21st Century Rex: maximising access to a privately owned *Tyrannosaurus rex* skeleton in the digital age

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A ~60-70% complete *Tyrannosaurus rex* skeleton known as 'Stan' recently sold for 31.8 million US dollars to an unknown buyer (announced in March 2022 as the Natural History Museum Abu Dhabi), pushing up the price of all such skeletons way beyond the budget of most museums. Wealthy private individuals who purchase expensive fossil specimens sometimes put them on public display but leave them in an intellectual limbo, unable to be studied and published. However, a partial *T. rex* skeleton known as 'Titus' was excavated in Montana in 2018, shipped to the UK in 2020, and had casts of Stan's bones added to complete the skeleton during mounting. It was loaned to the Nottingham Natural History Museum, Wollaton Hall, as the centrepiece to a temporary exhibition called 'Titus: *T. rex* is King'. This was the first time a mounted *T. rex* skeleton containing fossil bones had been on display in England for many decades. Importantly, before the mounting process began, all the real bones were 3D scanned in detail using photogrammetry. The resulting digital 3D models were sent to palaeontologists in America who studied them and produced a paper describing the palaeopathology before the mounting process was even complete. Replicas of all the identifiable bones were 3D printed for display in the exhibition and were accessioned into the museum collections, along with the 3D digital models and all associated data. This ensured that physical as well as digital replicas of the bones would remain accessible, and in theory publishable, forevermore.

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Introduction

In September 2014 palaeontologist Craig Pfister was searching for fossils in the Hell Creek Formation of Carter County, Montana, USA, with permission from the landowners. He discovered a single tooth and a handful of very fragmented bones that he was certain belonged to an adult Tyrannosaurus rex skeleton. However, he could not excavate the site properly until July 2018 because he was preoccupied with digging up a Triceratops skeleton nearby. Pfister describes the eventual excavation of the T. rex skeleton (the fourth he has found) as an endurance test: he mainly worked alone to uncover the bones and during the autumn months he was often working in cold conditions (down to minus 12oC) and in the summer it was very hot (up to 40oC). At times the site was also plagued by mosquitos (Craig Pfister pers. comm.).

After cleaning and preparing the very dark, almost black, bones with mechanical preparation tools, Pfister ascribed tentative identifications to most of them. Pete Larson from the Black Hills Institute (an expert in T. rex osteology) also looked at photographs of the bones and checked the identificaetions. Between them they concluded that the skel some surface finds that were too fragmentary to be identified. This partial skeleton was sold to a private individual who specifically wanted the bones to be mounted in association and put on display as a named T. rex specimen, but also wanted the bones to be as accessible as possible to researchers in perpetuity. A decade or so ago this would have presented a conundrum: how can a specimen be mounted and on display, yet remain easily available to researchers? And how could researchers publish papers in peer reviewed journals if the skeleton remained owned by a private individual rather than owned by an accredited museum with an associated accession number?

The owner, who still wishes to remain anonymous, knew that a mounted T. rex skeleton (as opposed to individual or associated but unmounted bones) had not been displayed in England for several decades (Ingram 2021) so a newly named T. rex skeleton should be well received there. The owner had heard about the temporary 'Dinosaurs of China' exhibition in 2017 at the Nottingham Natural History Museum (NOTNH), Wollaton Hall, that was very well reviewed so approached staff there to ask if they would like to have a real T. rex skeleton on display in their museum for a year. Importantly, the owner arranged for the museum to have detailed physical and digital replicas of all the bones to permanently accession into the museum collection. The offer was accepted and Nottingham City Museums service proceeded to develop an exhibition with the skeleton as a centrepiece alongside associated displays. The specimen was named Titus. As well as being pleasantly alliterative ('Titus the *T. rex*') the name relates to the protagonist in William Shakespeare's play Titus Andronicus.

Material

Stratigraphy

The upper middle Portion of the Hell Creek Formation (Maastrichtian, Late Cretaceous) (Craig Pfister pers. comm.) is comprised of sandstones, siltstones, claystones and mudstones from ancient rivers, peat bogs and floodplains that formed in the riverine environment (Clemens and Hartman 2014).

Preserved elements

Elements of the skull and postcranial skeleton were recovered (Table 1, Figures 1 and 2). The bones have well-preserved periosteal surfaces but there is some crushing and breakage of most of the bones. Only two of the bones are complete, a left metatarsal and a right pes phalange (IV-3). All of the bones are within the same size range as other, more complete, adult *T. rex* specimens and are identical in size to those of the *T. rex* skeleton known as Stan (Larson et al. 2008). The specimen is referred to *Tyrannosaurus rex* Osborn, 1905, based on the complete metatarsal IV (David Hone pers. comm.).

Estimating the completeness of Titus

The early estimate of the completeness of Titus' skeleton was ~10-20% based on the number and size of discrete elements preserved in their entirety or as fragments. In total, 59 elements are preserved, approximately 20% of the ~300 bones in an adult *T. rex*.

