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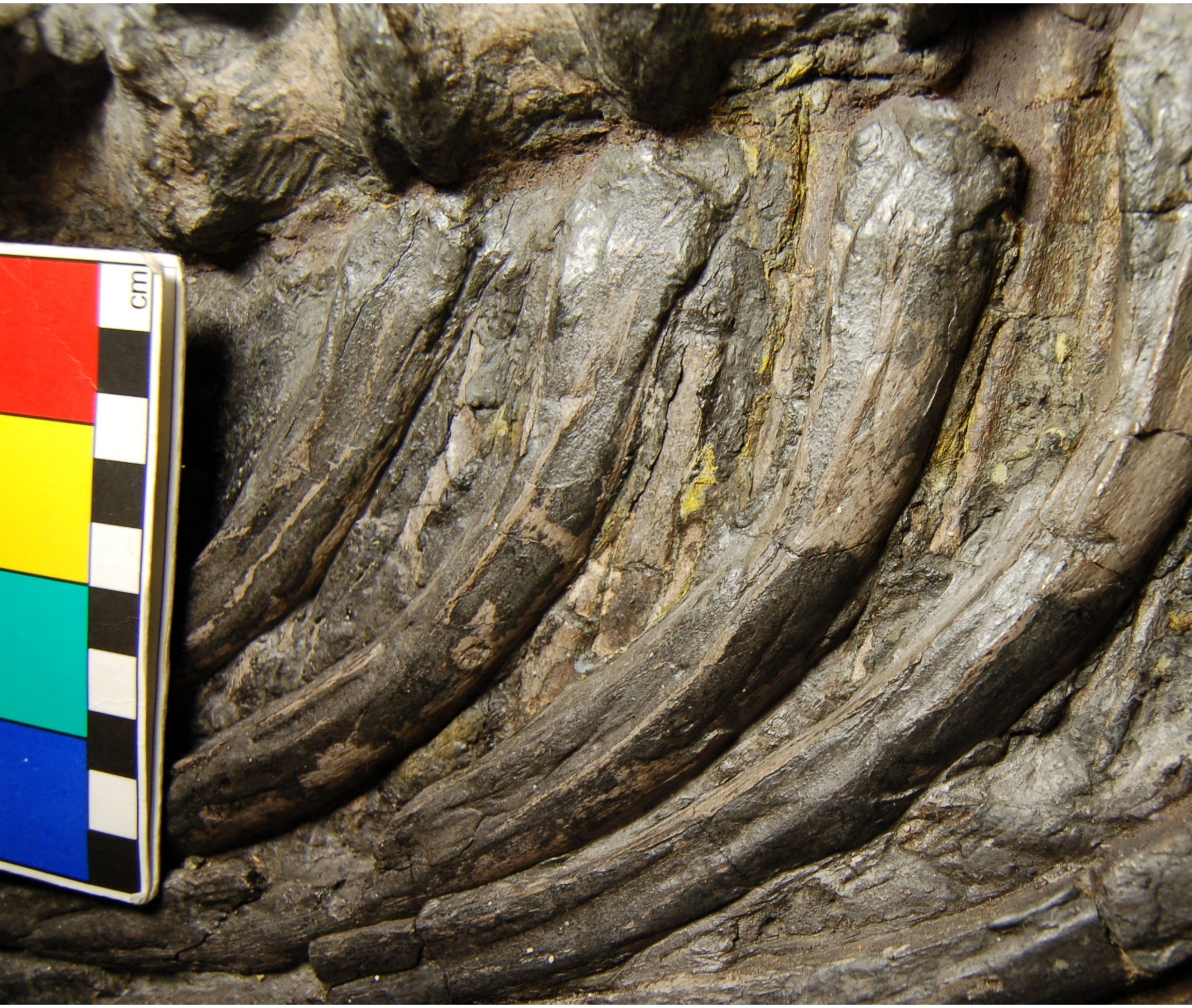

GEOLOGICAL CURATORS' GROUP

Geological collections thriving for science and society

The Geological Curators' Group (GCG) is a membership organisation founded in 1974, and a charity registered in England and Wales (no. 296050). We are affiliated to the Geological Society of London (the oldest national geological society in the world) and recognised by Arts Council England as a Subject Specialist Network (SSN). Further information can be found at www.geocurator.org.

Geological collections (rocks, minerals and fossils) are vital Earth heritage that help us understand the natural world. The Geological Curators' Group strives to connect every geological collection with appropriate resources, knowledge and skills to thrive and positively impact science and society.

We do this by:

- Supporting everyone working with and caring for geological collections of all types
- Advocating the value of expertise in the care and use of geological collections, and their importance for scientific research and education
- Connecting people, skills, information, and collections

GCG has always been a community, run by members elected from its membership. We take pride in our goals and enjoy working hard to reach them. Geological collections enrich lives and stimulate cutting edge science.

2020 COMMITTEE

Cover image: see Figure 1 in Petrera et al., inside. Cover designed by Nicolas Baird.

Geological Curator

Volume 11, No. 3

Contents

Editorial

Welcome to issue 11 (3).

I have now officially taken over as Editor for the Geological Curator and I would like to take this opportunity to say a huge thank you to Matthew Parkes, who has been Editor for the past 13 years. Only now do I understand the huge task in front of me!

In addition to a new editor, the journal is undergoing a few changes, most in response to feedback from our members, readers and contributors. First, you may notice that we have updated the style of the journal. The journal now has a dedicated page on the Geological Curators' Group website (https://www.geocurator.org/journal), with updated policies and guidelines and updated instructions for authors. We also have a new international editorial team. We hope to further expand our team to represent other areas of expertise relevant to geological collections and to other countries.

Another change, albeit temporary, is to the digital-only publication of issue 11 (3). Due to risks associated with Covid-19, the GCG committee decided to delay the distribution of print copies of this issue to minimise pressure on postal services and risk of further spreading the virus. Whilst we urge all members to consider both the environment and the costs incurred in producing physical copies of the journal, we understand that some members still prefer to receive physical copies. As such, a physical copy of the current issue will be delivered to all members who have requested it at the same time as issue 11 (4). We hope you understand and support us in our efforts. In the meantime, you can change to online-only delivery of the journal by logging into your membership account online and changing your preferences (https://www.geocurator.org/membership).

Whilst Covid-19 has fortunately had minimal impact on the production of the journal, it is of course profoundly affecting cultural and scientific institutions around the world. We are in a time of great uncertainty with regards to the future of our sector. With the trickle of closures of geological collections and loss of specialist curators over the last couple of years, we are gravely concerned regarding the potential additional impacts of the Covid-19 outbreak.

Generation of income, particularly through visitors and events, is increasingly seen as a preferred business model for the sector (although there is little evidence that this translates into longevity). However, it is those institutions which have relied most heavily on income generated through physical visits which will be most affected by recent lockdown measures. How, or if, this will translate into loss of museums, collections or experts is yet to be seen. I urge everyone who is responsible for geological collections to contribute to and build upon projects such as Mapping Museums (www.mappingmuseums.org) to monitor trends in the sector and to provide hard data to support future decision making.

Many institutions have begun adapting to the changing landscape by recognising the need for increasing digital innovation and online delivery of services. To sustain this and continue to provide rich, innovative and rewarding content which benefits society, it is vital there is investment into digitisation of collections in this time of financial hardship. To meet this challenge, the sector needs to be able to generate income through digital content as well as physical visits.

It has never been more important that we are able to demonstrate the value of geological collections for the economy and society at large. The committee and the editorial team are proud and eager to work with you all to support you as best we can during these difficult times.

Pip Brewer
Editor

An unusual papier-mâché replica of a fossil (?) from the Free Church of Scotland College collection

by Michael A. Taylor[1,2] and Lyall I. Anderson[1]

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A puzzling item of hollow painted papier-mâché, apparently a replica of a fossil and purportedly made about 1837, was acquired by the then Royal Scottish Museum in 1966 from the Free Church of Scotland College, Edinburgh, presumably from the latter's natural sciences teaching collection. It resembles a fossil reptile vertebra or chunk of plant root, but the original specimen and identification remain unknown. The replica does not appear to be a cast from a mould. The inherent limitations and potentials of the technique used, apparently combining three-dimensional modelling and accentuated paintwork, raise the possibility that it was made for Professor John Fleming by his wife Melville Christie as a teaching aid for his lectures at King's College, Aberdeen, or the Free Church College. The use of papier-mâché and paper to make replicas of fossils is briefly discussed.

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Introduction

The Free Church of Scotland College in Edinburgh was established in 1843. John Fleming (1785–1857), Professor of Natural Science there from 1845, taught natural science to the College's trainee ministers, so that they could better understand natural theology and argue against atheistic transmutationist notions (Fleming 1851). Fleming therefore created a collection for teaching purposes. In time, the collection fell out of use, and in 1966 some of the natural science material, both geological and zoological, was donated to the Royal Scottish Museum (now National Museums Scotland; Swinney 1982; Stace *et al.* 1987, pp. 123–124).

The object described in the present note presumably came with the Free Church collection in 1966 but was not formally accessioned at the time, perhaps because the then Royal Scottish Museum staff were unsure of its provenance and nature (it is now accessioned as NMS.G.2019.32.1). Today, the only surviving documentation is an undated note in the handwriting of Robert J. Reekie, of the then Department of Geology of the Museum, and signed by him, reading, 'Cast made from paper about 1837. Found in attic of Free Church at Mound June, 1966'. (The Mound is where the offices of the Free Church of Scotland are located in Edinburgh, next to the old Free Church College building, which now houses the University of Edinburgh's New College.) We do not know the original source for the date of 1837. However, if this is correct, then the object plainly preceded the establishment of the College in 1843 and John Fleming's arrival in 1845. Perhaps it was made for his personal collection or used in his teaching duties while he held his former chair at King's College, Aberdeen (now part of the University of Aberdeen).

We publish this puzzling replica in the hope that someone will recognise the original fossil on which it is modelled, and because it is unusual, though not unique, in being a palaeontological specimen replicated in papier-mâché. We later discuss the use of this technique in palaeontological collections.

Abbreviations and terminology. ELGNM, Elgin Museum, Moray Society, Elgin, Moray; NMS, National Museums Scotland, Edinburgh. In this note, the word *model* does not necessarily indicate a reduced-scale replica, such as a model railway; it could mean a life-size replica, or one enlarged compared to the original. Also, words such as *replica* are not to be understood as indicating only items produced by direct mechanical reproduction (such as actual casting).

Description and possible identification

The replica (Figures 1–4) has been slightly squashed at some time and is crumpled in places, but even now it cannot be much smaller than its original size. It appears to be hollow and made of papier-mâché composed of pasted layers. More precisely, the papier-mâché seems to be *carton collé* made up of pieces of wet paper pasted together one over the other.

Strictly speaking, the replica is not obviously a cast. There are no parting lines or joint lines to indicate that it was taken from a two-part or multi-part mould, perhaps made in sections lining each part of the hollow mould and then married together much as Easter eggs used to be produced. However, this is not conclusive, as the lines could have been obliterated by extra layers of wetted paper, as in the nineteenth-century anatomical models of animal hearts or human ears produced by L. T. J. Auzoux. Even so, the replica seems more like something sculpted by hand rather than created in a mould.

The replica is painted in various shades of brown and grey, with detailing in graphite pencil. These appear to show areas of remaining matrix, or mineral encrustation, in a very specific way. The strong impression is that the replica is intended to represent a

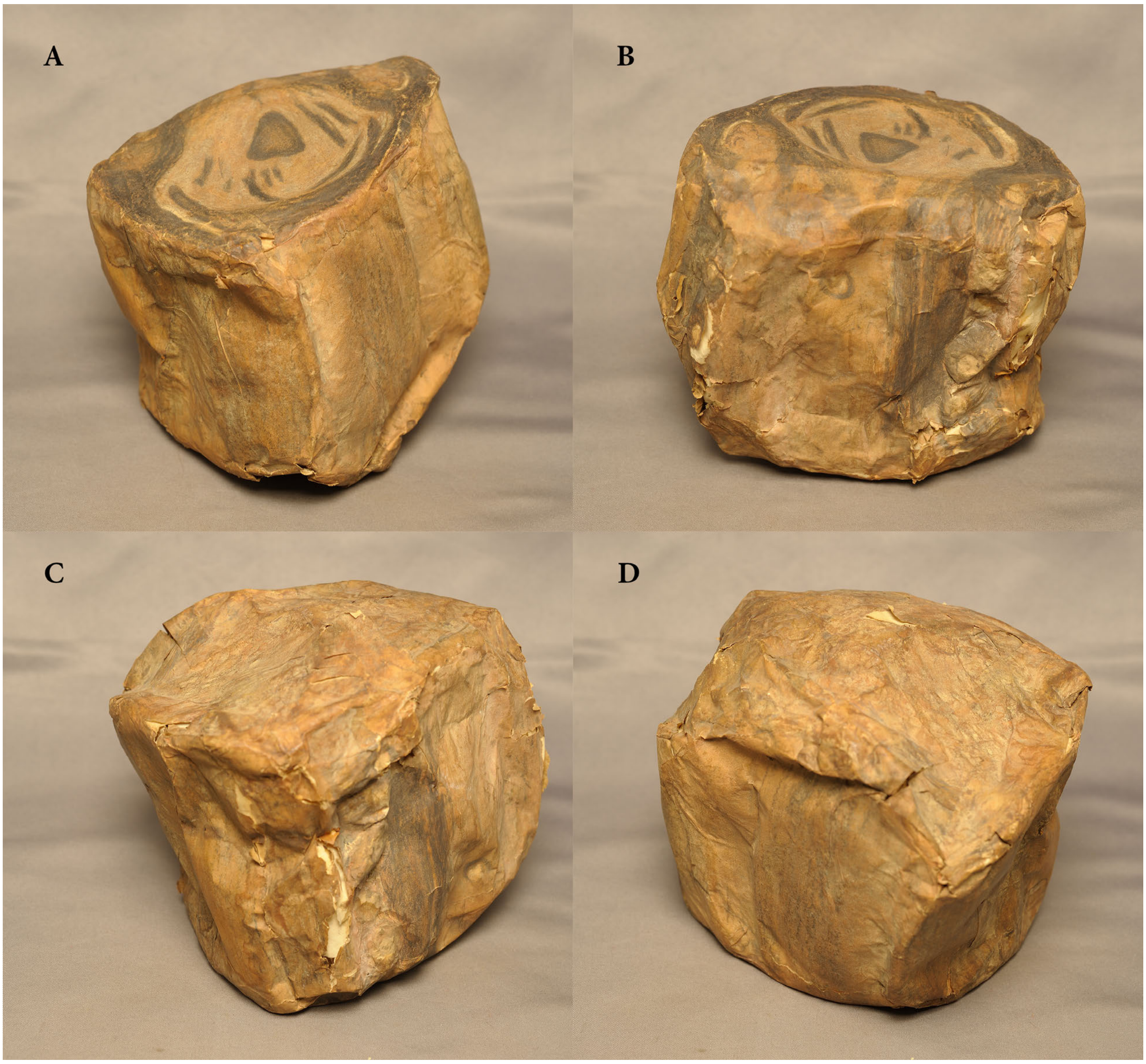

Figure 1. NMS.G.2019.32.1, problematic fossil replica in different views. A. Note shape similar to a vertebral centrum and painted features, texture, and patterns. Maximum dimension approximately 138 mm from lower left to upper right, measuring parallel to the apparent 'articular face'. B. Note apparent series of simulated nodules, some 'broken' across, right of centre in this view, running from top downwards on this side and reminiscent of a fossil plant root. They are executed in part in paint, rather than three-dimensional modelling. C-D. Note crumpling and damage to the papier-mâché. Photographs W. R. P. Crighton, copyright and courtesy National Museums Scotland.

specific individual fossil.

We have not been able to locate the original object of which this is a replica, despite initial inquiries in the most obvious repositories as far as was possible in the run-up to the COVID-19 lockdown (University of Aberdeen Museums and Special Collections, Hannah Clarke, pers comm. 19 February 2020; National Museums Scotland, Andrew Kitchener, pers comm. 18 February 2020). We have not even identified the original object itself, which was apparently a fossil rather than an inorganic structure. It has two roughly flat faces opposite and parallel to each other, and its maximum dimension parallel to these faces is about 150 mm. It is reminiscent in size and shape to a slightly angular vertebral centrum of a pliosaur or a dinosaur such as *Cetiosaurus*, or a cetacean, but the replica was not recognised by a conference of vertebrate palaeontologists who were shown images of it. The replica is also reminiscent of a section of plant root with a row of little nodules, carefully detailed on the replica. But, again, a palaeobotanist was unable to recognise it definitively as plant (Jason Hilton, pers comm. 2009). We considered the possibility that it represents an endocast of a cavity or mouldic fossil, but again its identity escapes us. It was presumably something scarce enough for Fleming not to be able to obtain his own specimen, which hints at a vertebrate rather than plant.

