The Application of Digital Reconstruction Techniques in Taphonomy of an Upper Cretaceous Dinosaur Site in Eastern Wyoming

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High-resolution Global Positioning System (GPS) technology, together with Geographic Information Systems (GIS) software provide powerful new tools for the taphonomist. We have applied these techniques in our research on a massive Upper Cretaceous dinosaur bonebed in the Lance Formation in northeastern Wyoming, permitting centimeter accurate photographic reconstructions of the features of the quarry essential for taphonomic study. We can then query the resulting three dimensional mapping and answer essential taphonomic questions after returning from the field. We are able to process over two thousand specimens from a typical season's excavation and convert the data into accurate and addressable virtual quarry maps. Using the resulting quarry maps, we can visualize the positions of every bone. The maps and photographs and data on the specimens are available on the internet so that the integrity of the taphonomic data, now in excess of sixteen thousand specimens, is assured for the future.

Keywords: VIRTUAL QUARRY, LANCE, GPS, GIS, BONEBED

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Introduction

Taphonomy is the study of the process by which living things become fossils (Lyman, 2010). As such, taphonomic analysis of fossil assemblages requires the preservation of as much information as possible from the environment of a fossil (Wuttke & Reisdorf, 2012). Whether one approaches taphonomy as a paleontologist or as a sedimentologist, the location and orientation of the fossil materials in the ground are critical classes of information.

Traditionally paleontologists have relied upon tertiary attempts to reconstruct these data from drawings, diagrams and photographs made in the field. Modern optical tools like the Total Station (TS) and Robotic Total Station (RTS) allow for very precise millimeter vectors references from site datum. However a direct optical observation path from the instrument to the fossil or pole mounted prism is required. Sites with significant elevation changes might require multiple datum points and backsights for aligning the instrument with a site datum.

Global Positioning Systems (GPS) / Global Navigation Satellite Systems (GNSS) technology can greatly simplify the georeferencing of fossils. A single base datum point can serve sites for a large radius (perhaps as long as 5 km). No backsight is required as a geodetic north basis of bearings is directly available. No optical path to the receiver is required. Multiple sites are all framed to the same datum which enhances the comparison of height between sites. Since a single complex wide datum point can suffice for many sites, this single site datum fiduciary can be built to very high standards reducing the chance of destruction or movement. In this paper,

we will present a new approach to the taphonomic study of fossil bonebeds using GPS/GNSS technology in conjunction with Global Information Systems (GIS) software.

We began experimenting with the use of high resolution Global Positioning System (GPS) technology in other taphonomic projects (Esperante *et al*., 2002). Beginning in the 2000 field season, we decided to try replacing conventional mapping of quarry sites and specimens entirely with GPS surveying technology (Turner *et al*., 2000). The aim of the taphonomist is to visualize the bones as they lie in the ground with the sediment removed. While the use of high resolution survey equipment in the field, and GIS software to process data are not unique to this project (Jennings & Hasiotis, 2006; Chew & Oheim, 2009), we have gone beyond that to achieve accurate three-dimensional reconstruction of the photo-real taphonomic relationships on-site and in near real time. When properly implemented, these techniques promised the potential to view the fossil remains in field positions interactively, and to accurately reconstruct virtual photographic images of the fossil material as if it were still in place with the matrix removed. We should then be able to complement field studies with taphonomic analysis on the virtual site in the computer. A further advantage in the field would be that formal gridding of the quarry site would be a redundancy that the investigator could forego at his or her discretion, without losing context information.

With these goals in mind, we initiated taphonomic study of a quarry site in a productive bone bed in the Upper Cretaceous (Maastrichtian) Lance Formation in eastern Wyoming containing abundant remains of Upper Cretaceous fauna and flora.
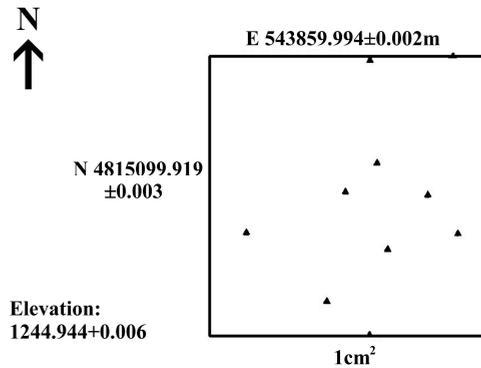
Figure 1. Ten test points taken over one benchmark with hand held rover. The resultant point distribution fits in one cubic centimeter. Such distributions are reproducible from season to season.

