Earth and Environmental Science Transactions of the Royal Society of Edinburgh, **103**, 205–216, 2013 (for 2012)

The development of "modern" palaeontological laboratory methods: a century of progress

Matthew A. Brown[1,2]

[1] Vertebrate Paleontology Laboratory, The University of Texas at Austin, 10100 Burnet Rd, R7600, Austin, TX 78758, USA.
Email: matthewbrown@utexas.edu

[2] School of Museum Studies, University of Leicester, Museum Studies Building, 19 University Road, Leicester LE1 7RF, UK.

ABSTRACT: Vertebrate fossils have been converted from natural history objects into research specimens through the act of preparation for over 200 years. All of the basic techniques applied to specimens in the 21st Century were already in use in palaeontological laboratories by the first decade of the 1900s. It behoves any worker in the field to be intimately familiar with processes for treatment of specimens, as these procedures almost always permanently alter material available for interpretation. Historic treatments also complicate attempts to re-treat or re-prepare specimens. Sometimes this results in damage to fossils and loss of information, and often in wasted resources. Most palaeontologists are unaware of the historical evolution of laboratory methods through this time; much of the documentation of this process is considered to be obscure. However, there is in fact a robust body of literature that chronicles the development of procedures for the preparation of fossils. Awareness of the past development of methods is crucial to guiding future directions in the palaeontological laboratory. Regular reporting of laboratory methods in the technical literature at a pace matching that of other analytical methods is integral to the function of palaeontology as a science.

KEY WORDS: Adam Hermann, fossil preparation, Francis Bather, history of science, laboratory techniques, palaeontology conservation

Fossil preparation is the act of exposing fossil information from the rock matrix in which it is encased and thereby transforming the object into a scientific specimen. This activity has by necessity accompanied palaeontological research for as long as people have studied ancient life. Peter Whybrow, a researcher and preparator at the British Museum Palaeontology Laboratory, credited Georges Cuvier with the first scientific description of a fossil preparation method in 1804 (Whybrow 1985, p. 12). Since then, many different techniques have been ascribed as laboratory processes, yet application of these methods to specimens is rarely recorded in precise detail. If performed imprecisely, these methods possess a strong likelihood of altering morphology (Hermann 1909; Camp & Hanna 1937; Wylie 2009; Lòpez-Polìn 2011). Despite being a necessary component of most palaeontological inquiry, the practice of preparation remains ill-defined and poorly understood within the field. The actions and responsibilities of preparators are generally characterised according to the nature of the individual preparator or institution (May *et al.* 1994, p. 113), or because of locality or taxon specific research requirements. This has been the case since the genesis of the "modern" preparation laboratory, over 100 years ago (Brinkman 2009).

The vertebrate palaeontology laboratory of today still shares much in common with that of the early 20th Century. Though the majority of current laboratory methods were well established by this period (Whybrow 1985; Brinkman 2009), more than a century later there remains no avenue for consistent training of these techniques. By contrast, conservators in other fields, such as art conservation, had already established academic programmes for training by the early 1900s (Bewer 2010, p. 55). A number of works outlining palaeontological techniques have been compiled through this time period (Mantell 1844; Hill 1886; Schuchert 1895; Bather 1908; Hermann 1908, 1909; Stromer 1920; Seitz & Gothan 1928; Prokhorov 1929; Efremov & Kuzmin 1931; Camp &Hanna 1937; McAnulty 1939; Kummel & Raup 1965; Rixon 1976; Converse 1984; Feldman *et al.* 1989; Leiggi & May 1994; Brown *et al.* 2009), but most are not well known today, and none of the recent contributions are comprehensive of current best practices. Additionally, the complete body of knowledge that they represent is not widely possessed in the preparation community. Training has almost exclusively taken place in a master/apprentice model throughout this period (Matthew 1919; Camp & Hanna 1937; May *et al.* 1994; Brown & Kane 2008; Brown 2009). This results in persisting misinformation in the field, as well as an enormous amount of duplicated effort.

The earliest of these papers (1844–1909) represent the historical development of laboratory methods; they demonstrate the evolution of equipment, techniques and materials within a few generations. Preparation in the 20th Century was marked by the early inheritance of a core group of methods and a subsequent refinement of those technologies, coupled with a steady improvement in the conservation properties of materials available. The technical literature published between 1895 and 1939 exhibit an international consensus on best practices; at no point since then has a body of knowledge been represented in such a widespread fashion with such a diversity of authors.

This paper describes the development of preparation and conservation methods prior to World War II through a review of historical publications, identifies three distinct transitions in the nature of the related technical literature from the beginning of the 19th Century through the present day, and critiques

 doi:10.1017/S1755691013000352

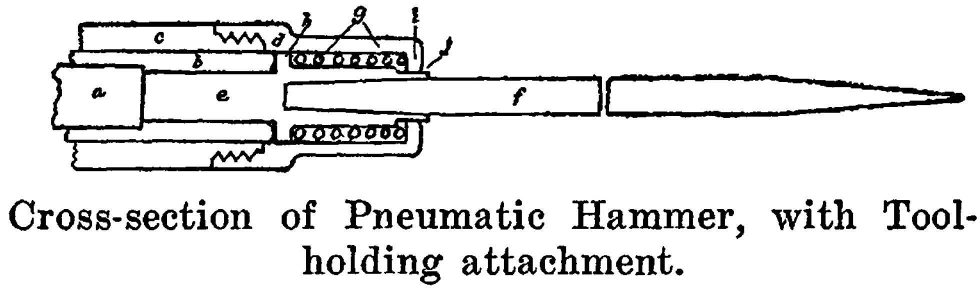

Figure 1 A pneumatic chisel as modified by Elmer Riggs for use in palaeontological preparation (from Riggs 1903, p. 748). This tool design remains very similar in airscribes today.

the consciousness of laboratory methods today. Methods are limited here to mechanical and chemical exposure of fossils, consolidation and adhesion, conservation, housing, and thin-section and serial grinding techniques. Due to limitations of space, fieldwork, moulding and casting and mounting methods are largely excluded.

1. Why study old methods?

1.1. Practical effects

Students of palaeontology are obligated to understand the genesis of modern techniques for several reasons. The acts of preparation and conservation alter fossils permanently, and these modifications can interfere with study or re-treatment. The historical methods literature may be the only documentation of past preparation and conservation treatments. Understanding trends in methods is also an underlying element of professional development.

First, and perhaps most importantly, historical treatments applied to fossil specimens do not remain in the past – they endure as an integral component of the fossil into the future. They typically cannot be reversed, and continually affect observations and interpretations of fossil material. An understanding of the long-term impact that methods and materials have on fossils is crucial to accurate interpretation of morphology.

An awareness of the functional properties of materials already present in fossils is an essential component of responsible handling. Specimens cannot be reliably and safely treated without knowing how pre-existing components of them will react to new applications of chemicals and processes. When considering re-treatment or re-preparation of specimens, every possible effort should be made to identify all previous procedures and materials that have been applied to specimens. Early publications are often the only record of materials applied to specimens. A paper that described a new technique can provide geographical or temporal clues useful in reconstructing the past treatment history of fossils, based on common practices in a given place or time. Familiarity with the methods literature benefits the research team when diagnosing materials or techniques.

Understanding of past techniques allows for a mature and historically informed understanding of modern methods. While palaeontologists have largely remained cognisant of more than two centuries of literature relating to anatomical descriptions of fossils, the technical literature is almost entirely ignored. This leads nearly every generation of researchers, conservators and technicians to repeat work, damage specimens and expend unnecessary resources.

Due to this lack of emphasis on techniques publications, the worker in a palaeontology laboratory rarely performs a literature search before attempting a new treatment; often investigation of methods is restricted to a query to a mailing list or consultation with close colleagues. The lack of academic training and focus on apprenticeship accompanying laboratory work is partially responsible for the absence of a canon of knowledge. Consequently, fossil preparators and conservators are often characterised by possessing great ingenuity (e.g. Rixon 1976; Wylie 2009), and working in relative isolation (Leiggi & May 1994, p. xv). This leads to a natural self-reliance and independence in technique development.

Nevertheless, a thorough understanding of the body of knowledge of the field is a key component to professionalism and a prerequisite to development of a rationale for selecting and applying appropriate treatments to specimens. One method for rebuilding an awareness of best practices is by resuming regular publication of methods papers. Historically, research or curation department members, rather than laboratory staff, generated methods publications. Even when laboratory personnel made significant contributions, it was often at the direction of supervisors. For example, even American Museum Chief Preparator Adam Hermann's landmark papers were a result of prompting from Director H. F. Osborn (Matthew 1919, p. 742).

