pore spaces with water, because the trapped air is held in by the capillary force of the ingressing water, rather than displaced.
2. **Microporosity.** This is the proportion of the interconnected porosity that is made up of voids less than a certain size across, usually 5 micrometres. It is measured in testing systems that work in one of two ways: either as the force needed to suck water out of a wet sample (small pores exert a stronger capillary holding force against the experimental sucking force), or else as the force exerted to drive mercury into the pores of a dry sample (more small pores require a greater blowing force).

Of the various types of pore space that are listed above, some are predominantly made up of macropores, some of micropores, and some of a mixture. In particular, Types 1, 2, and 4 tend to be macroporous; in contrast, 6-10 are dominated by micropores. Types 3 and 5 range across the sizes, depending on detailed circumstances.

Porosity and microporosity together have been empirically shown to interact in a way that correlates with stone weathering behaviour. A property of a stone that is routinely measured by stone technologists is the Saturation Coefficient — a proxy for microporosity (see Honeybourne 1982). Saturation Coefficient is a measure of the proportion of the volume of a stone that is filled by capillary seepage when a dry sample of standard size (usually a 50 mm cube) is laid in a shallow dish of water for a fixed time. The connected microporosity exerts a strong capillary attraction for water and holds onto it tightly, like a sponge. A classic study at the Building Research Establishment (Honeybourne & Harris 1958) is little known beyond specialists.

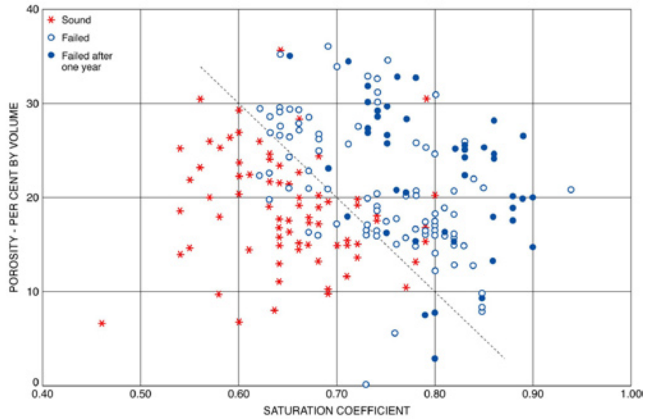


Fig. 4 *Relationship between porosity, saturation coefficient, and durability in an exposed situation. Each point represents a limestone sample that was exposed to English weather for a number of years and monitored regularly for progress of decay. See text for further details. Redrawn from Honeybourne and Harris (1958).*

Samples of different limestones of known porosity and Saturation Coefficient were left exposed to the weather (including frosts) for a number of years and the time taken for them to decay or otherwise was noted. The results of the original study are redrawn in Fig. 4. They indicate that there is not a simple tendency for weathering susceptibility to increase as porosity increases, but that such a tendency does become marked as the proportion of small pores within the overall porosity increases.

Microporosity and decay The mechanism by which increasing microporosity exerts a deleterious effect is through increased water retention in the smaller pore spaces (capillary retention). The principal ways in which stone decays or loses its external shape in the weathering environment are affected by the presence of water within the pore system. These mechanisms have been widely discussed (Bell 1993, provides a summary), and include the following.

1. Mechanical weakening in the vicinity of many small interstitial pores between many small micrite crystals. Capillary water lubricates frictional contacts between adjacent crystals (the source of much of the compressive strength of a stone) and greatly reduces the mechanical strength of a wet stone, and hence resistance to mechanical abrasion, wind erosion, etc. This is probably also the reason why stone straight from the ground (containing 'quarry sap' or ground water within the smallest pores) is softer and easier to work than stone that has been allowed to dry. Subsequent wetting does not fully penetrate the microporosity and the easy workability, once lost, is not readily restored.
2. Biological erosion by organisms such as lichens and unicellular algae and cyanobacteria. These favour sites where water is held for longer within microporosity, and the displacive effects of their cell growth and rhizoid penetration are greater in mechanically weaker areas (see 1 above).
3. Dissolution of calcite from the surfaces of the constit-

uent crystals. Microporosity provides increased surface area and is further correlated with minute crystals with higher surface energy and thus increased solubility.
4. As 3 above, but pore waters are acidic and react with the calcite to give rise to salts in solution (HCO3-, NO2-, NO3-, SO3-, SO42-). This is the decay mechanism from acid rain in air polluted by combustion of fossil fuels. Limestones with significant microcrystalline pyrite in their structure give rise to further sulphur-based pore acids as they decay.
5. Displacive crystal growth of salts derived from the processes outlined in 4 above, particularly of gypsum, as drying occurs on external surfaces or within the stone structure. Growing crystals exert a mechanical force that jacks apart the pore walls, which are closely adjacent and weakly attached in regions of increased microporosity and abundant small crystals.
6. Displacive crystal growth with mechanical disruption as in 5 above, but by salts derived from external sources such as sea-spray and salt-laden rain around coastlines, or salting of roads and pavements. Water containing dissolved NaCl is also more aggressive towards calcium carbonate.
7. Displacive growth by ice as water occupying pore space freezes and expands.