Materials and methods

Use of GPS in the Quarry

During previous years, we had done work using standard excavation practices. Mapping was carried out using a conventionally surveyed grid system, and specimens were drawn with a decimeter-scaled meter square overlay grid. At the start of the 2000 field season we initiated the use of GPS technology on an experimental basis for mapping bone locations in one quarry. The acquisition of three-dimensional positional data with accuracy of a centimeter requires sophisticated and expensive survey grade GPS equipment. Such equipment is available for purchase or rental from several commercial sources. GNSS (GPS + GLONASS) receivers from a variety of manufacturers have routinely yielded accuracies in the sub-centimeter range. At our sites we have implemented a number of conveniently located check points and procedures to 'Check-in' and 'Check-out' on them at the beginning and

end of production shifts, repeatedly storing these positions along with the fossil locations. Experimentally we have observed sub-centimeter repeatability (±3 mm) from shift to shift and from season to season. The use of these check points also allows us to immediately detect and remedy configuration blunders. Figure 1 illustrates a typical scatter of points taken during a 30 second interval with a handheld rover from a single benchmark.

Suitable equipment consists of two nearly identical instrument packages: a Base receiver and one or more Rover receivers. The permanent fixed Base receiver is attached to a very stable concrete monument. This monument is engineered to provide a long-term, single-fixed-datum point from which all site measurements are based.

We first determined the UTM coordinates for the Antenna Reference Point (ARP) of the monument by submitting 8-hours of static dual-frequency data to the NGS (National Geodetic Survey) Online Positioning User Service (OPUS) system (Silver, 2013). These coordinates were then

Figure 2. GPS base with associated equipment. Blue radio is near battery power source on right. Solar panel on left used to maintain charge. Tall mast on far right is radio antenna.

held fixed (as a local reference frame datum) for all future seasons, eliminating coordinate shift due to plate movement and future reference frame adjustments by the NGS. The basis-of-bearings for site measurements is aligned to UTM Grid North by the GPS system. Thus a single point controls all horizontal and vertical elevation measurements at the site.

The Base GPS receiver (Fig. 2) consists of the receiver itself, containing the Global Navigation Satellite System (GNSS) antenna and the GNSS engine, shown atop the white monument, which acquires GPS satellite data, computes its location from the satellite data, compares this value with the permanent static position and computes a correction factor. This correction factor is broadcast to all Rover receivers via a UHF radio link.

The Rover receiver does the actual data accumulation (Fig. 3). It consists of a GNSS antenna, UHF radio antenna, a GNSS

engine to process and combine the satellite pseudo ranges and corrections from the base, and a data collector to store collected points. Using Real-Time Kinematic (RTK) techniques (Hatch, 1991), a fix on any position within UHF radio range of the base station (more or less line of sight, up to several km) can normally be achieved in less than a second. By using radio repeaters, the range and utility of the system can be extended as needed. Because of the critical nature of the GPS data to the project, and the degree of sophistication required to set up and run the equipment, we designate and
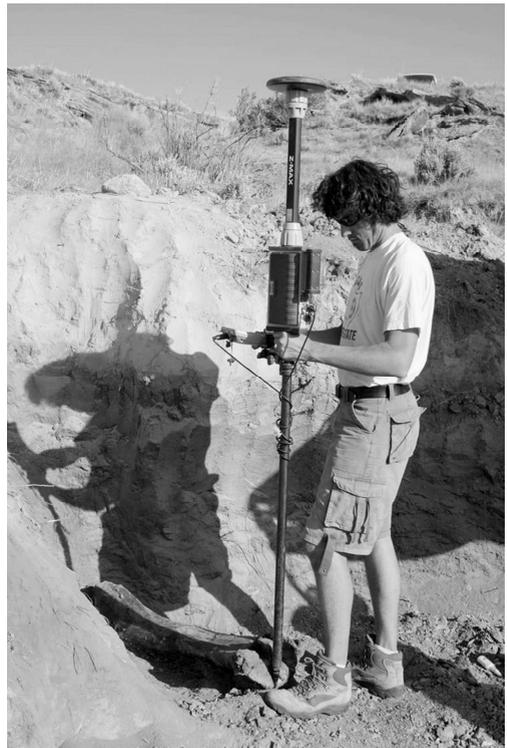
Figure 3. GPS Rover being used to acquire positional data on an exposed dinosaur bone.

train participants specifically to operate the GPS equipment. Individual quarry workers still record details of each find in log books, but we now acquire and log positional data entirely through GPS receivers.