Estimating the completeness of a fossil skeleton based on the number of elements preserved is not necessarily the most accurate way to judge its completeness: not all bones are equal and the completeness of the preserved bones of Titus range from <5% to 100%. It does not factor in the actual completeness of every element, nor the actual size of the bones compared to one another. For instance, the volume of the completely preserved metatarsal is equal to the combined volume of many of the missing vertebrae but each bone is counted equally.

Table 1. List of the preserved elements of the Tyrannosaurus rex *skeleton known as Titus. Numbers in this list are the original field numbers. See also Figures 1 and 2.*

1 Right tibia, mid-section (Figure 2D). This was found in pieces but adhered together, with some gap-filling necessary

2 Femur, midsection (Figure 2C)

3 Left metatarsal, one of only two complete bones (Figures 2E and F)

4 Left prearticular (Figures 1I and J)

5 Right angular (Figures 1E and F)

6 Caudal vertebra (Figures 2K and &L)

7 Right pedal phalanx complete (no IV-3), one of only two complete bones (Figures 2G and H)

8 Caudal vertebra, complete centrum (Figures 2I and J)

9 Right articular (Figures 1 A and B)

10 Caudal vertebra centrum partial

11 Caudal vertebra centrum partial

12 Caudal vertebra centrum partial

13 Nasal partial (right)

14 Quadrate, left (Figures 1K and L)

15 Quadrate, right

16 Cervical rib (Figures 2O and P)

17 Caudal vertebra, lateral spine of caudal vertebra

18 Chevron, almost complete but one side only (Figures 2M and N)

19 Cervical rib fragment

20 Cervical rib fragment

21 Bone not identified

22 Chevron fragment

23 Cervical rib fragment

24 Cervical rib fragment

25 Right prearticular (Figures 1G and H)

26 Cervical rib fragment

27 Upper part of the right maxilla

28 Not identified

29 Fragment of vertebra

30 Fragment of vertebra

31A Tooth (Figures 1C and D)

31B Mid-portion of right femur (Figures 2A and B)

31C Fragments as surface finds x 26

Figure 1. Some of the better-preserved skull elements of the Tyrannosaurus rex *skeleton known as Titus. Figure annotations relate to Table 1. Grey lines connect different views of the same element. Scale bars = 10 cm.*

Methods

Photogrammetry and 3D printing

Before the mounting of the skeleton could begin, all of the fossilised bones and bone fragments were recorded in great detail using 3D photogrammetry scanning. Photogrammetry is a computational method that can transform multiple digital photographs of an object or specimen into a high-resolution colour 3D digital model (Falkingham 2012). Photogrammetry is particularly well suited to 3D modelling textured objects such as bones and fossilised bones where experience has shown point accuracies of under 100 microns are easily achievable. It outperforms most commercially available 3D structured-light scanners for these types of subjects and has the important advantage that it can produce much higher resolution colour digital textures in the final digital model. It was for this reason that photogrammetry was selected as the method to 3D scan the fossilised bones and bone fragments of Titus.

Photogrammetry software requires a series of input digital photographs of the target object taken from multiple angles in orbits around the object. The software analyses common points on consecutive photographs and from them calculates camera positions and angles in a digital 3D space. After removing spurious points and further optimisations, the software, through a process of depth triangulation, then calculates a detailed digital 3D point surface. This is subsequently meshed into a 'closed-hull' digital 3D model and finally, the original photos are

Figure 2. Some of the better-preserved postcranial elements of the Tyrannosaurus rex *skeleton known as Titus. Figure annotations relate to Table 1. Grey lines connect different views of the same element. Scale bars = 10 cm except for C and D = 5 cm.*

projected back onto the 3D model surface to give a detailed colour surface texture.

For the Titus project, 31 bones were photographed using a full-frame sensor Canon 6D DSLR camera. Objects were diffuse lit with daylight bulbs using fixed studio box lamps. A custom designed automated and powered turntable (designed by S Dey) incorporating an automatic camera shutter release was used to ensure that every angle of each specimen was photographed efficiently (Figure 3). Each specimen was imaged ~300 to ~400 times. The photogrammetry software used was Agisoft Metashape (Standard Edition).

Figure 3. Steven Dey with one of the T. rex *bones being photographed on the automatic turntable.*

The final outputs of the work were two sets of 31 models; a high-resolution set with 5 million polygons per model and a lower resolution set with 1 million polygons per model (for online presentations). Both sets had 8K photo textures (Figure 4A-C).

The finished models were metrically scaled using Blender 3D, version 2.8. (Blender is an open source 3D modelling and animation application useful in multiple post-processing and presentation roles including preparing 3D models for 3D printing). The Blender scaling process relied on an additional 3D model showing a physical reference scale with the target bone imported into Blender to act as a digital measurement scale. The necessity of this Blender scaling step is because the photogrammetry software utilised does not produce an accurately scaled 3D model overall. Relative proportions within the model, however, are accurately proportioned in the X,Y and Z dimensions.

