

SOURCE OF ROMAN STONE FOR *AQUAE SULIS* (BATH, ENGLAND): FIELD EVIDENCE, FACIES, pXRF CHEM-DATA AND A CAUTIONARY TALE OF CONTAMINATION

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Abstract

The Roman town of Bath (*Aquae Sulis*), renowned for its Temple to Minerva and thermal baths complex, is estimated here to have required around 500,000 cu m of stone for its construction. This huge amount of stone was likely to have been supplied from quarries within 5 km of the town, located towards the tops of the hills around Bath. Observations at the many old quarries show few features indicating Roman exploitation except for one Lewis bolt-hole and reports of chisel marks. The features of the majority of the stone in the Roman Baths-Temple Complex all suggest that the stone was sourced largely from the Combe Down Oolite Member (CDO)(Jurassic, Bathonian stage), rather than the Bath Oolite Member (BO), of the Great Oolite Group. A portable X-Ray Fluorescence (pXRF) instrument, used to determine the trace element geochemistry of Bath Stone for comparison with the Roman stone, shows that the CDO and BO are very similar, except for different contents of Si, Al, Fe and Mn. These likely reflect variations in clay and organic matter content. However, with regard to the Roman stone and sculptures in the Baths-Temple Complex, all analyses of surfaces show enrichment in virtually all elements, but especially in P, Si, K, Al, S, Cl, Fe, Pb, Zn, Nb and As. This contamination is largely attributed to the buried nature of the site (5-8 metres) from the 5th century AD until the end of the 19th century, during which time the stone would have been affected by groundwater, mostly derived from the hot-springs with its high content of many elements. Analyses of cores cut into blocks of Roman stone show that the contamination is absent after 1-2 cm. This study demonstrates that care must be exercised in using geochemical analyses of ancient building materials for provenance studies, and that fresh surfaces of the material may well be required.

Keywords: Roman stone, Roman quarries, Bath Stone, Great Oolite, *Aquae Sulis*, pXRF

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1. Introduction

Roman activity at Bath and the establishment of a town, *Aquae Sulis*, began around AD 60, not long after the invasion of Britannia in AD 43, by order of Emperor Claudius. An important temple and sacred site were constructed first, largely of stone near the site of the thermal springs where a large bathing complex was developed and continued to expand over the following 300 years, before being abandoned sometime in the later 5th century (Burnham and Wacher 1990; Gerrard 2007). A Roman town slowly developed next to this complex and eventually covered an area of approximately one square km (Davenport 1994; Cunliffe 2000). Both the settlement and the sacred/bathing areas were contained within the town walls (some remains still visible), but there was likely significant development outside, along the River Avon, especially to the east. *Aquae Sulis* was situated on the Fosse Way (Figure 1), a major Roman trade and communications route running from Exeter (*Isca Dumnoniorum*) to Lincoln (*Lindum Colonia*). Roman roads also extended from Bath to London (*Londinium*), Bristol-South Wales (*Via Julia*), notably to Caerleon (*Isca Augusta*), and to Cirencester (*Corinium*).

The stone for the Roman town and the Roman Baths at *Aquae Sulis* has long been referred to as Bath Stone (Cunliffe 2000; Pearson 2006). This is an important freestone used extensively in the 18th-19th centuries in the building of the Georgian city of Bath, but also in earlier times, especially for major churches (like Bath Abbey) and mansions in the surrounding region (e.g. Longleat, Wiltshire). However, there are other good freestones in this southwestern area known to have been used by the Romans elsewhere, e.g. Dundry Stone, Doultong Stone, Cotswold Stone and Ham Stone, which they might have considered for *Aquae Sulis*.

This on-going project, conceived by Stephen Clews, Roman Baths Curator, is designed to compare the Roman stone at Bath with occurrences of Bath Stone in the vicinity, with a view to characterising these stones in terms of their facies (texture, composition, sedimentary features and fractures) and their chemical composition as determined by a portable X-Ray Fluorescence instrument (pXRF). The intention is to try to establish the stratigraphic unit which was exploited by the Romans and in addition, if possible, to determine the source of the stone in the region, and which quarries supplied the stone. A future application of the results of this study is that the data could be used to identify Bath Stone in other Roman settlements in southern England such that trade routes for the movement of the stone can be identified. The volume of Roman stone required for the construction of *Aquae Sulis* is calculated and assessed with regards to the number of quarries. The scant direct evidence for Roman quarrying is also reported. Following many observations and the collecting of samples from old quarries in the vicinity of Bath and study of the stone at *Aquae Sulis* itself, this paper compares the sedimentological features of the two units of Bath Stone (Bath Oolite and Combe Down Oolite) and Roman stone, and explores the likely sites of stone exploitation. We also present geochemical analyses and discuss the potential of pXRF to distinguish between the two Bath stones. Results are compared with analyses of Roman stone but a major issue is encountered there, namely contamination.

2. Methods

The Roman stone at the Roman Baths has been examined closely to determine its sedimentological features (see Tucker 2011 for approach) and Bath Stone has been documented and sampled from the many old quarries around Bath (Figure 1). Rock thin-

sections have been examined for the various units of the Great Oolite in the Bath area to determine the microfacies, texture and composition (see Tucker 2001 for procedure). A pXRF instrument, a non-destructive analytical tool widely used in archaeological studies of provenance (e.g. Williams-Thorpe 2010; Liritzis and Zacharias 2011), has been used on surfaces of Roman stone in the Roman Baths Museum (with permission of the Curator) and on freshly-cut surfaces of stone collected from outcrops around Bath, to determine the major and minor element contents. In addition, a 2 cm-diameter core was taken from three ‘spare’ blocks of Roman stone in the store of Bath & NE Somerset Council at Pixash Lane, Keynsham, kindly organised by the Roman Baths Museum Curator, and Collections Manager, Susan Fox. The pXRF instrument used was Bournemouth University’s Niton XL3t GOLDD as it allows analyses to be recorded both in the field and laboratory using a series of in-built calibrations (in this instance, ‘mining mode’ was used). Underpinning these modes are the instrument’s fundamental parameter calibrations that give relative, semi-quantitative concentrations based on the theoretical relationship between X-Ray intensity and elemental concentration. These data can then either be externally calibrated using standard reference materials or, in the instance of this study, be used to produce an internally consistent comparative dataset. Data are presented in Table 1 for 16 elements, with contents given in ppm (parts per million).