GPS Quarrying Procedure

When a fossil is encountered during quarrying activities, its upper surface and outline are exposed using standard quarrying techniques. The northernmost point is marked with a colored dot to facilitate the correct association of the GPS data with digital photographs of the bone. The investigator then fills out a preprinted card indicating the specimen number, with blanks for field worker's name, date, page in the workers book, and description and containing a scale ruled in centimeters, and places it next to the specimen. The GPS worker then photographs the specimen with the card using a digital camera, and surveys the position of the bone with the GPS rover (Fig. 3). Beginning with the colored dot, the worker takes as many points as required to effectively outline the object (minimum total of three). These GPS data are acquired by the Rover's data collector using the specimen number of the bone as a descriptor, so no post-acquisition data manipulation is required. The investigator then completes excavation of the specimen. A temporary adhesive label preprinted with the specimen number is affixed to the bone and the data card is enclosed with the bone to provide redundancy.

At days end, the digital photos are renamed to the specimen number on the card in the photograph and the photographs and GPS data are uploaded via satellite uplink to servers on the home campus, which are backed up daily.

Digital Data Analysis

During the time between field seasons, we process the field-acquired data into digital reconstructions using the ArcMap module of ESRI's ArcGIS software. We are currently using version 10.1. During the latest (2016) season, we excavated 1268 bones and other objects.

After returning from the field, we processed the photo of each bone (Fig. 4A) to remove extraneous background using the Photoshop manual selection tool, leaving the bone on a white background (Fig. 4B). We saved the resulting images as TIFF files with the specimen number of the bone as a name of the photo. The GPS data are accumulated in a Microsoft Access database file. Next we individually combine the processed bone photographs with the corresponding 3-D GPS data for that specimen using the georeferencing tool in ArcMap (Fig. 4C). The specific procedures for georeferencing can be found in Appendix A.

After georeferencing was complete, the entire array of bones for a given quarry were imported into ArcMap and saved in ArcMap mxd format. We then generated a quarry map from all of the bone images belonging to that quarry, and exported this map as a 2-D JPG file with world coordinates. World coordinates attached to a JPG or TIFF file enable the photograph to be placed accurately as a spatially oriented two-dimensional object. This JPG image and the associated world file represent a permanent record of the spatial positions of the bones. From the mxd file, we can quickly generate additional figures for a specific quarry showing various bone types or combinations of bones or particular elevations in the quarry, etc., as needed to

facilitate analysis. We can combine the current year quarry map with world coordinated images from previous years to reconstruct the entire history of a quarry.

Description of Quarry Site

The principal bone bed in which the quarries are located covers at least 6 hectares, and probably considerably more than this. The bed containing the bones is a light gray claystone to siltstone sandwiched between moderately indurated, fine grained, tan immature quartz sandstones. Typically, the bones are suspended in the mudstone, but occasionally, irregular topography of the underlying bed leaves the bones nearly in contact with the basal sandstone. The bone

bed was originally flat lying, but currently exhibits regional dip of about three degrees toward the west. We are presently working eight quarries (Quarries 1, 2, 4, 5, 8, 11, 12, 15 shown in Fig. 5) in this bed.