1.2. Generational perceptions

American Museum palaeontologist Gilbert Stucker (1961, p. 332) pointed out that "the aim and scope of palaeontology have changed since the early days … this has brought a demand for more exacting laboratory preparation" and that "if a laboratory is to keep pace with the research rooms, new tools and new techniques must constantly be sought." However, this same point was the topic of a paper by Efremov & Kuzmin (1931) and was also reflected by Hermann's recollections of the work performed under the direction of O. C. Marsh, E. D. Cope and Joseph Leidy: preparation, Hermann wrote, "was carried out in a rather crude manner. Bones were cut out of the matrix in the simplest way with poor tools, and as they came out in pieces they were cemented together with common carpenter's glue. This held them together as long as the glue retained some moisture; they fell apart just as soon as the glue became dry" (Hermann 1909, p. 283). This focus on the development of new methods does not mean that older techniques and philosophies have no place in the modern laboratory. Rather, the "tool box" of the preparator is constantly expanding. A proven challenge is for workers in the laboratory to remain aware of these early techniques and philosophies, their benefits and limitations, all the while experimenting with new ones.

Evidence of this challenge is readily apparent in the literature. For example, at the American Museum of Natural History, Stucker *et al.* (1965, p. 272) described air abrasive sandblasting as "a method of fossil preparation [that] has come into use recently" despite the development and first publication of this technique over seventy years earlier (Bernard 1894), and shortly after that within his own institution (Osborn 1904). Rixon (1976, p. 79) similarly ignores Riggs' 1903 adaptation of pneumatic chisels (Fig. 1) to the work of preparation when he

https://doi.org/10.1017/S1755691013000352 Published online by Cambridge University Press

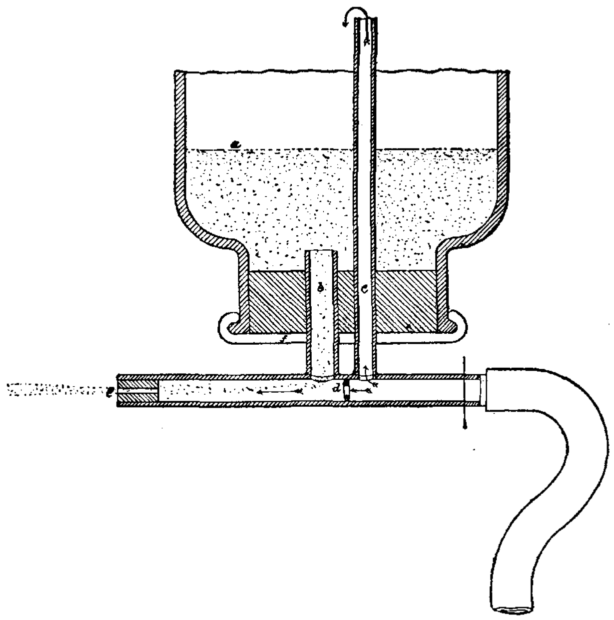

Figure 2 Part of H. M. Bernard's device for cleaning fossils via sand-blasting techniques (from Bernard 1894, p. 555).

introduces the same as a tool available "in recent years". It may be that in the 1960s, Stucker and colleagues were unaware of Bernard's work on trilobite preparation (Fig. 2). It is likewise possible that Riggs' short paper in *Science* (Riggs 1903) may have been difficult to locate sixty years after publication; however, the technique itself rapidly spread from the Field Columbian Museum to the American Museum of Natural History and the United States National Museum (Osborn 1904; Brinkman 2009, p. 33) and was promoted by Hermann in both his 1908 and 1909 papers. These latter works were cited widely (e.g. Stromer 1920; Camp & Hanna 1937). Efremov & Kuzmin (1931) also experimented with pneumatic tools in Russia. Rixon had been involved in both the preparation of fossils and publication of methods papers since at least the mid-1930s (Toombs & Rixon 1959, p. 304), making it hard to believe that he was unaware of so much previous work on the topic. More recently, Leiggi & May (1994, p. xv) discuss their development of a preparation manual beginning in 1983, asking why "a techniques volume had never been specifically written for the science of vertebrate palaeontology." However, British Museum palaeontologist A.E. Rixon's 304-page, heavily referenced textbook had accomplished this objective just seven years earlier in the UK (Rixon 1976).

In an age of instant electronic communication, there is little reason for preparators, conservators and others in palaeontology to remain unaware of the history and use of best practices in laboratory methods. For example, even though early materials choices for stabilising fossil material do not meet current museum conservation standards (Howie 1984; Horie 2010), those choices represent an evolution of method as workers continually experimented with new materials in an effort to determine best practices. However, adoption of better materials has not been universal, as palaeontologists still sometimes use products such as shellac or Glyptal for consolidation of specimens, even 30 or more years after conservation scientists demonstrated that these products are unstable (Damiani & Hancox 2003; Sidor & Welman 2003).

Other recent examples of this information gap between the literature and the workbench include Cavin's (2011) attempts to develop small-scale moulding and casting methods, initially without knowledge of existing descriptions of similar techniques and equipment (e.g., Waters & Savage 1971; Reser 1981), despite requests for information from online mailing lists (J. Cavin pers. comm. 30 Apr 2011). Likewise, early drafts of Cavigelli (2009) were revised by the author and editors without knowledge of or credit to (M. Brown pers. obs.) prior publications regarding the use of polyethylene glycol to stabilise fossils (e.g., Rixon 1965; Converse 1984). To be sure, each recent author has generated novel uses of materials in their respective endeavours (e.g., Cavigelli's (2009) recycling of polyethylene glycol), yet this is hardly the most effective approach for development of a field. These are examples of failings, not of the individual authors, but of a science that does not prioritise laboratory methods. Whybrow makes this point in his scathing assessment of this situation: "Vertebrate palaeontology must be one of the few 'sciences' where the techniques used to establish the facts appear to be of little consequence" (Whybrow 1985, p. 5). In part, this is a result of the absence of a taught body of knowledge for laboratory techniques.

2. Historical literature review

2.1. Establishing modern methods: 1804–1909

The record of technical publication of laboratory methods extends back to at least 1804 (Whybrow 1985). Cuvier described his basic technique for exposing morphology: "I dug carefully, using a fine steel needle, and had the satisfaction to have discovered the whole anterior portion of the pelvis" (Cuvier 1804, p. 286). This methodology was crucial to confirming his predictions, and he took pride in demonstrating his ability to anticipate the morphology of anatomical structures (Huxley 1880). In addition to describing his methods in the literature, he also arranged an audience to validate his results. "This operation took place in the presence of a few to whom I had announced the result in advance, with the intention of proving in fact the justness of our zoological theories: since the true character of a theory is unquestionably the faculty that it gives to predict phenomena" (Cuvier 1804, p. 286). Whybrow interprets this undertaking as evidence that Cuvier "recognised the historical significance" of his preparation activity, a step further would be to suggest that Cuvier realised that a record of the methods used to expose morphology supports the validity of the operation as a scientific enterprise. In sum, that publication of laboratory methods is a logical and requisite component of the scientific method.

While several collectors discussed techniques that they developed for recovery of specimens from the field, information about fossil preparation methods is sparse throughout the early and mid 19th Century. The notable standout is Gideon Mantell's 1844 *Medals of Creation,* followed by the revised 1854 Second Edition. An overview of the nascent field of palaeontology, Mantell incorporates directions for preparing fossils as a preliminary step in the process of study, instructing that the student of palaeontology should "visit some of the localities described; collect specimens, and develope [sic] them with his own hands; examine their structure microscopically; nor rest satisfied till he has determined their general character, and ascertained their generic and specific relations" (Mantell 1844, p. xiv). He briefly describes techniques for mechanical and chemical preparation, histological sample preparation and microscopy techniques, and experimentation with consolidants and adhesives. Each method is related as relevant to specific localities or taxonomic groups. Importantly, Mantell notes examples of anatomical insights gained during the preparation process, echoing Cuvier. Just as Cuvier was likely the first to describe the process of preparation, forty years later Mantell was likely the first to illustrate it (Fig. 3).

https://doi.org/10.1017/S1755691013000352 Published online by Cambridge University Press