The problem with achieving a modern identification may partly arise because the mystery item is only an approximate replica in three dimensions. We suspect that the basic shape was made up by eye and measurement. The painted coloration did not just represent the original coloration but seems to have been used to provide finer detail and further refinement of three-dimensional shapes which were too difficult or time-consuming to represent in papier-mâché without going to the trouble of making moulds (for instance, the detail of the nodular structures visible on one side in Figure 2).

Likely function

Such a replica would be of little value for serious research as it would not bear close examination. But it would be perfectly adequate for a lecture or demonstration class. The replica's approximate shape, accented with the *trompe l'oeil* coloration seen in our example, would be an acceptable representation when seen at a distance. Moreover, papier-mâché had advantages. It was much lighter and cheaper than a plaster cast, more portable, and less prone to damage and chipping under the careless handling meted out by students. Significantly, William Buckland (1784–1856) used leather models of fossils in his lectures (Kölbl-Ebert 2012, p. 283). Like our replica, these can only have been approximations. But they would have been adequate to portray, say, a *Megalosaurus* femur without risking the heavy and brittle original. In any case, one could not use a mould if making a model enlarged or reduced in scale to a more convenient size or from a published illustration without access to the actual specimen. However, an initial search of the most likely of Fleming's works and Cuvier's books yielded no candidate. In any case, the coloration seems to have been executed in the kind of detail taken from an actual fossil rather than a two-dimensional and probably uncoloured plate.

We also wonder if our mystery replica was made by Fleming's wife, Melville Christie (1797–1862), for her husband to use in his teaching. She certainly helped him by acting as an amanuensis and artist in support of his research, including copying plates in scarce publications (in 'such a style of drawing and colouring as to surpass the original'; Duns 1859, p. xiv clearly includes painting as well as drawing) and preparing the originals to illustrate his works (Fleming 1822, vol. I, p. xv; Duns 1859, p. xiv). William Buckland's wife Mary Buckland (1797–1857) produced at least some of the leather models that her husband used in lectures. Interestingly, she also made inflated paper globes to teach geography to village schoolchildren: not far from the kind of skills needed to produce a hollow papier-mâché bone (Kölbl-Ebert 1997, p. 37; 2012, p. 283).

Discussion: papier-mâché modelling in nineteenth-century palaeontology

Our mystery replica appears to be made of the simplest and crudest kind of papier-mâché, *carton collé*, made up of pieces of wet paper pasted over each other. During the nineteenth century, papier-mâché was a common material for items such as tea-trays and screens. There was at least one 'manufactory' for papier-mâché in Edinburgh around 1837 (Anonymous 1867, p. 151). However, the fossil replica is much rougher than one would expect of the product of a commercial company. It could very well be home-made, so to speak. This arts and crafts technique was, and still is, commonly taught to children.

Papier-mâché, like decorative work with shells and feathers, was also seen as a suitably feminine skill for upper- and middle-class ladies in early nineteenth-century Britain. Thus, it would not be surprising if, as we suggested above, the mystery replica was made by Mrs. Fleming.

A more specialist variety of papier-mâché was *carton pâté*, a pasty compound forced into special moulds. It was used, for instance, in the exquisite anatomical models of L. T. J. Auzoux (Alberti *et al.* 2019). But those were executed to a far higher level of refinement and detail than the replica discussed here, which does not seem to have been produced using a mould.

A third paper-based material was printer's 'flong'. Flong, presumably from the French word *flan*, was made of layers of blotting paper and tissue paper pasted together. Each sheet was wetted and then beaten forcibly down onto frames of set type, then dried and peeled off. It was then used as a mould for casting stereotype plates in printer's metal, which were then used for the actual printing work. This allowed the original typeset matter to be broken up and the expensive moveable type to be reused. Flong caught our attention because the Free Church-supporting newspaper *The Witness* was edited by the geologist Hugh Miller (1802–1856) and had its printing workshop near the College. However, if the 1837 date is correct, the replica antedates Miller's arrival in Edinburgh (to take up the editorship in 1840) and the likely introduction of flong in printing, even in Edinburgh, which was a major centre of the trade. Gaskell (1995, pp. 203–204) stated that the flong method was patented in 'England' only in 1839—admittedly when England was separate from Scotland for the purposes of patent law—and that it was only in the mid-1850s that flong itself became generally used in 'England', which may or may not be intended to include Scotland. So, even if Edinburgh was (as one would expect) abreast of such technical developments, flong cannot have been used on the mystery replica, in which, in any case, thinner paper seems to have been employed.

Flong, however, sounds such a useful material that we are surprised not to have come across its use in palaeontology. More generally, we would have thought it obvious to use ordinary blotting paper or papier-mâché, in a gentler version of the flong technique, to make a quick copy of such fossils as are preserved as a shallow but three-dimensional object, rather like a modern latex or silicone peel. But it is surprising how little mention there is of such things, even when paper was cheap and common. Interestingly, Elgin Museum holds correspondence between the Reverend George Gordon (1801–1893) of Birnie near Elgin, the Reverend James M. Joass (1829–1914) of Golspie, and Sir Philip de M. G. Egerton (1806–1881). In 1867–1868 they discussed, amongst other things, the use of paper to cast sculptured stones and fossils (Collie and Bennett 1996, e.g. pp. 90, 92, items 67.24, 68.1, 68.3, 68.4). It is not clear whether Joass invented the precise method, which he described to Gordon in a letter of 16 October 1867 (ELGNM, Gordon correspondence, item 67.24). To replicate a large archaeological item (such as, presumably, a Pictish carved slab, which would be fairly flat), Joass soaked two sheets of thin brown paper in water, pasted them together, and laid them, wet, over the object. He laid a damp towel over the paper sheets and forced it down into the deeper parts of the carving with a 'stiff hair brush rounded on the face', then removed the towel and adjusted the fit of the paper with his finger where needed. When dry, the paper could be rolled up and carried easily. For fossil plants and fishes such as *Glyptopomus*, two sheets of white paper, thinner than brown paper and impressed by hand, were sufficient for the specimen to be, as he put it, 'nature-printed'. (In fact, 'nature printing' usually had a quite different meaning: the laying of leaves, seaweeds, and such on top of light-sensitive paper to form silhouetted prints.) Of course, Gordon's sheets of indented paper would be moulds rather than casts (unless the fossil itself was a mould). But they would still be quick, easy, and cheap to make and post, compared to casts in plaster or gutta-percha. Egerton was impressed with Joass's impressions of a fossil fish, writing that the method was 'very effective and gives a better idea of the original' than plaster or gutta-percha (letter of 25 January 1868, ELGNM, Gordon correspondence, item 68.1).

Again what is surprising is that the method seems to have been new to Gordon and his colleagues. The implication is that it was rarely used, although Traquair (1894) did mention papier-mâché 'casts of tolerably entire plates' of the Old Red Sandstone fossil fish *Psammosteus paradoxus* that the British Museum (Natural History) had been sent from Russia. Hugh Miller himself did use paper to make life reconstruction models of his eponymous Old Red Sandstone fish *Pterichthyodes milleri*. But his representations of this rather angular and partly armoured fish were created with the very different technique of folded and pasted paper in the manner of origami, or perhaps rather the card cut-out-fold-and-glue buildings sold as scenery for model railways (Forey 2003; Taylor and Anderson 2017, p. 347).

Nevertheless, papier-mâché must have been one of the cheapest modelling compounds available to nineteenth-century palaeontologists, and we have found sporadic examples of its employment. It was used, for instance, in the restoration of missing parts in mastodon skeletons in America, and for making casts of skeletons of the Cenozoic mammal *Dinoceras* using 'paper cast in plaster moulds' (Emerton 1888, p. 343; Howie 1986, pp. 14, 19–20). But all these examples of papier-mâché in palaeontology date to the second half of the nineteenth century. Even Auzoux's anatomical, zoological, and botanical models do not date back earlier than the 1840s. We are not aware of any other papier-mâché fossil replicas contemporary with the (apparent) 1830s date of the Free Church College example. This makes it harder to assess our mystery replica. Perhaps, in fact, such things used to be much commoner, and our replica is an accidental survivor. In the long term, one would expect papier-mâché and similar replicas to be vulnerable to damp and to mechanical damage (even if strengthened with varnish such as shellac, which would provide only superficial protection). They would surely also attract insect pests such as silverfish, which would relish any starch or animal glues used. Moreover, if damaged or of no further use, they were apt to be seen as mere replicas of much less value than original specimens and were therefore prone to be discarded, as were plaster casts (Taylor and Clark 2016). The standards and techniques of decorative arts curators and conservators could profitably be examined when considering the care of those paper-based replica fossils that do survive.

We welcome suggestions as to the identity of the original of the Free Church replica.

Acknowledgements

We thank Andrew Ross and Stig Walsh for assistance with the replica, Bill Crighton for taking the photographs, Andrew Kitchener and Hannah Clarke for collections information, Janet Trythall for copies of the letters at Elgin Museum, and Jason Hilton, Nigel Larkin, Martin Rudwick, Hugh Torrens, and two anonymous referees for discussion. We are grateful for the support of the libraries of National Museums Scotland and the University of Leicester.

References

ALBERTI, S. J. M. M., BLACKWELL, A., DAVIDSON, P., GOLDBERG, M. and SWINNEY, G. N. 2019. The art and science of replication. Copies and copying in the multi-disciplinary museum. *In* B. Brenna, H. Dam Christensen and O. Hamran (eds). *Museums as Cultures of Copies: the Crafting of Artefacts and Authenticity*. London: Routledge. 13–26.

ANONYMOUS, 1867. Memoir of John Stewart. *Friends' Quarterly Examiner* **1**, 147–165.

COLLIE, M. and BENNETT, S. 1996. *George Gordon: an Annotated Catalogue of his Scientific Correspondence.* Aldershot: Scolar Press.

DUNS, J. 1859. Memoir. *In* J. Fleming. 1859. *The Lithology of Edinburgh* [...] *Edited, with a Memoir, by the Rev. John Duns, Torphichen*. Edinburgh: Kennedy. i–civ.

EMERTON, J. H. 1888. '[...] restoration of the skeleton of *Dinoceras* [...]'. *Proceedings of the Boston Society of Natural History* **23**, 342–343.

FLEMING, J. 1822. *The Philosophy of Zoology; or, A General View of the Structure, Functions, and Classification of Animals*. Edinburgh: Constable.

FLEMING, J. 1851. Introductory lecture on natural science. *In* Anonymous. *Inauguration of the New College of the Free Church, Edinburgh* […]. Edinburgh: Johnstone & Hunter. 213–232.

FOREY, P. 2003. Palaeozoic origami. *Set in stone. The NHM Palaeontology Dept. Newsletter* **1** (3), 11–12.

GASKELL, P. 1995. *A New Introduction to Bibliography.* Corrected reprint. New Castle, Delaware: Oak Knoll Press.

HOWIE, F. M. P. 1986. Conserving and mounting fossils: a historical review. *Curator* **29** (**1**), 5–24.

KÖLBL-EBERT, M. 1997. Mary Buckland (*née* Morland) 1797–1857. *Earth Sciences History* **16**, 33–38.

KÖLBL-EBERT, M. 2012. Sketching rocks and landscape: drawing as a female accomplishment in the service of geology. *Earth Sciences History* **31**, 270–286.

STACE, H. E., PETTIT, C. W. A. and WATERSTON, C. D. 1987. *Natural Science Collections in Scotland (Botany, Geology, Zoology)*. Edinburgh: National Museums of Scotland.

SWINNEY, G. N. 1982. Some Richardson type specimens in a collection of Australian fishes, with notes on their collector Robert Neill. *Archives of Natural History* **11**, 17–25.

TAYLOR, M. A. and ANDERSON, L. I. 2017. The museums of a local, national and supranational hero: Hugh Miller's collections over the decades. *Geological Curator* **10** (7), 285–368.

TAYLOR, M. A. and CLARK, R. D. 2016. Ichthyosaurs from the Lower Lias (Lower Jurassic) of Banwell, Somerset. *Geoscience in South-West England* **14**, 59–71.

TRAQUAIR, R. H. 1894. On *Psammosteus taylori*, a new fossil fish from the Upper Old Red Sandstone of Morayshire. *Annals of Scottish Natural History* **9**, 225–226.

Large reptiles, localised solutions: investigating alternative delivery systems for the treatment of oversized pyritic specimens

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Ethanolamine thioglycolate and sepiolite paste is a traditional method for localised treatment of pyrite oxidation products, but there are drawbacks to the technique. The paste can be difficult to apply, especially on non-horizontal surfaces, and is occasionally ineffective. This article documents trials of solvent gel delivery systems and proposes Laponite RD (a synthetic colloidal clay) as an effective alternative.

Petrera, L., Allington-Jones, L. and Miles, K. 2020. Large reptiles, localised solutions: investigating alternative delivery systems for the treatment of oversized pyritic specimens. *Geological Curator* **11** (3): 213-216.

Introduction

Pyrite in its pure form and as a constituent of fossils and mineral specimens is a common component of earth science collections and is inherently unstable in our atmosphere: pyrite will oxidise in the presence of moisture. The by-products of this reaction usually comprise sulphur dioxide, sulphuric acid, and hydrated ferrous sulphates (Miles 2019). These decay products are a health hazard and will lead to acidic corrosion of other minerals, labels, and storage media. Expansion cracks may also occur because the oxidation products, and their hydrates, are much larger in volume than the original minerals (Larkin 2011). If left unchecked, pyrite oxidation can destroy specimens and their labels.

To prevent continued deterioration, oxygen and relative humidity levels must be controlled (Allington-Jones and Trafford 2017), but this is not always possible for oversized specimens such as entire marine reptile specimens in slabs (a small detail of such a specimen is shown in Figure 1). Ammonia vapour treatment of the oxidation products (Irving 2001) is beneficial, but again problematic with large specimens (Andrew 1999). The alternative is localised treatment with ethanolamine thioglycolate paste (Cornish and Doyle 1984). This method will not prevent future oxidation, but it stabilises the decay products, removing harmful mineral hydrates from the surface and reducing susceptibility to damage at the standard relative humidity for museum galleries and storerooms that contain mixed collections.

Ethanolamine thioglycolate and sepiolite (a natural clay) paste has been used for decades to treat large specimens with active pyrite oxidation (Cornish and Doyle 1984; Fenlon and Petrera 2019) but it is difficult to apply on non-horizontal surfaces, due to its tendency to crumble. With developments in solvent gels for cleaning water-sensitive objects (*Stavroudis 2017)*, it became time to explore alternative delivery methods.

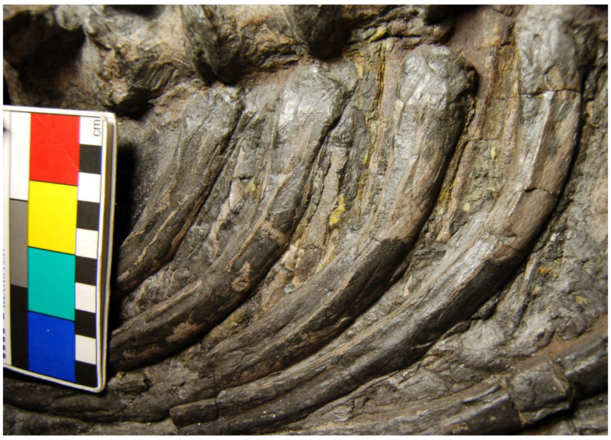

Figure 1. Archive image of active pyrite oxidation in the stomach area of a plesiosaur at the Natural History Museum in London (UK).

A gel is a liquid formulation thickened with a polymer or other high molecular weight material. Gelled formulations are used to lengthen solvent retention time and to control the depth of penetration by limiting capillary action. This occurs because the solvents are held within the gel and will not evaporate or spread as rapidly as unconstrained solutions. They are also used to control the cleaning process on vertical or other complex surfaces or to increase the gel's effectiveness in extracting the soiling or stain as the gel dries. The advantages of gels include control of solvent evaporation rate and of capillary flow into

Gel/paste	Components (before adding ethanolamine thioglycolate)	Source for recipe
Laponite RD	5% w/v Laponite RD in ethanol	Umney and Rivers 2003
Methyl cellulose	5% w/v methyl cellulose in pure water, then add ethanol to reduce methyl cellulose to 2.5%.	Umney and Rivers 2003
Sepiolite	Sepiolite in ethanol, mixed to a paste consistency	Cornish and Doyle 1984
Klucel G	7% w/v Klucel G in ethanol	Umney and Rivers 2003
Carbopol	Carbopol and ethomeen C25 gel with ethanol as the polar solvent	Umney and Rivers 2003

Table 1. The delivery systems trialled.

surrounding areas and underlying layers (a particularly important factor for moisture-sensitive objects as they require a limited depth of penetration), control of the surface contact time to increase effectiveness of a chemical agent and reduce potential effects on the surface, and minimising human exposure to solvents (Khandekar 2004). Gels significantly increase viscosity and therefore reduce evaporation rate of the solvent from the surface being treated and from the surface of the gel, by altering the surface-to-volume ratio. The disadvantage of gels is that clearance of residues from a surface may present problems since gels are by definition non-volatile.