The inability of limestones with large amounts of microporosity to withstand these destructive effects can be inferred from the large number of different limestone types that have a lot of micrite in them (and thus lots of Type 6 microporosity), which have traditionally been rejected for building external structures. Chalk is an obvious example. Only early-cemented units of coarse, winnowed sediment from within the Chalk have been used historically (under the name of Clunch), and even they have a poor reputation for durability. The lagoonal Bathonian limestones across Oxfordshire (White Limestone; Palmer 1979) and Northamptonshire (Blisworth Limestone; Sutherland, 2003) offer other examples, only yielding reasonably durable stone from locally-developed, coarser and better-cemented beds. In other stones, local micrite-rich patches or layers occur within a background lithology that is coarser or better cemented. These examples offer a direct experimental test of the weathering response of the micrite-rich as opposed to the micrite-poor parts of the stone under identical weathering environments. Headington Stone in Oxford often shows cavernous weathering where micrite-filled burrows have weathered out faster than the background grainstone (Fig. 5a). In the same city, Milton Stone was used during the nineteenth and early twentieth centuries as an alternative to Taynton Stone, but it contains micrite-rich laminations that decay back differentially (Fig. 5b). In some parts of the country, use of microporous limestone has been a necessity because more suitable alternatives were not available, and weathering decay is a familiar problem. The Blue Lias, used in a belt from Somerset up to Warwickshire, illustrates this.

Fig. 5a *Differential weathering of limestones that have local patches of micrite with high microporosity in them. 5a, micrite-rich burrows in (probable) Headington Stone weathering out to give cavernous texture. 5b, micrite-rich laminae in Milton Stone.*

Fig. 5b

Macroporosity and drying In contrast, substantial macroporosity, such as is seen in stones that have very little cement filling primary intergranular or extensive biomouldic porespace, seems to have no deleterious consequences, or even to be beneficial. Such stones can dry out much more quickly after wetting. Also, their porosity does not fill completely through capillary draw under normal circumstances, leaving a network of space within the stone into which any freezing water that is held by adjacent microporous grains can expand.

In summary, the net effect is that the tendency of a limestone to take up and hold onto water as a consequence of the capillary forces exerted by its different porosity characteristics, is the principal correlate of its weathering behaviour. Microporosity is bad because it is very water-retentive and correlates with poor durability, whereas macroporosity is good because it readily allows water to pass out of the stone by evaporation and does not have the same deleterious effects. The petrological differences between the four main stone types chosen for further description in this paper have bestowed different porosity characteristics on them. These are discussed below with relation to their reputation and their durability performance.

PETROLOGY OF FOUR DIFFERENT TYPES OF JURASSIC BUILDING STONE

Bath Stone The Bathonian (Upper Middle Jurassic) lime-

Fig. 6 *Typical texture of Bath Stone seen in thin-section. Ooliths and shell fragments touch at point contacts; intergranular and secondary macroporosity are completely filled by calcite spar. This example is Box Ground Stone, which has well-developed layers of shell debris.*

stones of the Bath region provide some of the most famous of the classic building stones of England. The limestone outcrop (Great Oolite Group) extends from south of Bradford on Avon northwards, through Bath itself and eastwards to the Corsham region, into the Cotswolds. The essential character of the stone remains constant across the whole region, such that the generic name of Bath Stone has been applied throughout the belt of oolitic grainstones from Westwood and Limpley Stoke in the south, even as far northward as Farmington, near Northleach — a distance of some 70 km.

Most of the Bath stones are grainstones, made up overwhelmingly of ooliths with a smaller proportion of comminuted shell fragments touching each other at point contacts to provide a grain-supported fabric that originally supported macropores (type 1 above) in between (Fig. 6). The ooliths range from about 0.2 to 0.8 mm in diameter. The shell fragments are larger, a few mm across at maximum, and are derived from a variety of calcite and aragonite invertebrate groups. The calcite ones (epifaunal bivalves, bryozoans, echinoderms, brachiopods, serpulids, rare calcisponges and foraminiferans) are preserved with their original microstructures and mineralogy, whereas aragonite fragments (coral, gastropods, some bivalves, many unattributable grains) have been replaced by calcite during diagenesis, following dissolution to give type 4 porosity at an early stage in the history of the rock.

Many of the Bath stones show evidence of the original depositional bedding, and the smaller ooliths are distributed in different laminae (millimetres to a few centimetres in thickness) from the larger bioclastic fragments, from which they were sorted by the currents on the sea-bed. The lamination is frequently oblique to the horizontal, and locally large-scale examples of this cross bedding can be studied for sedimentary character and dip direction to give an idea of the circumstances under which the whole oolite sand-body was deposited. The work of Sellwood et al. (1989) and Lewis (1987) indicate that, in the Bath region, a shallow shelf deepened toward the south. The geography of the shelf area was ultimately controlled by east-west trending faults at depth. Shoals of oolite sand built out across the shelf into the deeper water, and cross-bedding directions are consistently southward. Probably the ooliths grew on large-scale sand-waves along the leading edges of the southward-prograding sand units, as is seen in the active areas of oolith production on the Great Bahama Bank today. The abundance of shell debris suggests transient areas of more stable sea floor, possibly in somewhat deeper water between the crests of the sand waves, where a benthic fauna was able to flourish. Although many of the fossils are broken and rounded by abrasion, some of the fauna is better-preserved and cannot have come from far away. In the deeper water to the south of the advancing front of the oolite zone, muddier, shelly and oncolitic carbonates accumulated. They received periodic influxes of oolite as the banks of oolitic sand slowly encroached. In time, these became buried beneath the oolites so that the whole sedimentary package is one that coarsens upwards from deeper, calmer to shallower, higher-energy facies. Lewis (1987) has discussed the further sub-environments that were likely to have been present, caused by processes such as tidal channelling, but the sedimentological detail of the region is not sufficiently well known to permit mapping of these features. North of the zone of highest energy where the ooliths were actively growing, it is likely that a rich biota was established and bioturbation was active in the shallow water of the oolite shoal top. Intermittent high-energy episodes in which the sediment was winnowed and redeposited with internal sedimentary structure (cross lamination) probably alternated with longer periods during which biological processes dominated and internal lamination became churned up by an infauna. Thus, locally in the stone the sedimentary lamination is not readily apparent.