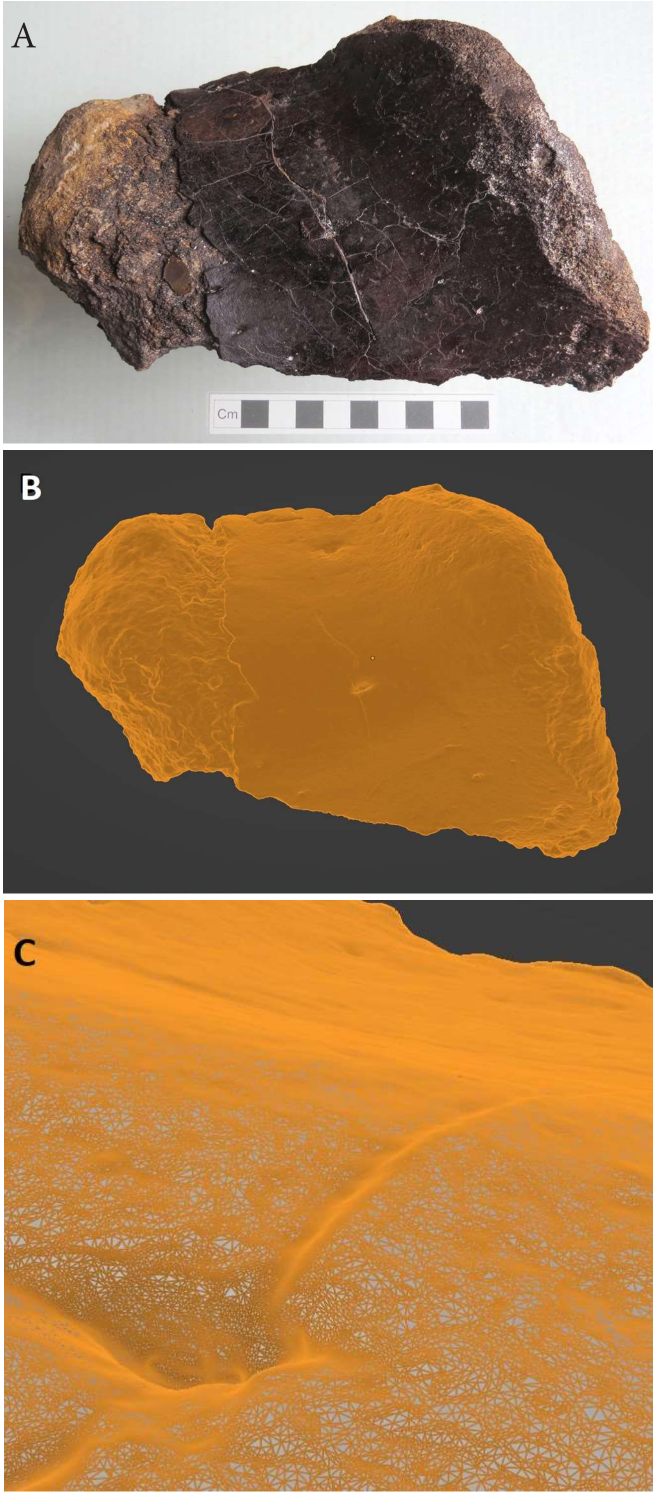

Figure 4. Example of the 3D digital models of the fossilised remains of Titus created for the project using the process of photogrammetry scanning: A) A photograph of bone 10, a partial centrum of a caudal vertebra; B) The 3D digital model of the same bone as in 4a but with the natural colour turned off, showing the morphology only; and C) a tiny detail of B, showing the polygons (though the models are so dense it is difficult to see the wireframe).

Various presentations of the digital 3D models were prepared for the remote scientific studies including high resolution orthographic 2D colour renders and special renders using radiance scaling shaders and virtual raking-lights. The scientific 3D application Meshlab was used in this work. All of the models were loaded into the online platform Sketchfab for 3D model viewing online. Here, the models were prepared for general presentation by creating a virtual 3D space with appropriate virtual lighting and post-process filters to best show off the detail of each bone. Also, notes and labels were added. On completion of the presentation tasks, the digital models proved detailed enough to allow Burnham *et al.* (2021) to undertake a detailed pathological and taphonomical study of Titus even though they were unable to physically handle the bones in person due to international coronavirus travel restrictions.

The digital models were used to create physical replicas of the bones, 3D printed in colour on a professional gypsum 3D printer at ThinkSee3D Ltd and hand finished for display in the exhibition at Wollaton Hall (Figure 5). The idea behind making physical replicas of the bones of Titus was both to have a physical set of replicas that the museum could accession permanently into its collection and to enable the public to get a better view of the bones that were preserved (because the original fossils would be mounted high above the visitors within the skeleton of Titus and therefore not so easy to see). The 3D printed replica bones were exhibited in low child-friendly display cases on the plinth around the specimen. There was also, in another room, a further collection of replicas showing a mock-up of the find site and a further display explaining the photogrammetry method with more replicas. In a third room a few replicas were mounted as an open exhibit so that the public could touch them.

Figure 5. Some of the replicas of the preserved bones of Titus on display at Wollaton Hall, Nottingham, 3D printed (in colour) in gypsum.