The ideal gel would retain integrity when mixed with ethanolamine thioglycolate, allow effective treatment of the oxidation products, leave no trace on the specimen surface, and allow treatment of vertical surfaces.

Methods

Table 1 shows the six delivery systems that were trialled with the addition of ethanolamine thioglycolate. The gels were chosen for their compatibility with ethanol, the solvent used in ethanolamine thioglycolate paste and immersion treatments (Cornish and Doyle 1984). Rigid gels were not tested, since fossil surfaces are usually very uneven, and contact from a gel sheet would have been insufficient. Setting a rigid gel directly onto the surface would have increased the treatment time unacceptably—with ethanolamine thioglycolate immersion, treatment time must be limited to prevent the ferrothioglycolate anion from oxidising to an insoluble precipitate on the specimen surface (Cornish 1987). Success was judged by several parameters: whether adding the ethanolamine thioglycolate disrupted gelling consistency, how well the gel adhered to the surface of a specimen, whether residues remained on the surface, and how effective the treatment of oxidation products was. Treatment time for each gel was one hour (with cling film cover), followed by clearing with ethanol swabs. The sepiolite was cleared using a sepiolite and ethanol pack for one hour, then allowed to dry overnight before being brushing off. Residues were detected by adding Fluorescin (as recommended by Sullivan *et al.* 2017) to the gel at initial mixing stage and the treatment area was inspected using UV light after clearing. Figure 2 shows the application of the gels and paste trialled.

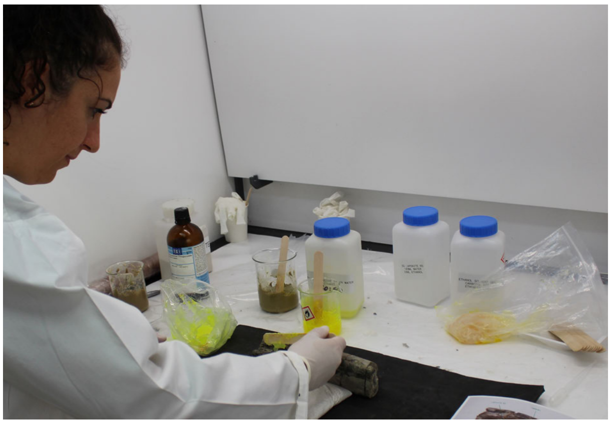

Figure 2. Application of the trial gels and paste within a fume cabinet. The bright yellow colouration is due to the presence of fluorescin dye, added only for the purposes of this trial.

Results

The results of the trials are shown in Table 2 and Figure 3. Laponite RD remained the most localised and therefore gave the most controlled treatment; it was easy to remove and clear. It can be applied to angled surfaces and does not leave a residue. Physical treatment also takes much less time than the sepiolite technique. Although preparation time is longer than for sepiolite, a large batch of gel can be made up in advance and the ethanolamine thioglycolate added to the required amount when necessary. Ethanolamine thioglycolate oxidises rapidly, so should not be mixed more than an hour in advance of application. Since the initial trials, the Laponite gel method has been used to treat larger areas on several specimens

Before Treatment (showing gel test sites) **After Treatment**

Figure 3. The test sites in normal visible light before and after treatment. The sites to be treated with each gel/paste are labelled in the image on the left.

at the Natural History Museum (London, UK) and it proved to be very successful, even on inverted surfaces.

Water is a risk for pyritic material but should not be a problem in this case – the gel delivery system ensures that the water only affects the surface being treated and treatment time is limited to one hour. The very nature of pyrite decay means that cracks form in the specimen, and the surface of the bone can become very degraded and porous. In such areas the gel should not penetrate the specimen, but the treated area can be flushed with ethanol if there are concerns that swabbing has not removed all components of the gel. It was found that the oxidation products of pyrite decay actually fluoresce slightly under UV light (Figure 4), so great care was taken when interpreting the results.

Conclusion

The most effective method proved to be Laponite RD, but care must be taken when adding the ethanolamine thioglycolate, since the physical act of overmixing disrupts the gel and creates a soupy consistency. Laponite RD gel is, therefore, still not an ideal delivery system, but it is nevertheless a significant improvement on sepiolite paste. A large batch of the gel can be made in advance and stored, only adding the ethanolamine thioglycolate to a small amount when required for use. This treatment will not stop further oxidation occurring, but it will at least remove the oxidation products and prevent damage from sulphuric acid and continued expansion by mineral hydrates. The risk of undertaking remedial treatments must always be considered by creating a condition report and assessing if any previous treatments, such as adhesives, may be compromised by the gel. Further work is required in trialling other methods such as attapulgite clay, which may survive overmixing more effectively. Unfortunately, a source of conservation-grade attapulgite has not yet been identified. During these tests, it was found that the oxidation products of pyrite decay fluoresce slightly under UV light. This may form a method for veri-

	Remained localised	Can be applied on non-horizontal surfaces	Gel colour change	Easy to remove	Effective treatment of decay products	Fluorescent traces remain (gel not cleared sufficiently)	Recommended
Laponite RD	Yes	Yes	Yes	Yes	Yes	No	Yes
Methyl cellulose	No	No	Yes	Yes	No	Yes	No
Sepiolite	Yes	No	Yes	Yes	Partial	No	No
Klucel G	Yes	Yes	No	Yes	Yes	Partial	No
Carbopol	Solidified when mixed with ethanolamine thioglycolate, became unusable as a gel						No

Table 2. Results of trials.

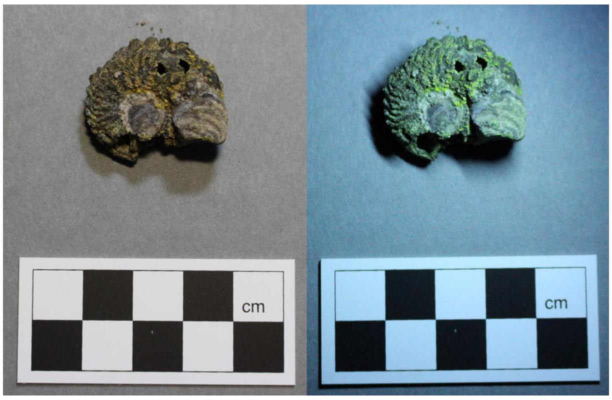

Figure 4. Ammonite with oxidation products on the surface. Left: under normal visible light. Right: under UV light.

fying the presence of active pyrite decay products, which could replace the use of an aqueous pH test and therefore reduce the need to apply water to susceptible specimens.

Recipe

1. 5 g Laponite RD in 100 ml distilled or deionised water (gradually add the powder and stir)
2. Add 33 ml ethanol (stir)
3. When ready to use, add 5% by volume of ethanolamine thioglycolate (85% solution)
4. Apply to the oxidising area with a brush or spatula, cover with cling film, and leave for one hour
5. Remove the gel and then swab the surface with ethanol

Health and Safety Information

Laponite RD powder is an irritant for eyes and lungs and by ingestion. Ethanol is flammable and causes severe eye irritation and respiratory tract irritation. It may cause central nervous system depression, adverse reproductive and foetal effects, and liver, kidney, and heart damage. Ethanolamine thioglycolate 85% in water is toxic if swallowed and causes skin irritation and serious eye irritation. Safety spectacles, disposable nitrile gloves, and a lab coat must be worn, and fume extraction must be utilised at all stages.

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References

ALLINGTON-JONES, L. and TRAFFORD, A. 2017. Conservation in a Barcode Age: A cross-discipline re-storage project for pyritic specimens. *ICOM-CC 18th Triennial Conference* **49** (9), 4–9.

ANDREW, K. J. 1999. Conservation of the Whitby Saurians—Large scale, on site geological conservation in North Yorkshire, United Kingdom. *Journal of the Canadian Association for Conservation* **24**, 3–10.

CORNISH, L. and DOYLE, A. 1984. Use of ethanolamine thioglycolate in the conservation of pyritized fossils. *Paleobiology* **27** (2), 421–424.

CORNISH, L. 1987. The treatment of decaying pyritiferous fossil material using ethanolamine thioglycolate. *Geological Curator* **4** (7), 451–454.

FENLON, A. and PETRERA, L. 2019. Pyrite oxidation: a history of treatments at the Natural History Museum, London. *Geological Curator* **11** (1), 9–18.

IRVING, J. 2001. Ammonia: a practical guide to the treatment and storage of minerals. *Natural Science Conservation Group Newsletter* **17**, 18–32.

KHANDEKAR, N. 2004. Gelled systems: theory and early application. *In* V. Dorge (ed.) *Solvent Gels for the Cleaning of Works of Art: The Residue Question*. Los Angeles: The Getty Conservation Institute. 5–11.

LARKIN, N. R. 2011. Pyrite decay: cause and effect, prevention and cure. *NatSCA News* **21**, 35–43.

MILES, K. 2019. The role of pyrite in fossilisation and its potential for instability. *Geological Curator* **11** (1), 3–8.

RIVERS, S. and UMNEY, N. 2003. *Conservation of Furniture*. Oxford: Butterworth-Heinemann.

STAVROUDIS, C. 2017. Gels: evolution in practice. *In* L. V. Angelova, B. Ormsby, J. H. Townsend and R. Wolbers (eds.) *Gels in the Conservation of Art*. London: Archetype, 209–217.

SULLIVAN, M., DUNCAN, T., BERRIE, B. and WEISS, R. 2017. Rigid polysaccharide gels for paper conservation: a residue study. *In* L. V. Angelova, B. Ormsby, J. H. Townsend and R. Wolbers (eds.) *Gels in the Conservation of Art*. London: Archetype, 250–256.

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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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 m^3 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.

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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 kilometre (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

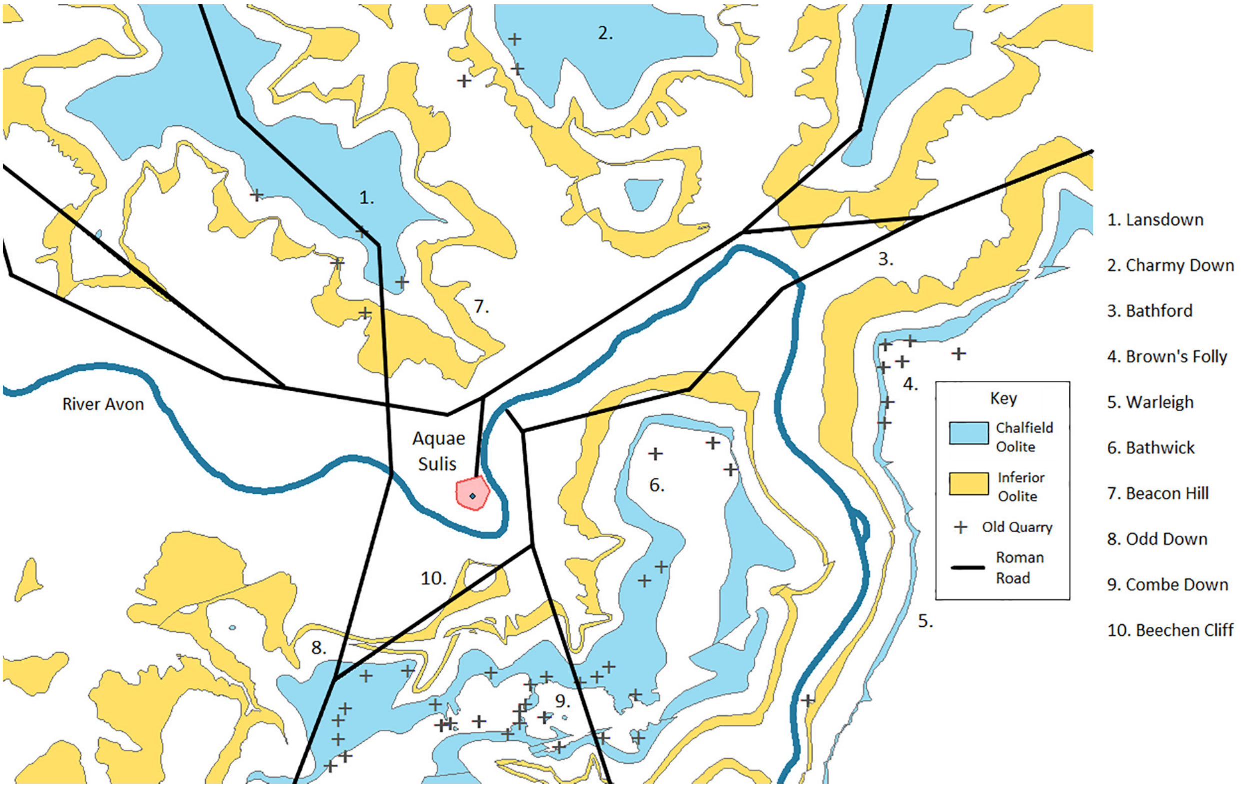

Figure 1. Map of the area around Bath showing the location of* Aquae Sulis*, sites of old quarries, the distribution of the Chalfield Oolite (blue shading) with the Bath Stone and the Inferior Oolite (yellow shading), and the known Roman roads. Modified from Davenport (1994)

known to have been used by the Romans elsewhere, e.g. Dundry Stone, Doulting 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.

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 (B&NES) Council at Pixash Lane, Keynsham, kindly organised by the Roman Baths Museum Curator, Stephen Clews, 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).

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).

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, Oo = Oolite, Gp = Group.

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).

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 m^3 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 1,250 to 1,666 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 m^3 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 four or five underground quarries working the stone. Upper Lawns Quarry has a rectangular area of approximately 100 m by 50 m and a CDO thickness of 9 m (freestone thickness 5 m), giving 45,000 m^3 of stone, of which 25,000 m^3 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 18th–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 tens of kilometres 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).

Bath Stone and old quarries

Bath Stone sedimentological features

Combe Down Oolite Member (CDO): The CDO is 9–18 metres thick with 5–12 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 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

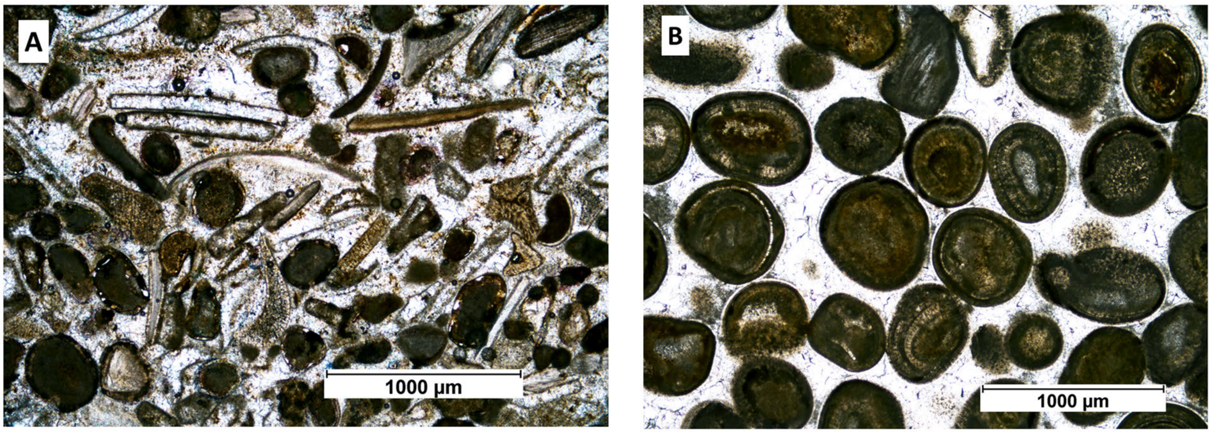

Figure 3. Bath Stone in thin-section. A. Combe Down Oolite: ooids, generally smaller than in Bath Oolite, with more shell fragments (bioclasts). B. Bath Oolite: dominated by ooids, with a calcite spar cement. Thin-sections prepared by Ron Smith. Brown's Folly, near Bathford.

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. Dagham Stone near Cirencester), there are several levels of spongestone (Green and Donovan 1969) – a limestone with many centimetre-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 (BO): 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

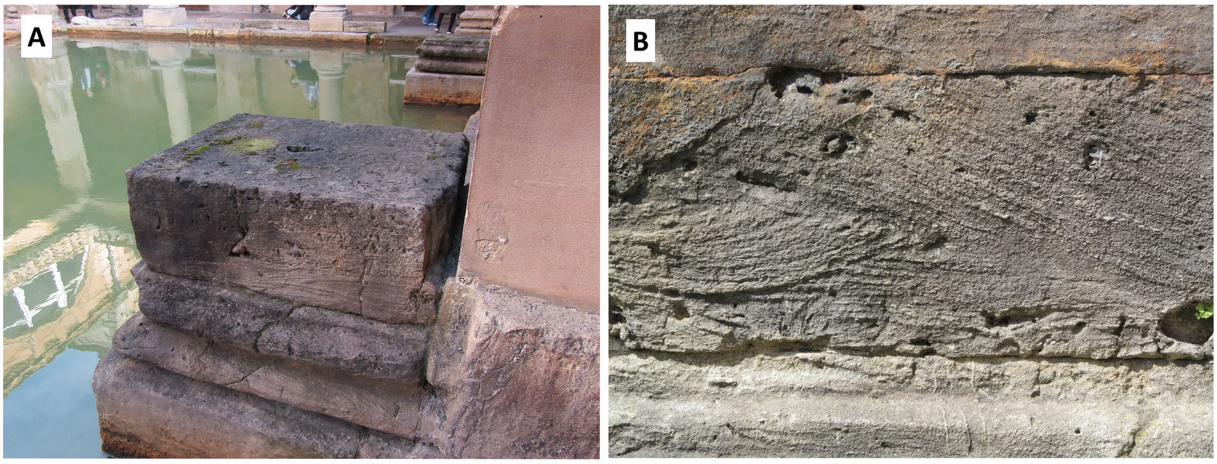

Figure 4. A. Base of a Roman column by the side of the Great Bath with cross-bedding, cavities from burrow structures, and fractures. Note the Lewis bolt-hole on the top surface. The columns in the background are late 19th century. Rectangular block of Roman stone 70 x 40 cm. B. Cross-bedded shelly oolitic grainstone with burrows and cavities, a stone from the base of a Roman column. Field of view: 40 x 25 cm.