Twice during the deposition of the Bathonian oolites of the Bath region, rising sea-level flooded the oolite shoals, pushing back the regions of active oolite production to the north and allowing deeper water packstones and wackestones to accumulate on the drowned top of the earlier oolite sands. Each time, oolite production subsequently pushed back southwards to lay down the upper part of another shallowing-upward cycle. The oolite shoals (and hence the productive freestone units) of the two lower cycles constitute successively the Coombe Down Oolite and the Bath Oolite (Green & Donovan 1969), and the topmost cycle has been called the Corsham Oolite by Lewis (1987).

Bath Stone essentially consists of three components which are clearly seen under a hand-lens or in any thin section: ooliths, shell fragments, and the original primary porosity which, together with the secondary porosity within dissolved aragonite bioclasts, is now more or less completely filled with a cement of well-formed drusy calcite crystals. Of the two grain types, ooliths are by far the most important volumetrically, and the bioclastic fragments typically form cm-scale (or less) laminations (referred to as bars by masons). A few local varieties of stone are bioclast-dominated (deposited as shell gravels) and are referred to as ragstones. The proportion of bioclasts to ooliths is greater in the Coombe Down Oolite than in the Bath Oolite (Green & Donovan 1969).

Fig. 7 *Weathered surface of a spar-prominent stone in which the microporous ooliths have weathered out to leave the shell fragments and the encasing calcite cement conspicuously exposed.*

The essential weathering characteristics of Bath Stone are exemplified by Box Ground Stone from the Coombe Down Oolite of Corsham, which was widely distributed throughout England and Wales for external use during the nineteenth and early twentieth centuries. The shell bars stand proud on the weathering face whereas the oolitic layers tend to weather back, because the individual ooliths are soft and crumbly. Magnified, the weathered surface shows resistant shell fragments and calcite cement, pocked with quarter to half mm sized holes from which the individual ooliths have decayed and fallen away (Figs 7 and 10a). The principal strength and resistance lies in the low-porosity crystalline calcite cement (spar) that forms the petrographic matrix of the rock, filling primary porosity and the dissolved aragonite bioclasts. Thus the stone is described as being spar prominent (Hudson & Sutherland 1990). In addition, the calcite shell fragments are mechanically strong, and any primary cavities within them (e.g., in bryozoans and echinoderms) are also filled with spar cement.

Because the cement and the calcite grains form a strong rigid structure that is continuous, the performance of the stone is not compromised by the fact that the individual ooliths are weak and crumbly. They effectively play very little part in the mechanical strength of Bath Stone and in other spar prominent stones. Their crumbly and poorly aggregated character is clearly seen under the SEM, but to what extent this is a diagenetic or an original feature is not clear. Modern ooliths are made of aragonite, and consist of concentric laminations of felted aragonite needles with a high proportion of organic material embedded within the cortex. Jurassic ooliths were largely made of calcite, but are similarly likely to have been organic rich. The frequency with which they are iron-rich, reflecting early reducing bacterial decay of an organic substrate that gave rise to microcrystalline pyrite, supports this inference. Under the SEM, the ooliths typically consist of anhedral crystallites, typically long and wide, arranged in layers with their long axes radial. There is a considerable microporosity between them, particularly in concentric zones between the calcite layers (Fig. 3d). Probably this microporosity (type 9 in the scheme above) represents the sites of original organic matter which has been enhanced to a greater or lesser degree by later diagenetic dissolution. Some individual ooliths also show slightly larger cavities that were caused by microbial boring on the sea floor (type 3 above). Undoubtedly it is a combination of these two types of microporosity that is responsible for the high overall porosity characteristics of Bath Stone and for the typically high Saturation Coefficient (for example, 23.8 per cent and 0.85 per cent respectively in Monks Park Stone; (http://projects.bre.co.uk/ConDiv/stonelist/monkspark.html). Water can travel between adjacent microporous ooliths at point contacts particularly where, as is common, there is slight overcompaction. In addition, there is evidence that certain varieties of Bath Stone have microporous micrite bridges linking neighbouring grains (Figs 3c and 8), thus promoting capillary take-up of water, and that these varieties are less durable.

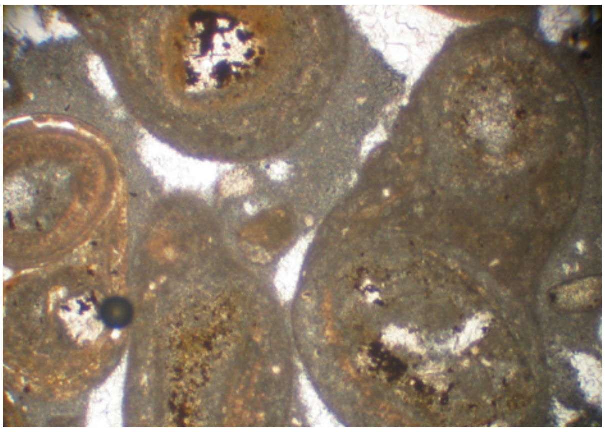


Fig. 8 *Microporous micrite bridges linking the ooliths in a variety of Bath Stone that is not used for masonry (see Fig. 3c for close-up detail).*

The sparry calcite cement that forms the durable component of Bath Stone is made up of a three-dimensional jigsaw of intergrowing and tightly packed calcite crystals. In the geological history of the stone when it was buried beneath younger rocks, these grew outwards from the surfaces of the grains into the primary porosity, being supplied by a continuing supply of calcium and carbonate ions in solution in circulating groundwater. Calcite is not very soluble in water and thousands of volumes of pore water need to pass through the pores and give up their dissolved calcite in order to produce one volume of calcite spar cement. Therefore the circulation must have been efficient and long-lasting. It would have slowed as the pores became choked with growing calcite crystals, but eventually there was no further space for the crystals to grow into, and the natural cementation process was essentially complete.