3. Geological background

Bath Stone is a general term for building stone within the Great Oolite Group (Bathonian stage, Middle Jurassic, see Figure 2), extracted mainly from the area to the south (Odd Down, Fox Hill, Combe Down), east (Bathwick Hill-Bathampton Down), east-south-east (Limpley Stoke and Bathford to Monkton Farleigh) and east (Box-Corsham) of Bath (Figure 1)(Hawkins 2011; King 2011). There are two horizons supplying freestone (that is a stone, usually fine-grained and of uniform texture, that can be cut freely in any direction) within the Chalfield Oolite Formation of the Great Oolite Group in the Bath area: the Combe Down Oolite Member (9-18 m thick) and the Bath Oolite Member (5-15 m thick), separated by the Twinhoe Member (0-11 m thick)(Barron et al. 2012; British Geological Survey 2015)(Figure 2). The Twinhoe Beds are limestones, commonly with iron-shot ooids, but rubbly, clayey, and poorly bedded, rarely used as a building stone (King 2011). Above the Bath Oolite Member, within the Corsham Limestone Formation (formerly Upper Rags), there is a basal metre-thick ‘roof-bed’, succeeded by a further oolite (1.5 m thick at Bathford). As the name suggests, the roof bed is the ceiling in the underground workings, being extremely hard and laterally extensive; it contains many corals, as well as bivalves. The third oolite unit thickens to the south from Bath and in the vicinity of Bradford-on-Avon (8 km SE of Bath), it reaches 10 m in thickness and has been exploited as a freestone known as Bethel Stone and Bradford Ground (Hawkins 2011). In 2019 Bath Stone was designated a Global Heritage Stone Resource (GHSR) by the International Union of Geological Sciences (IUGS).

The lowest unit of the Great Oolite Group is the Fuller’s Earth Formation with several thin limestones, and below that is the Inferior Oolite Group, another carbonate unit up to 23 m thick with horizons that have provided freestone: Dundry Stone from south of Bristol, Doulting Stone from near Shepton Mallet, and Painswick Stone (‘Cotswold Stone’) from the Cheltenham-Cirencester region. Above the Corsham Limestone Formation is another limestone, the Forest Marble Formation, a thin-bedded shelly stone, only useful for walls.

The City of Bath lies close to the River Avon, an area of thin alluvium resting upon Lias Group mudstone and limestone (Lower Jurassic) and Triassic sediments (Figure 2); the Middle Jurassic strata form the surrounding slopes and hilltops. The Inferior Oolite Group crops out about half-way up the slopes, in Beechen Cliff and Beacon Hill for example (Figure

1). The Great Oolite Group occurs at the top of the hills around the City (British Geological Survey 2015; Tucker 2019).

4. Archaeological background and the quantity of stone

Aquae Sulis was a medium-sized Roman town (population 10,000; area 22 acres/9 hectares), with a large walled temple-baths complex. It does not appear to have been a garrison town, more of a sacred space (*temenos*, Dark 1993), with the hot springs for recreation and pleasure, catering mostly for visitors, as was the case for Bath during the Georgian era, and as it still is today. By way of comparison, *Corinium* (now Cirencester) was much larger (220 acres/90 hectares) with an estimated population of 30,000. However, there are numerous Roman remains of buildings in the vicinity of the walled town, especially to the east, in the area of Walcot, along the London Road and at Bathwick, on the south side of the River Avon, connected by a bridge (Davenport, 1994)(Figure 1).

The quantity of stone required for the construction of *Aquae Sulis* and the surrounding suburbs would have been considerable. Calculations of the volume needed for the town walls (length 1000 m, height 5 m, thickness 2 m), give a figure of at least 10,000 cubic metres. This compares favourably with the estimate of Elliott (2018) of 35,000 m³ for the volume of stone for the walls around *Londinium* (London), which were 3200 m long, 6 m high and 2.5-3 m wide. An estimate of the number of houses within the city-walls (100) and outside (500) is based on reconstructions of the town in the Roman Baths Museum. The volume of stone per house (walls and flooring) is estimated from the wall area (10 x 3 m x 4) and thickness (1 m), plus floor area (10 x 10 x 0.1 m), as recorded in recent excavations of Roman villas and houses in the Bath area (e.g. Roberts 2016) and elsewhere. Another approach is to consider the number of houses for the population, estimated to be 10,000: with 6-8 persons per house, there would be around 1250 to 1666 houses. In addition, there is the huge baths-temple-amphitheatre complex itself, plus stone for paving, roads and other walls. Finally, there would be a substantial amount of discarded-unsuitable stone, as seen in the ancient waste dumps close to overgrown outcrops of Great Oolite around Bath where once stone was likely extracted. From these rough calculations, a figure in the order of 500,000 m³ can be suggested (by MET).

Although half a million cubic metres of stone is a very rough estimate, it is clear that an extremely large amount of stone would have been required for the construction of the Roman town and facilities. To put this into perspective, one can calculate the amount of stone a typical quarry might have produced. There is only one open quarry still active in the Bath area, Upper Lawns Quarry in Combe Down (clearly visible on Google Earth, 51°21'38.76"N 2°20'19.12" W), although there are still 4 or 5 underground quarries working the stone. Upper Lawns Quarry has a rectangular area of approximately 100 metres by 50 m and a CDO thickness of 9 m (freestone thickness 5 m), giving 45,000 cu m of stone, of which 25,000 cu m is freestone. Thus, it would appear that at least 20 quarries of the size of the last remaining one today would have been necessary to supply the stone over the several centuries that *Aquae Sulis* flourished and expanded. At least 50 old quarries can be recognised in the Bath area (Figure 1), although many of these would have been worked in the 18-19th centuries.