Permanent Storage and Accessibility of Data

If the quarry data are to have lasting usefulness, they must be published and accessible in a form that assures reasonable permanency. We have developed techniques described elsewhere (Woods & Chadwick, 2007) to preserve the entire dataset for the quarry sites in a permanent and user addressable format. The quarry maps and bone data are available in an online museum and database which is fully searchable. The
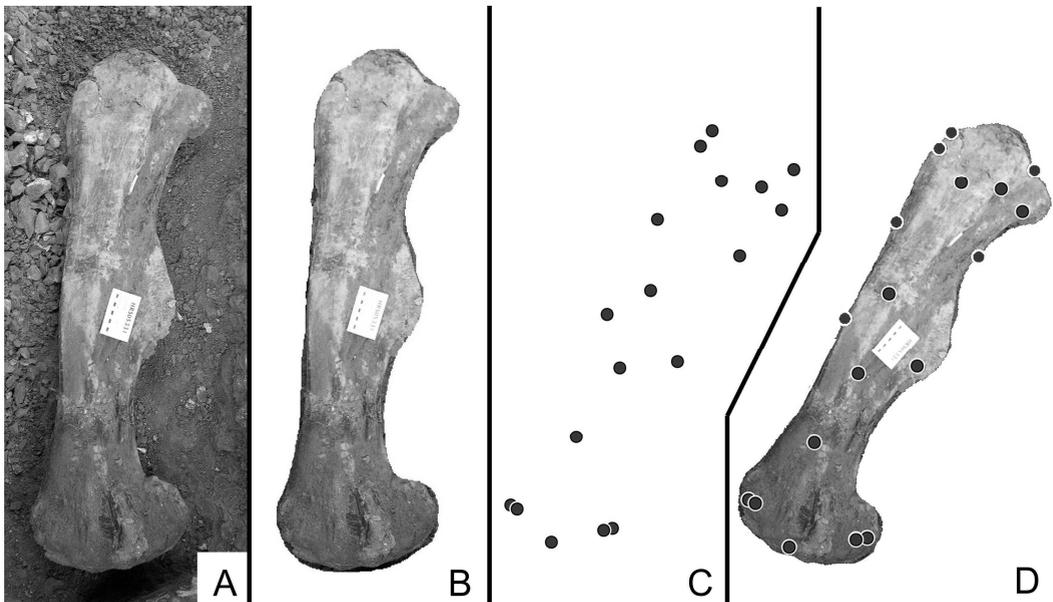
Figure 4. Steps in georeferencing bones. A. Photograph of pedestaled 127 cm *Edmontosaurus* femur in place in the quarry. Scale on white card in cm. B. Same photo with quarry background removed digitally to leave only bone. C. Array of GPS points taken from bone. D. Image of femur after georeferencing to GPS data.
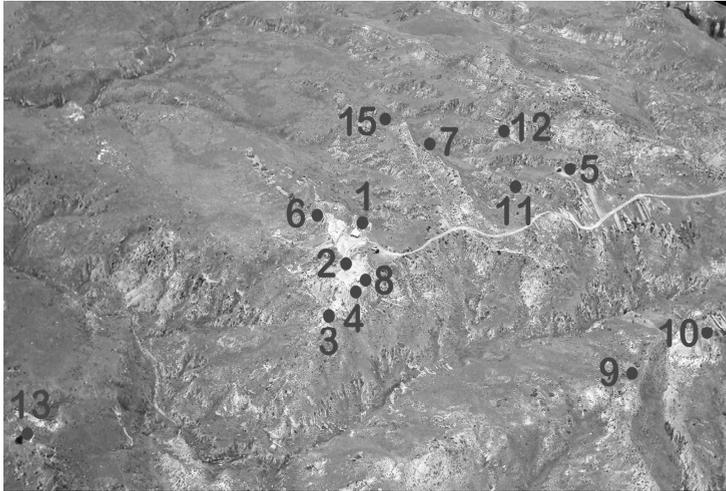
Figure 5. Quarry map indicating the locations of several quarries mentioned in text. Distance from Quarry 13 to Quarry 9 is 600 m.

user can visually determine the quarry positions of all bones, and view photographs and 3D virtual reality images of most bones. The website address is http://fossil.swau.edu.

Results

We have excavated and mapped a total of 20155 bones, bone fragments, teeth and other fossils using the GPS equipment during the past 17 field seasons. In addition, we have collected several thousand microfossils during screen washing. Quarry 1 in Figure 5 is the site where the most extensive excavation has taken place. Complete data are available for seventeen years of excavation (2000-2016) and a few data have been interpolated from field diagrams for one previous year (1999). The quarry diagram (Fig. 6) depicts the virtual reconstruction of the distribution of bones in the entire quarry for the years 1999 through 2016 in plan view. A total of 5390 bones, fragments and teeth are represented in the virtual quarry diagram. A portion of the quarry indicated by the red box in Figure 6 is shown at increased resolution in Figure 7 to illustrate the resolving power of the technique. The data can also be viewed in the plane of the quarry using the ArcScene module of ArcGIS, as shown in Figure 8 for a portion of the same quarry. Here the bones, viewed from the side, reveal the topographic relief on the base of the bone layer. Figure 9 demonstrates the results of adding virtual quarry diagrams in successive years to build up a composite picture of the entire history of the quarry.