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 5B). 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 12th–16th centuries. Many Roman quarries will have been extended in these later phases of activity, 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.

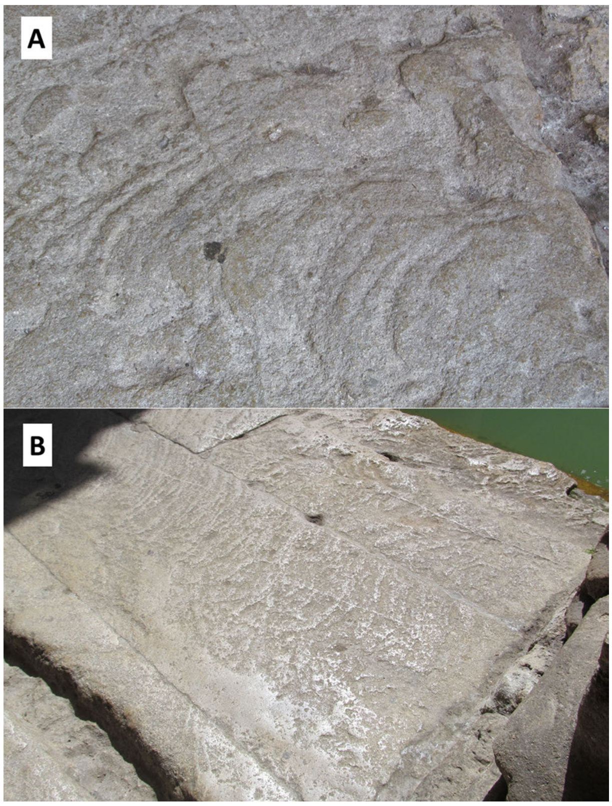

Figure 5. Paving stones adjacent to the Great Bath with curved ripple cross-lamination visible on the bedding plane surface (A. field of view 70 cm across) and fractures crossing a well-dressed and also partly polished slab with cross-lamination (B. width of slab 50 cm).

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 to many centimetres 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.

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.

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 three 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^{th}–19^{th} 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.

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.

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*.

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 cal-

P	Si	K	Ca	Fe	Mn	Al	Sr	S	Zr	Mo	Ba	Pb	Zn	Cr	Ti
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	2.2	66	ND
ROMAN STONE FROM AQUAE SULIS, BATH, 144 sites															
520	25400	5450	324,460	19060	500	6080	500	127,180	11	8	240	660	300	110	570
ALL BATH STONE ANALYSES, 220 samples															
ND	5410	800	515,800	6430	570	2000	360	1400	5	5	230	1.5	3	58	ND
ROMAN STONE 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**	**Ti**

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 Brown's Folly and Bath Oolite at Warleigh; Roman stone from Aquae Sulis; All Bath Stone analyses, and Cores from three Roman blocks. ND = not detected.

cite (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 tens of thousands ppm), high Sr (several thousand ppm) and high Na (a few thousand 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 and 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 $\delta^{13}C$ and $\delta^{18}O$ 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 tens to a few thousand 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 5 x 3 x 1 cm tablets. With the tablets and Roman stones, three analyses were made from each and averaged.

The objectives with the chemical analyses are: 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: ST796–664), 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, FeS_2, 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 and 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 hundred 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 1,500 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, SO_4, Ca, Cl, Na, HCO_3, Mg, Si, and Fe are extremely high; arsenic (As) is present in spa water at 7 ppb (μg 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 x400 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). 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 *c.* 1,500 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

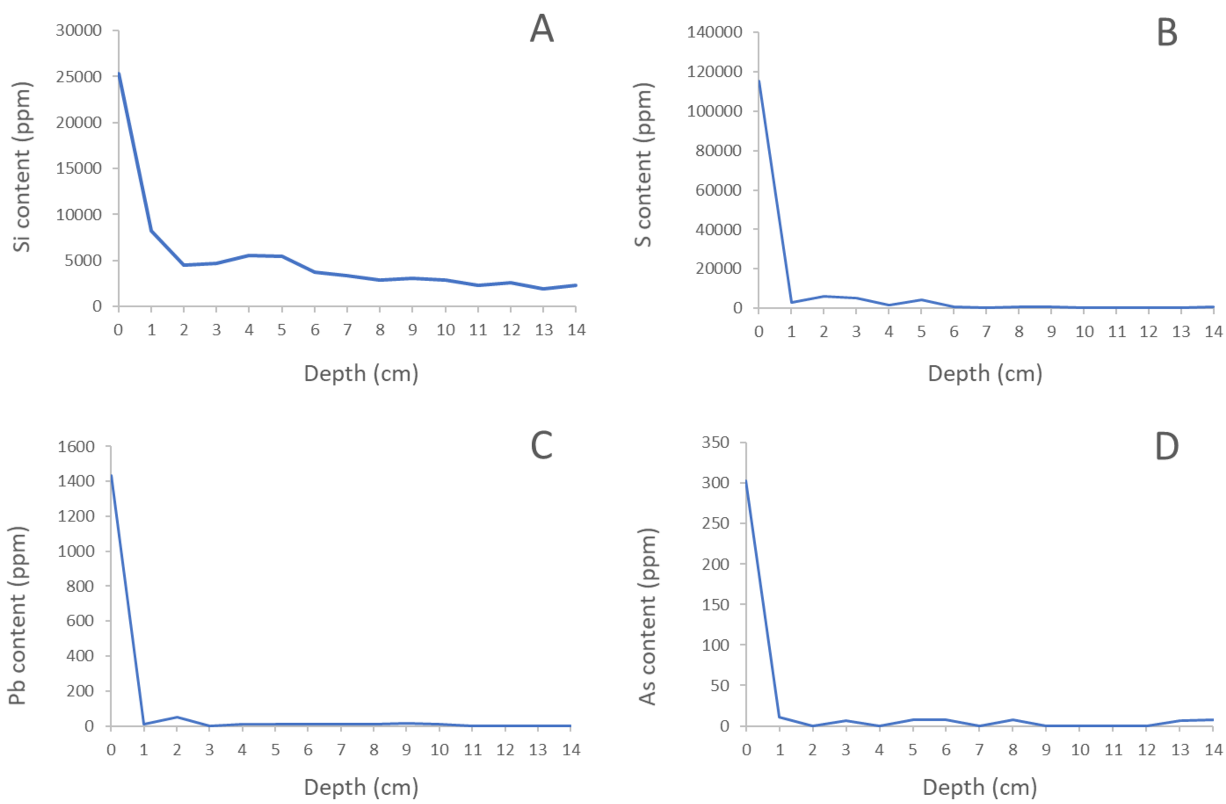

Figure 8. Concentrations of Si, S, Pb, and As from a core taken from a block of Roman stone, with readings taken at approximately 1 cm intervals from the outer surface to 14 cm into the stone, showing the sharp decrease in values after c. 1–2 cm.

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.

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 sole 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. 15-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 reflect the true chemistry of the stone.

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References

ANTONELLI, F. and LAZZARINI, L. 2015. An updated petrographic and isotopic reference database for white marbles used in antiquity. *Rendiconti Lincei* **26**, 399–413.

ASHKANANI, H. J., TYKOT, R. H., AL-JUBOURY, A. I., STREMTAN, C., PETŘÍK, J. and SLAVÍČEK, K. 2019. A characterisation study of Ubaid period ceramics from As-Sabbiya, Kuwait, using a non-destructive portable X-Ray Fluorescence (pXRF) spectrometer and petrographic analyses. *Arabian Archaeological and Epigraphy*

30, 1–16. https://doi.org/10.1111/aae.12143.

BARRON, A. J. M., LOTT, G. K. and RIDING, J. B. 2012. Stratigraphical framework for the Middle Jurassic strata of Great Britain and the adjoining continental shelf. *British Geological Survey Geology and Landscape Programme Research Report.* NERC. RR/11/06.

BEVINS, R. E., IXER, R. A. and PEARCE, N. J. G. 2014. Carn Goedog is the likely major source of Stonehenge doleritic bluestones: Evidence based on compatible element geochemistry and principal component analysis. *Journal of Archaeological Sciences* **42**, 179–193.

BRITISH GEOLOGICAL SURVEY. 2015. *Geology of the Bath District.* NERC. Sheet 265.

BURNHAM, B. C. and WACHER, J. 1990. *The 'Small Towns' of Roman Britain*, 341–476.

COLUMBU, S., ANTONELLI, F. and SITZIA, F. 2018. Origin of Roman-worked stones from St. Saturno Christian basilica (South Sardinia, Italy). *Mediterranean Archaeology and Archaeometry* **18**, 17–36.

CUNLIFFE, B. W. 2000. *Roman Baths Discovered* (4th Edition). English Heritage.

DARK, K. R. 1993. Town or Temenos? A reinterpretation of the walled city of *Aquae Sulis. Britannia* **24**, 254–255.

DAVENPORT, P. 1994. Town and country: Roman Bath and its hinterland. *Bath History* **5**, 7–21.

EDMUNDS, W. M. 2004. Bath thermal waters: 400 years in the history of geochemistry and Hydrogeology. *In* J. D. Mather (ed.) *200 Years of British Hydrogeology. Geological Society, London, Special Publication* **225**, 193–199.

EDMUNDS, W. M., DARLING, W. G., PURTSCHERT, R. and CORCHO-ALVARAD, J. A. 2014. Noble gas, CFC and other geochemical evidence for the age and origin of the Bath thermal waters, UK. *Analytical Geochemistry* **40**, 155–163.

ELLIOTT, S. 2018. Roman History in Kent. https://www.kentonline.co.uk/kent/news/what-did-the-romans-do-for-us-188634.

EVERETT, P. A. and GILLESPIE, M. R. 2019. Hand-held X-Ray Fluorescence; a method for non-destructive compositional analysis of sandstone building stones. *British Geological Survey Internal Report*. NERC. OR/16/008.

FARRANT, A. R. and SELF, C. A. 2016. British Cave Research Association field guide to the Bath Stone quarries, Box, Wiltshire. *British Geological Survey Internal Report.* NERC. IR/16/031.

FORT, R., CHAPA, T. and REVERO, S. G. 2019. Selective use of limestone in Iberian Iron Age sculptures and monuments: a case study from Jutia (Albacete, Spain). *Archaeological and Anthropological Sciences* **11**, 853–870.

FÜRSICH, F. T. and PALMER, T. J. 1975. Open crustacean burrows associated with hardgrounds in the Jurassic of the Cotswolds, England. *Proceedings of the Geologists' Association* **86**, 171–181.

GERRARD, J. 2007. The temple of Sulis Minerva at Bath and the end of Roman Britain. *The Antiquaries Journal* **87**, 148–164.

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.

HAWKINS, D. 2011. *Bath Stone Quarries.* Monkton Farleigh: Folly Books.

KING, A. 2011. *A Building Stone Survey of Avon. Strategic Stone Study.* English Heritage.

LIRITZIS, I. and ZACHARIAS, N. 2011. Portable XRF of archaeological artefacts: Current research, potentials and limitations. *In* M. S. Shackley (ed.) *X-Ray Fluorescence Spectrometry (XRF) in Geoarchaeology.* Springer Science. https://doi.org/10.1007/978-1-4419-6886-9_6.

MÜSKENS, S., BRAEKMANS, D., VERSLUYS, M. J. and DEGRYSE, P. 2018. Egyptian sculptures from Imperial Rome. Non-destructive characterization of granitoid statues through macroscopic methodologies and *in situ* XRF analysis. *Archaeological and Anthropological Sciences* **10**, 1303–1318.

PALMER, T. J. 2005. Limestone petrography and durability in English Jurassic freestones. *England's Heritage in Stone (Proceedings of Conference).* York. 66–78.

PEARSON, A. 2006. *The Work of Giants: Stone and Quarrying in Roman Britain*. Stroud, Glos.: Tempus Pub.

PECCHIONI, E., MAGRINI, D., CANTISANI, E., FRATINI, F., GARZONIO, C. A., NOSENGO, C., SANTO, A. P. and VETTORI, S. 2019. A Non-invasive approach for the identification of "Red Marbles" from Santa Maria del Fiore Cathedral (Firenze, Italy). *International Journal of Architectural Heritage*. https://doi.org/10.1080/15583058.2019.1629045.

ROBERTS, T. 2016. Update on Archeoscan excavations at Doynton and Hanging Hill Roman sites. *Gloucestershire Archaeology Newsletter* **139**, 4.

TUCKER, M. E. (ed.). 1988. *Techniques in Sedimentology*. Oxford: Blackwell Science.

TUCKER, M. E. 2001. *Sedimentary Petrology*. Chichester: John Wiley.

TUCKER, M. E. 2011. *Sedimentary Rocks in the Field*. Chichester: John Wiley.

TUCKER, M. E. 2019. Bath rocks. *Bath Magazine* **202**, 64–68.

TYKOT, R. H. 2016. Using non-destructive portable X-Ray Fluorescence spectrometer on stone, ceramics, metals and other materials in museums: advantages and limitations. *Applied Spectroscopy*. https://doi.org/10.1177/0003702815616745.

TYKOT, R. H. 2017. A decade of portable (handheld) X-ray Fluorescence spectrometer analysis of obsidian in the Mediterranean: Many advantages and few limitations. *Materials Issues in Art and Archaeology XI* **2**, 1769–1784. https://doi.org/10.1557/adv.2017.148.

WHITAKER, R. J. 2000. *Bathampton and Claverton Downs. A Study of an Historic Landscape, Bath, Somerset*. M.Sc. Dissertation, University of Bristol.

WILLIAMS-THORPE, O. 2010. The application of portable X-ray Fluorescence analysis to archaeological lithic provenancing. *In* P. J. Potts and M. West (eds.). *Portable X-ray Fluorescence Spectrometry Capabilities for* in situ *Analysis*. 174–205.

Preparing detailed morphological features of fossil brittle stars (Ophiuroidea, Echinodermata) for scanning electron microscopy using a combination of mechanical preparation techniques

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The comprehensive taxonomic study of fossil brittle stars (Echinodermata: Ophiuroidea) requires the plates of the disk and arms to be cleared of matrix as fully as possible to reveal significant characters, such as spine articulations, ornament and clear plate boundaries. However, this needs to be done delicately, as the plate surfaces and boundaries are fragile and easily obliterated when only using air abrasive techniques. Ophiuroid fossils are frequently over-prepared, which becomes apparent particularly when examined by scanning electron microscopy (SEM), hampering taxonomic studies.

Preparation may be further complicated by the entanglement of the arms of multiple individuals.

In order to facilitate detailed SEM analysis of recently available, undescribed fossil ophiuroid material from the Aptian, Lower Cretaceous, Atherfield Clay Formation of the Isle of Wight, Hampshire, UK a combination of careful mechanical preparation techniques was employed to great effect. Specimens were initially exposed using standard air abrasive techniques, but the final few millimetres of matrix were removed using pins. To get individual arm pieces exceptionally clear of matrix, they were removed from the blocks using a mini pedestalling technique and then further cleaned using an ultrasonic pen. This combination of techniques fully exposed all the elements required for full taxonomic study without causing severe damage to the plate surfaces and greatly improved the overall aesthetic of the specimens. These techniques could be more widely applied in fossil preparation.