One potential extra source of stone for *Aquae Sulis* is underground. Since the 18th century, much of the Bath Stone has been obtained by mining; indeed there are many 10s of km of tunnels beneath Odd Down-Combe Down (now filled with expanded concrete), Warleigh-Farleigh and Box-Corsham from which stone has been removed (Hawkins 2011). It could well be that the Romans also exploited the stone by mining, a method they employed extensively in Rome and Naples. Although there is no direct evidence for this here, it has

been suggested that stone was mined by the Romans in the Box area, 8 km west of *Aquae Sulis*, where there were several Roman villas (e.g. Farrant and Self 2016).

5. Bath stone and old quarries

Bath Stone sedimentological features

Combe Down Oolite Member (CDO): The CDO is 9-18 metres thick with 5 to 12 m of freestone. The lower 1-2 metres are generally much harder, being a better cemented bioclastic (shelly) pack-grainstone, in some cases with thin clay partings, and this could have been used as paving or rubble rather than cut into blocks. The upper 1-2 metres of the CDO are much more thinly-bedded and would have been used for paving and flooring. The main body of the CDO, the freestone, is largely a bioclastic-oolitic grainstone, with 50 to 80% of reworked shell fragments, largely of bivalves, with minor brachiopod and echinoderm debris, as well as rare pieces of gastropod, bryozoan, calcareous algae, ostracods, coral and peloids (Figure 3A). The bioclast grain-size is quite variable, fine (0.25 mm) to very coarse sand (2 mm) with some larger fragments, but most is well sorted within layers. Ooids are generally 100-300 microns in diameter but may reach 1 mm; many have a poorly-developed internal structure.

Lamination and cross-bedding are usually conspicuous, the result of relatively moderate to strong waves and currents moving the sand-grade sediment across the shallow seafloor as ripples and small dunes. A further feature of the CDO is the presence of burrows, mostly simple vertical-subvertical tubes, 1-2 cm in diameter, some with a thin outer wall of micrite. In the lower part of the CDO (and in some other Jurassic limestones of the Cotswolds, e.g. Daghams Stone near Cirencester), there are several levels of *spongestone* (Green and Donovan 1969) – a limestone with many cm-sized holes, likely to have been crustacean burrows (Fürsich and Palmer 1975), where the burrow-fills have been weathered out to give a honeycomb structure. This stone was commonly used in Georgian-Victorian gardens and grottoes (in Bath at Combe Lodge for example).

In addition to the sedimentological features, the CDO is characterised by the presence of fractures, generally vertical to subvertical, which traverse the rock and are filled by coarse calcite spar crystals. These are overburden and tectonic features, generated during burial, and could relate to the fact that the CDO rests on the clay-dominated Fuller's Earth, which would have compacted during burial. These features were referred to as watermarks by the stonemasons.

Bath Oolite Member: The BO is around 10 m in thickness and much of this is freestone; it is quite different from the CDO, being a much more uniform oolitic grainstone with larger ooids, 300-800 microns in diameter. Many of these have a radial-concentric fabric, and they are generally well-sorted in most beds (Figure 3B). Bioclasts are generally rare, less than 10%, with bivalve fragments dominant. The oolite usually has a massive appearance; sedimentary structures are weakly preserved (because of the uniform grain size) – hence the excellent freestone properties. In some instances, however, a large-scale cross-bedding is visible. Burrows are rarely observed and fractures are also far less common. The BO is also cemented by calcite spar, but commonly there is an earlier isopachous marine cement around the grains. The cement is commonly more resistant to weathering than the grains themselves, so that on exposed surfaces the ooids commonly fall out.

With both Bath Stone units, the degree of induration, and so resistance to weathering, does depend on the bioclast content. Higher shell contents, as in the CDO, lead to levels of more intense cementation through dissolution and reprecipitation of carbonate derived from

bioclasts composed of metastable aragonite (King 2011). The porosity in general is relatively high for the Bath Stone, typically between 23-27%, with much of the pore space residing within the ooids themselves as a microporosity (Palmer 2005). More bioclastic-rich levels are generally more tightly cemented and have a lower porosity.

Stone in the Roman Baths-Temple Complex

The majority of the stone forming the Roman columns and walls around the baths and the remains of the buildings related to the temple complex show features indicating that the stone is the Combe Down Oolite. The abundance of bioclasts is obvious and sedimentary structures, lamination and cross-bedding are commonly observed (Figures 4A, B). In addition, burrows and fractures are present. The paving stones around the Great Bath are large, up to 1.5 x 1 m, and 10-20 cm thick. On the surfaces of these slabs, the parallel and curved lines of cross-bedding can be observed (Figures 5A, B), brought out by variations in grain-size of the sediment layers, and burrows are present too. Fractures are also visible (Figure 5 B). These stones likely come from the upper part of the CDO which is typically thin-bedded and could have provided such material. In addition, where the CDO stone is close to the surface, the upper beds are commonly split into thin layers, as a result of freeze-thaw and temperature changes. Many of the sculptures and carved stones in the museum area are also composed of bioclastic oolitic grainstone, with cross-bedding and fractures (e.g. Figures 6A, B), indicating a CDO provenance.