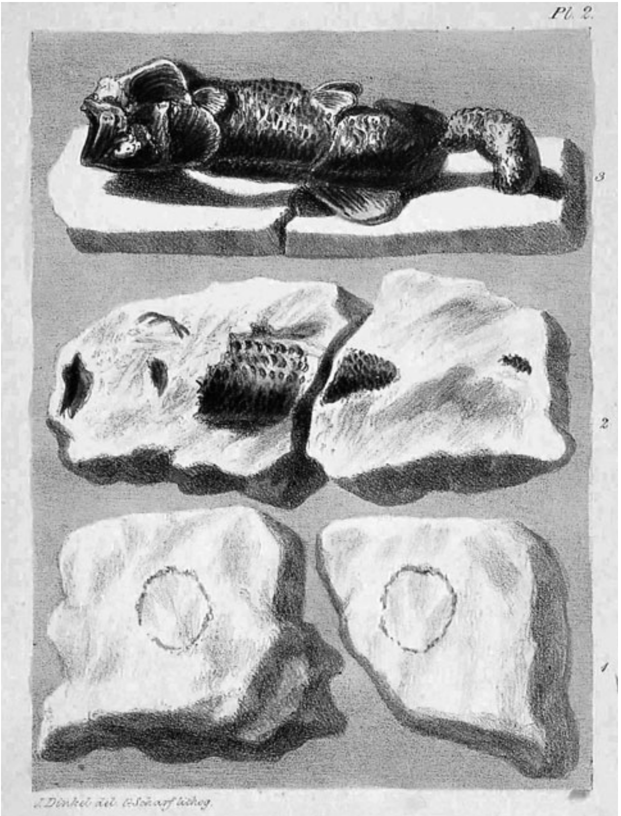

Figure 3 The earliest illustration of the process of preparation, showing the stages of preparation of the fossil fish *Osmeroides mantelli* from a block of chalk (from Mantell 1854, p. iv): "(1) The two corresponding surfaces of a block of Chalk split asunder. The irregular oval lines, seen on each surface, are the only apparent indications that the stone contains an extraneous body; (2) In this figure the two pieces represented above are shown cemented together; care having been taken that the oval markings on each surface were accurately adjusted. The chalk has been chiselled away in the supposed longitudinal direction of the enclosed extraneous body, and part of the scaly surface of a fish has been thus brought to light. A portion of chalk has also been removed towards both ends, with the view of ascertaining the extent and direction of the fossil; and at each place indications of its presence are visible; (3) Represents the specimen completely developed. It proves to be a fish almost perfect, lying on its back, with the body uncompressed, the mouth open, the arches and opercula of the gills expanded, and the dorsal, pectoral and ventral fins entire. The caudal fin, or tail, is imperfect. The original is nine inches long, and is one of the most extraordinary fossil fishes ever discovered. It belongs to the Salmon family, and is allied to the Osmerus, or Smelt; it is now in the British Museum. We thus perceive the oval markings on the surface of fig. 1 were occasioned by the section of the scales covering the cylindrical body of the fish (see p. 627). A magnified view of one of the scales is figured Lign. 185 fig. 4, p. 567" (Mantell, 1854, p. v).

Several authors (Buckland 1866; Hill 1875) published recipes for adhesives, but another forty years passed following Mantell's work before a volume approaching a manual for laboratory preparation was published, appearing in 1886 (Hill 1886). Though described as one of the first publications devoted solely to mounting techniques (Howie 1986, p. 20), Princeton Geological Museum curator Franklin Hill's pioneering report was the first to outline the tools, equipment and philosophies that guide palaeontological preparation and conservation. Hill described a laboratory setup complete with the now-familiar hammers, chisels, sharpened steel needles and brushes. He also outlined the need for sufficient lighting, magnification and support for specimens.

Beyond tools, Hill also seems to be the first author intentionally to address conservation concerns. Though Howie (1986, p. 13) highlights Richard Owen's (1855) direction to staff to place plaster casts on exhibit rather than real bones to preserve their utility as research specimens as an early step on the path of conservation, Hill explicitly documents his concerns about the storage, handling and treatment of fossils in the context of damage prevention. He also describes the recipe and properties of mucilage, the preferred consolidant for use on fossils in his laboratory, based on years of testing against other concoctions. This is the first documented example of archival materials testing in the fossil preparation laboratory.

Hill poses the question of "how to keep [a fossil] safely and show it to advantage" once preparation and consolidation is complete. In contrast to the modern collections standard, where priority is placed on housing research specimens in stable storage isolated in cabinets, Hill endeavoured to create anatomical mounts of important specimens. This was because "experience shows that a bone in its natural position … is easier to understand than when reversed, while if several bones are combined so as to form a foot, or leg, a spinal column or a skull, the value of each is greatly increased" (Hill 1886, p. 355). Additionally, Hill was motivated to mount specimens as a protective measure, since "a single ramus of a lower jaw … in a tray … is liable to be thrust aside and jostled, to the great danger of its teeth and coranoid" (Hill 1886, p. 355). Hill's mounts were designed to be "so obvious that the most careless or dull student can hardly fail to see it … because if a blunder be possible some persons can always be depended on to make it, and hence come many breakages" (Hill 1886, p. 356). This is a topic we will return to later.

Charles Schuchert (1895), of the Smithsonian Institution National Museum of Natural History, was the next palaeontologist to address preparation and collecting comprehensively. He described the process of laboratory preparation systematically, beginning with sorting of specimens from the field into boxes and trays. He recommended washing and sieving bulk matrix for microfossils, and scrubbing larger specimens with wire brushes to remove mud. Rock, he advised, should be removed with a progressively finer series of hammers and chisels, small picks, knives and needles. Acid preparation was a technique already in use in palaeontology, and had been described for use both on vertebrates and invertebrates (Mantell 1844; Holm 1890). Schuchert noted that the National Museum employed muriatic (hydrochloric) acid and vinegar (acetic acid), as well as caustic potash (potassium hydroxide). Schuchert intentionally omitted discussion of techniques for preparation of large-scale vertebrates "since none but the large institutions attempt to prepare such bones" (Schuchert 1895, p. 27).

Schuchert's handbook contains much in the way of excellent advice, and its instructions for applying techniques are very thorough. However, some recommendations are cause for concern, due to their implications for researchers studying historic specimens. For example, Schuchert (1895, p. 27) directed that scratches or marring occurring during the preparation process should be eradicated with a brushing of muriatic acid. It is unclear whether he meant these marks should be removed from matrix or bone, but the latter seems most likely. Scratches in the surface of the bone are evidence of modification; eradication of that evidence forever alters the real morphology of the fossil. A consequence of preparation by caustic potash is a white film blooming on the surface of the bone if not adequately removed. This may effloresce for years afterward, and both Schuchert and Bather (Bather 1908, p. 88) suggest that it be removed by scrubbing with acid. If this fails, Schuchert recommended staining the white film with India ink. While Schuchert's treatment masks the unsightly precipitate, it does nothing to halt or reverse the conservation issue and likewise obscures morphology.

https://doi.org/10.1017/S1755691013000352 Published online by Cambridge University Press

Several conservation treatments were in use during Schuchert's era for the prevention of pyrite oxidation within specimens (Schuchert 1895; Bather 1908; Wylie 2009). Schuchert noted that none of these treatments were capable of halting oxidation without altering the natural colour of vertebrate specimens. A promising treatment was then being developed at the National Museum for minerals, whereby specimens were painted with "retouching varnish" (further identified only as a fixative for crayon artwork). Established methods at that institution involved coating or submerging the specimen in molten wax, or soaking it in petroleum jelly. None of these treatments are completely reversible, and can result in considerable difficulty to re-expose covered morphology.

Not long after Schuchert's paper, F. A. Bather experimented extensively with chemical preparation and conservation at the British Museum, including procedures for dealing with pyrite. Indeed, his 1908 paper, *The Preparation and Preservation of Fossils*, was the next major work published on palaeontology laboratory methods, and it detailed a broad range of chemical and mechanical innovations. In addition to introducing methods in development by Bather, this paper also synthesised the work of his contemporaries, explaining techniques used to solve locality or preservation-specific problems. Examples include little-known contributions on mechanical preparation, such as Rowe's (1896) use of the dental engine on specimens in soft chalk, extraction of fossils from the Tully Limestone via thermal shock (Clarke 1903), and a technique for splitting nodules along the plane of the specimen by expansion due to freezing (Moysey 1908). Incidentally, Moysey acknowledges that his method was not novel (Moysey 1908, p. 221), and that many geologists had probably employed the method. In fact, Mantell had reported its use as early as 1844 (Mantell 1844, p. 49).

Schuchert and Bather also dedicated sections of their papers to methods of hardening or preserving (consolidating) fossil specimens. Schuchert's instructions call for the application of "hot, thin, glue water," or the faster but more expensive alternative of using a shellac mixture. A noted disadvantage to the "glue water" option is that an overly thick mixture will result in a glossy surface coating which then adheres to other surfaces under humid conditions. Bather likewise advocated for the use of shellac for small specimens, but noted concern over mould growth and humidity. He introduced a mixture of copal (a tree resin) and paraffin wax in a petroleum solvent as a replacement. Although highly flammable and generating unsafe fumes, this treatment penetrated specimens more deeply than other options, and was durable enough to protect against atmospheric damage. Noting safety concerns, Bather reported recommendations to replace the solvents benzene or petroleum with carbon tetrachloride as a safer alternative; although this material is now known to be hazardous and subject to regulation.

Several materials that were to see long usage in the preparation laboratory entered the literature at this time. Bather mentioned silicate of potash (potassium silicate, commonly known as water-glass, isinglass, or sodium silicate), a widely used material (Stromer 1920; Efremov & Kuzmin 1931; Howie 1984), even though it lacks penetrating ability, has a propensity to effloresce and sometimes to form a scale and flake off. Two formulations of water-glass became available under the trade name "Perpetuin." These were purportedly more stable and capable of greater penetration than traditional water-glass. A type of cellulose acetate branded "Zapon" was marketed at this time and was used to seal specimens, as well as to change the colour or contrast of elements to improve the visibility of fossil structures (Bather 1908, p. 87).