We can carry out post-processing data analysis by filtering the data we choose to display. We were able to demonstrate the normal grading of the bonebed using this technique. Figure 10 shows the bone size distribution in four successive 2 decimeter depth intervals within Quarry 2, beginning
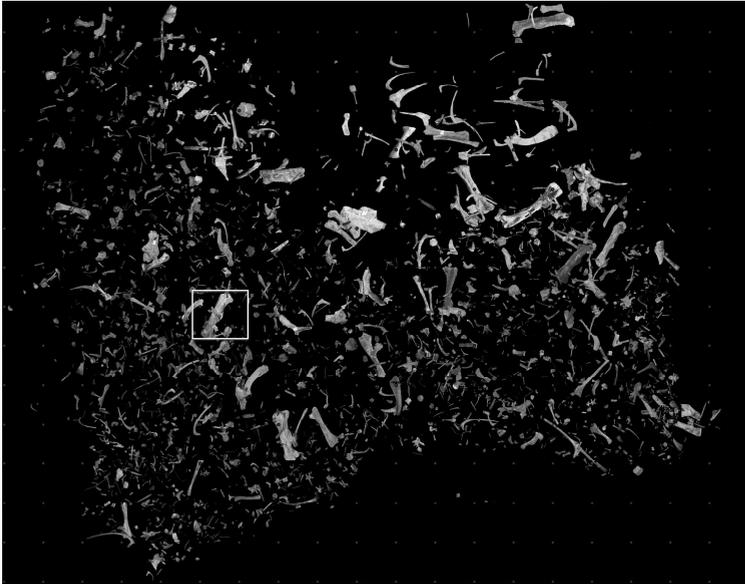
Figure 6. Full virtual quarry map of Quarry 1. Box shown as Figure 7. Dots are on one meter centers North is up.
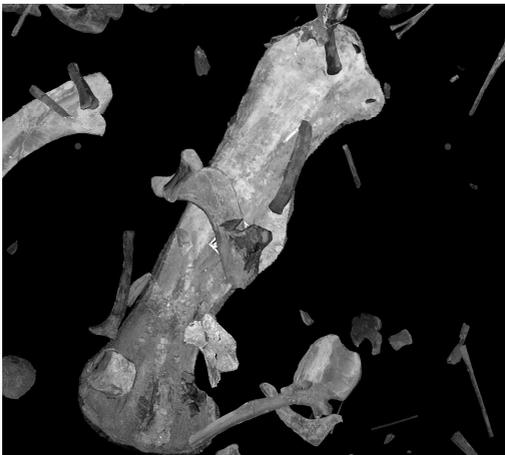
Figure 7. Close-up of the portion of virtual quarry map of Quarry 1 enclosed in box of Figure 6. Dots on 1 meter centers.

at the left with the bottom of the quarry. Another analysis of taphonomic importance was the display of the distribution of bones of a specific type. For example, Figure 11 shows the results of choosing to display

only ribs. Many other analyses can be done as well.

Discussion

Applying the techniques described above to all of our quarry sites, we were able to generate accurate virtual photographic maps of the quarries. We are able to visualize nearly every bone, tendon, and even objects as small as teeth in the image reconstructions. This level and extent of resolution enables us to determine relationships between bones, distribution of bones, and to perform other analyses from the desktop. We are also assured of preservation of nearly all of the detail from the excavation. We were able to show that the bonebed was graded by the analysis of the vertical distribution of bones, and to show that bones such as ribs were distributed in a fashion consistent with