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Introduction

Brittle stars (Echinodermata: Ophiuroidea), like all echinoderms, are composed of numerous calcitic skeletal plates (Figure 1A). These plates are not solid, instead the calcite is arranged in a series of interconnecting rods (trabeculae), forming a characteristic mesh-like texture, called stereom (Figure 1E). As these plates are relatively hard, they have provided ophiuroids with a long fossil record. It has recently been demonstrated that phylogenies based on detailed characters of certain skeletal parts, particularly the lateral arm plates, are largely congruent with those based on robust and detailed molecular studies of modern ophiuroids (Thuy and Stöhr 2016). This has unlocked the fossil record of crown group ophiuroids, as detailed morphological analysis of lateral arm plates, in conjunction with other characters, can now be used in both recognising species and inferring higher taxonomy. Unfortunately, as stereom is not particularly hard and because the mesh-like texture fills with fine matrix, it is difficult to produce a clean, undamaged external surface. The plate surface is therefore easily damaged by preparation techniques such as air abrasion using dolomite or other harder powders when removing the relatively harder adherent matrix. Thus, whilst an ophiuroid developed by air abrasion may appear superficially well-prepared and free of matrix, a detailed examination, particularly using SEM, often reveals that the surfaces of the plates are heavily worn and that the boundaries between plates may even be blurred. We have even seen some extreme instances where most of the external plates of the arm have been complete-

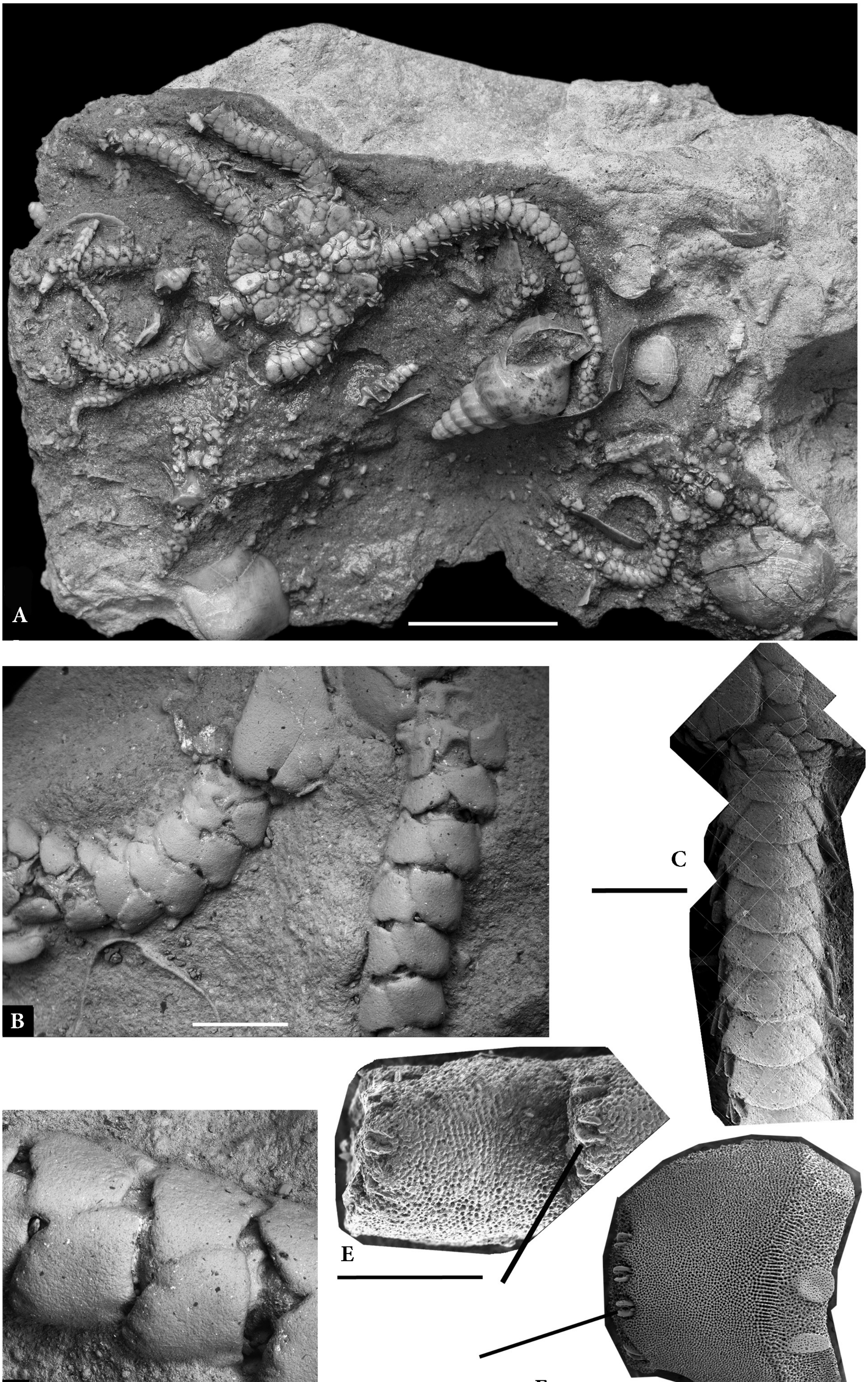
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Figure 1 (previous page). Eozonella sp. nov., Aptian, Lower Cretaceous, Atherfield Clay Formation, Atherfield Point, Isle of Wight, Hampshire, UK: A. Showing the exquisite preservation of an exposed disk and arm plates with clear boundaries, as well as spines (borne on lateral arm plates) still in articulation along the arm. NHMUK PI EE 17208. Scale bar 10 mm. B, D. SEM images of the surface of material prepared using traditional air abrasion. Note the loss of surface detail, particularly the stereom cavities and spines, as well as a loss of definition of the spine articulations and softening of the plate boundaries. IWCMS: 1994.78. Scale bar 1 mm. C. SEM image of material prepared using some of the methods outlined in this paper but not ultrasonic cleaning. Note the clear plate boundaries and articulated spines; however, the stereom is not completely free of matrix, especially when compared with Fig. 1E. NHMUK PI EE 17208. Scale bar 1 mm. E. SEM image of lateral arm plates of an isolated disarticulated arm fragment removed using the new methods including ultrasonic cleaning. Note stereom cavities free of matrix, clear plate boundaries and the small circular ridges (highlighted by the line) where the spines would have articulated. Note that these features are lost in Figs. 1B and 1D. NHMUK IP EE 17212. Scale bar 1 mm. F. Ophiozonella nivia, Gulf of Mexico, modern. Lateral arm plate showing the stereom trabeculae and lobed spine articulations (highlighted with black line). Note the similarity with the fossil plates prepared using the ultrasonic technique in Fig. 1E. Scale bar 1 mm.

ly prepared away, resulting in a superficially clearly defined arm but with only the central internal arm plates (called 'vertebrae') remaining (*e.g.* plate 57, figures 1, 3, 5 of Hunter 2010). Such damage is unfortunate as it obliterates the very taxonomic characteristics needed to accurately identify and classify these fossils.

In 2013, well preserved fossil ophiuroids collected by J. Quail from Aptian rocks of the Isle of Wight, Hampshire, UK were identified as *Eozonella* sp. nov. (Ewin and Thuy 2015). However, assessment of the taxonomically important features using SEM was hampered as the available material, although well preserved and carefully cleaned of matrix, was prepared exclusively by air abrasive techniques and had lost much of the surface detail (Figures 1B, D).

Subsequently, eight blocks of unprepared material from the same locality and containing multiple articulated and disarticulated ophiuroids were generously donated to the Natural History Museum (NHM) by M. Simpson in 2018. This provided the perfect opportunity to attempt to prepare the material without losing the detailed morphology of various parts necessary for thorough taxonomic description and comparison. This was successfully achieved using various different mechanical techniques to first remove the overlying matrix and then that surrounding the tangle of arms and disarticulated parts. The results of our method are compared to approaches using solely air abrasive techniques to demonstrate that important delicate structures can be exposed without excessive abrasion of the plate surfaces.

Methods and Materials

The material used in this study was collected at various times over a 40-year period from the Aptian, Lower Cretaceous, Atherfield Clay Formation near Atherfield Point on the Isle of Wight, UK by M. Simpson and J. Quail (Figures 1A, 2). The fossil ophiuroids comprised disarticulated arm fragments and more complete individuals comprising discs varying in diameter from 2 mm to 10 mm with very narrow (1 mm wide) arms up to 20 mm in length. There were typically numerous individuals on a single block of rock (moderately calcified fine sandstone) and their three-dimensional preservation resulted in arms that were frequently entangled and positioned on top of each other (Figure 2). To expose as many individuals as possible while minimising damage to the plate surfaces, manual work was carried out with a combination of air abrasion and then carbide steel pins under a Leica M80 stereoscopic microscope at 32x magnification with illumination.

The majority of the mechanical preparation was done by air abrasion using a Texas Airsonics HPW series machine, and the optimal abrading set-up was found to be sodium bicarbonate No.4 particle size (50 μm) delivered at 2.5 bar (35 p.s.i.) via a 0.75 mm diameter air abrasive nozzle (Graham & Allington-Jones 2018). The very finest areas requiring abrasion (*e.g.* the boundaries in between plates and arm spines) were prepared with a 0.5 mm diameter nozzle. Sharpened carbide pins (1 mm, ground to 0.5 mm at the tips) were used to remove the final layer of matrix to expose the plate surface.

The areas surrounding the ophiuroid arms were trenched by air abrasion to a depth of approximately 2 mm to reveal the sides, as well as the dorsal surfaces; effectively mini-pedestalling the specimens on small supporting blocks of matrix. The central discs were air-abraded to expose mouthparts, ossicles, spines and plate boundaries (Figures 1A, C). To achieve the necessary level of control of the air

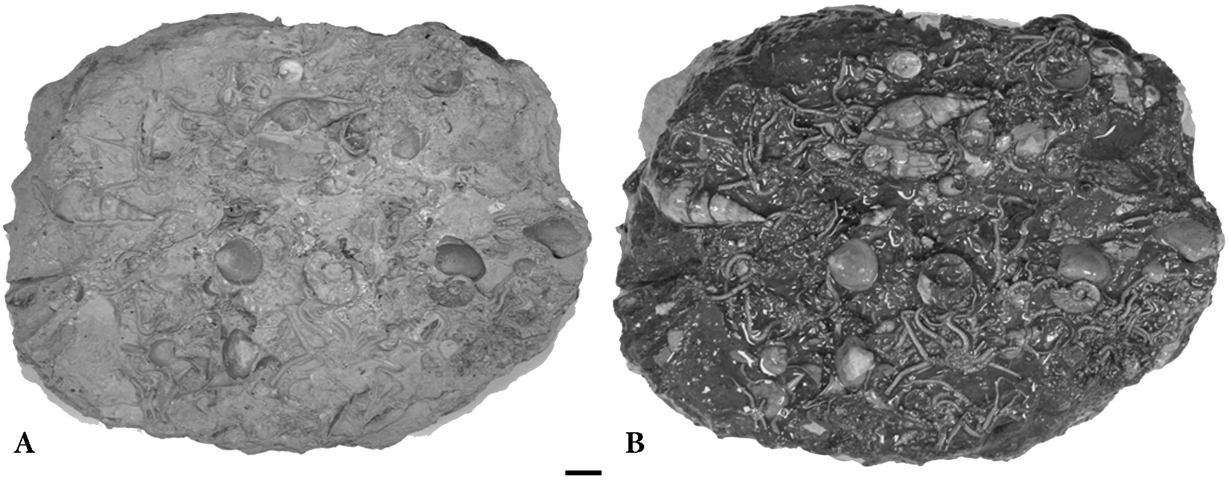

Figure 2. NHMUK PI EE 17212 Aptian, Lower Cretaceous, Atherfield Clay Formation, Atherfield Point, Isle of Wight, Hampshire, UK containing Eozonella sp. nov. A. Block dry. B The same block wetted with IMS demonstrating greatly increased contrast between the ophiuroid fossils and matrix. Also note the tangled nature of the ophiuroid arms. Scale bar 10 mm.

abrasive setup, the machine was set to manual (rather than automatic) flow, and a foot pedal was used to deliver the powder in short bursts. Because of the need for unhindered microscopy and good illumination, it was impractical to undertake the work in a blast cabinet; instead, a ventilation hose was located next to the microscope and behind the specimen, and protective Perspex barriers were placed around the workstation to further contain dust and powder. A face mask was also necessary because particulates bounce off surfaces and can be ingested even when compressed air is delivered at low PSI.

The small colour variation between the specimens and matrix made it difficult to discern when the matrix had been fully removed without over-abrading the plate surfaces and risking loss of detail. To overcome this, areas being worked upon were wetted frequently with industrial methylated spirit (IMS). This greatly increased the contrast between the fossils and the matrix, enabling finer details to be developed (Figure 2B). The IMS evaporated after a couple of minutes and left no residue on the specimens but lasted sufficiently long to enable a significant amount of work to be undertaken. Acetone can be used, but evaporates too quickly to permit much time working on the specimens with the aforementioned techniques.

So that arm plates might be thoroughly examined by SEM after mechanical preparation, individual arms were selected for removal from the blocks (by undercutting the matrix pedestals with a fine scalpel) and placed in small, sealable plastic bags containing a few drops of distilled water. The exterior of the bag, immediately adjacent to the arm plates, was then touched with the 2-mm-wide chisel tip of a Sonotec Split V model ultrasonic pen (Figure 3) (see Doyle *et al.* 2004), and the frequency adjusted until the specimen could be seen to agitate gently in the water droplets and the remaining matrix began to dislodge (Figure 3B). When the water became discoloured by the suspended matrix residue, it was changed and the process repeated until it remained clear on treatment with the ultrasonic pen, indicating no further matrix could be removed. The specimens were undamaged by this process as the bag and water prevented the tool from coming into direct contact with their fragile surfaces. Once completely cleaned, the specimens were left to air-dry.

The plates of these isolated fragments were then scanned on a Leo LV1455VP low-pressure environmental SEM without coating. The resultant images were used to establish how effective the matrix removal had been and the amount of damage (if any) sustained by the ossicles. The newly prepared specimens were also compared to material previously donated by J. Quail and to lateral arm plates of a modern ophiuroid to establish how effectively the matrix had been removed and the amount of damage sustained (Figures 1B-F).

Repositories and institutional abbreviations: The specimens used in this study prefixed NHMUK PI EE are housed in the Echinoderm collections of the Invertebrate and Plant Division, Earth Sciences Department, The Natural History Museum London,

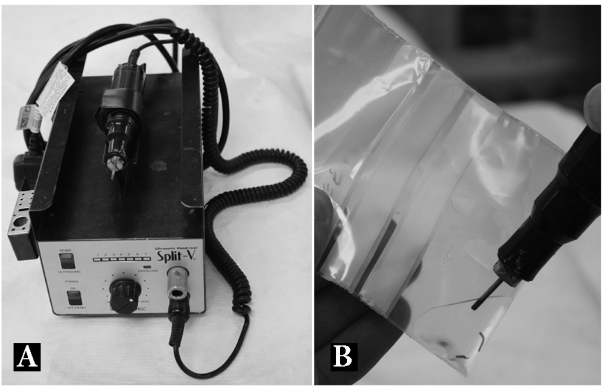

Figure 3. A. The Sonotec Split V ultrasonic pen. B. The application of the ultrasonic pen to bagged specimens, one of which is shown in detail in Fig. 1E.

UK. That prefixed IWCMS is housed at Dinosaur Isle Museum, Isle of Wight, Hampshire, UK.

Results

Figures 1B-E show a comparison under SEM of the specimens prepared using the aforementioned techniques with those prepared using solely air abrasion. The spine articulations on the lateral arm plates can be clearly seen as two bent lobes, open distally but proximally connected by small knobs in Figure 1E, which compares well to those of modern ophiuroids (Figure 1F). These spine articulations are clearly missing in the material prepared using solely an air abrasive (Figures 1B and 1D). Note also that the stereome cavities (or the mesh-like nature of the stereom) are completely obliterated in the specimens prepared solely using an air abrasive (Figures 1B and 1D) and are obscured by matrix in material that could not be subjected to ultrasonic cleaning (Figure 1C). In those specimens prepared with an ultrasonic treatment (Figure 1E), the stereom is clear of matrix, well-defined with a suggestion of ornamentation and comparable with that seen in modern ophiuroids (Figure 1E). Figure 1A further demonstrates that with careful preparation even the spines, articulated and in life position, can be exposed providing useful additional information about spine length variation along the margin of the lateral arm plates.

The contrast of the fossil ophiuroid skeleton with the matrix is greatly improved by wetting with IMS, as can be seen in Figure 2.

Discussion and recommendation

The combination of techniques described above (controlled air abrasion, pin and ultrasonic pen) fully exposed all the elements required for full taxonomic study without causing severe damage and loss of significant surface detail. The technique is so effective that we were able to clearly compare the detailed surface structures of the fossil material with modern and disarticulated material to facilitate a more complete comparison (Figure 1E-F and work in preparation).

The use of the ultrasonic pen was particularly effective in removing adherent matrix within the stereome cavities and other depressions, such as within the spine articulations on the arms (Figure 1E). This technique has advantages over the use of ultrasonic baths, which frequently damages the surface of the stereom as it repeatedly comes into contact with the vibrating metal wall or floor of the bath. The technique also enables easier and closer examination of the fragments to assess that they are clean to ensure minimal treatment. This ultrasonic pen technique was not so suitable for use on material still embedded within the matrix as it tended to chip off parts of the stereom when the tip made direct contact with the specimen. Thus, the plate surfaces could not be completely cleared of matrix if they remained within the block (compare the lack of clear stereom cavities in Figure 1C with 1E).