The Bath Stone type of petrographic structure, with weathering-resistant cement and bioclasts but with crumbling ooliths, is the most common lithology seen in the Middle Jurassic building limestones of southern England. Further north-eastwards along the Great Oolite outcrop are many limestones that accumulated in quieter water conditions (e.g., Palmer 1979; Sutherland 2003) and which contain much higher proportions of mud, pellets, and microporosity of Types 6–8. These may be used locally for walling (where their susceptibility to decay is often appar-

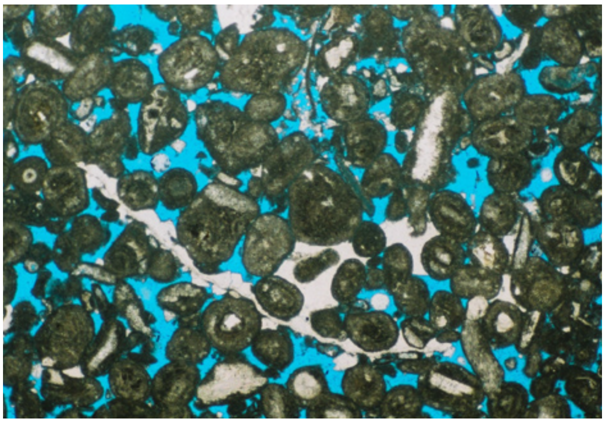


Fig. 9 *Fabric of Portland Whit bed seen in thin-section. Much connected macroporosity remains (filled with blue resin in this picture). The (white) cement crystals are large overgrowths on echinoderms (below centre) or isolated prisms (seem as squares in section) growing on the sides of the ooliths.*

ent) but were never considered suitable as freestones. Locally, grainstones appear to have been deposited episodically with quieter intervening periods during which thin micrite layers settled. The latter decay back more rapidly from the dressed surface of the stone. Milton Stone appears to be an example (Fig. 5b).

Portland Stone Portland Stone, although also an oolitic limestone, is very different in appearance and sedimentary character from the limestones of the Bath region. Its peerless reputation among English freestones has grown from more than 300 years of use, often in the most polluted city areas. Its colour is paler than Bath Stone because the early geological history of the parent Portland sediment took place above sea level under meteoric conditions (the Portland Stone beds on Portland are immediately overlain by the basal Purbeck palaeosol). As a result, the bacterial effects of the sulphate reduction zone that operate in sea water to give rise to strongly coloured iron minerals did not take place as they did in most other English Middle Jurassic limestones (Palmer 2004). Additionally, 'bars' of broken shell debris are absent from most varieties of the stone because the sediment was less pervasively winnowed by wave and tide action whilst it accumulated on the shallow sea floor. The fine shelly debris that was present was distributed throughout the oolitic matrix of the stone by the mixing action of burrowing organisms. Primary sedimentary structures are often inconspicuous, but the major beds seem to have been deposited as decimetre to metre scale tabular cross-bedded units progressing southwards into deeper water. Following depositional events, the sea-bed became colonised by a mollusc-dominated epifauna that now defines the surfaces of the main stone beds (Fürsich et al. 1992). In all varieties of the stone (but particularly noticeable in the Roach bed), aragonite shells are dissolved out and represented by biomoulds, but calcite bioclasts are well preserved. These act as sites for the nucleation of calcite cement crystals, particularly as syntaxial overgrowths on echinoderm and prismatic-shelled bivalve debris. Large scattered rhombohedral cement crystals also grew on oolith surfaces (Fig. 9), and smaller ones (meniscus cement) are sometimes seen to be concentrated at slightly overcompacted grain contacts. Large volumes of the primary porosity remain unfilled, a significant difference when compared with the Bath-type stones. It probably reflects the limited amount of cement that was available for cementation purposes, being derived only from dissolution of the aragonite component of the parent sediment. The Portland limestone sequence and the overlying Lower Purbeck are stratigraphically sandwiched between impervious sediments that, after burial, excluded potentially cementing ground waters derived from further afield.

The dominant grains in Portland Stone are small to medium-sized, somewhat micritised ooliths nucleated on peloids or bioclasts. Some show a cortical microstructure, like Bath stone, of concentric rings of minute anhedral crystallites separated by high microporosity, and thus again are likely to be mechanically weak and to hold on tightly to decay-enhancing water. However, nearly all the ooliths show some or extensive traces of boring on the sea-floor by microendoliths, to leave galleries that were filled early in diagenesis by calcite cement microspar (Palmer 2004, fig. 5). This intricate system of convoluted and interconnecting spar-filled microborings has much lower microporosity than the surrounding unaltered oolith cortices, and gives strength to the affected grains. In addition, the substantial interconnected intergranular macroporosity offers open