Figure 8. Cross-sectional view of a portion of Quarry 1. Two meters separate the two planes.
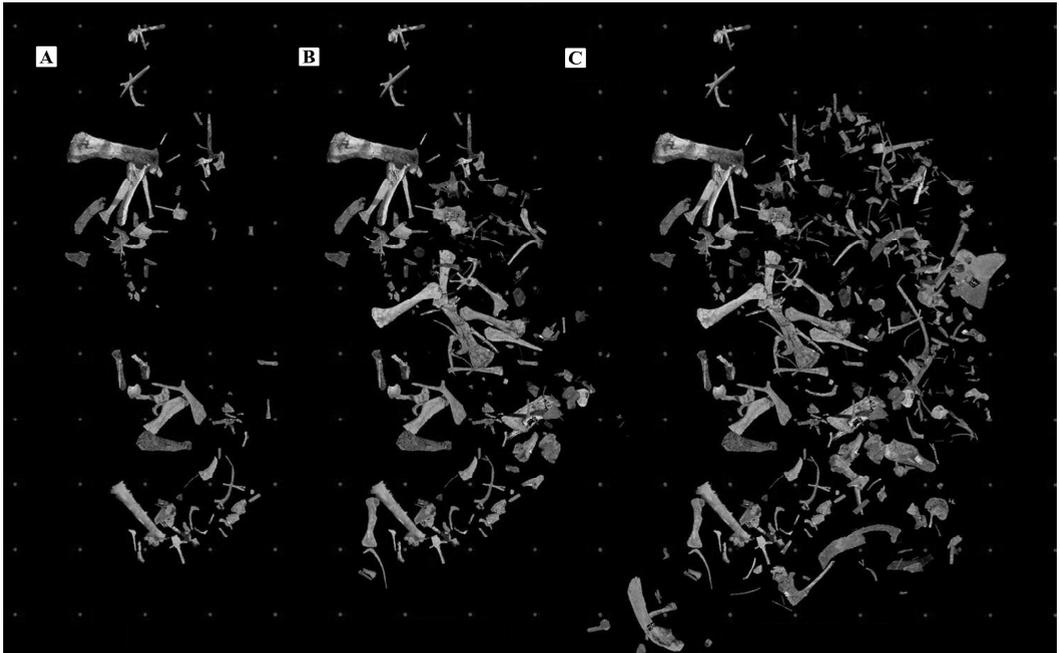
Figure 9. Method of reconstructing quarry map year by year, by adding each successive year's virtual quarry map. A) Data from 2001. B) Combined data from 2001 and 2002. C) Combined data for 2001 to 2003. Dots on one meter centers. Diagram of Quarry 2.
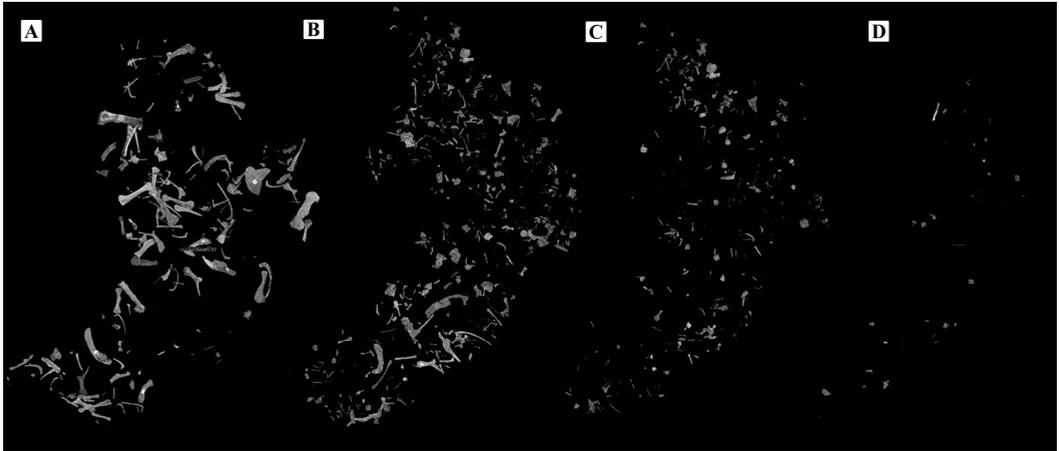
Figure 10. Virtual reconstruction of distribution of bones by depth, at successively higher intervals (left to right) in Quarry 2, generated from quarry map. A) Bottom 20 cm. B) 20-40 cm. C) 40-60 cm. D) 60-80 cm.

transport from another area, rather than the accumulation of bones from carcasses stranded in the present locality. We can view profiles of the quarry site, giving information about the vertical extent of the deposit and revealing where within the site unusual concentrations of fossil material may exist. We can analyze the virtually reconstructed site sedimentologically for paleocurrent trends, and accumulations at "logjams" that might indicate the influence of depositing currents. We can derive information about the overall shape of the deposit and make deductions based upon that shape. We can determine the distribution of size classes of fossils. We can make predictions based upon the behavior of the deposit as a whole that enable us to focus our activities in areas of greatest potential. By study of the vertical profile, we can reconstruct the surface upon which the bones were deposited and determine the relative positions of bones within the bed. We can derive a great deal

of taphonomy from the post processed data, including critical indicators of the depositional processes themselves. All of these analyses are helping us in the development of a taphonomic model for the site.