Frequent dousing in IMS throughout the preparation process greatly improved contrast between the specimens and the matrix, enabling a more accurate assessment of when the matrix was fully removed from the surface of the plates (Figure 2). Without this it is very difficult to judge when the fossil is matrix-free owing to the similarity in colour between the fossil ophiuroid and matrix. This is perhaps a contributory factor in the previous over-preparation of specimens from this locality.

The pedestalling of the specimens was effective as a means of demarcating the delicate elements from one another and allowing for a scalpel tip to be inserted laterally into the trenched areas, enabling individual arms to be cut out and lifted with minimal matrix attached. This facilitated the effective use of the ultrasonic tool to remove the small amounts of remaining matrix from the isolated elements.

The authors recommend that this approach should be more widely adopted in the preparation of other small, delicate fossils, particularly echinoderms, in order to retain and reveal as much taxonomic information as possible.

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References

DOYLE, A. M., FLETCHER, J. and RATCLIFFE, P. R. 2004. A new tool for palaeontological preparation: the Split V pen. *Geological Curator* **8**, 37–42.

EWIN, T. A. M., and THUY, B. 2015. Two new British Mesozoic ophiuroid localities, preliminary observations and determinations. *In* S. ZAMORA and I. RABANO (eds.), *Progress in Echinoderm Palaeobiology*. Madrid, Spain: Publicaciones del instituto geológico y minero. Serie: Cuadernos del Museo Geominero **19**, 53–57.

GRAHAM, M. R. and ALLINGTON-JONES, L. 2018. The air-abrasive technique: A re-evaluation of its use in fossil preparation. *Palaeontologia Electronica* **21.2.2T**, 1–15. https://doi.org/10.26879/815.

HUNTER, A. W. 2010. Lower Lias ophiuroids of the Dorset coast. *In* A. R. LORD and P. G. DAVIS (eds.) *Palaeontological Association Field Guide to Fossils: Number 13, Fossils from the Lower Lias of the Dorset Coast*. London, UK: The Palaeontological Association.

THUY, B. and STÖHR, S. 2016. A new morphological phylogeny of the Ophiuroidea (Echinodermata) accords with molecular evidence and renders microfossils accessible for cladistics: *PLOS ONE* **11** (5), e0156140. https://doi.org/10.1371/journal.pone.0156140.

The benefits of regional collection-based undergraduate projects: an example from Nottingham

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Hands-on access to natural history museum collections is often limited for undergraduates. An ongoing collaboration between staff at the Nottingham Natural History Museum, Wollaton Hall, and staff and students at the School of Science and Technology, Nottingham Trent University, was established in 2013 to allow final year undergraduate students to undertake collections-based research projects. A successful pilot project conducted on dinosaur fossils in 2013-14 led to subsequent projects based on the geological collections. The projects provide mutual benefits to students, university staff, and museum curators and their collections. In particular, students benefit from hands-on practical learning engagement with collections, university staff benefit from using the collection as a teaching resource, and the museum collections benefit from increased usage and identification or reidentification of specimens. Overall, the only notable cost is the time commitment required to develop and facilitate projects, however, this investment is richly rewarded by numerous positive outcomes.

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Introduction

Science education is most successful when it focuses on authentic inquiry-driven experiences with active participatory learning (Brewer and Smith 2011; Cook *et al.* 2014). All natural history museum collections have the potential to play a critical role in such education, because "natural history specimens are ideal subjects for inquiry-based research at all educational levels" (Powers *et al.* 2014, p. 25). Indeed, the number of programs designed to engage undergraduates in this way is growing (Powers *et al.* 2014; Hiller *et al.* 2017). However, hands-on access to natural history museum collections is often limited for undergraduates (Powers *et al.* 2014), especially in universities without their own museums, and the benefits and efficacy of participatory learning is rarely justified with robust quantifiable evidence (Linn *et al.* 2015).

An ongoing collaboration between the Nottingham Natural History Museum, Wollaton Hall (NOTNH, or "the museum" hereinafter), and the School of Science and Technology, Nottingham Trent University (NTU, or "the university" hereinafter) has adopted this learning approach through collections-based final-year undergraduate research projects. The NOTNH-NTU collaboration was initiated in 2013 with an undergraduate project based upon the museum's small dinosaur collection. This research resulted in updated identifications of the *Iguanodon* material housed in the NOTNH, as well as material stored in the British Geological Survey's Biostratigraphy Museum (BGS). This pilot project demonstrated the viability of collections-based undergraduate projects, and so several further projects were undertaken in subsequent years: two projects in 2014–15, two in 2015–16, two in 2017–18, and one in 2018–19 (Table 1). The collaboration experienced a necessary break in 2016–17, because the curator was fully committed to a major temporary exhibition (Smith and Wang 2017). To date, the major focus of the research projects has been on the museum's fossil collection, which contains c. 40,000 specimens (Turner 1993, 2000; Smith 2015). However, over the short duration the collaboration has been running, it has been expanded to include other staff and collections at Wollaton Hall and NTU and nearby institutions including the BGS and Creswell Crags Museum and Heritage Centre (CCMHC). So far, all of the projects have focused specifically on vertebrate material, a reflection of the specialist interests of the students and supervisors. However, similar projects could be conducted on a broad range of natural history collections.

This paper provides a summary of the research projects completed to date and their main outcomes. It outlines the benefits of the projects from the perspectives of the undergraduates, NTU staff, and NOTNH staff, and also considers some of the potential drawbacks and barriers to be overcome when conducting regional collections-based undergraduate research projects.

Academic Year	**Student**	**Project (short description)**	**Specimen(s) and identification(s)**	**Outcomes**
2013-14	E. Catherine Strickson	Identification of fossil '*Iguanodon*' material (including BGS)	NOTNH: 8 bones in total, 5 vertebrae, 2 tibiae and 1 femur. The tibiae and femur may represent *Iguanodon bernissartensis*. BGS: 45 specimens in total, 12 phalanges; 12 vertebrae; 7 teeth and 1 pes consisting of 3 metatarsals and 11 phalanges. Of the vertebrae, 1 may be *Iguanodon*, 1 large specimen *Barilium dawsoni,* and 2 of the smallest specimens may represent a large dryosaur. The pes may represent *I. bernissartensis* or *Barilium dawsoni*. Total = 53 specimens	Most specimens reidentified as *Mantellisaurus atherfieldensis*. Some smaller specimens resemble dryosaurs, while others may represent *Iguanodon bernissartensis* and *Barilium dawsoni*.
2014-15	Joanne Horne	Assessment of Steetley Quarry fossils (including CCMHC)	NOTNH: 140 specimens in total, 137 bones and 13 teeth. Cranial fragments (3), mandibles (4) and teeth (13) = 20. 120 Post-cranial skeletal remains. Identifications: 65 bovid, 4 *Bison*, 21 bear, 4 wolf, 26 reindeer, 4 deer, 1 fox and 15 indeterminate. CCMHC: 116 specimens in total. 9 *Bos*; 3 Bovidae; 4 *Capreolus*; 3 *Cervus*; 2 Cervidae + 1 Cervidae?; 22 *Sus*; 4 *Meles meles*; 4 *Ovis/Capra*; 1 *Vulpes vulpes*; 2 *Lynx lynx* and 1 bird. 60 indeterminate specimens. Total = 256 specimens	256 specimens studied, 75 indeterminate, the rest identified. Many indeterminate specimens identified to element and side. An additional 15 specimens could not be located in the CCMHC collection.
	Zoé C. Wiggins	Identification of fossil elephantids	48 molars (37 woolly mammoth/*M. primigenius*; 1 steppe mammoth/*M. trogontherii*; 1 southern mammoth /*M. meridionalis*; 5 straight-tusked elephant/*P. antiquus*; 4 Asian elephant/*E. maximus);* 8 woolly mammoth/*M. primigenius* tusks, 1 scapula; 1 ulna, 2 refitting sections of the same cranium - all woolly mammoth/*M. primigenius*. Total = 60 specimens	All 60 elephantid specimens were identified to element and taxon. Important identifications included recognising *M. trogontherii* for the first time in this collection and correcting the identification of four 'woolly mammoth' molars to recent Asian elephant remains. Aspects such as age, sex and side of paired elements also identified. 1 tusk was conserved.

Academic Year	Student	Project (short description)	Specimen(s) and identification(s)	Outcomes
2015-16	Callum Clarkson	Identification of bear fossils (including CCMHC)	NOTNH: 18 from Steetley, 12 from Creswell Crags, 1 from Germany. CCMHC: 1 from Creswell Crags, 1 from Dead Man's Cave, South Yorkshire, 1 from Germany. Total = 34 specimens	No specimens found to represent the cave bear (*Ursus spelaeus*), with most identified as brown bear, *U. arctos*. One 'bear' specimen was confirmed as spotted hyena and a previously unidentified bear phalange was identified. Specific identifications of one bone and two teeth also made.
	Charlotte A. Smith	Assessment of deer fossils and subfossils	3 *Megaloceros giganteus* (Irish or giant elk): 1 atlas, 1 mandible and 1 metatarsal, 21 *Cervus elaphus* (red deer): 10 antlers/Fragments; 1 cranium; 3 mandibles; 1 metacarpal; 2 metatarsals; 2 tibiae and 2 vertebrae. Total = 24 specimens	All specimens were identified to element and species. Estimates of age at death were provided for 13 specimens. Several taphonomic observations regarding traces of human butchery and feeding by ancient carnivores were also made. Live stag antlers also studied for comparative purposes.
2016-17	N/A	N/A	N/A	N/A
2017-18	Nicole A. Mantl	Assessment of human fossils (including CCMHC)	NOTNH: 8 specimens in total, 3 crania/fragments; 2 mandibles, 1 tibia, and fragments of an ischium and ulna. CCMHC: 17 specimens in total, 7 crania/fragments; 2 mandibles; 2 teeth; 3 vertebrae and 3 tibial fragments. Total = 25 specimens	Detailed descriptions (including element, sex, age at death, side), measurements and photographs. At CCMHC the precise identities of four specimens were established or corrected, some were identified as lacking labels, accession numbers and/or entry into the collection databases. One specimen was identified as suffering damage/partial loss since its original description. Additionally, the sources and ages of specimens was established through comparison with the literature.
	Leah Smith	Taphonomy of ichthyosaur specimen	A slab (split into two sections) containing a single sub-complete skeleton of I*chthyosaurus larkini* consisting of many elements. Total = 1 specimen	Peri- and post-mortem damage indicated loss of elements due to water movement, and possible carcass explosion through escaping decompositional gases. Excavation damage was also identified.
2018-19	Emma M. Malpass	Bite marks and pathologies on Jurassic marine reptile bones	1 complete left humerus of a juvenile *Cryptoclidus oxoniensis* plesiosaur, 1 complete right humerus of a *Cryptoclidus oxoniensis* in two parts, 1 right clavicle of an adult *Ophthalmosaurus* ichthyosaur. Total = 3 specimens	Bite marks and ante-mortem disease were identified by this analysis.

Table 1. Timeline of undergraduate projects conducted at NOTNH and nearby institutions, with summaries of the material studied and the project outcomes. In total, 456 specimens were studied, with a mean of 57 specimens per student.

Research topics 2013–2019: summaries and main outcomes

The following summaries provide descriptions of the eight projects completed between 2013 and 2019, together with their main outcomes. Some specific metrics, including the number of specimens studied in each project, are given in Table 1.

Dinosaur project

The pilot project taxonomically reassessed the '*Iguanodon*' material in the NOTNH and BGS collections (Strickson 2014). Most historical large ornithopod dinosaur specimens are assigned and labelled '*Iguanodon*' (Paul 2008). Many species were also referred to this taxon, resulting in it becoming a 'wastebasket genus' (Carpenter and Ishida 2010). Ultimately, key holotypes were reassigned to new genera (Norman 2010), leaving *Iguanodon bernissartensis* as the sole remaining species in the genus until the discovery of *I. galvensis* in 2015 (Verdú *et al.* 2015). Many historical dinosaur collections in museums, however, await reassessment. Most of the specimens studied during this project were actually *Mantellisaurus atherfieldensis* (Figure 1A), while some smaller specimens resemble dryosaurs, with others resembling *I. bernissartensis* and *Barilium dawsoni*.

Figure 1. A. A left femur identified as **Mantellisaurus atherfieldensis** *(NOTNH FS12182), previously referred to* **Iguanodon***. Scale bar = 10 cm. B. Section of left upper deciduous third premolar of* **M. trogontherii** *(steppe mammoth; NOTNH FS4729), from Cromer, Norfolk. Scale bar = 2 cm. C. Left first metacarpal (NOTNH FS4705) of a brown bear,* **Ursus arctos***, from early in the last glacial stage, Steetley Quarry Cave, Nottinghamshire (FS4705). Disease has severely deformed the specimen, and several proliferative lesions are present (examples arrowed). Scale bar = 2 cm.*

Elephantid project

This project re-evaluated and updated identifications of fossil elephantid material in the museum collection (Wiggins 2015; Figure 2A). Many of the tusks and molar teeth were also assigned to sex and age groups. Historical misidentifications were corrected, including recognition of a molar tooth of *Mammuthus trogontherii* (NOTNH FS4729; steppe mammoth; Figure 1B), a species previously considered absent from the collection. Similarly, a molar from Wilford near Nottingham, labelled as *Mammuthus primigenius* (woolly mammoth), was reidentified as *Elephas maximus* (Asian elephant). This demonstrates the confusion caused when recent material is found in unlikely places due to human transportation.

Steetley Quarry project

This project clarified previous research and documentation of the vertebrate fauna from Wood Quarry near Steetley, Nottinghamshire, housed in the NOTNH and CCMHC collections (Horne 2015; Figure 2B). This was especially important because two separate caves existed in this vicinity that can be easily confused with each other. 'Steetley Cave' yielded a rich Holocene vertebrate fauna (Bramwell *et al.* 1984; Jenkinson 1984), while the distinct but similarly named 'Steetley Quarry Cave', contained both an Early Devensian fauna and younger Holocene material (Pike *et al.* 2005). The Devensian vertebrate fauna studied suggests that the cave occasionally served as a wolf den. The remains of an elderly brown bear indicate that it died *in situ* during hibernation. This study's results concur with Pike *et al.* (2005), that this fauna dates from the Banwell Bone Cave mammal assemblage-zone of Currant and Jacobi (2001), corresponding with Marine Isotope Stage 4 *i.e.* 71,000–57,000 years ago (Lisiecki and Raymo 2005).

Pleistocene bear project

All Pleistocene *Ursus* specimens in the NOTNH collection, and some specimens from CCMHC, were analysed in this study (Clarkson 2016; Figure 2C). The material originated from several British sites, including Creswell Crags and Steetley Quarry Cave locally, but some German material was also assessed. By comparing unidentified *Ursus* specimens to those known to belong to brown bears (*Ursus arctos*) and cave bears (*Ursus spelaeus*), all identifiable material was assigned to *Ursus arctos*. Additionally, some pathologies were identified (Figure 1C), a previously unrecognised bear specimen was identified, and some material that had previously been erroneously identified as bear was correctly reidentified as spotted hyena (*Crocuta crocuta*).

Red and giant deer project

All of the giant deer ('Irish elk', *Megaloceros giganteus*) fossils and palaeontological and archaeological specimens of red deer (*Cervus elaphus*) in the NOTNH geological collection were studied in this project (Smith 2016; Figure 2C). In addition to identifying all of the specimens, some taphonomic observations

Figure 2. Photographs of NTU students at work in the Nottingham Natural History Museum, Wollaton Hall. A. Photographing elephant remains—Zoé Wiggins snaps to her mammoth task! B. Lecturer Fred Owen oversees Joanne Horne studying Pleistocene vertebrate remains from Steetley Quarry Cave – using the collection as a teaching resource. C. Callum Clarkson and Charlotte Smith studying Pleistocene bones in the NOTNH—it was a more efficient use of the curator's time to host students simultaneously rather than separately. D. Nicole Mantl measures a human specimen and communicates the data for Leah Smith to input—an example of teamwork. E. Emma Malpass studying and illustrating a plesiosaur humerus—an example of practical hands-on collections experience.

were made concerning human butchery and gnawing by animals. Additionally, the herds of deer that live on the grounds of Wollaton Park that surround Wollaton Hall were used for comparative purposes through a study of how their antlers develop ontogenetically.

Ancient humans project

This project focussed on the ancient human (*i.e. Homo sapiens*) material in the NOTNH and CCMHC collections and resulted in detailed descriptions and photographic records of the prehistoric human remains (Mantl 2018; Figure 2D). The findings also led to a further significant successful outcome in the form of a peer-reviewed paper (Mantl 2019). Much of the material originated from Creswell Crags and the surrounding area, but other specimens from Nottinghamshire and Northamptonshire were also studied. Descriptions of each element included their identity, condition, and whenever possible, the sex and age at death. The project also corrected some erroneous identifications and indicated some missing specimens.