The gypsum 3D print powder (known as the core) used to print the replica bones is proprietary, so its exact formulation is not known but independent tests suggest it is mostly plaster of Paris with a probable starch non-sticking agent. It is understood that whilst this gypsum material in 3D printed form should be stable long term, the stability of the resin used in the infiltration process and the inks in this context are less well understood. However, the inks used are not specific to 3D printing but are standard water-based inks with natural pigments as would be used in 2D printed material. Museum conservators are familiar with protecting inks and dyes of this type in other objects so if 3D prints are treated similarly there is nothing to suggest the colours could not be preserved longer term. Anecdotal evidence, from ThinkSee3D's productions over 7 years, shows gypsum 3D prints if treated correctly do not appreciably change in form or in colour. The resins used to infiltrate and coat the 3D prints are not mandatory but are added to reinforce and protect the 3D prints. The 3D prints are initially held together by the reaction of the water in the ink and the gypsum in the core. The synthetic epoxy coating resins used to strengthen and protect the outer surface of the 3D print from UV light are the same resins as those used in more demanding industrial applications; their properties are well understood by industry and have been used for several decades.

The physical 3D printed replicas of the bones are very useful for display, in tactile public engagement activities and to help to give a proper appreciation of scale, and their accession into the museum's collection will mean that they are available for research in the long term. For research purposes, it is generally accepted that digital 3D models are a more convenient and a more accurate way to obtain metrics compared with measuring physical 3D prints. Measurements from 3D prints can be made but the accuracy of the 3D printer involved would have to be taken into account and expressed as a tolerance. Generally, accuracies from 3D printers will be under 1 millimetre and in some technologies under 0.1mm. Since measuring on-screen is far easier and digital models can be readily shared this is the preferred method for measurement and having detailed digital 3D models with a clear documented 'construction history' is a valuable scientific asset. One advantage 3D prints offer is to give a proper appreciation of scale and the ability to use fingers to feel structure. On-screen representations of models are 2D so can lead to confusion over the scale of objects and features.

Digital 3D model files can be widely shared through global repositories such as Morphosource, providing the data with a permanent DOI. The source photographs used for generating the models should also be archived and shared, in case future improvements in photogrammetric processes mean the models could be usefully regenerated. For the time being, all the 3D data and the original photographs used to generate the digital models of the bones of Titus are archived at the Nottingham Natural History Museum and can be accessed upon request but they may be shared more widely in due course.

Mounting

It was decided that Titus should be reconstructed as a full-sized complete skeleton in a walking position, as if searching for prey or returning home after a hunt, with a pleasing lateral undulation (S-shape) to the whole vertebral column. The missing 80-90% of the skeleton was filled by purchasing a complete set of unmounted replica bones of the *T. rex* known as Stan (formerly BHI 3033), one of the more complete *T. rex* specimens to have been found at about 63% completeness (Larson et al. 2008). This set of casts includes a furcula and various gastralia that were not preserved in Stan's skeleton. They are apparently replicas made from the skeleton known as 'Bucky', a juvenile *T. rex* and they are therefore about 20% smaller than Stan's might have been.

The complete set of polyurethane casts were purchased directly from the Black Hills Institute of Geological Research in South Dakota and are of good quality with a lot of detail. Titus was exactly the same size as Stan, judging by how well the complete metatarsal and pes and almost complete tibia, articular, prearticular and angular of Titus matched the replicas of Stan's bones. The Black Hills Institute gave permission for the new skeleton to be called by another name as it represented a different individual.

The bones of Titus that were complete simply replaced the relevant bones in Stan's skeleton. For the incompletely preserved bones of Titus, the relevant replica bone of Stan in each case was cut and shaped to accommodate the portion of real bone, and the gap between the two was filled with Apoxie Sculpt (a self-hardening epoxy resin paste) which was then shaped and given relevant texture (Figures 6 and 7). Paraloid B72 consolidant had already been applied to the bone surfaces to form a reversible barrier layer between the epoxy and the fossil material. All the casts of Stan were a homogenous plain brown colour but very glossy so were first dipped in acetone and scrubbed with wire brushes to remove the gloss. All the casts and associated Apoxie Sculpt fillers were then painted with artists acrylic paints to closely match the colour of the real fossil bones.

Figure 6. Bone 8, a caudal centrum of Titus, joined to a cast of Stan's caudal vertebra no.15 with Apoxie sculpt before matching the colour of the cast and filler to the fossilised bone with artists acrylic paints.

Figure 7. Posterior portion of the left mandible (lingual view), with the fossilised left prearticular of Titus at the bottom in the centre, surrounded by replica bones of Stan (yet to be painted). Note the metal armature is largely hidden (if in buccal view, i.e. from the public viewpoint) within the arrangement of replica bones.

Detailed plans of a generic *T. rex* skeleton were produced in the agreed pose (Figure 8) and the armature was designed and fabricated (by N Larkin) according to this pose and the actual size and shape of Stan's replica bones, to reduce handling of the original fossil material. Appropriate lengths of steel were heated and shaped, cut and MIG welded (Figure 9) then bolted together as required to provide an armature that could safely hold the real and replica bones in place in a way that meant the skeleton could be assembled, disassembled and transported with relative ease. Standing 12 m long (Figure 10) and 4.35 m high (allowing for a plinth 1 m high under its feet) this did still involve gantries, chain hoists, slings and quite a bit of effort.