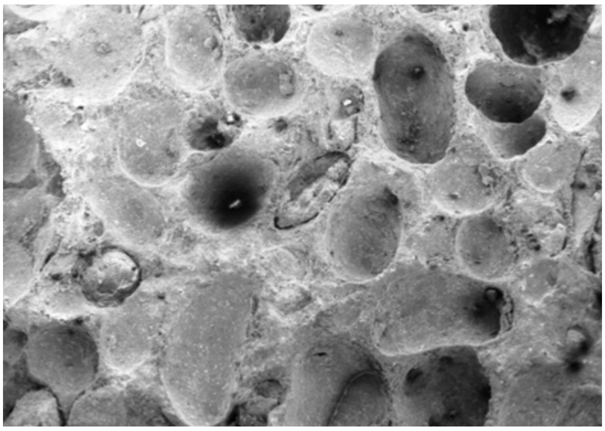


Fig. 10a *Low magnification scanning electron micrographs comparing (a) spar-prominent Bath Stone with (b) grain-prominent Portland Stone.*

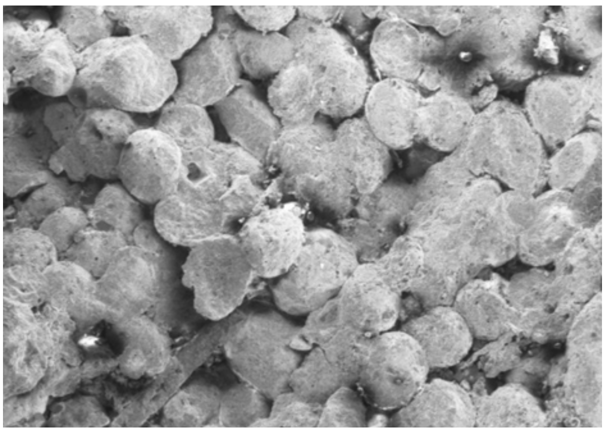


Fig. 10b

pathways by which the stone may dry out quickly after wetting (Fig. 9). Such large open pores have long been recognised as enhancing durability (Watson 1911). These two substantial differences between Portland and Bath stones, one affecting the grains and the other affecting the intergranular porosity, provide the likely explanation as to why Portland is the more durable in the weathering environment.

The Bajocian freestones of the Upper Lincolnshire Limestone The main freestones from Northants, Rutland, and Lincs have varied in relative importance as building stones since the Middle Ages. They include the limestones of Clipsham, Ancaster, Barnack, Weldon, Edith Weston, and Ketton. They are all from the Upper Lincolnshire (Lincs) Limestone and represent well-winnowed, high-energy oolitic and shelly grainstones that tend to pinch and swell along the outcrop, locally cutting down in channels into the Lower Lincolnshire Limestone on which

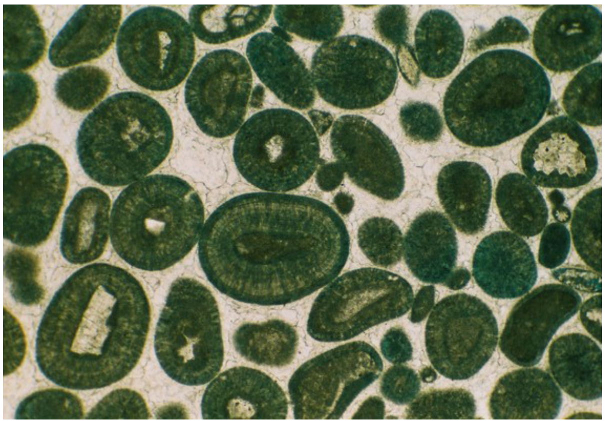


Fig. 11 *Reduction of microporosity within ooliths in many Lincs Limestone and Inferior Oolite freestones by development of a fabric of radial calcite crystals in the oolith cortices.*

they sit unconformably. Different beds of stone at a single locality often have different lithological characters, and are identified by different names. Lincs limestones that have gained a particularly high reputation for durability include: the shelly and oolitic Barnack stone and the shelly Barnack Rag (of which examples reclaimed from demolished monasteries in the sixteenth century are still in good condition in Cambridge colleges – Purcell 1966); the similar but somewhat finer-grained Weldon Stone; and Clipsham Stone which started to be used outside its source area in the nineteenth century because it was found to perform well in sulphur-polluted atmospheres.

The Lincolnshire stones are somewhat variable in petrographic character, but at their best display a combination of some of the better-weathering features of both Bath and Portland Stones. The best of them, exemplified by Barnack Stone, show a mixture of ooliths and broken shell material equally prominent on weathered faces of the stone (Fig. 1). Others show a dominance of one of these grain types over the other. Ketton, and to a lesser extent, Weldon (which also has characteristic thin layers of small oysters) are dominated by ooliths: Clipsham and Ancaster Weatherbed are largely made up of bioclastic fragments with subordinate intraclasts.

Fig. 12a *Effects of large calcite cement crystals growing across grain boundaries. a, the edges of formerly aragonite shell fragments are usually represented by microporous lines of weakness where lines of small seed crystals run along the junction of the primary and the secondary (biomouldic) porosity (the micrite envelope). b, if some crushing took place after the aragonite dissolution but before the start of spar growth, then the micrite envelopes became broken and discontinuous. This allowed a stronger fabric of larger calcite crystals to cross through the gaps from primary to secondary porosity and hence interrupt the weak zone that run along the edges of the grains. This fabric is often seen in the shellier Lincs Limestone and Inferior Oolite freestones.*