Ichthyosaur taphonomy project

Building upon previous work by Lomax and Gibson (2015), an assessment of an *Ichthyosaurus larkini* specimen (NOTNH FS4940) from Barnstone, Nottinghamshire, was conducted with the aims of establishing its taphonomic history and possible cause of death (Smith 2018). The specimen was scrutinised for any damage or alterations it may have been subjected to both during and after the fossilisation process. It was determined that the specimen probably suffered both peri- and post-mortem damage, that some missing elements were most likely removed by the effects of water movement carrying skeletal material away, and that breaks showing cross sections through some bones were due to excavation damage. Exposed matrix edges show no evidence of bioturbation or tectonic movement, so the disrupted arrangement of some bones suggests a rapid high-energy event, possibly the carcass exploding due to the rapid escape of decomposition gases.

Marine reptile pathology project

This project focused on the identification and analysis of pathologies on Jurassic marine reptile specimens from the Oxford Clay Formation at Peterborough in the museum's collection (Malpass 2019; Figure 2E). The fossils examined were both humeri of a juvenile plesiosaur, *Cryptoclidus* (NOTNH FS5880 and FS5881) and the right clavicle of an adult ichthyosaur, *Ophthalmosaurus* (NOTNH FS5797). The study highlighted two prominent bite marks on the left humerus consistent with the teeth of a large predator, and lesions on the right humerus consistent with the teeth of a lamniform shark. Breaks in the *Ophthalmosaurus* clavicle showed clear signs of deformed ossification due to disease, indicating that this lesion occurred pre-mortem.

Benefits of undergraduate research projects

The benefits of these undergraduate research projects, and of the collaboration between NTU and NOTNH in general, can be considered from the perspectives of the students, NTU staff, and curator, respectively.

The students' perspective

Natural history collections have the potential to help transform undergraduate education from a passive learning experience into a participatory exploration of the natural world (Cook *et al.* 2014). These projects provided the students with the freedom to choose a collection-based final-year research topic of interest to—and, most crucially, personally selected by—them. This resulted in a sense of responsibility and investment, especially as the projects were open-ended with no pre-prepared 'guide' to follow. This contrasts with most other types of final-year project, which are often confined to a specific supervisor-led title with a strictly timetabled schedule and often a predetermined outcome. The students regarded this as an exciting opportunity to gain hands-on experience outside of the university or laboratory setting (Figures 2A–E).

The element of 'entering into the unknown' on a collection-based topic may be off-putting to some students. However, it also means that they are heavily involved in structuring their own research, through which they gain a realistic insight into how the scientific process works. The students appreciated the opportunity for independent learning and making genuine discoveries during their research on their own, individual projects. Undergraduates from both NTU's Biological Sciences (Environmental Biology) and Forensic Science areas have gained access to fields of research and resources that were previously unconsidered, or unavailable, during their degree courses. This extended beyond the specimens, for example, the students also benefited from access to the museum archives and the expertise of curatorial staff. There were also opportunities for networking with other experts besides university lecturers, including several internationally recognised experts. Teaching sessions from specialists at the Natural History Museum, London (NHM), and field visits to several localities, provided the skills required to conduct these projects, as well as insights into research and curatorial careers. Field-specific techniques, such as the identification and measurement of fossil bones, were developed that would be difficult to develop fully on material of this nature without the involvement of museum collections. Various transferable skills were also developed, such as time management and teamwork (Figure 2D). Although the projects were selected and conducted on an individual basis, students working in the same space sometimes provided each other with assistance.

Collections-based undergraduate research projects demand motivation and efficient organisation. Therefore, they are best suited to committed students prepared to embark upon their research as early as possible and to work independently. Ultimately, the rewards of such projects include their successful completion and contribute towards the successful award of their degrees. Beyond this, several students have taken their palaeontological studies further by undertaking PhD and MSc qualifications, and one project has been converted into a peer-reviewed publication (Mantl 2019).

The university lecturer's perspective

Supervising collections-based undergraduate research projects provided an excellent opportunity to offer non-formulaic projects to students. Involving the students and curatorial staff in the selection of the material helps ensure that the outcome is genuinely useful to all concerned and does not simply result in the production of yet another typical 'bone report'. This approach is beneficial to each student since the material selected for study is genuinely interesting to them personally and thus maintains their enthusiasm. University staff also gain from involvement in the selection process by gaining an increased appreciation of what is curated locally and also through networking and forming links with other researchers, curators, and institutions. University and curatorial staff must guide the students in the formulation of their projects, for example, in agreeing an appropriate workload within the timeframe allocated for project completion. Students can get excited and may wish to spend a disproportionate amount of time on this aspect of their final year, which could prove detrimental to their other studies, so staff must ensure that an achievable workload is agreed.

The projects also provide the opportunity to teach content and skills beyond the scope afforded by the delivery of lecture content and practical sessions alone, and this was very rewarding (Figure 2B). For example, guiding the students in the appropriate handling of specimens and measurement techniques, from the beginning of their studies, is a considerable bonus for all concerned. These projects also allow supervisors to learn new information and skills, such as greatly broadening their existing knowledge of the groups and aspects selected and the specific methodologies employed in their study. It also allows them to recognise and address their personal limitations concerning the specific research methodologies and unfamiliar software used by the students.

These projects allow new contacts to be made and existing links to be strengthened. So far, the collaboration has involved staff from the BGS, CCMHC, NOTNH, NTU, NHM, Bassetlaw Museum, several universities, and the British Museum. Much information has also been exchanged through meetings, exchanging literature, and assisting in the identification of material generated from public enquiries, and AS has delivered lectures at NTU.

The teaching opportunities, together with the establishment and strengthening of partnerships with other institutions, are powerful incentives to initiate such projects with regional museums. Given the clear success of the projects to date, more NTU staff are being encouraged to engage with museum collections and for the university to become generally more active in their support. A pleasing sign of this occurring was the decision of NTU's School of Science and Technology to fund the conservation and display of a mammoth tusk as a direct consequence of the elephantids project (Figures 3A and B; and see below).

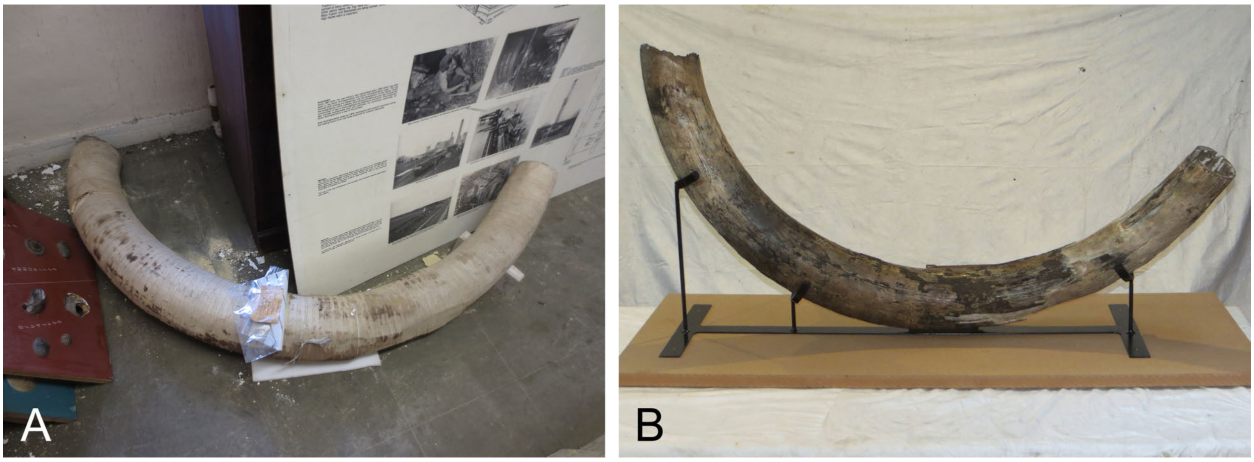

Figure 3. A large, left male tusk of* M. primigenius *(woolly mammoth) dredged from the North Sea near Lowestoft, Suffolk (NOTNH FS12321). The specimen has an outer length of 195.5 cm and a maximum diameter of 13 cm. A. The specimen was wrapped in a protective coating prior to its restoration and display. B. The restored tusk.

The curator's perspective

Collaboration with local universities and undergraduate students brings a variety of benefits to the museum. In the broadest sense, it is imperative that museums demonstrate the value of their collections by using them. This raises awareness of the collections internally and externally, helps justify the need for curatorial staff and collections care, improves the reputation of the collection as an educational and scientific resource, and increases visitor numbers.

These research projects have enhanced collection knowledge in the form of identifications, measurements, images, and other data. This data can be tied into collections development through documentation, digitisation, and interpretation (in displays and exhibitions), and the final student reports provide a record of the findings for future reference (Strickson 2014; Horne 2015; Wiggins 2015; Clarkson 2016; Smith 2016; Mantl 2018; Smith 2018; Malpass 2019). There is also potential for projects to lead to publications, which helps to publicise and demonstrate the value of the museum's collection (*e.g.* Mantl 2019), although this depends upon the significance of the outcomes and the quality of the work. The students benefited from input from external experts, so that expertise can be applied to the collections vicariously through the students.

The student projects also provided a justification for the curator to undertake focused collection audits, *i.e.* to generate lists from the collections database of certain specimens and to verify their store locations. In total, 456 specimens were studied by the students during the course of these projects (Table 1). The number of specimens per project varied widely depending on the nature of the project, ranging from a single specimen (technically consisting of many bones or elements) for the ichthyosaur taphonomy project, to 256 specimens for the Steetley Quarry project.

Providing access for undergraduate students to work directly with collections also helps curators to identify conservation issues. For example, a large bandaged tusk (NOTNH FS12321) was found in need of urgent conservation attention and was only partially accessible to ZCW during her research project (Figure 3A). This led to funding from NTU's School of Science and Technology to conserve the tusk for study and display, a mutually beneficial outcome for the university and the museum (Figure 3B).

The specialist contacts made or strengthened during these projects have also led to expertise being shared for mutual benefit. For example, FJO has assisted with specialist museum enquiries (specimen identifications) from the public.

Discussion

Scientific outcomes

The projects conducted to date have led to several significant contributions to our knowledge of material dating from the dinosaurs to the Devensian. The dinosaur project demonstrated the importance of updating collections containing '*Iguanodon*' material. The elephantids project established the presence of *M. trogontherii* in the museum's collection and updated several other identifications. Similarly, the Steetley Quarry, bear, and deer projects all helped to clarify the origins of the material and their specific taxonomic identifications. The students' identifications are not the final word—even specialists can disagree. However, the new identifications are based on modern criteria, so they are an improvement over decades-old, or even century-old, identifications based on outdated taxonomies and literature. The ancient humans project (Mantl 2018) led to material being cited and figured in the peer-reviewed scientific literature (Mantl 2019), while the marine reptile pathology projects identified pathologies that had not been formally documented previously (Smith 2018; Malpass 2019). Undergraduate research projects can, therefore, lead to genuine scientific outcomes and benefits to collections.

Costs and potential barriers

The most significant barrier to collections-based research is "the challenge of unlocking—in many cases, literally—the cabinet drawers housing specimens and their associated data" (Cook *et al.* 2014. p.727). In particular, a time commitment is required from curatorial staff to help identify suitable collections for projects, provide useful documentation of the material, provide access to collections, and supervise students when they are on site. For projects such as these, this typically equates to approximately two or three non-consecutive full working days in the collection. However, curators can arrange to host students simultaneously in the same space whenever possible to help mitigate the impact on their time (Figure 2C). University staff (project supervisors) must also be prepared for an initial time commitment in order to identify and agree suitable projects, as well as providing the specialist training required for the students to begin their research (Figure 2B). This was typically around two working days, although in the years where two students undertook museum-based projects, this additional instruction was delivered to both students simultaneously. The commitment to provide a suitably fast turnaround of the students' draft manuscripts and to answer queries and provide specialist literature was no greater than for any non-collections-based student project. The students must be prepared to fit their research visits around classes, coursework, and the availability of curatorial staff.

Some risk to the collections is introduced by allowing students with minimal hands-on experience to access and use them. This risk can be mitigated by close supervision and through informal object handling training and specimen measurement instruction by staff (Figure 2B). Collections at regional museums are typically smaller than those of larger national museums. This can potentially be problematic because of the lack of material from other sites of similar stratigraphic ages, which could restrict comparative studies. Similarly, there are fewer subject-specific experts available to consult and less access to technical equipment and facilities. For museums and universities that contemplate the adoption of this approach, the above considerations should be taken into account and balanced against the benefits.

Evaluation

At NTU, all student work is assessed against marking matrices produced by Module Leaders. The Final Year Research Project Module provides students with an opportunity to undertake extended individual research and to report upon it in the style of a paper for publication. This accounts for 70% of the module grade, with a presentation based upon their research and the construction of a skills portfolio completing the module's coursework. The students complete feedback relating to their experience on each module, but this is always anonymized, and feedback to staff relates to the mean responses for the entire cohort of several hundred science students.

Linn *et al.* (2015) called into question the existing evidence for learning and personal benefits of laboratory-based undergraduate research experiences, because assessment of the outcomes predominantly relies on self-reporting surveys or interviews. The NOTNH-NTU collaboration is at fault in this sense because no systematic indicators of success were built into the model and so the general learning and teaching benefits outlined in this paper are anecdotal. However, certain outcomes can be quantified or qualified objectively without the need for a systematic assessment. For example, published papers resulting from student projects, specimens conserved as a direct result of a student project, numbers of specimens reidentified, or museum database entries updated all provide evidence for certain benefits of undergraduate research projects, whether or not the students objectively benefit from the learning experience relative to others who do not undertake collections-based research projects.

The future

The NOTNH-NTU collaboration is already continuing with two projects (one on moa bird material, the other on fossil wolves) being conducted in the current academic year. The collaboration will continue into the future. Key future aims include expansion of the model to other parts of the NOTNH collection (*e.g.* the botany and zoology collections), the involvement of more staff at both the museum and NTU, and the development of a way to evaluate the learning outcomes and other benefits (or drawbacks) more stringently. Future projects may also include collections and staff from other institutions beyond those involved to date.

Conclusions

Natural history collections are vast, irreplaceable repositories of information, but undergraduates are often unable to access such valuable resources. The NOTNH-NTU collaboration shows making regional museum collections accessible to undergraduate students can increase collection usage and provide opportunities and benefits to the students, staff, and collections. The students learned a great deal from their hands-on experience and found their projects to be engaging and rewarding. The university staff benefited from using the collection as a teaching resource and from knowledge exchange. The museum curator benefited from increased collection usage, re-identification of historical specimens, and investment in the collection. Overall, the only significant cost is the time required to identify, facilitate, and supervise projects, which is difficult when curators and university staff are often stretched to capacity with other commitments. However, the example from Nottingham outlined here shows that the investment of time can be rewarded with numerous mutual benefits stemming from increased collection usage.

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References

BREWER, C. A. and SMITH, D. 2011. *Vision and Change in Undergraduate Biology Education: A Call to Action.* Washington, DC: American Association for the Advancement of Science.

BRAMWELL D., CARTLEDGE, K. M., GILBERTSON, D. D., GRIFFIN, C. M., HUNT, C. O., JENKINSON, R. D. S. and SAMSON, C. 1984. Steetley Quarry Cave: A "lost" Ipswichian interglacial site and Steetley Cave: A 5000-year-old badger den. *In* D. D. Gilbertson and R. D. S. Jenkinson (eds.) *In the Shadow of Extinction: A Quaternary Archaeology and Palaeoecology of the Lake, Fissures and Smaller Caves at Creswell Crags SSSI.* Sheffield: Department of Prehistory and Archaeology, University of Sheffield. 75–87.

CARPENTER, K. and ISHIDA, Y. 2010. Early and "Middle" Cretaceous iguanodonts in time and space. *Journal of Iberian Geology* **36** (2), 145–164.

CLARKSON, C. 2016. *Pleistocene Brown Bears* (Ursus arctos) *at the Nottingham Natural History Museum, Wollaton Hall.* Unpublished undergraduate thesis, Nottingham Trent University.

COOK, J. A., EDWARDS, S. V., LACEY, E. A., GURALNICK, R. P., SOLTIS, P.S., SOLTIS, D.E., WELCH, C.K., BELL, K.C., GALBREATH, K. E., HIMES, C., ALLEN, J.M., HEATH, T.A., CAR-

NAVAL, A.C., COOPER, K.L., LIU, M., HANKEN, J. and ICKERT-BOND, S. 2014. Natural history collections as emerging resources for innovative education. *BioScience* **64** (8), 725–734.

CURRANT, A. and JACOBI, J. 2001. A formal mammalian biostratigraphy for the Late Pleistocene of Britain. *Quaternary Science Reviews* **20**, 1707–1716.

HILLER, A.E., CICERO, C., ALBE, M.J., BARCLEY, T.L., SPENCER, C.L., KOO, M.S., BOWIE, R.C. and LACEY, E. A., 2017. Mutualism in museums: A model for engaging undergraduates in biodiversity science. *PLoS Biology* **15** (11), p.e2003318.

HORNE, J. R. E. 2015. *A Palaeoenvironmental Reconstruction of Steetley Quarry Cave, Worksop Based Upon the Vertebrate Fauna*. Unpublished undergraduate thesis, Nottingham Trent University.