Adam Hermann's two papers, *Modern methods of excavating, preparing and mounting fossil skeletons* (1908) and *Modern laboratory methods in vertebrate paleontology* (1909) foreshadow much of 20th-Century laboratory work (Fig. 4). Hermann had both witnessed and contributed to the bulk of the development of palaeontological methods, having worked as a preparator since 1877. To support a commitment to high quality fossil preparation, Hermann's laboratories in the American Museum of Natural History were constantly being upgraded (Brinkman 2010, p. 221). Hermann appears to be the only author employed principally as a preparator who published on laboratory methods until 1959.

Hermann presented the "best results … and present practice" (Hermann 1909, p. 283) in palaeontological preparation, advocating for the adoption of more efficient techniques in laboratories. Like previous accounts of laboratory techniques (e.g., Hill 1886; Schuchert 1895), Hermann described conditions of specimens upon collection from the field, and how the state of the specimen at this stage influenced the requirements for laboratory preparation. Hermann provided recommendations for the use of specific tools, including both hand tools and newer pneumatic and electric options. For instance, Hermann presented instruction for forging custom chisels, scrapers and awls specific to the needs of the fossil preparator and credited Marsh with their initial use in palaeontology (Hermann 1909, p. 291). Looking forward, he reviewed Riggs' pneumatic hammer in use at the Field Museum of Natural History in Chicago (Hermann 1908, p. 44). Hermann also described the adoption of electric dental lathes and dental hammers, the pneumatic abrasive unit and chemical preparation (Hermann 1909, pp. 291–293), as well as uses for overhead trolley and hoist systems, rotary diamond saws, lathes, blast furnaces and the electric drill (Hermann 1909, pp. 330–331).

While many of the advances described by Hermann were innovated at other institutions, the American Museum laboratory was the first to compile them into a work flow and promote them as an integrated system. Nor are Hermann's papers unique in discussing early 20th-Century techniques and philosophy alongside new applications of larger tools and equipment, yet they serve as the model for each methods text that followed in the subsequent thirty years. The tone he takes to report "the latest and most practical methods for general use in a vertebrate paleontological laboratory" (Hermann 1909, p. 283), coupled with his prominence as the Chief Preparator at the American Museum, accounts for the comparatively wide familiarity with Hermann's publications through time. These papers succinctly and authoritatively summarise the best ideas in use for lab design, equipment, materials selection and preparation philosophy (Matthew 1919; Camp & Hanna 1937), and their influence is evident in the literature (e.g., Fig. 5).

2.2. The Inter-war years: 1920–1939

Where laboratory methods are concerned, the two decades between the first and second World Wars can be characterised by a shift in technical publications away from descriptions of new methods at specific institutions. Instead, authors built on Hermann's 'modern methods,' establishing and championing a system of best practices. This was the era of the practical handbook, texts intended for the training of palaeontology students in essential aspects of field, laboratory, and curatorial work.

Six works epitomised this period. Four of them – Ernst Stromer's *Paläozoologisches Praktikum* (1920), O. Seitz and W. Gothan's *Paläontologisches Praktikum* (1928), M. Prokhorov's *Instruktsiia Dlia Raskopok Preparirovki I Monthirovki Iskopaemykh Pozvonochnykh* (1929) and Charles Camp and Dallas Hanna's *Methods in Paleontology* (1937) – provided detailed instruction in the principles of laboratory techniques in the manner of a textbook. Each started with field

https://doi.org/10.1017/S1755691013000352 Published online by Cambridge University Press

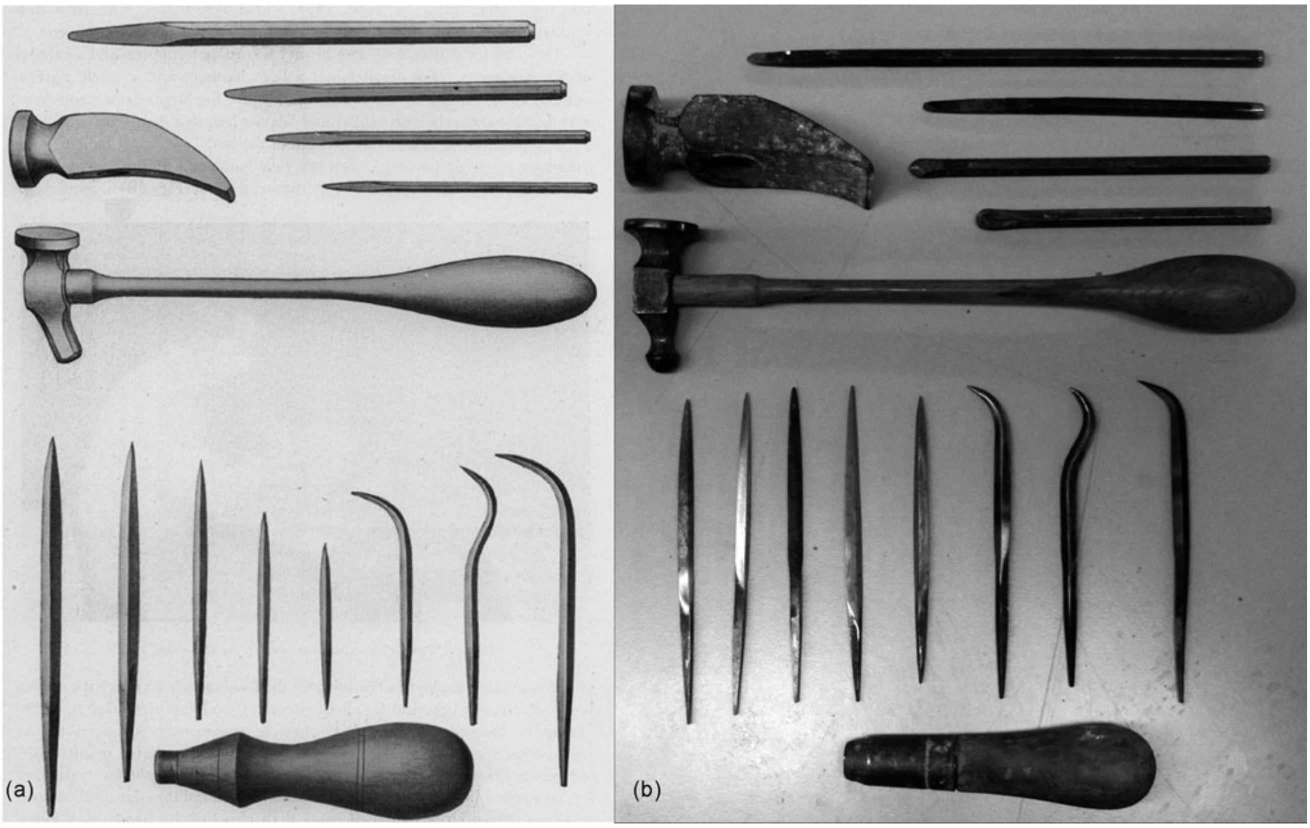

Figure 4 (a) Common fossil preparation and excavation tools in use in the early 20th Century. Custom-made chisels were used with chasing and cobblers' hammers to chip matrix from bone. The modified harness awls at the bottom were introduced by Marsh. (from Hermann 1909, p. 289). (b) Identical tools still in use for the same purpose at The University of Texas at Austin Vertebrate Paleontology Laboratory.

work and a brief discussion of geological processes that lead to the preservation, discovery and recovery of fossils. Topics were usually subdivided into techniques for macroscopic, microscopic, mechanical and chemical preparation. Specific methods were identified for vertebrate, invertebrate and palaeobotanical preparation techniques. Following Hermann (1909), a frequent theme was protection of the welfare of the specimen (e.g., Stromer 1920, p. 16). The ultimate aim of each of these texts was to provide guidance for the novice preparator through collection, preparation, curation, casting and mounting.

The remaining major inter-war publications, *Preparation of the remains of the oldest Tetrapoda in hard stones* (Efremov & Kuzmin 1931) and *The Laboratory Unit* (McAnulty 1939) approached laboratory methods from unique perspectives. Ivan Efremov and F. M. Kuzmin (1931) recounted the introduction of the "modern" preparation methods and philosophy in Russia, beginning in 1921. Efremov, a preparator and influential researcher, was highly critical of the state of palaeontological research in Russia and around the world. Efremov and Kuzmin admonished their colleagues: "to our sorrow, in the greatest scientific institutes of Europe and America, exceptionally interesting remains of Paleozoic Reptilia and Amphibia are preserved that were written about by many authors who did not even do the basic preparations of their objects" (Efremov & Kuzmin 1931, p. 2). Efremov and Kuzmin argued for an understanding of the importance of preparation to the process of science; their instruction in preparation was, like Mantell before them, framed from the context that palaeontological research is predicated on an understanding of the laboratory methods.