Old Roman quarries around Bath

There are numerous old stone workings in the Great Oolite Group around Bath, towards and at the tops of the hills surrounding the City. There was of course extensive exploitation of the stone in the 17th through late-19th centuries, as well as some quarrying in the 12-16th centuries. Many Roman quarries will have been extended in these later phases of activity, so destroying evidence of Roman workings. At many old quarries, now commonly showing a few metres of weathered outcrop, there are extensive spoil tips of discarded material covered in large trees and bushes, indicating some significant time since quarrying activity there. Such is the case at the Tumps, Odd Down (Grid Ref: ST741-628), Bathwick Woods (ST766-651), Bathampton Down (ST770-653), along the ridge of Brown's Folly (ST796-664) to Warleigh (ST796-644) and at Lansdown (e.g. ST739-672)(Figure 1), but whether these old workings are Roman cannot be established of course.

In a few rare instances, there is evidence of Roman stone extraction: the presence of round chisel holes and a Lewis bolt hole. Whitaker (2010 and pers. comm.) recorded circular holes, several-many cm deep, of a consistent 44 mm diameter at old quarry workings in Bathwick Woods and on Bathampton Down. These are interpreted as Roman. The exposures of Combe Down Oolite in Bathwick Woods would actually be some of the closest to *Aquae Sulis*; indeed, there is an ancient trackway leading downhill from the site and a large Roman settlement has been excavated by the River Avon at Bathwick.

Of particular interest, however, is a Lewis bolt-hole at Brown's Folly near Bathford (Figure 7). The Lewis bolt was a device used by the Romans to pull and lift large blocks of stone out from a quarry face. A rectangular-shaped hole (10 x 2 cm), increasing in length into the stone, was dovetailed into the middle of a face of a block; into this was inserted the bolt, consisting of 3 metal pieces (the outer two triangular) through which a ring was placed. The stone block could then be lifted out by crane or pulled along. These bolt-holes can be seen in several places at the Roman Baths, notably on the upper surfaces of pieces of Roman column (as in Figure 4A), and they are identical to the one present at Brown's Folly. The Georgians

in the 18-19th centuries also used Lewis bolts to move blocks of stone, but they had a smaller device (8 cm in length) so that the holes they cut were smaller than the Roman ones.

Other circumstantial evidence of Roman quarrying activity comes from artefacts found near old quarries. Hawkins (2011) for example reported Roman coins and pottery fragments from old workings at Warleigh. He suggested that stone extracted from here, 5 km SE from Bath, could have been transported by barge downriver to *Aquae Sulis*.

6. Limestone geochemistry through pXRF analysis

The geochemistry of stone has been used to identify provenance and it has been particularly successful when igneous rocks are involved, as in tying down the bluestones of Stonehenge to particular locations in the Preseli Mountains (Bevins et al. 2014). However, with carbonate rocks, there are several issues to consider. Modern carbonate sediments are composed of grains which may be of three common mineralogies, aragonite, high-Mg calcite and low-Mg calcite, depending on several factors, notably the organisms present, seawater chemistry and water temperature-salinity (Tucker 2001). Once deposited, carbonate sediments are usually much affected by diagenetic processes, such as contact with freshwater, recrystallisation / neomorphism, dolomitisation, compaction and pressure dissolution, which lead to alteration of the original mineralogy and chemistry, such that all ancient limestones are composed of calcite (low Mg), and some are dolomitised. Some elements are lost from a limestone during diagenesis; others are gained. For example, modern carbonate sediments generally have high Mg (several 10s of 1,000s ppm), high Sr (several 1000 ppm) and high Na (a few 1000 ppm), but very low Fe, Mn, Pb and Zn (Tucker 2001). Ancient limestones by way of contrast generally have much lower Mg (unless dolomitised), Sr and Na, but increased levels of Fe and Mn, and other metals, picked up during burial diagenesis, especially in suboxic-anoxic porewaters, with clay minerals or organic matter the source.

The use of pXRF has been very successful in archaeology to link lithic artefacts, such as flint and obsidian tools, volcanic rocks as used in ancient pavements, granite statues and obelisks to their provenance (e.g. Tykot 2016, 2017; Müskens et al. 2018), and a recent study has shown how pXRF can differentiate between common sandstone building stones in the UK (Everett and Gillespie 2019). With regard to carbonate lithics, marbles used in antiquity can be distinguished on their trace elements, but particularly through their $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$ isotope signatures (e.g. Antonelli and Lazzarini 2015; Columbus et al. 2018), since they are metamorphosed limestones, altered under different conditions of temperature and pressure, leading to changes in original isotope values. However, there have been relatively few studies of limestone geochemistry for provenance. Pecchioni et al. (2019) successfully used pXRF data, particularly the Sr values, to assign different Jurassic red marbles (but actually these are limestones, of ammonitico rosso-type, being unmetamorphosed), used in the Santa Maria Del Fiore Cathedral, Florence (Italy), to particular quarries in the region. In one other example, Fort et al. (2019) successfully compared pXRF analyses of Iron-Age sculptures in Spain to local Eocene limestone formations.

The pXRF instrument gives the content of many elements in a sample very quickly and non-destructively; hence it has great potential for analysing archaeological artefacts, sculpture and stone. pXRF is good for analysing elements from Al (atomic number 13) onwards in the periodic table; hence, Na (11) and Mg (12), which could be useful, do not give reliable results with the technique. In addition, the extremely high content of Ca (400,000 ppm, i.e. 40%, in a pure CaCO_3 limestone), compared to many other elements present which are mostly in the 10s to a few 1000 ppm, means the Ca contents are unreliable, even being in excess of 40%. In total 34 different elements were automatically determined by the instrument, although in

many samples certain minor elements were below the detection limit (ND in Table 1). The contents of 16 elements, namely P, Si, K, Ca, Fe, Mn, Al, Sr, S, Zr, Mo, Ba, Pb, Zn, Cr and Ti, are presented here in Table 1, as the average values of all samples analysed from old quarries for the CDO and BO and for stone from the Roman Baths and Museum. It should also be noted that the pXRF instrument gives the content of elements in the whole-rock of the limestone, i.e. within the calcite as well as in other minerals, likely to be clay, quartz and pyrite. In many studies of limestone geochemistry, it is the acid-soluble fraction that is analysed to obtain the values of trace elements occurring within the carbonate lattice, not the whole-rock (see Tucker 1988).