Conclusions

The techniques described in this paper enabled us to permanently acquire critical taphonomic data during the excavation of over 20,000 bones from quarries on an active dig in northeastern Wyoming. We demonstrated the ability to retain data of types that are generally not recorded during quarrying such as tendon fragments and the positions and sizes of ubiquitous hadrosaur teeth. The results of successive years of quarry activity can be displayed seamlessly, and we can generate permanent virtual photographic maps of the quarry sites. We can also carry out significant taphonomic

analyses long after the bones were removed from the ground. In our hands these techniques have provided invaluable insights into the taphonomy of our bonebed. The specimen reconstruction generated in the ArcGIS ArcScene window closely approximates the true spatial representation of the fossils in the quarry. Most significantly, we have made the entire dataset for the quarry site available in a permanent and user addressable format. The quarry maps and bone data are available in an online museum and database at http:// fossil.swau.edu.

Appendix

Creating the Georeferenced Images

Processing the images can be done by a number of different pathways. We describe here the method we believe to be the most efficient. The procedure that follows is a step-by step description intended to enable a non-specialist to produce the results we describe above. The procedure is as follows: Open the ArcMap module of ArcGIS. ArcMap will open with a viewer on the right and a "Table of Contents" on the left.
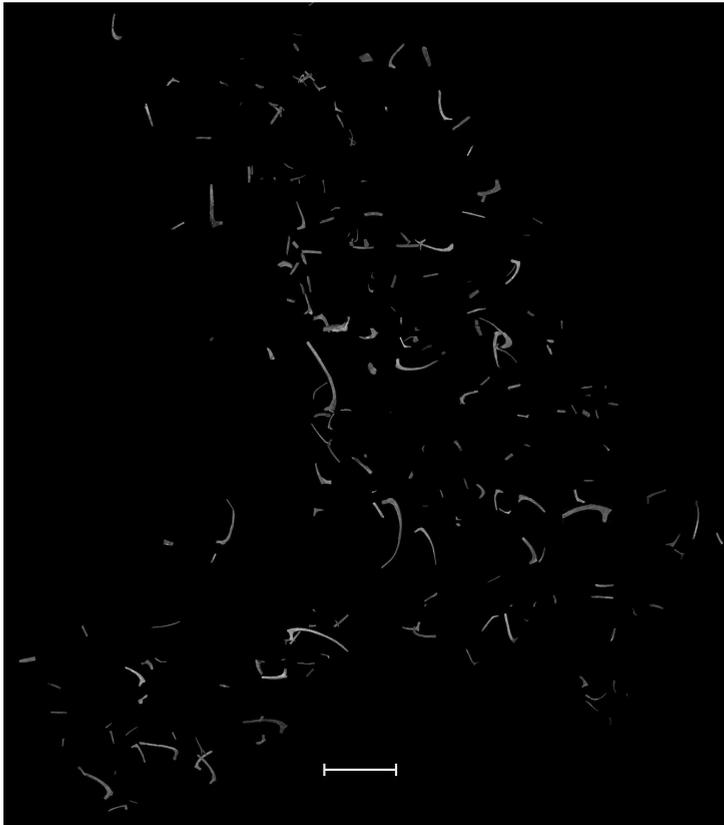
Figure 11. Quarry map displaying only ribs or rib fragments. Bar is 1m.

Add the "Georeferencing" toolbar from the "Customize" header, if not already present. Click the "+" symbol and import the database containing your GPS data. We use an Access database with columns for (GPS point) Number, Easting, Northing, Elevation, and Description, where "Description" is the field number for the fossil or object being mapped. The database can next be converted into a point array by right clicking the database and choosing "Display XY Data…," then assigning the appropriate columns in the database to the proper axes (generally this will be Easting = X, Northing = Y, Elevation = Z.) The coordinate system should also be edited appropriately in this window. This operation will generate a point file with all of the GPS data in it.

Next, import a suite of the fossil image files that have previously been modified by removing the background as described in the paper. For economy, we import them into a Group Layer (right click on Layers in Table of Contents, choose "New Group Layer" double click on the "New Group Layer" that results, choose "Group" tab, choose "Add", then find the image files) about 50 at a time, and turn the Group layer off by ticking the box to the left of the Layer, to prevent the display of the images. Using the mouse, lift the images outside of the Group Layer one at a time, and construct a database query to reveal only the points for that image (right click the GPS point array and choose "Properties", then choose "Definition Query" tab (the built-in query generator is useful). A typical query for us (for image file HRS34311.tif) will be "[Description] = 'HRS34311'" where "Description" is the heading of the descriptor column from the GPS data, and "HRS34311" is an array of points associated with a bone of that field

number. Click "OK" to apply the definition and close the window. Now right click the GPS point array in the Table of Contents, and choose "Zoom to Layer," and the points will fill the viewer window.