Efremov and Kuzim document specific cases where specimens were obscured or damaged through inattention in the laboratory, and describe how this affected research. They point out (Efremov & Kuzmin 1931, p. 5) that typical practice involving grinding of matrix for aesthetic purposes "destroys and distorts" the fossil. Impact tools must be used to ensure good separation. To achieve this end, the authors provide instructions for forging chisels, discussing ideal properties of steel for specific applications, and appropriate sizes of hammer and chisel combinations for varying hardness in matrices. They also introduced an electric dental hammer for use when bone was not overly fragile, and highlight the optical and ergonomic benefits of using quality magnification. Through these methods, they announce that "a new period of exact palaeontology begins with a new, braver and much more detailed preparation," and stress the importance that "in the future a close contact be established between Russian and foreign laboratories" (Efremov & Kuzmin 1931, p. 14).

McAnulty's (1939) work comprised a section in a larger handbook for a very specific project, a Depression Era Works Progress Administration palaeontological survey of 219 of the 254 counties in the State of Texas. The majority of the manual is devoted to field work and collecting logistics. However, the enterprise employed an average of 38 preparators at a time between 1939 and 1941, and thousands of specimens were prepared during this period (McAnulty 1941). Consequently, the scope of the operation presented challenges, especially relating to the amount of laboratory space required and the difficulty in training so many unskilled workers (McAnulty 1939, p. 76). Tools and furnishing for the laboratories, including the physical spaces required to support so many preparators, were scaled to accommodate the tens of thousands of fossils collected by the end of the project in 1941. Each worker was issued a standardised tool kit to facilitate uniform results (Table 1), and for the first time, rudimentary laboratory records were required, that tied the worker to a specimen and accounted for labour expended (McAnulty 1939).

https://doi.org/10.1017/S1755691013000352 Published online by Cambridge University Press

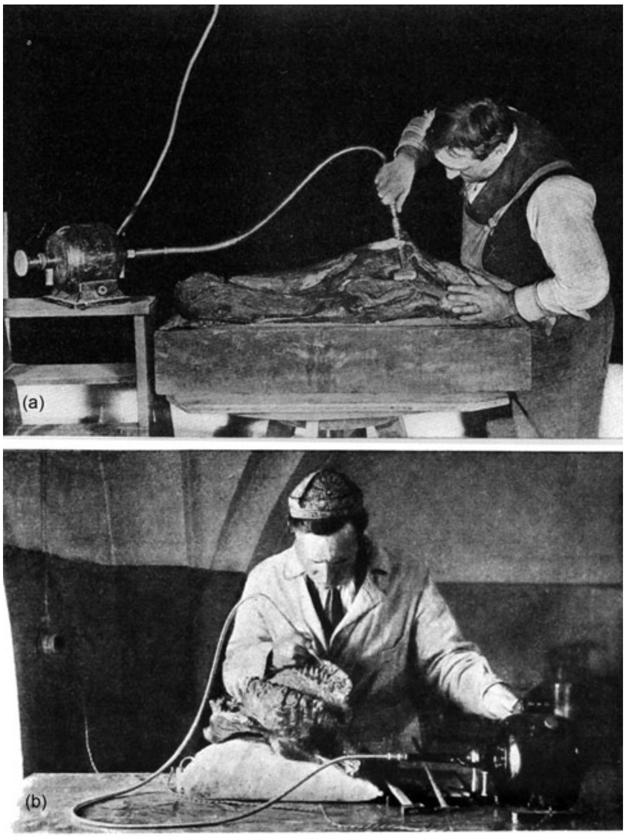

Figure 5 (a) A preparator using an electric motor and flexshaft to prepare a fossilised skull at the American Museum of Natural History (from Hermann 1909, p. 293). (b) A preparator using an electric motor and flexshaft to prepare a fossilised skull in Russia in the 1920s (from Prokhorov 1929, p. 78). Adam Hermann's publications had an impact not only on methods and tools employed throughout the 20th Century, but also upon their visual representation.

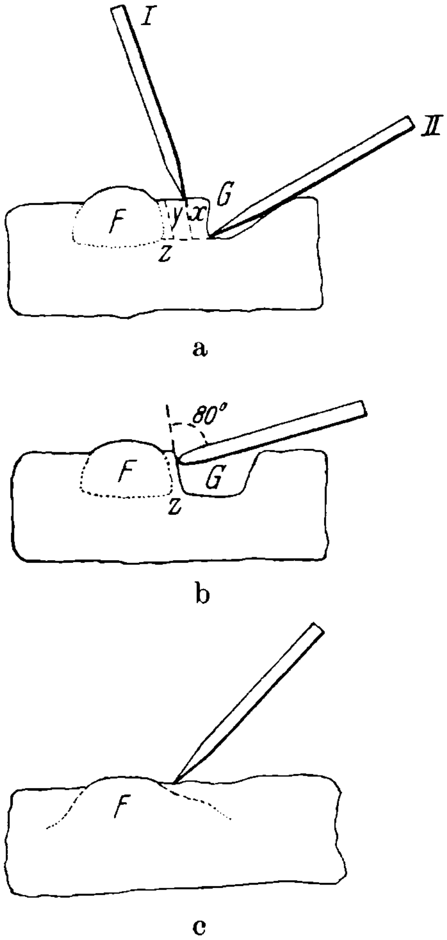

Figure 6 A rare example of explicit instructions for the application of hammer and chisel to remove rock matrix from fossil specimens (from Seitz & Gothan, 1928, p. 59). Reprinted with kind permission of Springer-Verlag, Berlin/Heidelberg.

Table 1 Tools and supplies issued by the Works Progress Administration to each fossil preparator during the Texas Survey (McAnulty, 1939, p. 75)

1 Pocket knife
1 Teasing needle
1 rubber plaster cup (made from hollow rubber balls cut in half
1 ice pick
1 2 inch brush
2 ¼ inch round brushes, with long handles
1 small cup
1 medicine dropper
1 syringe bulb
1 spatula, 3″ × ½″
1 6-oz. bottle of acetone-celluloid glue
1 12-oz. bottle of shellac (one part shellac, 3 parts alcohol
1 12-oz. bottle of gum acacia (solution)
1 12-oz. bottle of yellow dextrin (solution)
1 12-oz. bottle of Alvar (solution)

As there had not been extensive change in the basic techniques and tools since 1909, the majority of methods described in this interwar period were repeated from the works of Schuchert, Bather and Hermann. When existing techniques or equipment had been refined, or new ones innovated, they were described accordingly. This was especially true of chemicals, where the most change had taken place. For example, Camp & Hanna (1937, p. 34) reported on the use of the synthetic resin Bakelite by previous authors (Case 1925; Swinton 1933) and provided instructions for application to both vertebrate and invertebrate fossils. Trends in chemical choices for adhesives and consolidants were beginning to shift further in favour of synthetic chemicals; this movement was far from complete, as shellac and plaster of Paris were still commonly used (e.g., Camp & Hanna 1937; McAnulty 1939). There were instances of exacting guidance, as well. Seitz & Gothan (1928, p. 59) imparted explicit direction for the use of hammer and chisel to remove matrix from fossils (Fig. 6), these instructions established angles of approach and sequence of stroke with the tools with a specificity that have not been published elsewhere. Some pieces of equipment were of such importance that authors not only identified the type of tool, such as a "binocular microscope on extension arm" (Camp & Hanna 1937, p. 31), they also recommended particular brands, i.e. Zeiss or Leitz (Efremov & Kuzmin 1931), and even specific models (Fig. 7), such as the Zeiss XB binocular microscope with boom stand (Seitz & Gothan 1928, p. 108). The Zeiss XB was used in laboratories around the world for many decades after (e.g., Fig. 8).

Methods in Paleontology (Camp & Hanna 1937), the most widely known of these works today, represents the legacy of this period (Schuchert 1938; Hildebrand 1968; Rixon 1976). Like the works of Hermann (1908, 1909), Camp & Hanna (1937) remained significant not necessarily for the novelty of the content within, but rather for the comprehensive synthesis of then-current palaeontological practices. Charles Camp's

https://doi.org/10.1017/S1755691013000352 Published online by Cambridge University Press