The areas chosen for analysis on a limestone in the field *in situ*, or for a sample collected for later analysis, were generally from the centre of a bed of rock, away from the margins which would likely have a higher clay content and so higher Si and Al and other elements. For Bath Stone from old quarries, in most cases rock samples were collected and cut into 5x3x1 cm tablets. With the tablets and Roman stones, three analyses were made from each and averaged.

The objective with the chemical analyses is 1) a comparison of the chemistry of different beds within the same oolite at the same locality (CDO), 2) a comparison of the same oolite at different localities (for both the CDO and BO), 3) a comparison of the chemistry of the two oolites (Bath Oolite and Combe Down Oolite) at the same locality (Brown's Folly), 4) a characterisation of the chemistry of the Roman stone from *Aquae Sulis* and 5) a comparison of the Bath Stone analyses with those from Roman stone.

Bath Stone geochemistry

Several hundred samples have been collected and analysed from various old quarries around Bath, including Brown's Folly (Grid Ref ST 796-664), where there has been stone exploitation for centuries, and probably also by the Romans in view of the Lewis bolt-hole there. The whole Great Oolite Group succession is accessible. Comparing results from two different beds of the CDO at Brown's Folly, beds A and B, it can be seen that there are similar contents of many elements with some below the detection limit (ND, Table 1). There is a large difference in S (x3). In comparing the results from the CDO from Brown's Folly with Bathwick Hill (5 km apart, along strike), it can be seen that many elements are similar, but that Si is a little higher (x1.5), also Al (x1.4), in the CDO at Bathwick Hill. Hence, overall, it can be concluded here that there is little difference with most elements between the two beds of CDO and between these two localities for that oolite. Higher values of Si and Al at Bathwick could indicate a higher clay-silt content in the samples/beds analysed, and the higher S likely reflects the presence of pyrite.

The data in Table 1 from the Bath Oolite at Brown's Folly and at Warleigh, 1.5 km to the south, down-dip, show many elements with similar contents. Of note, however, are the higher contents of Si (x2), Fe (x1.7), Mn (x1.6), Al (x3) and S (x2) at Warleigh over Brown's Folly. The higher Si and Al could be a reflection of a higher clay content, probably since Warleigh is a little farther into the basin (south), where oolite passes to clay. The higher S and Fe (+Mn) could indicate more pyrite, FeS₂, which could also reflect the more basinal location and the presence of organic material in the sediment. Thus, for the Bath Oolite at two localities, overall, there are many similarities in element content, with the few differences probably reflecting location on the carbonate platform, proximal to distal.

Comparing the Combe Down Oolite with the Bath Oolite (Table 1), many elements are similar; clear differences though are the higher Si (x2), Fe (x1.7), Mn (x1.7) and Al (x3) in the Combe Down Oolite, over the Bath Oolite. These differences likely reflect the less 'pure',

‘dirtier’ (more clay-silt) Combe Down Oolite versus the cleaner, dominantly oolitic Bath Oolite. The higher Fe+Mn in the CDO could also reflect either more clay and/or suboxic-anoxic conditions during diagenesis (burial), through a higher organic matter content. Of note is the fact that the Combe Down Oolite occurs upon the Fuller’s Earth; clay may have been reworked from this formation during deposition of the CDO.

Roman stone geochemistry

The results of analyses of 144 Roman stones and several sculptures from *Aquae Sulis* and the average of all analyses of Bath Stone from outcrop, 220 samples, are shown in Table 1. The composition of the surfaces of Roman stone shows huge differences from those of Bath Stone. The majority of elements are enriched to highly enriched, including P (x5), Si (x5), K (x7), Fe (x3), Al (x3) and Cl (x5). Elements enriched to a staggering amount in the Roman stone are S, Zn and Pb, to the extent of x100, x100 and x400 respectively. Two extra elements that are recorded in Roman stone, but not in Bath Stone are As (arsenic) with 50 ppm and Nb (niobium) with 10 ppm; these figures are remarkably high; a ‘normal’ limestone would have a few 100 ppb. It is interesting to note that the only element with a ‘normal’, unchanged content is Ba.

It is clear from the analyses of the Roman stones that the surfaces analysed are extremely contaminated. This applies to the basal stone plinths of the columns around the Great Bath (Figure 4), and stones in the Tholos area and Precinct (by the Temple of Minerva). In addition, the sculptures analysed (e.g. the well-known, large Lady’s Head on display in the museum) also have the extremely high values.

The contamination of the surfaces of the Roman stone is likely to have been the result of many centuries of burial. For much of the last 1500 years or so, a large part of the Roman site was abandoned, until major excavations during the last part of the 19th century (Cunliffe 2000) revealed the extent of the complex. Thus, much of the site was buried, beneath soil, vegetation, domestic rubbish (probably) and waste materials, to a depth of 5-8 m. In addition, groundwater, largely derived from the hot springs, would have been permeating the former baths and the stonework; these waters would have been, as they still are, very rich in a whole range of elements (Edmunds 2004; Edmunds et al. 2014). In particular, SO₄, Ca, Cl, Na, HCO₃, Mg, Si and Fe are extremely high; arsenic (As) is present in spa water at 7 ppb (μ g per litre); river water has 0.1-0.8 ppb. In addition, the Romans did use lead in their plumbing system at *Aquae Sulis*, and for the lining of the spring itself, which may in some way have contributed to the 400 times increase in Pb in Roman versus Bath Stone.