JENKINSON, R. D. S. 1984. *Creswell Crags: Late Pleistocene Sites in the East Midlands*. BAR British Series 122. Oxford: BAR. 127–129.

LINN, M. C., PALMER, E., BARANGER, A., GERARD, E., and STONE, E., 2015. Undergraduate research experiences: Impacts and opportunities. *Science* **347** (6222), p.1261757.

LISIECKI, L. E. and RAYMO, M. E. 2005. A Pliocene-Pleistocene stack of 57 globally distributed benthic d18O records. *Paleoceanography* **20**, PA1003. https:/doi.org/10.1029/2004PA001071.

LOMAX, D. R. and GIBSON B. J. A. 2015. The first definitive occurrence of *Ichthyosaurus* and *Temnodontosaurus* (Reptilia: Ichthyosauria) in Nottinghamshire, England and a review of ichthyosaur specimens from the county. *Proceedings of the Geologists' Association* **126** (4–5), 554–563.

MALPASS, E. M. 2019. *An Analysis of Bite Marks and Pathologies in Oxford Clay Marine Reptiles.* Unpublished undergraduate thesis, Nottingham Trent University.

MANTL, N. A. 2018. *Osteological study of prehistoric human material from the Nottingham Natural History Museum (Wollaton Hall) and the Creswell Crags Visitor Centre.* Unpublished undergraduate thesis, Nottingham Trent University.

MANTL, N. A. 2019. Prehistoric human material in the Nottingham Natural History Museum, and the Creswell Crags Museum and Heritage Centre. *Geological Curator* **11** (1), 93–106.

NORMAN, D. B. 2010. A taxonomy of iguanodontians (Dinosauria: Ornithopoda) from the lower Wealden Group (Cretaceous: Valanginian) of southern England. *Zootaxa* **2489**, 47–66.

PAUL, G. S. 2008. A revised taxonomy of the iguanodont dinosaur genera and species. *Cretaceous Research* **29** (2), 192–216.

PIKE, A. W. G., EGGINS, S., GRÜN, R., HEDGES, R. E. M. and JACOBI, R. M. 2005. U-series dating of the Late Pleistocene mammalian fauna from Wood Quarry (Steetley), Nottinghamshire, UK. *Journal of Quaternary Science* **20**, 59–65.

POWERS, K. E., PRATHER, L. A., COOK, J. A., WOOLLEY, J., BART Jr, H. L., MONFILS, A. K. and SIERWALD, P. 2014. Revolutionizing the use of natural history collections in education. *Science Education Review* **13** (2), 24–33.

SMITH, A. S. 2015. Fossils at the Nottingham Natural History Museum, Wollaton Hall, UK. *Palaeontology Newsletter* **88**, 35–38.

SMITH, A. S. and WANG, Q. 2017. *Dinosaurs of China: Ground Shakers to Feathered Flyers*. Nottingham: Nottingham City Council.

SMITH, C. A. 2016. *History of* Cervus elaphus*: A Palaeontological Study of Remains from the Nottingham Natural History Museum and Living Examples.* Unpublished undergraduate thesis, Nottingham Trent University.

SMITH, L. 2019. *A Taphonomic Assessment of Damage to Fossilized* Ichthyosaurus larkini *Remains (NOTNH: FS4940) to Determine Probable Cause of Death.* Unpublished undergraduate thesis, Nottingham Trent University.

STRICKSON, E. C. 2014. *A Description in Taxonomic Appraisal of* 'Iguanodon' *Fossils from Nottingham Natural History Museum and the British Geological Survey, Keyworth*. Unpublished undergraduate thesis, Nottingham Trent University.

TURNER, N. S. 1993. The geological collections of the Natural History Museum, Wollaton Hall, Nottingham. *Mercian Geologist* **13** (2), 66–67.

TURNER, N. S. 2000. A catalogue of the type, figured and cited fossils in the Nottingham Natural History Museum, Wollaton Hall, Nottingham, U.K. *Geological Curator* **7** (3), 111–121.

VERDÚ, F. J., ROYO-TERRES, R., COBOS, A., and ALCALÁ, L. 2015. Perinates of a new species of *Iguanodon* (Ornithischia: Ornithopoda) from the lower Barremian of Galve (Teruel, Spain). *Cretaceous Research* **56,** 250–264.

WIGGINS, Z. C. 2015. *A Taxonomic Investigation into the Fossil Elephantid Material at Nottingham Natural History Museum*. Unpublished undergraduate thesis, Nottingham Trent University.

The Texas Vertebrate Paleontology Collections – TxVP

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The purpose of this note is to establish the museum collection acronym "TxVP" for the Texas Vertebrate Paleontology Collections (hereafter referred to as "the collection") and to briefly discuss its history as the Texas state repository as codified in the general laws of the state of Texas. The Texas Vertebrate Paleontology Collections rank among the largest vertebrate fossil collections in the world and have enjoyed continuous support from the state of Texas. However, owing to the multiple functions of the collection—as a museum object collection, state repository, source of teaching material, and international research institution—its governance over the years has shifted with the relative emphasis of those roles. Repeated administrative changes over the past 130 years have resulted in a confusing array of institutional acronyms being applied to the collection. The most recent internal administrative change at The University of Texas at Austin transferred the collections from the Texas Memorial Museum to the Jackson School of Geosciences. This move prompted the curatorial committee to unanimously decide on the creation and establishment of TxVP as the permanent collection acronym from now on. The purpose for this new designation is to correctly ascribe vertebrate fossils to the State Collections, rather than to prior governing institutions that are unaffiliated with, and geographically removed from, the collections.

Sagebiel, J. C. 2020. The Texas Vertebrate Paleontology Collections – TxVP. *Geological Curator* **11** (3): 249-251.

A brief history of the Texas Vertebrate Paleontology Collections

The Texas Vertebrate Paleontology Collections were first established by state legislation in 1858 as a result of the Geological and Agricultural Survey of Texas, in which fossils were collected throughout Texas for 'final preservation in the State Cabinet' (Shumard 1859, p. 8). Unfortunately, practically all of the accomplishments and collections of this survey were destroyed during the American Civil War and subsequent fires (Hill 1887, p. 28).

In 1870, following the Civil War, the Texas Legislature re-established the geological collections as part of the short-lived and under-funded 'Geological Survey of the State of Texas' (often referred to as the second survey):

> With specimens of the useful native and introduced plants, and all other substances and objects that may be necessary to illustrate the economic and scientific geology, and render the collection a complete museum of practical geology… the Governor shall procure safe and suitable rooms at the capital of the State for the permanent deposit and arrangement of the collections above mentioned; that said collections shall be arranged and classified in the same by the said State Geologist (General Laws, chap. LXI sec. 3 and 4)

The 20th Texas legislature added to the value of the State Collections with its establishment of a third state-wide effort, the 'Geological and Mineralogical Survey':

> [The state geologist] shall also preserve specimens of minerals, coals, stones, and other natural substances… as practicable add specimens of organic remains and other objects of natural history peculiar to this State (General Laws, chap. XIII sec. 3)

This third survey, directed Edwin T. Dumble, lasted eleven years. It officially ended in 1901 when the survey moved to the University of Texas. Fossils collected as part of the third survey were sent to E. D. Cope and described in his 1894 report (Flawn 1965; Ferguson 1981).

Texas Vertebrate Paleontology Collections at The University of Texas

In 1909, the Bureau of Economic Geology was established at The University of Texas. The Texas legislature shifted the state survey responsibilities (and collections) to the Bureau shortly thereafter, and the Bureau continues to function as the State Geological Survey, with its director serving as State Geologist (Flawn 1965).

With Works Progress Administration (WPA) funding, the Bureau conducted the largest vertebrate fossil collecting effort in our history—the Statewide Mineralogical and Geological Survey in 1939, which coincided with the completion of a state museum on The University of Texas campus. As such, the Texas Memorial Museum (TMM) became the gallery for state collections, while further adding to the collections with its own efforts. In 1941, war would again cut short another state geological survey. After World War II, professor John A. Wilson gathered together not only the vertebrate fossils collected under the state surveys, but also UT geology department collections into a single facility on the war-surplus campus known as Balcones (now J. J. Pickle) Research Center in north Austin, Texas (J. A. Wilson collection, Texas Vertebrate Paleontology Archives).

Functioning as the State Vertebrate Paleontology Collection

Although responsibility for running the Geological Survey and the TMM shifted to The University of Texas, the collections remain the state repository as codified in state law. This status has been iteratively asserted, not only through legislative actions described above, but also through its functionary history. For example, after losing university support in 1969, the Texas A&M Museum was demolished, and its fossil collections transferred to join the collection in Austin. Unfortunately, the process was somewhat hasty, resulting in a number of items being lost in the process (Walker 2016). A 1984 memorandum among the Presidents of Texas A&M, The University of Texas, and their respective legal offices recognized the status of the collections as the Texas state repository and officially transferred the Texas A&M Museum vertebrate fossils to the collection in Austin (Mark Francis collection, Texas Vertebrate Paleontology Archives).

Over the years, many vertebrate fossil collections have been donated to the Texas Vertebrate Paleontology Collections as professors retired or institutions closed. These include the Midwestern State University (MWSU/MSU) collections made by Walter Dalquest and Frederick Stangl, Texas A&I / Texas A&M Kingsville (TAMUK) collections Jon Baskin built with Ronny Thomas and colleagues, the East Texas State University (ETSU) collection built by Joan Echols and the collections of James Stevens, Margaret Stevens, and Jim Westgate of Lamar University. Additionally, the collections have served as the *de facto* repository for fossils found in Big Bend National Park and maintained collections from the public lands of Texas and all branches of the Federal Department of Interior.

Branding TxVP

Although administrative responsibility for the collections has shifted over the years, they have always been labelled and referred to as the Texas Vertebrate Paleontology Collections. Unfortunately, administrative changes have caused confusion in all aspects of collections use, particularly with literature citations and loans. Additionally, ignorance of the collections' status as State Repository has caused vertebrate fossil collections to be inappropriately placed into historic or archaeological collections. As a result those collections are not only less accessible to palaeontologists, but specimen damage has resulted from the differences in collection protocols and practices.

Because of this history, the Texas Vertebrate Paleontology Collections is now branded with the collections acronym TxVP. The Global Registry of Scientific Collections (GrSciColl, managed by GBIF) record for the Texas Vertebrate Paleontology Collections is amended to TxVP, and this acronym will become the prefix to the catalogue numbers. Several acronyms have been used in publications over the years. However, because the fossils and collection labels are very rarely labeled with those acronyms, the TxVP prefix can easily be appended to both specimens and labels. For donated collections items bearing numbers from other institutions, our standard practice has been to append a new catalogue number and to include the previous institution's numbers as an alternate catalogue number on labels, specimens, and databases. New labels are used in the collections, clearly printed with the older catalogue numbers, and the original labels are archived. Incorporated into this collection are the major fossil collections of several institutions previously cited under the following acronyms:

BEG –Bureau of Economic Geology

ETSU – East Texas State University

MSU – Midwestern State University

MWSU – Midwestern State University

TAMU - Texas A&M University Museum

TAMUK - Texas A&M University, Kingsville

TMM – Texas Memorial Museum

TMM-TAMU – Texas A&M University Museum collections at the TMM

TNSC – Texas Natural Science Center

UT - The University of Texas

VPL – Vertebrate Paleontology Laboratory (a University code for our building)

TxVP, the Texas Vertebrate Paleontology Collections, at the Jackson School Museum of Earth History, The University of Texas at Austin is the official state repository for the state of Texas. The collection is housed on the J. J. Pickle Research Campus of The University of Texas at Austin.

References

FERGUSON, W. K. 1981. *History of the Bureau of Economic Geology, 1909–1960*. Austin: The University of Texas Press.

FLAWN, P. T. 1965. Geology in the State Government of Texas. *Bureau of Economic Geology Geological Circular* **65** (5), Austin: The University of Texas Press.

General Laws of the Twelfth Legislature of the State of Texas. 1870. Chapter LXI. *An Act Providing for a Geological Survey of the State of Texas*. Austin: Tracy, Siemering & Co.

General Laws of the Twentieth Legislature of the State of Texas. 1888. Chapter XIII. *An Act to Authorize the Commissioner of Agriculture, Insurance, and History to Have a Geological and Mineralogical Survey Made of the State of Texas, and to Make an Appropriation Therefor*. Austin: State Printing Office.

HILL, R. T. 1887. The present condition of knowledge of the geology of Texas. *Bulletin of the United States Geological Survey* **45**. Washington: Government Printing Office.

SHUMARD, B. F. 1859. *First Report of Progress of the Geological ad Agricultural Survey of Texas*. Austin, TX: John Marshall & Co., State Printers.

WALKER, J. K., Jr. 2016. *Over at College: A Texas A&M Campus Kid in the 1930s*. College Station, TX: Texas A&M University Press.

BOOK REVIEW

***North Pole: Nature and Culture*. Michael Bravo. Published by Reaktion Books, London, 2019. UK £14.95, paperback, 254 pp. ISBN 978-1-78914-008-8.**

The 'Earth Series' of Reaktion Books, now including 25 titles, are all focussed on some aspect of our planet, although none is strongly predisposed towards geology. Subjects that are obviously important geological features are covered, such as *Earthquakes* or *Caves*, but subjects are also considered at some depth and breadth as they relate to culture and the human environment. I acknowledge this bias, yet also admit to being a great admirer of this series, with over half the titles on my bookshelf. Few are without points of relevance and interesting asides on mineralogy, tectonics, palaeontology, and so on. It is therefore quaint that *North Pole* by Bravo works hard, almost grudgingly, at ignoring two key factors: Earth science in the broadest sense; and 19th and 20th Century explorers and exploration (p. 16). Yet they can no more be ignored than if a treatise on toes ignored the rest of the foot. These key factors are, for me, the most interesting aspects of the North Pole and are side-lined, yet keep popping up nonetheless. Rather, Bravo is focussed on superstition, the supernatural, legends, vague speculations, and solid ideas about the North Pole (or poles), yet all of these have relations to the physical landscape of the Arctic. *North Pole* is interesting and readable, taking the reader into some murky historical corners which are, again, of interest to an Earth scientist. In truth, *North Pole* is a lively book, jumping hither and thither with aplomb, likely to capture the attention of any reader, as it did me.

North Pole is well-written, readable, and with a logical structure. A preface and seven chapters are supported by references and selected bibliography, index, and acknowledgements. As is standard in the Earth Series, printing is on heavyweight art paper with most paintings and photographs reproduced in full colour. The book is a thing of beauty.

A North Pole has been known of since long before it was ever visited, but was it on, above, or below the Earth, if not all three? Was it all things to all men or a nationalistic chimera? Bravo spends much of *North Pole* discussing these positions and does not so much provide answers as show the breadth of each of these questions. But how many North Poles are there? For example, the Pole Star is one of the North Poles, a celestial North Pole, friend of navigators (except, obtusely, when they are in the Arctic north) and widely apparent, 'suspended' above the Earth when it was the centre of the Cosmos.

Despite some of my critical comments, Bravo does account for relevant aspects that provide an adjunct to the polar landscape, such as astronomy (Chapter 1, 'The Upward Gaze') and the development of the cartography of the North Pole (Chapters 2 and 3, 'Holding the North Pole' and 'The Multiplication of Poles'). The concept of the North Polar Prizes is a fascinating one (Chapter 4, 'Polar Voyaging'), encouraging as they did a certain amount of British ineptitude in exploration by gentlemen amateurs, leading to that nationalistic perversity of polar exploration, manhauling (p. 121).

One pseudo-geological aside is a reference to a Jules Verne novel that I had not heard of, perhaps not one of his better works, called *The Purchase of the North Pole* (pp. 171–175). The purchasers are the villains, in pursuit of untapped coal resources. Their intent is to shift the Earth on its axis, moving the North Pole further south, melting the ice and exposing the coal beds. It is a mix of dubious pseudoscience and improbabilities piled high in the style of late 19th Century escapist literature.

Despite my caveats in my first paragraph, *North Pole* should be entertaining reading for many who got this far in my review. *North Pole* contains much of educational and entertainment value, grudgingly discussing anything of geological interest, while telling a story that will enthral many geologists. The volume is so well produced and the price so reasonable by modern standards that anyone with even only a marginal interest in the poles should consider adding it to their home library.

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GEOLOGICAL CURATOR

About the journal

The Geological Curator is the official journal of the Geological Curators' Group (GCG) and has been published by the GCG since its first issue in 1974. There are two issues per year: in June and December, available in both electronic and print format. The most recent content (last two years) is available to GCG members only. Funding for the publication is derived from GCG income (primarily membership fees). Issues older than two years are freely available from the GCG website (www.geocurator.org) via a Creative Commons Attribution-NonCommercial-NoDerivatives 4.0 International Public Licence (CC BY-NC-ND 4.0: https://creativecommons.org/licenses/by-nc-nd/4.0/). Attribution should follow standard academic format, with the author(s) and year and link to a full reference. All accepted articles have been through peer review.

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