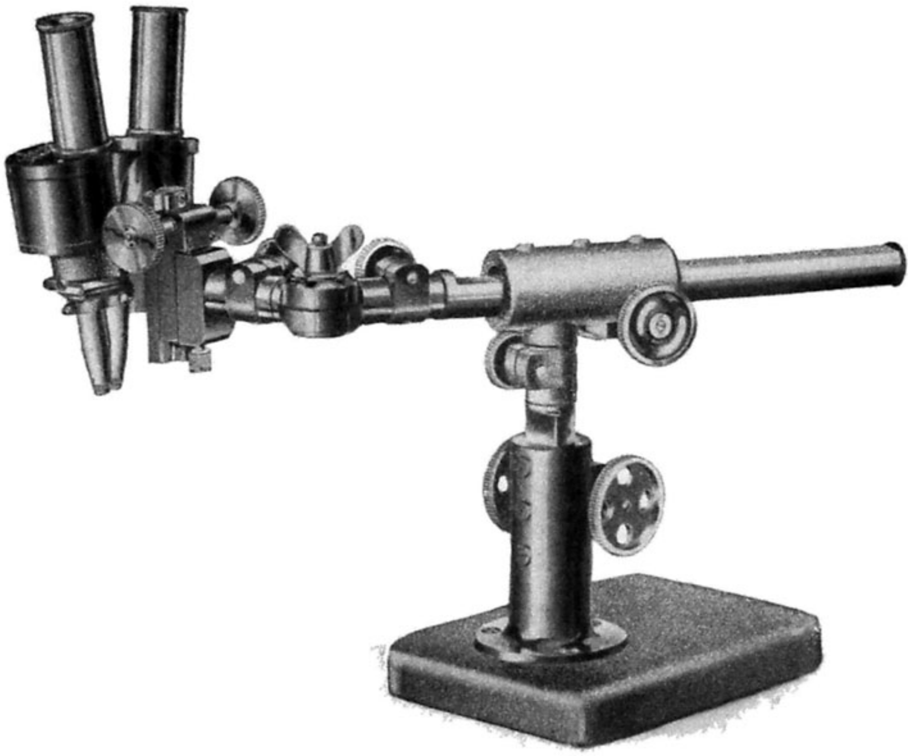

Figure 7 An example of a stereomicroscope used in many palaeontology laboratories through the middle of the 20th Century, the Carl Zeiss XB (from Seitz & Gothan, 1928, p. 108). Reprinted with kind permission of Springer-Verlag, Berlin/Heidelberg.

prominent positions as Chair of the University of California, Berkeley Department of Paleontology and Director of the University of California Museum of Paleontology also contributed to the longevity of this volume.

2.3. Post-World War II

Shortly after World War II, palaeontologists began consistently sharing refinements in established methodologies. This shift in publication reflects a more scientific approach to methods reporting. Papers appeared in publications catering to the museum professional, such as *The Museums Journal* and *Curator*.

The refinement of chemical preparation techniques through the mid-20th Century by H. A. Toombs and A. E. Rixon is a well-documented example of this progression. Innovation upon a method for using organic acids (e.g. acetic) to replace mineral acids (e.g. hydrochloric) in the preparation of fossils is recorded in articles spanning thirty years. Beginning with the development of the technique by Toombs (White 1945, p. 216), constant experimentation with acids and synthetic resins (Toombs 1948; Rixon 1949, 1976; Toombs & Rixon 1950, 1959) led to the establishment of a method that remains little altered today (e.g., Rutzky *et al.* 1994; Bergwall 2001; Padilla *et al*. 2010). Modification of transfer preparation practices first described by Holm (1890) uses plastics instead of less solvent-resistant natural resins such as gum dammar or Canada balsam. Toombs and Rixon thus provided a way for fossil specimens to be permanently embedded in a transparent plastic resin block to preserve anatomical relationships or delicate structures while undergoing both preparation and study.

Generally, the literature of the mid–late 20th and early 21st centuries followed this model of experimentation and reporting. As specialised knowledge grew, publications reflected concentrated examination of techniques (e.g., Kummel & Raup 1965; Feldman *et al.* 1989; Leiggi & May 1994; Brown *et al.* 2009). Between 1958 and 1987, the journal *Curator* alone published over 30 papers on vertebrate palaeontology techniques (Nicholson 1987). Only rarely did workers again attempt a handbook for preparation (Rixon 1976; Converse Jr. 1984), and as present there is no comprehensive text of modern techniques and philosophies.

3. Discussion

3.1. The professionalisation of laboratory work

During the middle and late 1800s, the practice of science underwent a transformation; research was conducted more often by professional scientists rather than amateur "natural philosophers" (Orosz 1990). With greater frequency, this work took place in public natural history museums and university research centres. Historian Joel Orosz calls this shift "the American Compromise … the synthesis of popular education and professionalism" (Orosz 1990, p. 180). The popularity of enigmatic collections such as fossils fuelled public interest in museums and science, which in turn drove museums to bring in larger quantities of specimens to study and exhibit. The increased volume of newly backlogged material created a specialised role, that of fossil preparator. Division of labour meant that preparation once done by individual researchers (e.g., Cuvier, Mantell) was now handled by an increasingly diversified staff. The greater demand for large and impressive specimens propelled innovations towards efficiency, such as the progression from hand tools to power tools, which served to drive standards higher (Brinkman 2010, pp. 220, 228). A similar reciprocal effect was generated by the interplay between laboratory techniques and research questions. As preparation efforts became more skilled, more anatomical information was available for study, which led researchers to request more detailed exposure (Whybrow 1985, p. 5; Brinkman 2010, p. 220). This trend mirrors the increased frequency of reporting other types of data, such as stratigraphic or locality information (Brinkman 2010, p. 220).

https://doi.org/10.1017/S1755691013000352 Published online by Cambridge University Press

Figure 8 Lansing Craig, preparator at the University of Texas at Austin Vertebrate Paleontology Laboratory in the 1950s. Visible in this photo is a Zeiss XB stereoscopic microscope, a pneumatic airscribe, several types of adhesive, a hammer, chisel, brushes and other hand tools common to nearly every palaeontology laboratory.

The advancement of laboratory techniques led to the advances in the sophistication of research lines.

3.2. Historic practices and modern conservation

Elements of all of the fundamental palaeontological practices and philosophies in use today were in development by the end of 1909 (Whybrow 1985; Brinkman 2009, 2010). Mechanical preparation was taking place via brush and pick, hammer and chisel, dental drill, sandblasting and pneumatic tools. Chemical preparation was underway using acids and caustic bases, including transfer preparation techniques. Internal structure of specimens could be determined by cutting cross-sections of bone and making histological slides (Mantell 1844), by using the newly discovered X-rays (Brühl 1896; Lemoine 1896), or by serial grinding of bones (Sollas 1903). Protocols were initiated for handling and storage of specimens in a manner where they were protected from damage, and high priority was placed on the proper labelling and documentation of all locality and taxonomic information, as well as relationships of fragments of broken bone and associated skeletal material. Preparators were continuously experimenting with new materials, as they continue to do today.

The 21st-Century museum conservator will disagree with the suitability of methods employed at the end of the nineteenth and beginning of the twentieth centuries. In fact, there is abundant evidence that some of these techniques damage specimens (Evander 2009) and obscure data (Efremov & Kuzmin 1931; Camp & Hanna 1937; Wylie 2009). This includes applying non-reversible adhesives and consolidants to specimens, materials that fail mechanically or chemically or attract pests, or even drilling holes in bones for mounting or threading armatures. However, these early palaeontologists were using the technology and materials available to them to face the challenges of the day as well as possible (Matthew 1919; Stucker 1961). While complications from these processes must be mitigated, harsh judgment of the rationale for their decisions is inappropriate (Horie 2010, p. 8).

As has been shown, objects and materials conservation was a priority for most early authorities on preparation. When disadvantages of materials or techniques were noted, use of these materials was discouraged. Countless suggestions would be well heeded today. For example, Hill's instruction to house specimens such that they do not crowd and damage one another is often ignored in most collections 126 years later (Fig. 9).

Accepting past conservation issues as a necessary concession to preservation of the specimens at all, many points made in the historical literature remain applicable to the training of today's laboratory staff. Patience and skill are crucial components of success in the palaeontology laboratory (Hill 1886; Schuchert 1895; Hermann 1909; Camp & Hanna 1937; McAnulty 1939). Many consider these traits to be inherent abilities that cannot be taught (e.g., Camp & Hanna 1937; Wylie 2009). Selectivity of preparation staff is key. Good judgment must be developed through experience, and the work of beginners must be

https://doi.org/10.1017/S1755691013000352 Published online by Cambridge University Press

Figure 9 An overcrowded drawer in the collections of the Texas Memorial Museum, with specimens in contact with one another, with the walls of the drawer, and in trays stacked in multiple layers. This condition is common in collections around the world, despite the damage that regularly results from abrasion and shock.

carefully supervised; but even allowing this, "relatively few . . . ever qualify for the most exacting jobs" (Camp & Hanna 1937, p. 28). Camp observed that "a good technician will study and test the character of his specimen and its matrix before starting to work upon it," considering the varied needs according to quality of fossil preservation, requirements for consolidation and evaluation of potential for additional data (e.g., soft tissue) which "might easily be destroyed by a preparator whose attention rested only on the bony skeleton" (Camp & Hanna 1937, p. 34).

3.3. Documentation

Another critical issue addressed in the literature that remains valid is that of documentation. As phrased by Camp, "loss of data accompanying a specimen almost entirely destroys its scientific value" (Camp & Hanna 1937, p. 55). Hermann (1909) placed the responsibility for tracking both locality and accession information with laboratory staff, as well as that of maintaining a record of relative location of bones to one another within the matrix. McAnulty (1939) insisted upon creating laboratory record work sheets before work commenced on any specimen. This remains a fundamentally important practice that is inconsistently applied even today (Whybrow 1985, p. 5; Fitzgerald 1988, p. 39; Collins 1995, p. 16).

