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HIGH DYNAMIC RANGE IMAGING AS APPLIED TO PALEONTOLOGICAL SPECIMEN PHOTOGRAPHY

Jessica M. Theodor and Robin S. Furr

ABSTRACT

Paleontological photography is a time-intensive process. Collections ranges, exhibit spaces, and outdoor field settings present challenging lighting regimes, many specimens have complex 3D shapes and are often fragile and difficult to move. Even in ideal conditions, the complexities of photography may result in inferior or inadequate coverage of specimens.

Recently, software supporting High Dynamic Range Imaging (HDR), a technique first used in the special effects industry, has become widely available. This technique can solve or mitigate many of these issues and has the potential to improve images beyond traditional practices. HDR combines multiple exposures of the same subject into a single image file that represents the full range of dark to bright present in the real world, as opposed to the limited dynamic range used in traditional image formats.

These files can then be automatically processed to reduce unwanted shadows and glare, increase local detail, and preserve information that would otherwise be lost to rounding and clipping errors. Tests performed in real-world situations show that HDR practices reduce the need for equipment in many shooting situations to a camera and tripod. Because HDR images can be re-exposed to adjust lighting issues, it can eliminate or reduce the need to set up and adjust equipment and specimens.

We tested HDR practices and four software applications that support the technique, and found a consistent improvement over traditional paleontological photographic practices in difficult lighting situations.

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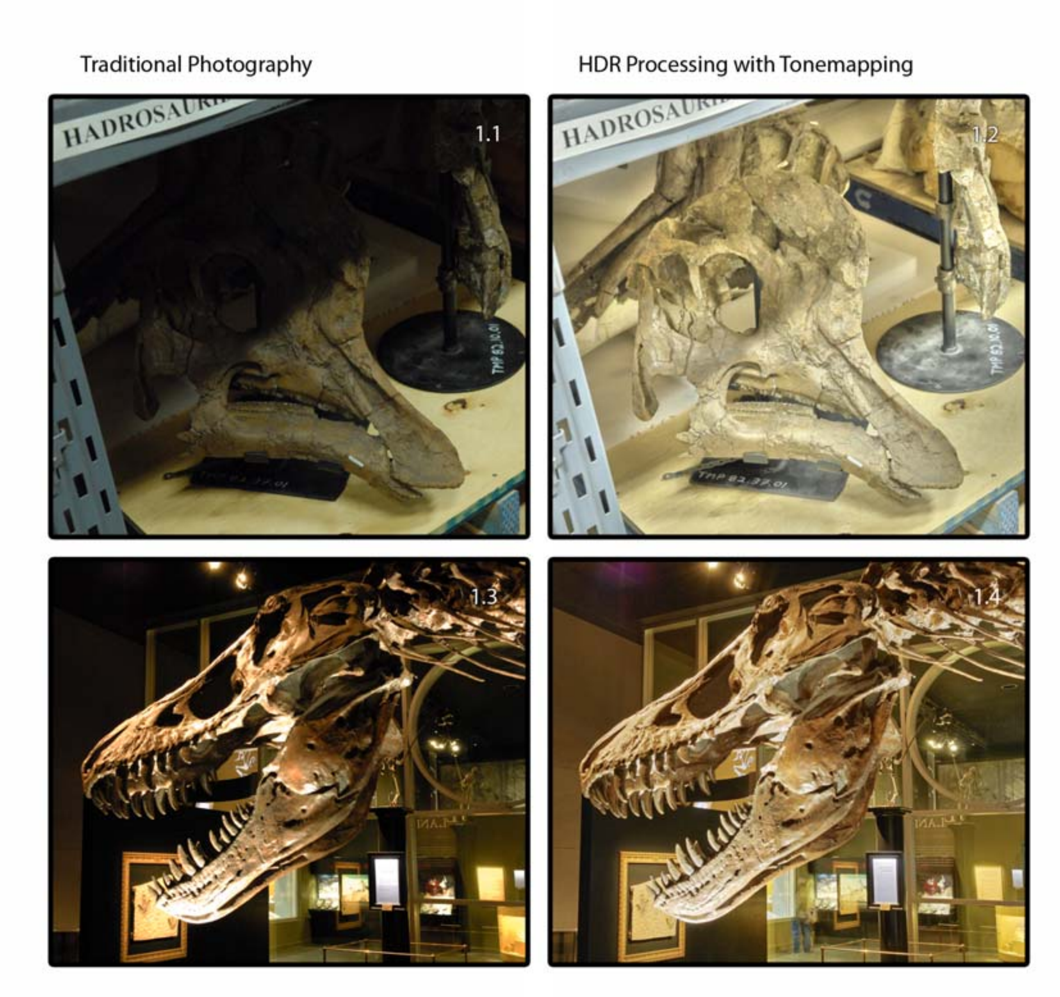