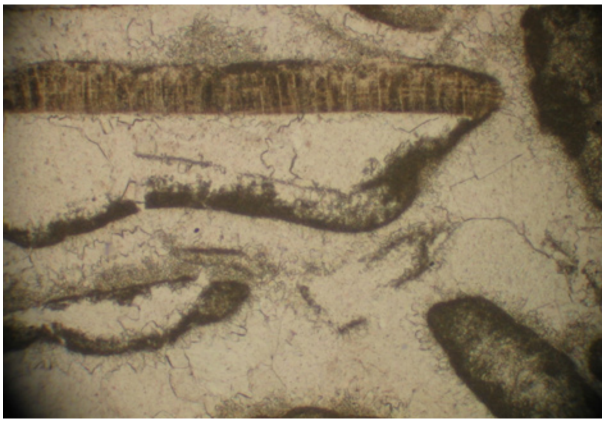


Fig. 12b

The ooliths in the oolitic varieties of Lincs Limestone show, like Portland, evidence of internal cementation that gives them strength. However, whereas in Portland this intracementation is located within microborings, in stones such as Ketton and Weldon it arises from a recrystallisation (probably during burial diagenesis) of the original calcitic cortical crystallites so that they lengthen radially and fatten concentrically to abut their neighbours, and in so doing they occlude significant volumes of the original microporosity (Fig. 11). Thus they developed an internal strength that is never seen in the ooliths of Bath Stone, and hence, unlike the spar-prominent oolitic limestones of that region, those from the Lincs Limestone are grain prominent. Pure oolitic varieties such as Ketton Stone show slight overcompaction between adjacent ooliths and this confers sufficient strength to the stone that no further calcite cement is necessary. The primary pore space is left completely open, thus facilitating rapid drying and excellent durability. The oolitic Weldon stone has more interstitial calcite cement, but still retains a high primary porosity (Fig. 3a). In contrast, the

Fig. 13 *Close-up of freshly cut surface of Dundry Stone, which is non-oolitic and largely composed of bioclasts. The small holes represent primary and secondary (biomouldic) macroporosity that are incompletely filled by calcite cement.*

shellier stones tend to have calcite-filled primary porosities, and the calcite cement also fills the secondary porosity left after dissolution of aragonite bioclasts. Many of these were broken by overcompaction after initial aragonite dissolution but before growth of later calcite spar, so that large single crystals often grow across the boundary between primary and secondary pore space (Fig. 12b), and no line of weakness runs along the boundaries of the aragonite bioclasts as it would if they were entire and thus delineating distinct zones on the exterior and the interior of the former shell (Fig. 12a).

The larger sizes of the spar crystals in the cemented facies of the Lincs Limestones has not been studied from the point of view of the durability properties of the stone, but there are likely to be some consequent differences from the similarly well-cemented stones of the Bath area. The latter typically have a drusy fabric growing into both primary and secondary pore space, so that close to the surfaces on which cement growth initiates there is a mass of small spar crystals with many intercrystalline sheet-pores between them (Type 5 porosity above). These may become slightly widened due to the effects of sawing or dressing near the surface of the stone and thus be enhanced as sites of some microporosity. In the Lincs limestones the blockier, more macrocrystalline late spar contains many less intercrystalline junctions and hence reduced Type 5 pore space. This is likely to enhance durability.

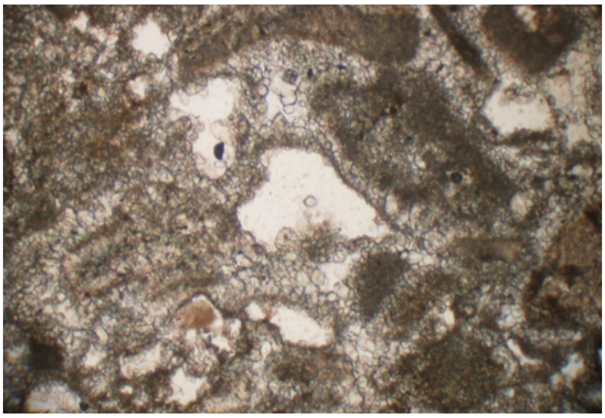


Fig. 14 *Thin section of Dundry stone. The clear white areas are regions of uncemented macroporosity.*

The size of individual calcite cement crystals is particularly affected by the character of the seed crystals on which they initiate. Limestones that contain bioclasts derived from echinoderms or from bivalve shells of prismatic calcite composition (Isognomon is a common example in Jurassic rocks) show the cement growing syntaxially on such grains, invariably to a much larger size than the individual crystals in the drusy array on a normal surface that is not composed of a large single crystal. These large (up to a couple of mm) crystals of overgrowth cement often stand proud from weathering surfaces of limestones and clearly have greater durability. However, there appears to be a limit to their size above which another effect comes into play, which is deleterious. Some of the Lincs Limestone stones (e.g. Ancaster Hard White) show a poikilotopic cement of huge calcite crystals, up to several centimetres across and entirely enclosing neighbouring grains. (The effect of light reflection at the surface of such stones is known as lustre mottling.) These crystals are also nucleated on scattered echinoderm debris in a predominantly oolitic parent lithology. Stones with this cement fabric have a poor reputation for durability and are rejected for masonry work (as at Ketton); older examples seen in masonry yards show that they tend to spall off in patches along the cleavage planes of the large cement crystals. Probably water can penetrate along these planes where they intersect the surface and be carried some centimetres into the stone, from where they can jack apart the stone when freezing occurs.

Dundry Stone The fourth stone considered specifically in this account is likely to be the one that is most unfamiliar to modern users. Dundry Stone was an important freestone in mediaeval use, and it was in production again for about a century from early Victorian times. Part of its wide regional use extending to Wales and Ireland is likely to have arisen from the relative ease with which it could be shipped from the quarries just south of Bristol, into boats on the River Avon and thence to faraway destinations. Its wide survival in mediaeval building, in exterior as well as interior work, shows its excellent durability.