There are few exemplar anatomical descriptions of fossil taxa that accurately report laboratory methods (e.g., Whybrow & Andrews 1978), and often methods have been ignored completely in anatomical or systematic publications (Whybrow 1985, p. 5). Laboratory records are often incomplete or nonexistent (Fitzgerald 1988). Therefore, the historic literature is often the only documentation of laboratory methods available to researchers. Some past publications (Hermann 1908, 1909; McAnulty 1939) are thorough enough to constitute a general Laboratory Master Report (Appelbaum 2007, pp. 414–417), whereby researchers can reconstruct a probable treatment history. In this way, they can make decisions for research or conservation appropriate to the materials present in a specimen (e.g., Evander 2009).

4. Conclusion

There are many lessons to be learned from seminal papers on palaeontology laboratory methods. Expectations of laboratory outcomes remain the same today; fossils should be prepared as accurately and expediently as possible, while preserving maximal information for future generations. This requires persistent attention to detail in the laboratory, great care in handling and materials selection, and diligence in recording data. Early authors maintain these points as universal themes. Like many others (e.g., Schuchert 1895, p. 5), Hermann argued that "no standard rules . . . can be prescribed as to the manner of treating different bones" (Hermann 1909, p. 286). However, the consensus reached by these early palaeontologists on many of the fundamental principles of laboratory work indicates otherwise. Camp and Hanna asserted that "a good technician develops his own methods, but even the expert finds it necessary to refer to manuals" (Camp & Hanna 1937, p. 28).

The consequences of poor preparation and lack of understanding of laboratory processes were often highlighted by early paleontologists. In their own words, they present a warning to workers of today. "I therefore say, that a beginner in a paleontological laboratory never ought to be trusted with a delicate and rare specimen. In my experience, I have seen irremediable damage done on account of poor judgment" (Hermann 1909, p. 331). Charles Camp explains the ramifications of this damage from the specimen's perspective: "Every museum contains sad examples of hastily collected and poorly prepared fossil material. Sometimes these broken specimens are irreplaceable, and similar ones will perhaps never be found again" (Camp & Hanna 1937, p. ix). As Bather examines the cost of damage in terms of research, he notes that "it is also interesting to remark how many of the specimens that have been described and figured by writers of a past generation have been wrongly determined, or have yielded only half their secrets, owing to the lack of adequate cleaning" (Bather 1908, p. 77). Efremov and Kuzmin summarise the exhortations of all of these authors succinctly, "every palaeontologist who is performing the hard work of studying the oldest Tetrapoda should be able to know the methods of preparation perfectly, so that his work would not pass by and become one of the many pseudo-scientific descriptions that stand in the way of simple and clear reasoning in the field. The quality of work that has been done improperly lowers the value of a scientific collection" (Efremov & Kuzmin 1931, p. 2).

Palaeontology suffers through the marginalisation of laboratory methods. Resumption of the regular publication of new and refined laboratory techniques is perhaps the most important mechanism to inculcate current and future generations of palaeontologists with an understanding of both historic and current best practices. At minimum, each institution should establish a system for documenting their laboratory practices in general, and treatments of specimens specifically. A standard system of rules governing palaeontological methods is certainly possible, and just as certainly necessary. However, best practices cannot be advanced without an awareness of the development of techniques over time. Nor can best practices be perpetuated without

https://doi.org/10.1017/S1755691013000352 Published online by Cambridge University Press

a commitment on the part of palaeontologists, especially preparators, to stay abreast of current technical literature.

5. Acknowledgments

This paper is dedicated to Dr. Wann Langston, Jr. who entered the field of palaeontology around the time this literature review ends. Professor Langston's education in vertebrate anatomy was in large part a result of his childhood experiences reproducing in clay the animals that he saw in museums and zoos. By high school, he was preparing fossils and conducting fieldwork for University of Oklahoma professor Willis Stovall. He published his first paper in 1948 on field methods. As a graduate student at the University of California, Berkeley under Charles Camp, he supervised the preparation and reconstruction of what would become the holotype of *Dilophosaurus weatherilli*, and later in his career became well known for his expertise reconstructing and mounting extinct reptiles. His famous library hosts one of the most comprehensive reference sections covering laboratory and museology methods in all of palaeontology. I count myself as fortunate indeed to have had the opportunity to work with and learn from Dr. Langston in the laboratory; he was a true rarity in the science, being just as comfortable in the field as the research office, in the preparation lab as with students, and in the welding shop as the library.

Thanks to Amy Davidson, Sarah Werning, Andrea Thomer, William Parker, Ernest Lundelius and Wann Langston, Jr. for discussion. Chris Bell provided hard copies of several publications. Thanks to Amy Davidson for comments on an early draft. Innumerable thanks to Editor Vicki Hammond. Critical reviews by Paul Brinkman and Caitlin Wylie dramatically improved this manuscript.

6. References

Appelbaum, B. 2007. *Conservation Treatment Methodology.* Oxford, UK: Butterworth-Heinemann/Elsevier. 437 pp.

Bather, F. 1908. The Preparation and Preservation of Fossils. *The Museums Journal* **8,** 76–90.

Bergwall, L. 2001. Preparing for acid preparation by embedding in resin – solving the problem of silvering. *Journal of Vertebrate Paleontology* **21**(Suppl. to 3), 33A.

Bernard, H. M. 1894. On the Application of the Sand-Blast for the Development of Trilobites. *Geological Magazine* (Decade IV) **1**, 553–57.

Bewer, F. 2010. *A Laboratory for Art: Harvard's Fogg Museum and the Emergence of Conservation in America, 1900–1950.* New Haven and London: Yale University Press. 365 pp.

Brinkman, P. 2009. Dinosaurs, museums and the modernization of American fossil preparation at the turn of the 20th century. *In* Brown, M. A., Kane, J. F. & Parker, W. G. (eds) *Methods in Fossil Preparation: Proceedings of the First Annual Fossil Preparation and Collections Symposium*, 21–34. Petrified Forest, Arizona.

Brinkman, P. 2010. *The Second Jurassic Dinosaur Rush*. Chicago, Illinois: The University of Chicago Press. 345 pp.

Brown, M. 2009. Preliminary report on professional development in vertebrate fossil preparation. *In* Cavigelli, J. (ed.) *Proceedings of the 15th Annual Tate Conference, Fossil Preparation and Collections Symposium June 5–7, Tate Geological Museum, Casper College, Casper*, 52–57. Casper, Wyoming.

Brown, M., Kane, J. & Parker, W. (eds) 2009. *Methods in Fossil Preparation: Proceedings of the First Annual Fossil Preparation and Collections Symposium.* Petrified Forest, AZ. 142 pp.

Brown, M. A. & Kane, J. F. 2008. Evaluation and certification of fossil preparators: ideas for the future. First Annual Fossil Preparation and Collections Symposium, Abstracts of Papers **1**, 8. Petrified Forest, Arizona.

Brühl, L. 1896. Über Verwendung von Rontgenschen X-Strahlen zu palaeontologischen-diagnostischen Zwecken. *Verh. Berliner physiol. Ges., Arch. Anat. Physiol. (physiol. Theil)*, 547–50.

Buckland, F. 1866. *Curiosities of Natural History*. 2nd Series. London: Bentley.

Camp, C. & Hanna, D. 1937. *Methods in Paleontology*. Berkeley: University of California Press. 153 pp.

Case, E. 1925. The Use of Bakelite in the Preservation of Fossil Material. *Science* **61**(1586), 543.

Cavigelli, J. P. 2009. Micropreparation … one sand grain at a time. *In* Brown, M. A., Kane, J. F. & Parker, W. G. (eds) *Methods In Fossil Preparation: Proceedings of the First Annual Fossil Preparation and Collections Symposium*, 41–52. Petrified Forest, AZ.

Cavin, J. 2011. Vacuum molding and casting for bubble free fossil replicas. *In* Olstad, T. & Aase, A. (eds) *Proceedings of the fourth fossil preparation and collections symposium. Brigham Young University Geology Studies*. **49**(B), 1.

Clarke, J. 1903. Report of the State Paleontologist. *New York State Museum Bulletin* **69**, 851–1294.

Collins, C. 1995. Documentation in geological specimen conservation. *In* Collins, C. (ed.) *The Care and Conservation of Palaeontological Material*, 15–20. London: Butterworth-Heinman. 140 pp.

Converse Jr., H. 1984. *Handbook of paleo-preparation techniques.* Gainesville: Florida State Museum. 125 pp.

Cuvier, G. 1804. Mémoire sur le Squelette Presque Entier d'un Petit Quadrupede du Genre Sarigues, Trouve dans Ie Pierre à Platre des Environs de Paris. *Annales du Muséum d'histoire Naturelle* **5**, 277–92.

Damiani, R. & Hancox, P. J. 2003. New Mastodonsaurid Temnospondyls from the Cynognathus Assemblage Zone (Upper Beaufort Group; Karoo Basin) of South Africa. *Journal of Vertebrate Paleontology* **23**(1), 54–66.