FIGURE 1. 1.1 and 1.2, TMP 82.37.01, hadrosaur skull on a shelf in the collections range; 1.3 and 1.4, TMP 1987.147.0001, mounted *Tyrannosaurus* skeleton. Both specimens shown with the metered exposure on the left, the processed image on the right.

INTRODUCTION

Paleontological photography has traditionally involved a significant investment in time and effort. In many cases, images may be sufficiently difficult to shoot that they are, for all intents and purposes, impossible to acquire. Outside of their own labs, paleontologists rarely have complete control of the lighting when shooting specimens: in collections spaces and exhibit areas, they may have none at all. In the field, not only do they lack control, the available light changes over time. Even if one has portable lights available, the time and space needed to correctly position them may be lacking. The specimens themselves may inherently be difficult to light, as areas of interest to a researcher may be shadowed by other parts of the specimen. Some environments may even prohibit lighting altogether, and the fragility of fossil material can prevent rotating or moving it for photographic purposes.

High Dynamic Range (HDR) imaging (and related post-processing techniques) allows a researcher to correct for inappropriate lighting situations, virtually equalize light levels, and improve detail (Figure 1). The use of these techniques can also permit the acquisition of usable images for research and reference work, or in some cases publication (albeit with some caveats) far more rapidly than previously possible.

This paper will present images representing high dynamic range image acquisition and processing under a variety of poorly lit conditions (including exhibits, collections, and outdoors), along with a description of the process involved in preparing these images, and results from commonly available software packages. As the exact workflow varies between packages, this paper will not provide step-by-step directions for using each program.

What Is HDR?

High Dynamic Range images are stored in a format that allows the recording of a wider dynamic range than is typically available in traditional image file formats. Many formats store image data using integer values, and limit how bright and dark particular pixels can be to the output capabilities of monitors or paper. HDR formats store pixel values as floating point numbers, and attempt to record the full range of light values present in the real world, even if the resulting information is too bright or too dark to be seen on a given output device.

The most common HDR file format, Radiance, which uses the extension .HDR, stores 32-bit floating point values for each of the R, G, and B channels, as well as a fourth channel containing an exponent value used in combination with the other channels. When compared with file formats such as 16-bit TIFF, this allows Radiance files to store larger, smaller, and more precise values; a pixel shown as black from a TIFF document would contain no additional information, whereas a pixel shown as black from a Radiance document can still contain data about the color of that pixel, even if it is too dark to represent on a given monitor. In practice, .HDR files retain details that cannot be directly displayed on a given output device, but that detail can be exposed through the methods described below.