The geochemical results of the Roman stone and their comparison with Bath Stone really do highlight the issue of contamination of ancient building materials, especially with limestone, which in many cases will be more porous than stone of igneous-metamorphic origin and tiles and bricks (ceramic building materials - CBM). Clearly in terms of provenance, the simple analysis of the surfaces of stone here is not sufficient to make comparisons with fresh surfaces of natural stone. Fresh surfaces of the ancient stone, especially if it is a porous limestone, are ideally required if pXRF is to be used as the instrument of choice. Comparing the natural surfaces of stone in ancient quarries could be a useful exercise, but the type of weathering will have been very different: open-air in the countryside versus the burial for ~1500 years of the Roman stone.

The need for fresh surfaces

To start to understand the issue of contamination, and to determine how deep it has penetrated, three 15 cm-long, 2 cm-diameter cores were taken from ‘spare’ blocks of Roman

stone housed at a B&NES Council storage facility, with permission of the Curator and Collections Manager of the Roman Baths Museum. These cores were then cut in half and readings were taken along the core with the pXRF instrument. As an example of the decrease in element content from the outer surface inwards, Figure 8 shows the results for Si, S, Pb and As. These graphs clearly show that after 2 cm the contamination has reduced to zero and values of the actual rock are then obtained. This demonstrates that fresh surfaces of stone are required if this geochemical fingerprinting technique is to be applied to obtain meaningful results for comparison with samples from outcrops that may well have been former sites of Roman quarrying. The average element analyses from the cores where uncontaminated, i.e. from 2 cm to 14 cm into the block, are given in Table 1. Most of these elements have a similar content to Bath Stone, as to be expected. Only three Roman stones were drilled, an insufficient number at this stage to make any conclusions as to whether the CDO or BO was the likely source of these particular blocks.

The next steps

It is clear that many geochemical analyses from fresh, uncontaminated Roman stone are needed to take this project forward so that the stone can be characterised and the different types of stone used can be categorised, if it is not all Bath Stone. In addition, many more analyses are needed of the Great Oolite Group limestones themselves from the old quarries around Bath to better refine the variations between beds and stratigraphic horizons. When more data are available, there will be a need for the application of multivariate statistics to determine which particular elements are useful in differentiating limestone types. Principal component analysis (PCA) can be applied to determine the correlations between elements and to suggest which groups are meaningful; PCA was successfully applied by Bevins et al. (2014) to the bluestones of Stonehenge and by Ashkanani et al. (2019) to Ubaid ceramics from Mesopotamia. Along with this approach, detailed petrographic work and microfacies analyses would be useful to ascertain primary differences between limestone units. Comparisons of the petrography of Bath Stone with that of Roman stone would be ideal but obtaining sufficient numbers of Roman stone samples for thin-sections (a destructive process) is not likely to be possible. Hence, the use of a large pXRF dataset, once available and its limitations appreciated, is the best way forward to search for meaningful comparisons between rock samples from likely old Roman quarries around Bath and the stone in the Roman Baths-Temple Complex.

7. Conclusions

Calculations of the amount of stone required for the construction of the Roman town of Aquae Sulis have indicated that vast quantities were needed, a volume in the order of 500,000 cubic metres. This is roughly equivalent to about 20 quarries of the size of the one remaining active open quarry in Combe Down, Bath. Sedimentological studies of the Roman stone at *Aquae Sulis* and comparisons with the limestones of the Great Oolite Group around Bath indicate that the Combe Down Oolite Member is the major source of the Bath Stone for the Roman Baths-Temple Complex, rather than the Bath Oolite Member. Numerous old quarries in the Great Oolite Group and their rock surfaces have been examined in the region of Bath and direct evidence of Roman exploitation, in the form of a Lewis bolt-hole and chisel holes, has only been found in the Bathwick Woods-Bathampton Down area and at Brown's Folly. The first of these are actually the closest former quarries to *Aquae Sulis*, and stone could simply have been carted downhill; Brown's Folly is farther away (6 km) but stone could have been transported downhill to the river for movement by barge.

The geochemistry of Bath Stone has been determined using a pXRF instrument on freshly-cut surfaces and although there are similarities in the contents of many elements, there are variations between the Combe Down Oolite and Bath Oolite, notably in the contents of Si, Al, Fe and Mn. These probably relate to the clay-silt content, reflecting the conditions of deposition. Analyses of Roman stone show that all surfaces measured in the Baths-Temple Complex are highly contaminated in virtually all elements, but especially in P, Si, Cl, Al, Pb, Zn, S, Fe, As and Nb. This enrichment is probably the result of the stone being buried since the 5th century AD, when the site was abandoned, with groundwater derived from the thermal springs providing the various elements picked up by the porous Bath Stone surface. Fifteen-cm long cores taken from several ‘spare’ Roman stone blocks show that after 2 cm the high values of all elements measured by pXRF were replaced by values typical of Bath Stone. This project shows that contamination is potentially a major issue in determining the geochemistry of ancient building materials, particularly a porous limestone, and that steps should be taken to ensure that data collected are reflecting the true chemistry of the stone.