Efremov, I. A., & Kuzmin, F. M. 1931. Preparation of the remains of the oldest Tetrapoda in hard stones. *Trudy Paleontologicheskogo instituta* **1**(1), 223–34.

Evander, R. 2009. Armature damage to a mounted specimen. www.vertpaleo.org/AM/documents/Evander_2009.pdf (accessed 1 Jan 2012).

Feldman, R., Chapman, R. & Hannibal, J. 1989. *Paleotechniques. The Paleontological Society Special Publication* **4**. 358 pp.

Fitzgerald, G. R. 1988. Documentation guidelines for the preparation and conservation of paleontological and geological specimens. *Collection Forum* **4**(2), 38–15.

Hermann, A. 1908. Modern methods of excavating, preparing and mounting fossil skeletons. *The American Naturalist* **42**(493), 43–47.

Hermann, A. 1909. Modern laboratory methods in vertebrate paleontology. *Bulletin of the American Museum of Natural History* **26**, 283–331.

Hildebrand, M. 1968. *Anatomical Preparations.* Berkeley: University of California Press. 100 pp.

Hill, F. C. 1875. Mucilage for minerals, etc. *American Journal of Pharmacy* **1–2**. Philadelphia, PA: College of Pharmacy and Science.

Hill, F. 1886. On the Mounting of Fossils. *The American Naturalist* **20**(4) 353–59.

Holm, G. 1890. Gotlands graptoliter. *Bih. K. svenska VetenskAkad Handl.* **16**(4, No. 7), 34.

Horie, C. 2010. *Materials for Conservation: Organic Consolidants, Adhesives, and Coatings.* 2nd Edition. Oxford: Butterworth-Heinemann. 489 pp.

Howie, F. 1984. Materials used for conserving fossil specimens since 1930: a review. *Adhesives and Consolidants, Preprints of the Contributions to the Paris Congress* **102,** 92–98.

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

Huxley, T. H. 1880. On the Method of Zadig: Retrospective prophecy as a function of science. *Popular Science Monthly* **17**. New York: D Appleton & Company.

Kummel, B. & Raup, D. (eds) 1965. *Handbook of Paleontological Techniques.* San Francisco and London: W. H. Freeman and Company 852 pp.

Leiggi, P. & May, P. (eds) 1994. *Vertebrate Paleontological Techniques* **1**, 113–29. Cambridge, UK: Cambridge University Press.

Lemoine, M. 1896. De l'application des rayon de Rontgen à la Paléontologie. *Comptes Rendus Académie des Sciences* **3**, 163–67.

López-Polín, L. 2011. Possible interferences of some conservation treatments with subsequent studies on fossil bones: A conservator's overview. *Quaternary International* 1–8.

Mantell, G. 1844. *The Medals of Creation or, First lessons in geology and the study of organic remains.* London: H.G. Bohn. 1016 pp.

Mantell, G. 1854. *The Medals of Creation or, First lessons in geology and the study of organic remains.* 2nd Edition. London: H.G. Bohn. 930 pp.

Matthew, W. D. 1919. Honor to Adam Hermann. *The Journal of the American Museum* **1919**(4–5), 491–93.

https://doi.org/10.1017/S1755691013000352 Published online by Cambridge University Press

May, P., Reser, P. & Leiggi, P. 1994. Macrovertebrate preparation. *In* Leiggi, P. & May, P. (eds) *Vertebrate Paleontological Techniques* **1,** 113–29. Cambridge, UK: Cambridge University Press.

McAnulty, G. 1939. The Laboratory Unit. *In* Evans, G. *Manual of Suggested Procedures To Be Employed By the State-Wide Paleontologic-Mineralogic Survey in Texas*, 73–91. Austin, TX: Bureau of Economic Geology.

McAnulty, G. 1941. Laboratory Units of the State-Wide Paleontologic-Mineralogic Survey-Final Report. *In The University of Texas Bureau of Economic Geology Final Report (March 4, 1939 to September 30, 1941.)*, 58–85. Austin, TX: For the State-Wide Paleontologic–Mineralogic Survey in Texas.

Moysey, L. 1908. VI. – On a Method of Splitting Ironstone Nodules by means of an Artificial Freezing Mixture. *Geological Magazine (Decade V)* **5**(05), 220–22. Cambridge, UK: Cambridge University Press.

Nicholson, T. 1987. Cumulative index to volumes 1 through 30. *Curator* **30**, 4.

Orosz, J. 1990. *Curators and Culture: The Museum Movement in America, 1740–1870*. Tuscaloosa: The University of Alabama Press. 304 pp.

Osborn, H. 1904. On the Use of the Sandblast in Cleaning Fossils. *Science New Series*, 1–6.

Owen, R. 1855. On the Megatherium (*Megatherium americanum*, Cuvier and Blumenbach). Part II. Vertebrae of the Trunk. *Philosophical Transactions of the Royal Society of London* **145**, 359–88.

Padilla, C., Páramo, M., Noè, L., Gómez Pérez, M. & Luz Parra, M. 2010. Acid Preparation of Large Vertebrate Specimens. *The Geological Curator* **9**(3), 85–92.

Prokhorov, M. G. 1929. Instructions for excavating, preparing and mounting fossil vertebrates. *Akademiia Nauk Soiuza Sovetskikh Sotsialisticheskikh Respublik. Geologicheskii Muzei Leningrad* **1929**, 1–75.

Reser, P. 1981. Precision casting of small fossils: an update. *Curator* **24**(3), 157–80.

Riggs, E. 1903. The Use Of Pneumatic Tools In the Preparation Of Fossils. *Science* **17**(436), 757–59.

Rixon, A. 1949. The use of acetic and formic acids in the preparation of fossil vertebrates. *Museums Journal* **49**. 116 pp.

Rixon, A. 1965. The use of new materials as temporary supports in the development and examination of fossils. *Museums Journal* **65**, 54–58.

Rixon, A. 1976. *Fossil animal remains: their preparation and conservation.* London: Athlone Press. 53 pp.

Rowe, A. W. 1896. The Preparation and Mounting of Chalk Fossils. *Natural Science* **9**, 303–11.

Rutzky, I., Elvers, W., Maisey, J. & Kellner, A. 1994. Chemical preparation techniques. *In* Leiggi, P. & May, P. (eds) *Vertebrate Paleontological Techniques* **1**, 155–86. Cambridge, UK: Cambridge University Press. 368 pp.

Schuchert, C. 1895. Directions for collecting and preparing fossils. Part K of *Bulletin of the United States National Museum* **39**, 5–31.

Schuchert, C. 1938. [Review of] Methods in Paleontology *American Journal of Science, Series 5* **36**, 231.

Seitz, O. & Gothan, W. 1928. *Paläontologisches Praktikum iv*. Berlin: Julius Springer. 173 pp.

Sidor. C & Welman, J. 2003. A second specimen of Lemursaurus pricei (Therapsida: Bunetiamorpha) Journal of Vertebrate Paleontology **23**(3) 631–42.

Sollas, W. 1903. A method for the investigation of fossils by serial sections. *Philosophical Transactions of the Royal Society, London B* **196**, 259–65.

Stromer, E. 1920. *Paläozoologisches Praktikum*. Berlin: Gebrüder Borntraeger. 104 pp.

Stucker, G. 1961. Salvaging fossils by jet. *Curator* **4**(4) 332–40.

Stucker, G., Galusha, M. & McKenna, M. 1965. Removing matrix from fossils by miniature sandblasting. *In* Kummel, B. & Raup, D. (eds) *Handbook of Paleontological Techniques.* San Francisco and London: W.H. Freeman and Company. 852 pp.

Swinton, W. E. 1933. Bakelite and the preservation of fossils. *The Museums Journal* **XXXIII**, 76–80.

Toombs, H. 1948. The use of acetic acid in the development of vertebrate fossils. *Museums Journal* **48**, 54–55.

Toombs, H. & Rixon, A. 1950. The use of plastics in the "transfer method" of preparing fossils. *Museums Journal* **50**,105–07.

Toombs, H & Rixon, A. 1959. The use of acids in the preparation of vertebrate fossils. *Curator* **2**(4) 304–12.

Waters, B. & Savage, D. 1971. Making duplicates of small vertebrate fossils for teaching and for research collections. *Curator* **14**(2), 123–32.

White, E. 1945. The genus *Phialaspis* and the "*Psammosteus* Limestones." *Quarterly Journal of the Geological Society, London* **101**(1–4), 207–42.

Whybrow, P. 1985. A History of Fossil Collecting and Preparation Techniques. *Curator* **28**(1), 1–22.

Whybrow, P. & Andrews, P. 1978. Restoration of the Holotype of *Proconsul nyanzae. Folia primatologica* **30**(2) 115–25.

Wylie, C. 2009. Preparation in action: paleontological skill and the role of the fossil preparator. *In* Brown, M., Kane, J., Parker, W. (eds) *Methods in Fossil Preparation: Proceedings of the First Annual Fossil Preparation and Collections Symposium*, 3–12. Petrified Forest, AZ.

MS received 1 February 2012. Accepted for publication 21 December 2012.