You are now ready to georeference the image. First check to see that the appropriate image file (e.g., HRS34311.tif) corresponding to the chosen point array is displayed in the "Layer" window of the Georeferencing toolbar, then click on the "Georeferencing" heading and choose "Fit to Display" from the dropdown menu. This will result in the image filling the viewer window along with the corresponding GPS points. Use the "Flip or Rotate" tools from the same menu as needed to properly orient the image to the point array. To attach the image to the points, choose the most northerly point in the array of points and attach it to the colored dot on the fossil using the "Add Control Point" tool. Click first on the bone and then on the point in the array that corresponds to that point on the bone. This will move the image to the appropriate position in the array and attach it to the correct array point. Next choose a second point, usually at the opposite extreme of the bone, and click on it, and click on the corresponding point in the array. This generally is sufficient to georeference the bone if the photo was taken from overhead. If skewing the bone image is required (picture taken from oblique angle), other points can be used. The bone is now georeferenced in three dimensions to the points corresponding to it.

The georeferenced image can now be saved by clicking on the "Georeferencing" heading, and choosing "Rectify….". We generally choose the default settings, set "NoData as:" 255 (white) if your photos have a white background, and make certain

the resulting file will be saved in an appropriate new directory, then choose "Save." Now remove the image file from the Table of Contents (right click on image, then "Remove"), grab the next image from the Group Layer, and modify the database query for the next array of points. This routine is repeated until all images are georeferenced.

Preparing the Backgrounds

At this point the images could be combined to make up the quarry maps in versions of ArcGIS earlier than 9.0. Unfortunately, changes made in Versions 9 and 10 make things more difficult. The background of the images will not be transparent unless you first process the images through a special filter available from ArcGIS or from the authors. The directions, after you have acquired the appropriate tools (Copy_Raster10.py and SetBackground.tbx), are as follows. Place the two files in a convenient place. Click on the red toolbox icon in the Tools menu in ArcMap. This will open the ArcToolbox index. Right click on the ArcToolbox heading and choose "Add Toolbox." In the window that appears, navigate to the location of the SetBackground.tbx and Copy_Raster.py modules and choose the former. This will add the new SetBackground toolbox to the index. Now choose SetBackground tools then choose SetBackgroundCopyRas. This should open a window, allowing you to navigate to the directory containing only the newly georeferenced image files you wish to convert. Click "OK", and the whole directory will be converted and the output will be written as TIF files in a subdirectory titled "ras_dir" created by the program. The backgrounds of the resultant image files will now display transparently when overlaid, so that bones below the image are not obscured.

Displaying the Georeferenced Images

When the georeferencing is complete, the individual georeferenced images in the "ras_dir" directory can be imported into ArcMap. Before you do this the first time it is helpful to make some changes to your default settings in ArcMap. Choose "Customize" then "ArcMap Options", and then choose the tab "Raster", then the subtab "Raster Layer." Set the "Display Background Value" to the background color of your processed photos (white is 255,255,255) to make the background transparent, and set the "Stretch Type" to "None" and accept the changes.

We import the georeferenced images in groups of 50 images to a Group Layer, named with the range of images it contains. To do this, right click on "Layers" in the Table of Contents, choose "New Group Layer," right click on the New Group Layer and choose "Properties," then click on the "Group" tab, then "Add" then find the "ras_dir" directory where the modified georeferenced image files are, and choose those for inclusion in this group, then choose "OK." Finally, rename the New Group Layer to the appropriate range of files. In order to collapse down all of the expanded image file legends in the Table of Contents, highlight them all, then ctrl-click the "–" sign beside one of them. Repeat this operation until all the images for a given quarry are included.

Bones will now display on the screen in two dimensions in precisely the positions they occupied in the quarry. When all of the bones for a given location are displayed, a

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two dimensional map of the quarry can be generated as described in the body of the paper by choosing "Export Map" from the "File" menu. Select the file type desired and choose the highest resolution you will need, and select "Write World File" to generate a file with the georeferencing data. We usually choose a black background ("View," "Data Frame Properties," "Frame" tab, "Background" color to black) as this seems to give the most attractive background for the bones.

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