The whole structure including the metal base, steel armature, bones and casts weighs about 630 kgs. The room in which the skeleton was to be displayed is on an upper floor of a large Grade 1 listed Elizabethan mansion and there was some concern about floor loading, particularly as the wooden plinth underneath the skeleton would also be extremely heavy. The skeleton would have to be positioned so that most of the weight was over the supporting wall in the room below. Whilst the original intention was to have only a single supporting vertical pole under the pelvis, a second upright pole was added between the forearms during mounting to help spread the weight. There could be no supporting cables attached to the ceiling due to the listed nature of the building.

It took almost a year's worth of work to assess and consolidate the bones, plan and make the steel armature to the desired shapes, blend the bones of Titus with the casts of Stan and paint the replicas to match the bones until the fully mounted skeleton was ready for display (Figure 11). The metal armature supporting the skeleton had been made in sections so that the mounted specimen could be dismantled, crated, loaded on to lorries and transported to the Nottingham Natural History Museum at Wollaton

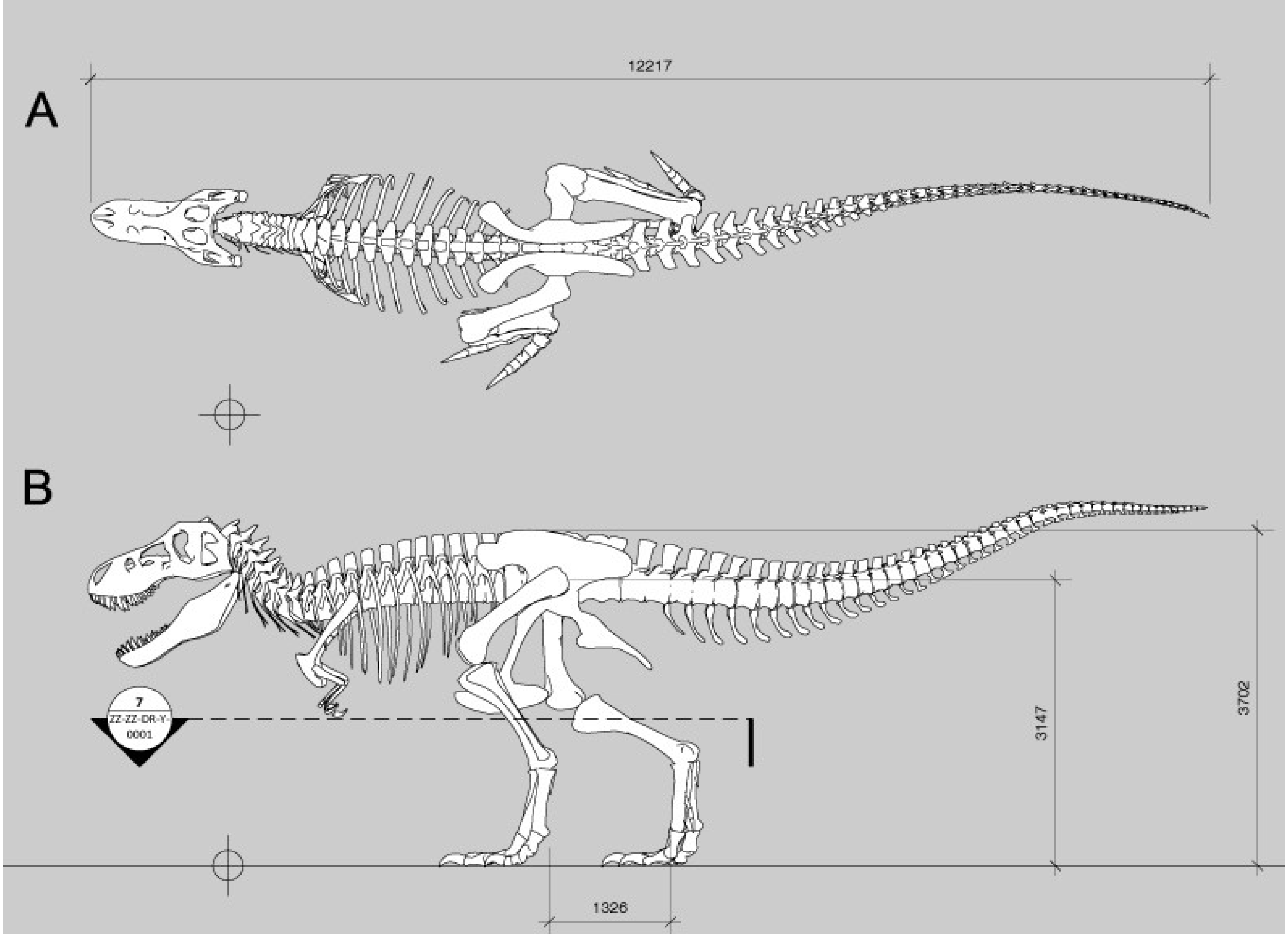

Figure 8. The plans for the pose of the skeleton of Titus: A dorsal view; B lateral view.