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FIGURES AND TABLES

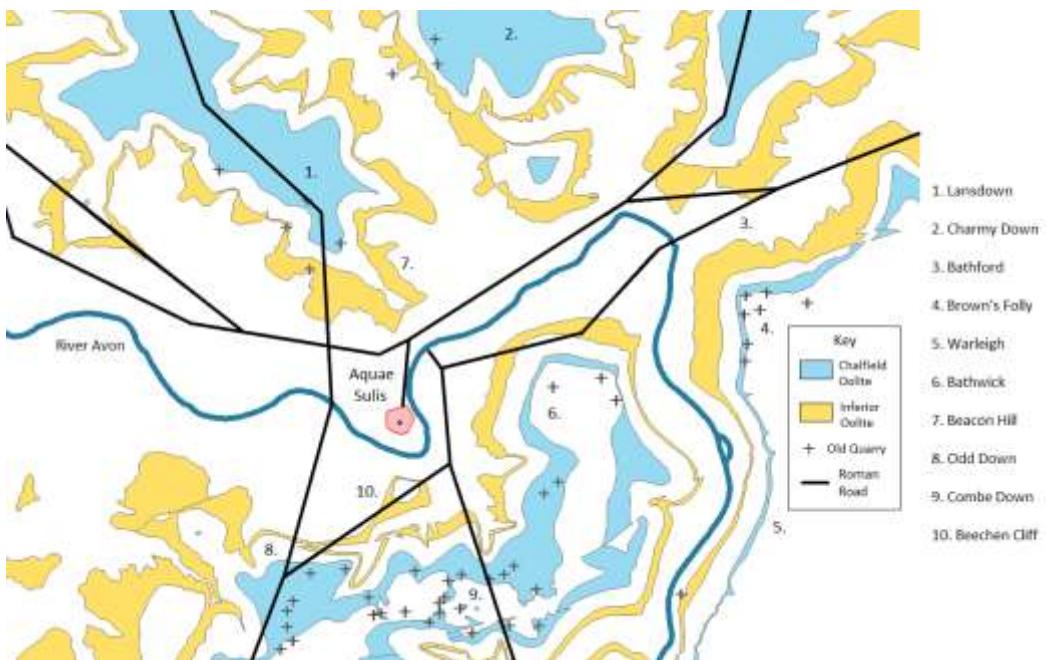


Figure 1. Map of the area around Bath showing the location of *Aquae Sulis*, sites of old quarries, the distribution of the Chalfield Oolite (blue shading) with the Bath Stone and the Inferior Oolite (yellow shading), and the known Roman roads. Modified from Davenport (1994).

Cornbrash	Cornbrash Fm	
Forest Marble	Forest Marble Fm	Great
Upper Rags/Corsham Lst	Corsham Lst Fm	
Bath Oolite Mbr		Oolite
Twinhoe Mbr	Chalfield Oolite Fm	
Combe Down Mbr		Group
Fuller's Earth	Fuller's Earth Fm	
Inferior Oolite	Inferior Oolite	Inferior Oo Gp
Midford Sands	Bridport Sand Fm	
Lias Clay	Charmouth Mudst Fm	Lias Group
Blue Lias	Blue Lias Fm	
Rhaetic	Penarth Group	
Mercia Mudstone	Mercia Mudst Gp	TRIASSIC
Carboniferous: Coal Measures, Pennant Sandstone, Limestone		

Figure 2. Jurassic stratigraphy of the Bath district from British Geological Survey (2011) Sheet 265. *Mbr* = Member, *Fm* = Formation, *Lst* = Limestone, *Mudst* = Mudstone, *Gp* = Group.

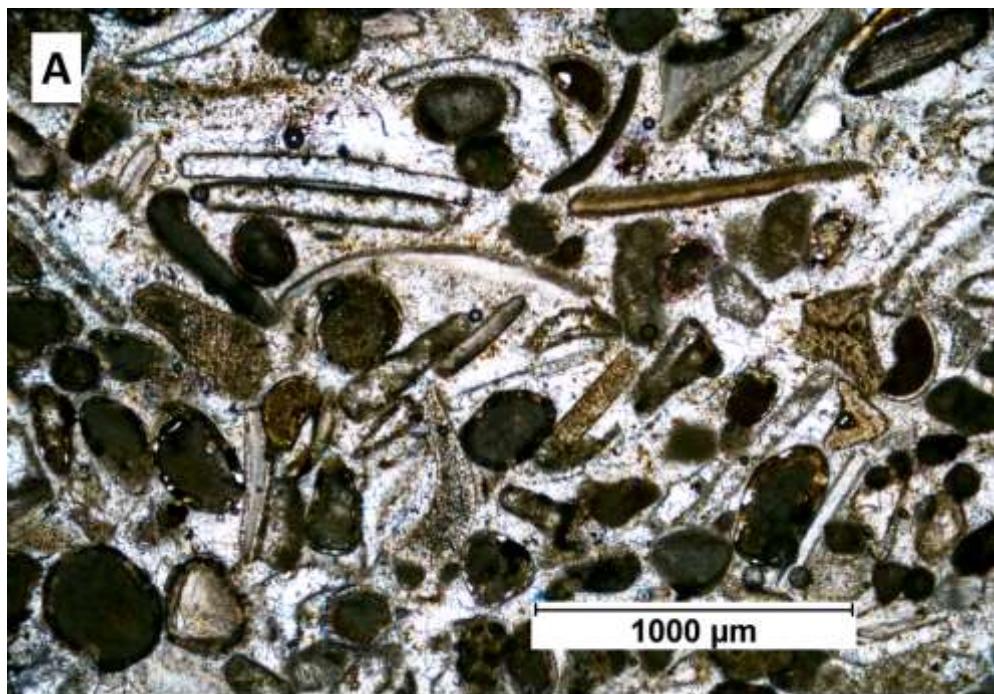


Figure 3. Bath Stone in thin-section. A: Combe Down Oolite: ooids, generally smaller than in Bath Oolite, with more shell fragments (bioclasts).



Figure 3. Bath Stone in thin-section. B: Bath Oolite: dominated by ooids, with a calcite spar cement. Thin-sections prepared by Ron Smith. Brown's Folly, near Bathford.



Figure 4. A: The base of a Roman column at the Great Bath with cross-bedding, cavities from burrow structures, and fractures. Note the Lewis bolt-hole on the top surface. The columns in the background are late 19th century. Rectangular block of Roman stone is 70 x 40 cm.



Figure 4. B: Cross-bedded shelly oolitic grainstone with burrows and cavities, a stone from the base of a Roman column. Field of view 40 x 25 cm.



Figure 5. Paving stones from the Great Bath area with curved ripple cross-lamination visible on the bedding plane surface (A, Field of view 70 cm across) and fractures crossing a well-dressed and also partly polished slab with cross-lamination (B, Width of each slab 50 cm).