Dundry Stone is not strongly barred like some of the Bath stones, but it does show bedding-related zones of two fabrics that appear slightly different on weathered surfaces. The first is an almost tufa-like fine porous structure, with the pores being clearly visible with a hand lens (Fig. 13). This fabric is composed almost entirely of fine bioclasts, up to 2 mm or so across. Some are from calcitic shells and they (like the scattered iron-stained intraclasts that are also seen in thin-section) are imperforate. But the majority are from originally aragonitic skeletons that dissolved out early in diagenesis. The resulting biomouldic porespace and the primary porespace between the grains are incompletely filled with later spar cement (Fig. 14). Thus the fabric of the stone has a high residual porosity of well-connected macropores, which dried readily. In this respect it is like Portland Stone, though the origin of the porespace is very different. When freshly extracted from the quarry and still containing a high proportion of the ground water, it would have been very soft to cut and carve.

The alternative facies of Dundry Stone is also dominated by bioclasts, but particularly by calcitic ones and with a high proportion of echinoderm debris. The origin of these bedding-related zones probably lies in the current-sorting of the two different sorts of shell debris. The more calcite-rich zones naturally do not display biomouldic porosity, and the predominance of echinoderm material with thick syntaxial calcite cement rinds also means that the primary porosity is more occluded. As in the other Jurassic limestones that contain a proportion of echinoderm material, the resulting fabric of large (typically 1–3 mm) interlocking calcite crystals in random crystallographic orientations produced a strong and durable fabric, rather like that of an older and more fully recrystallised limestone of greater diagenetic maturity such as some of the Carboniferous limestones.

Other Jurassic limestones in Southern England

The four examples described above have been picked because between them they show all of the main variations that seem to correlate with good durability performance and a high reputation amongst practitioners. Other famous and well-regarded Jurassic building stones appear to have similar petrographic characteristics to one (or occasionally more) of the exemplars discussed above.

The Cotswold stones from both the Inferior and the Great Oolite (including the Forest Marble), extending up from Wiltshire across Gloucestershire into Oxfordshire, appear to be variants of the theme exemplified by the Bath stones. The same is true of some of the minor stones from the Blisworth Limestone of Northamptonshire (Sutherland 2003). They are largely spar-prominent with their durability lying in their spar cement (in both primary and secondary pore space) and in their calcitic bioclasts. Ooliths tend to be microporous and weak, and readily weather out from the exposed surface of stonework. In a few of the more local stones within the Inferior Oolite of the south Cotswolds (around Stroud for example), the ooliths appear to have a better developed radial calcite microstructure and more coherence, and they remain for much longer periods of time at cut surfaces, tending towards the situation seen in the oolitic and shelly stones of the Lincs Limestone. Thus these stones tend towards being grain prominent, or at least a transitional condition between the most obvious spar-prominent stones of Bath type and the cement-poor, highly grain prominent stones such at Barnack.

Two other important fabrics, both encountered elsewhere, are represented by the two different facies discussed above with relation to Dundry Stone. The variety that is dominated by calcite bioclasts with a high preponderance of echinoderm debris also occurs in Doulting Stone from south of the Mendip Hills. These two stones, both of Upper Inferior Oolite age and deposited onto the marked unconformity of the so-called Vesulian transgression, suggest that these were times when coastlines were pushed back and extensive clear shallow-water platforms covered much of southern England, on which echinoderms (most likely cirrate crinoids) thrived. (Arkell's (1947) suggestion, following Woodward (1894), that the echinoderm debris in Doulting Stone were reworked from the underlying Carboniferous is not borne out by the petrography of the cement overgrowths.) Doulting is particularly resistant to weathering on exposed west coasts where the air tends to be salt-laden. Its mosaic of calcite crystals tend to be somewhat larger than those in Dundry Stone, and it weathers as well as a recrystallised Carboniferous limestone. It is let down only by locally-developed patches or thin laminae where the echinoderm debris is more sparsely distributed and where the blocky cement overgrowths did not develop.

The second of the Dundry-type fabrics, the tufa-like highly porous bioclastic grainstone that is dominated by incompletely-filled intergranular and biomouldic macropores, is seen in two other important and durable mediaeval freestones. One is Sutton Stone from the littoral Liassic of south Wales. This stone again is almost entirely composed of bioclasts with much porespace still remaining unfilled. The other is one of the varieties of the Wheatley Limestone from the Corallian beds east of Oxford. Those Corallian stones from Wheatley and Headington that were widely used in Oxford in the eighteenth century decayed very badly and their performance received wide condemnation in W.J. Arkell's *Oxford Stone* (Arkell 1947), but in fact these limestones are very variable in petrography and weathering character. Some varieties show excellent durability as can be seen in extant mediaeval structures in the city such as the old City Wall and Oxford Castle. Calcite-cemented bioclastic (often coral and echinoderm-rich) grainstones with residual interconnected porosity, in both primary and biomouldic pore-space, are a common fabric in well-preserved blocks of masonry. Also well-preserved are large coral lumps (Coral Rag) replaced by dense neomorphic calcite spar. The facies that seems to have been responsible for the terrible reputation of some of the stone from the Headington quarries is a packstone fabric that has a high microporosity within micrite that fills the interstices between the bioclasts. This variety of the Wheatley Limestone should not be allowed to divert attention from the high quality of other varieties of the local Corallian that were appreciated by mediaeval masons. It is incidentally interesting to note that these three stones (Dundry, Sutton, Wheatley Limestone) which were so highly appreciated in the Middle Ages were none of them oolitic. Possibly oolitic stones, from Northamptonshire southwards at least, were generally thought to be less suitable for good quality exterior work.