Hall. Here, the skeleton was carried up stairs and through narrow doorways into the Willoughby Room where it was reassembled and the wooden plinth built underneath it. The plinth hid the metal base, kept the public a meter or more away from the bones, and provided space for the display of the 3D printed replicas of the real bones.

Figure 9. Making the metal mount for the skull of Titus.

Not only is this the first time in decades that a skeleton of a *T. rex* containing fossil bones been put on display in England, this reconstruction of Titus is more complete than any replica of a *T. rex* currently on display in the UK. The replica of Stan in Oxford University's Museum of Natural History is missing all the gastralia, the furcula and some wrist bones, whilst the replica in Manchester Museum does have a furcula but lacks gastralia. Maybe when constructing replicas of Stan, there is a desire to exclude casts of the furcula and gastralia as they are known to be smaller than they should be, although including these replicas, even if they are slightly smaller, does give a more realistic impression of the whole skeleton. However, the replica of the 'Wankel' T. rex (found in Hell Creek, Montana) at The Great North Museum: Hancock in

Figure 10. Assembling the bones of Titus and the casts of Stan on the steel armature.

Figure 11. Titus fully mounted in the conservation facility in Shropshire before disassembly and transport to Nottingham.

Newcastle similarly does not have any gastralia present or a furcula and neither does the replica of the Wankel *T. rex* at The National Museum of Scotland, Edinburgh. The University of Leicester has a replica of the *T. rex* skeleton known as Jane; this is a juvenile, about half the size of Titus, and is also displayed with no gastralia or furcula.

Curation

A set of 26 replicas of selected identifiable fossil bones of Titus were 3D-printed in gypsum and put on display for the duration of the exhibition (Figure 12). These replicas were permanently accessioned into the Nottingham City Museums and Galleries service under the accession lot number NCMG 2021-7 and documented individually in the Nottingham Natural History Museum's collection under the specimen numbers NOTNH FS5035/1–26, where they will remain in perpetuity for future reference, study and potential display. Duplicates of four of the bones were also 3D printed as non-accessioned handling objects and permanently fixed onto a plinth in the exhibition. The digital 3D models of all the bones have also been archived at the museum and will be made accessible to any researchers who wish to study them.

Titus: *T. rex* is King

The exhibition 'Titus: *T. rex* is King' opened to the public on the 3rd July 2021 and is scheduled to run until the end of August 2022. The exhibition is divided into five sections or galleries: Titus Unearthed, Meet Titus, Past and Present, Explore Titus, and Create Titus (Hone *et al.* 2021).

'Titus Unearthed' explores how Titus was discovered, excavated and mounted. An audio-visual film showing the excavation, mounting and research into the pathology is supported by a display case which visualises the process from discovery to display. This display consists of a mock-up of the excavation site (constructed by Sarah Burhouse) which includes the unidentified fossil fragments of Titus that were not mounted, a mock-up of a workbench including Craig Pfister's notebook and site map, and an array of some of the accessioned 3D-printed replica bones. This section also uses fossils of Mesozoic reptiles from the NOTNH permanent collection to help place Titus into a broader geological and geographical context.

Figure 12. The mounted skeleton of Titus at Wollaton Hall. Note the 3D printed replicas of the fossil bones of Titus (NCMG 2021-7) exhibited in Perspex vitrines on the plinth.

'Meet Titus' presents the mounted skeleton of Titus alongside interpretation of its anatomy and taphonomy, plus stories about the discovery, biology and evolution of *T. rex* in general. Titus is mounted on a plinth in the centre of the gallery surrounded by vitrines containing relevant 3D-printed elements. A balcony area hosts the 'Past and Present' section, which uses specimens from the NOTNH collection to demonstrate the similarities between the skeleton of *T. rex* (scaled down model) and a chicken, and to showcase taxidermy and pinned specimens of organisms that represent groups of modern animals that lived alongside *T. rex* during the Cretaceous Period.

The 'Explore Titus' and 'Create Titus' sections are spread across two galleries. One gallery contains interactives including handling specimens and touchless digital interactive stations controlled manually by swiping the air (necessary to minimise the risk of spreading coronavirus). There are three digital interactives; six 'Create Titus' interactive stations allow visitors to get creative and add colour, patterns, texture (feathers) and sound to a base model of Titus. Four 'Explore Titus' interactive stations allow visitors to recreate the soft tissues over the skeleton of Titus. Two more interactive stations recreate the excavation of Titus by allowing visitors to first dig for the bones (digital 3D models produced from photogrammetry) and then fit them into the skeleton of Titus. These touchless digital interactives produced by Hot Knife Digital Media were particularly well-suited to minimise risks during the coronavirus pandemic in 2021.

The second 'Explore Titus' gallery is located in the museum's Africa Gallery (currently under development). Here a cast of a different *T. rex* skull (the 'Wankel rex', MOR 555, on loan from Queen Mary University London) is displayed next to a model of a juvenile *T. rex* skull. An African diorama is used to help push home the message that birds are dinosaurs. Lastly, a fleshed-out reconstruction of a juvenile *T. rex* head and torso roars visitors goodbye and provides a photo opportunity at the conclusion and exit of the exhibition.