Figure 6. A, B. Sculpture for a gravestone showing a hound chasing a hare, in cross-bedded bioclastic-oolitic grainstone (Combe Down Oolite) with calcite-filled fractures ('watermarks'). Face-on view 80 x 50 cm and side view 30 x 20 cm. Roman Baths Museum.



Figure 7. Lewis bolt-hole from Brown's Folly. The length is 10 cm, but that increases inwards, width 2.5 cm and depth 12 cm.

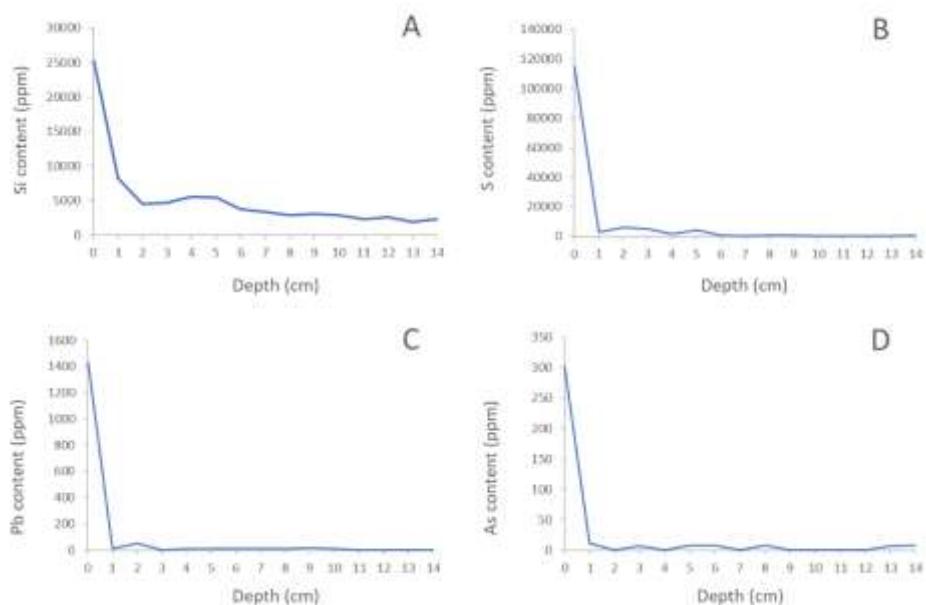


Figure 8. Concentrations of Si, S, Pb and As from a core taken from a block of Roman stone, with readings taken at ~1 cm intervals from the outer surface to 14 cm into the stone, showing the sharp decrease in values after ~1-2 cm.

P	Si	K	Ca	Fe	Mn	Al	Sr	S	Zr	Mo	Ba	Pb	Zn	Cr	Tl
COMBE DOWN OOLITE, BROWN'S FOLLY, BED A, 26 samples															
ND	4620	820	511,500	7010	700	2020	300	450	6	5	220	ND	2	42	ND
COMBE DOWN OOLITE, BROWN'S FOLLY, BED B, 33 samples															
ND	4110	510	520,400	6480	660	1450	340	1930	4	5	230	2	1	50	ND
COMBE DOWN OOLITE, BATHWICK HILL, 32 samples															
ND	6380	810	517,320	6540	640	2450	380	1700	5.2	5.6	230	2.4	2	40	ND
BATH OOLITE, BROWN'S FOLLY, 28 samples															
ND	2860	640	517,550	4160	410	710	360	610	3	5	210	ND	ND	20	ND
BATH OOLITE, WARLEIGH, 23 samples															
ND	5076	633	488,860	6700	635	1920	403	1143	5	5	216	2	2.3	66	ND
ROMAN STONE FROM AQUAE SULIS, BATH, 144 sampling sites															
520	25,400	5450	324,460	19,060	500	6080	500	127,180	11	8	240	600	500	110	570
AVERAGE ALL BATH STONE ANALYSES, 220 samples															
ND	5430	800	515,800	6430	570	2000	360	1400	5	5	230	1.5	3	58	ND
ROMAN STONE FRESH FROM CORES, 33 samples from 3 blocks															
ND	3049	457	384,330	5036	662	937	438	1031	5	3	211	4.5	1.9	50	ND
P	Si	K	Ca	Fe	Mn	Al	Sr	S	Zr	Mo	Ba	Pb	Zn	Cr	Tl

Table 1. Average values in ppm for 16 elements from pXRF measurements of:

Combe Down Oolite, beds A and B from Brown's Folly and Combe Down Oolite at Bathwick Hill; Bath Oolite at Browns Folly and Bath Oolite at Warleigh; Roman stone from Aquae Sulis; All Bath Stone analyses and cores from 3 Roman blocks. ND = not detected.

P	Si	K	Ca	Fe	Mn	Al	Sr	S	Zr
COMBE DOWN OOLITE, BROWN'S FOLLY, BED A, 26 samples									
ND	4620	820	511,500	7010	700	2020	300	450	6
COMBE DOWN OOLITE, BROWN'S FOLLY, BED B, 33 samples									
ND	4110	510	520,400	6480	660	1450	340	1930	4
COMBE DOWN OOLITE, BATHWICK HILL, 32 samples									
ND	6380	810	517,320	6540	640	2450	380	1700	5.2
BATH OOLITE, BROWN'S FOLLY, 28 samples									
ND	2860	640	517,550	4160	410	710	360	610	3
BATH OOLITE, WARLEIGH, 23 samples									
ND	5076	633	488,860	6700	635	1920	403	1143	5
ROMAN STONE FROM AQUAE SULIS, BATH, 144 sites									
520	25,400	5450	324,460	19,060	500	6080	500	127,180	11
ALL BATH STONE ANALYSES, 220 samples									
ND	5410	800	515,800	6430	570	2000	360	1400	3

ROMAN STONE FROM CORES, 33 samples from 3 blocks

ND	3049	457	384,330	5036	662	937	438	1031	5
P	Si	K	Ca	Fe	Mn	Al	Sr	S	Zr