CONCLUSIONS AND SUMMARY

This review of some of the better-known Jurassic building stones of Southern England suggests that some of their durability characteristics can be understood, and therefore predicted, on the basis of their petrographic characteristics, and particularly of their porosity attributes. As discussed above, this is a complex subject in limestones that are diagenetically sub-mature, because porosity and permeability have different origins, and develop (or are maintained) through a variety of processes. In contrast, limestones that are older and have been more deeply buried have reached a higher level of diagenetic maturity. More of the pore space has been filled with cement, and there has often been an aggrading neomorphism such that areas of many small calcite crystals have been replaced by areas of fewer, tightly-interlocking larger crystals. This confers a texture that is more akin to a marble than to the ancestral sediment, or to the sub-mature parent rock. This is essentially why the Carboniferous Limestones (for example) are more durable than the English Jurassic Limestones; it is also, of course, the reason why the former are harder and more difficult to dress.

The ideas discussed here can be applied beyond the English Jurassic building stones that are considered above. The many important sub-mature Jurassic limestones of central and northern France, for example, can be expected to follow the same patterns. Over a wider area in Europe and beyond, limestones of Cretaceous and Tertiary ages are often similarly sub-mature and may be expected to behave similarly. In contrast, older rocks (or Mesozoic and Tertiary rocks that have been more deeply buried and have matured into hard limestones that take a good polish) have much lower overall porosities and do not obey the same rules.

Recent European Standards' stipulations require that thin-section descriptions are made available for building stones in production, but they cannot be interpreted without a theoretical model of the relationships between petrology and performance, which can be tested against future experiences.

ACKNOWLEDGEMENTS

My grateful thanks go to J.D. Hudson and C.D. Palmer for their comments and input.

REFERENCES

Arkell, W.J. 1947. Oxford Stone. Faber and Faber.

Bathurst, R.G.C. 1976. Carbonate sediments and their diagenesis (2nd ed.). Elsevier.

Bathurst, R.G.C. 1987. Diagenetically enhanced bedding in argillaceous platform limestones: stratified cementation and selective compaction. Sedimentology, 34, 749-778.

Bell, F.G. 1993. Durability of carbonate rock as building stone with comments on its preservation. Environmental Geology, 21, 187-200.

Edmonds, F.H. and Schaffer, R.J. 1932. Portland Stone: its geology and properties as a building stone. Proceedings of the Geologists' Association, 43, 225-240.

Fürsich, F.T., Palmer, T.J. and Goodyear, K.L. 1992. Growth and disintegration of bivalve-dominated patch-reefs in the Upper Jurassic of Southern England. Palaeontology, 37, 131-171.

Green, G.W. and Donovan, D.T. 1969. The Great Oolite of the Bath area. Bulletin of the Geological Survey of Great Britain, 30, 1-63.

Hirschwald, J. 1908. Die Prüfung der Naürlichen Bausteine auf ihre Wetterbeständigkeit. Berlin.

Honeybourne, D.B. 1982. The Building Limestones of France. Building Research Establishment Report, HMSO.

Honeybourne, D.B. and Harris, P.B. 1958. The structure of porous building stone and its relation to weathering behaviour. Proceedings Tenth Symposium of the Colston Research Society, 343-363.

Howe, J.A. 1910. The Geology of Building Stones. Edward Arnold. (Reprinted 2001, Donhead Press, Shaftesbury).

Hudson, J.D. and Sutherland, D.S. 1990. The geological description and identification of building stones: examples from Northamptonshire. 16-32 in Parsons, D. (Editor), Stone: quarrying and building in England AD 43-1525.

Phillmore & R.A.I. Leary, E. 1983. The Building Limestones of the British Isles. Building Research Establishment Report, HMSO.

Lewis, J.J.M. 1987. Studies on reservoir heterogeneity and permeability anisotropy in lithified carbonate sands from the Great Oolite formation (Middle Jurassic) of southern England. Unpublished Ph.D. thesis, University of Reading.

Palmer, T.J. 1979. The Hampen Marly and White Limestone Formations: Florida-type carbonate lagoons in the Jurassic of central England. Palaeontology, 22, 189-228.

Palmer, T.J. 2004. What's so good about Portland Stone? Geoscientist, 14, 4-7, 13.

Purcell, D. 1966. Cambridge Stone. Faber and Faber.

Schaffer, R.J. 1932. The weathering of Natural Building Stones. HMSO (Building Research Establishment Facsimile, 1985).

Sellwood, B.W. and Beckett, D. 1991. Ooid microfabrics: the origin and distribution of high-intra-ooid porosity; Mid-Jurassic reservoirs, S. England. Sedimentary Geology, 71, 189-193.

Sellwood, B.W., Shepherd, T.J., Evans, M.R. and James, B. 1989. Origin of late cements in Oolite reservoir facies: a fluid inclusion and isotope study (M. Jurassic of S. England). Sedimentary Geology, 61, 223-237.

Sutherland, D.S. 2003. Northamptonshire Stone. The Dovecote Press.

Waterman, D.M. 1970. Somersetshire and other foreign building stone in medieval Ireland. Ulster Journal of Archaeology, 33, 63-75.

Watson, J. 1911. British and Foreign Building Stones. Cambridge University Press.

Woodward, H.B. 1894. The Jurassic rocks of Britain, Vol 4, The Lower Oolitic rocks of England (Yorkshire excepted). Memoirs of the Geological Survey of the United Kingdom, HMSO.