Discussion

Ethics

The skeleton known as 'Stan' is one of the more complete *T. rex* skeletons found, comprising about 63% fossil bones (Larson *et al.* 2008). Stan is augmented with casts of some of the bones that are repeated (e.g. some of the ribs) or casts of bones of other T. rex skeletons. Stan was sold in 2020 for 31.8 million US dollars to an unknown buyer (Greshko 2020) (announced in March 2022 as the Natural History Museum Abu Dhabi), pushing up the price of all such skeletons even further beyond the budget of most museums. Very wealthy private individuals can purchase such specimens and may sometimes put them on public display but this can leave the fossil in an intellectual limbo, without guarantee that the specimen will remain accessible for study, and leaving any research findings un able to be published in most peer-reviewed journals.

However, unusually, the owner of Titus was keen from the outset that although ownership of the physical specimen would remain in private hands, the skeleton should be on public display and, more importantly, as accessible as possible to researchers. They wanted this to be seen as an exemplar project to encourage other private owners of important fossils to go to similar lengths to make their material as accessible as possible. By providing the funds to 3D scan all of the fossil bones in detail and having replicas of the bones 3D printed, the owner enabled the whole specimen to be studied easily by proxy by anyone in the world. The material therefore became genuinely more accessible to researchers than many dinosaurs on display in museums where the museum is the owner of the material. A museum might have been able to afford to purchase this *T. rex* skeleton, but would they also have had the funds and/or desire to ensure the material was immediately 3D scanned in detail and make the subsequent digital 3D models available and have 3D printed replicas made immediately too? As a result of this work on Titus, a research project investigating pathological information preserved in the bones took place on the other side of the world using the online Sketchfab model sharing platform and this report was ready for submission before the mounted skeleton was even ready for display. The 3D printed replicas of the original bones became an integral part of the exhibition and will remain permanently accessioned in the museum collections when the exhibition is over, no matter what happens to the original remains of Titus in the future. This, along with the 3D digital models that the museum has archived, will enable the replica material to be referenced in academic papers.

The complex issues surrounding the ethics of scientifically important specimens remaining in private ownership and whether or not research should be published on such specimens are wide ranging, can be emotive, and have been discussed at length elsewhere. Of particular note are a couple of letters published recently: one in the Society of Vertebrate Paleontology by Rayfield *et al.* (2020), and a rejoinder by Haug *et al.* (2020) in PalZ, each expressing some quite different points of view but also some common ground. Whilst it can be agreed that the acquisition of an important specimen by a museum and its deposition in a ‘publicly accessible collection’ is the ideal scenario, sometimes this is simply not going to be possible – not least for financial reasons. And even specimens in museum collections may not actually be as accessible to researchers as they could or should be. When they do work with private collectors/owners of fossil specimens, museums can display to the public spectacular fossils that they would not be able to acquire on their own, and increasingly they should be able to share all the related data with researchers too, if the owners agree. In either case, the open sharing of data is the best way to accelerate the pace of science and as the number of researchers with access to data increases, the science that is generated from the data becomes more repeatable (Lewis 2019).

A fossil specimen – even one as large as a *T. rex* skeleton – can remain in private ownership and be on public display yet remain accessible to researchers through the use of relatively accessible 3D modelling technologies and 3D printing. Although there may be ethical and copyright issues to be addressed in each case and users might need to sign permission forms and correctly credit the data they are using, such 3D digital archives of palaeontological specimens are increasingly being made freely accessible online (Lewis 2019). Where there is a will, there is a way. Furthermore, publishing palaeontological research in peer-reviewed journals quoting the accession numbers of replicas held in museum archives rather than the original specimens is not a new idea. For example, when holotypes have been destroyed by fire or warfare but plaster copies have survived in other museum collections they have often been described and referred to in peer-reviewed journals out of necessity (e.g. Evans *et al.* 202; Jackson 2004; Massare and Lomax 2018; Smith 2015) and when fossils have existed as natural moulds from which casts or other replicas have been made (Clark *et al.* 2004; Watson 1958) although both the natural moulds and casts may have been accessioned. Vertebrate specimens have also been thoroughly described in peer-reviewed journals from CT scans alone, without the bones being prepared at all (e.g. Fernandez *et al.* 2013). However, the practice is more widespread than just these particular scenarios -for instance, when a specimen remains in private ownership but is described in a peer-reviewed journal quoting the accession number of a plaster replica held in a museum collection (e.g. Martill et al. 1996). Specimens have even been described in peer-reviewed journals when still in private ownership and no replica of any sort has been deposited in a museum collection (Frey *et al.* 2017; Kundrát *et al.* 2019).

Despite the many benefits replicas of fossils can provide they are not a completely satisfactory substitute for an original fossil in every research scenario. Although the external topology and surface texture of the fossils can be meticulously recreated there are some research limitations associated with replicas. For example, histological and chemical samples cannot be conducted on replicas. On the other hand, replicas often benefit from being lighter and therefore easier to handle than original fossils, and their use can prevent the original material from being damaged.

Materials

The replica bones of Titus were 3D printed in gypsum which should be the most enduring of all media currently used for 3D printing as it is essentially the same as plaster of Paris which, in the form of replica fossils and busts for example, has been stable in museum collections for over a hundred years. However, if the 3D prints do eventually deteriorate, they can easily be reproduced by simply 3D printing more copies from the digital 3D models held in the museum archives.

There are many practical as well as ethical issues to consider when mixing replicas with fossil specimens in a museum context. Firstly, the public should be aware of what is replica and what is fossil by at least noting it within the display text or labels. In the case of Titus this was made obvious: the 3D printed replicas of the real bones were placed in vitrines with labels near where the fossil bones appeared on the skeleton, to highlight which bones were preserved on what was acknowledged to be a mostly replica skeleton.

Many freshly 3D printed materials and resins used for casting can 'off-gas' for a length of time (e.g releasing volatile organic compounds) and this may affect the integrity of real specimens nearby. Ideally, the stability and likely longevity of all the materials used would be known but very few 3D printing materials have been tested and the results published. White nylon 3D printed models may "yellow" over time due to oxidation (Martyn Carter and Richard Beckett, University College London, pers. comm.) but most materials have been in use for such a short time that little is known about their stability. There is active research in this field but as yet no commonly agreed materials or protocols.

The 3D prints of the bones of Titus are made of gypsum but they are not mixed with the real bones. The real bones of Titus, however, are inevitably in close contact with polyurethane foam and epoxy putty. This is less than ideal but these products have been used with fossil bone for many decades now and no obvious issues have arisen. There is at least thick consolidant providing a barrier layer between the fossils and these materials and the skeleton is on open display so there is no build-up of any off-gassing products such as might occur within a sealed display case.

Traditionally, replicas of fossils have been in the form of casts (initially made from plaster of Paris but more recently from polyester, epoxy, polyurethane or acrylic resins). These were made from moulds taken from the original specimens. However, even museum-quality casts are not always perfect replicas of the original specimen because friable or porous areas in the specimen have to be covered and holes, cracks and undercuts have to be filled temporarily to protect the specimen during the moulding process. In this respect, good quality 3D prints made from detailed 3D digital models can often be a more reliable copy than a cast. Furthermore, 3D scanning is a lot less invasive and potentially damaging to the original specimen than the moulding process (Monge and Mann 2005). Care should be taken to 3D print replicas in the most durable of materials (such as gypsum) for long-term storage in a museum collection but as long as the 3D scans and/or 3D digital models are also archived in a durable digital format, there is scope for making new copies as and when the need arises.

Study of the 3D scans: Pathology and Taphonomy

As apex predators and possibly occasionally cannibals (Hone and Tanke 2015), many *T. rex* skeletons exhibit evidence of trauma as well as (sometimes associated) disease (Burnham *et al.* 2021) and Titus is no exception. Although the skeleton is only ~10-20% complete, the palaeopathology report on Titus by Burnham *et al.* (2021) shows that the skeleton preserves evidence of: a bone lesion in the right tibia with surrounding periosteal damage perhaps from a tooth or claw that penetrated the flesh, struck bone and became infected; the pes phalanx IV-3 has a spheroid bone defect and serpentine zones or resorption (possibly the first record of a tuberculosis-type disease in a dinosaur); and a caudal vertebra has a deep tooth puncture associated with a tooth drag on its ventral surface with reactive bone around the edge of the puncture. It is unknown if the trauma to the leg and tail occurred separately or at the same time but the animal survived long enough afterwards for some healing of the bone to take place. The specimen also has trace marks that show post-mortem scavenging (numerous tooth marks and breakage of bone that indicate feeding by a large dinosaur) and indications of trampling, followed by some subsequent transport in a fluvial system before final burial (Burnham *et al.* 2021). The lag deposit in which the body was originally preserved weathered out over the years and parts of the skeleton were lost. The isolated *T. rex* tooth crown that was collected on the surface with the other bones is interpreted as a shed tooth from a scavenger.

Conclusions

As the monetary values placed on significant palaeontological discoveries continue to rise at a time when the ability of museums to purchase them is in decline, it is more important than ever that 3D scanning, 3D printing and other methods of data capture - as well as effective data sharing - are routinely employed. Physical 3D printed replicas offer many opportunities for the public to engage more personally with a specimen, including the ability to see what the specimen looks like more clearly and up close and even to touch the specimen (both implemented with the Titus display at Wollaton Hall). Even for research purposes physical models can help to demonstrate the scale of objects and features better than on-screen views of digital 3D models. The detailed digital 3D models with clear, documented 'construction histories' are the primary scientific 3D assets because they can be shared widely and referenced easily – more so than the actual source material, the bones themselves. Also, if a distant researcher wants their own physical replica, they can locally 3D print their own copy from the digital models.

Such work will ensure that scientific material is genuinely available for study and private owners of important specimens should be encouraged to facilitate - or even pay for - this as a matter of course. Let us hope that Titus treads where other privately owned skeletons will follow.

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