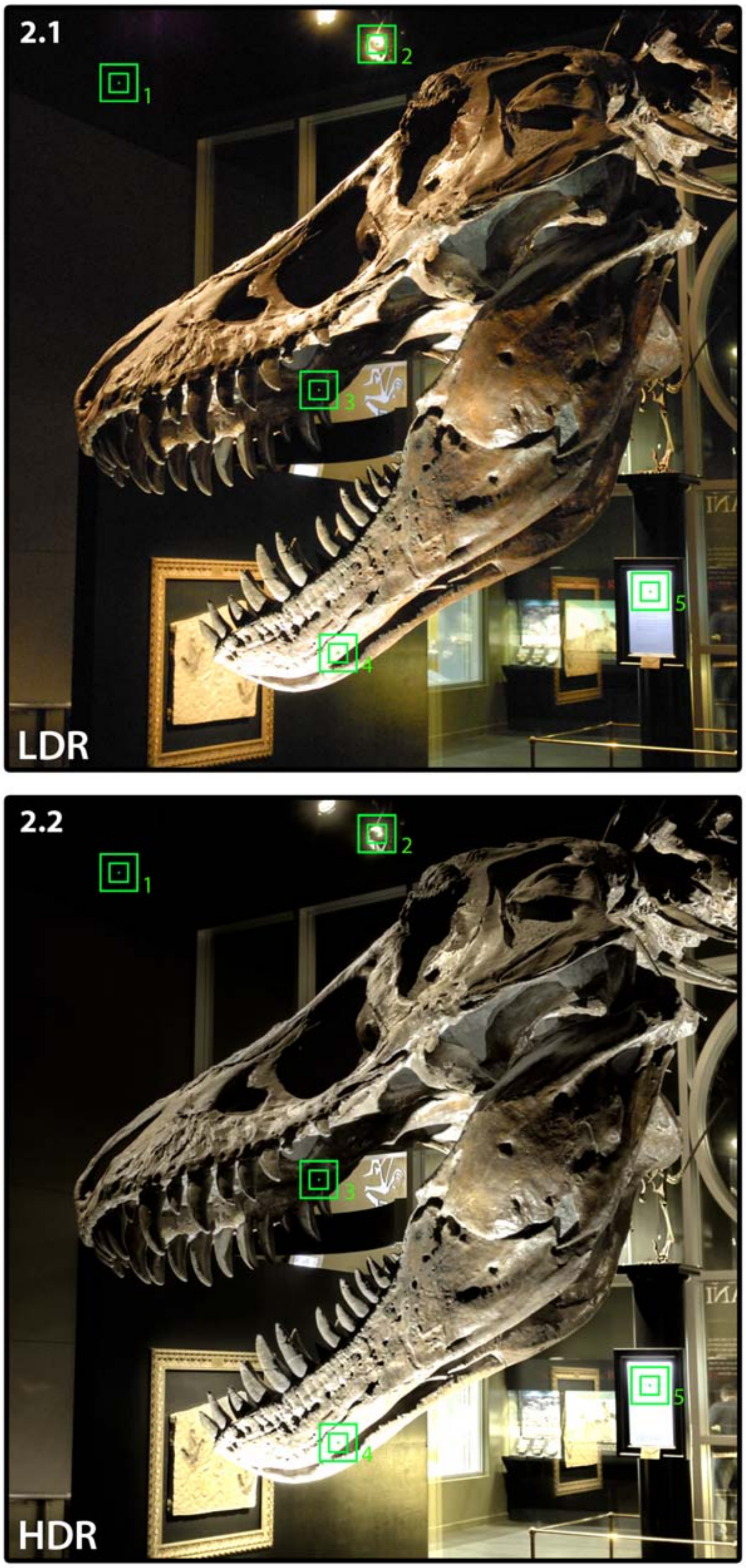
This permits HDR files to closely reflect real-world light values, to maintain those values even in situations where they cannot be seen by the eye, and to resist common difficulties arising from image processing.

As an example, two pixels from the center of two different TIFF files may both have color values of 255, 255, 255, or as white as a monitor can display, even if one of the files shows the sun, and the other shows a candle flame. A Radiance file might store the value of the pixel from the candle image as equivalent to 250, 200, 100, but it would also store the pixel from the sun image as $7.0x10^5$, $2.5x10^6$, $2.3x10^6$—thus representing both the true color of the pixel as well as its relative intensity, even if, in the final display of both files, those pixels are shown as white (Figure 2). Unlike traditional image formats, the color values are preserved regardless of how they are displayed, but the pixel that is shown as pure white from the center of the sun could be just as reasonably shown as extremely dim orange, depending on requirements and processing (Bloch 2007).

Traditional media formats have a low dynamic range—that is, the ratio between the brightest and the dimmest the format can show is relatively narrow. Because this range is narrow in comparison to the full range of light available, the emphasis in image acquisition and display is placed on the middle of this dynamic range, where the human eye is most perceptive. Information outside this area is frequently recorded with less precision or lost when it exceeds the capability of the format's dynamic range and is clipped (Figure 3). High dynamic range images, depending on how they are produced, can have a dynamic range many orders of magnitude larger, and can represent conditions in the real world more precisely as a result.

The necessity to record information that represents real-world light levels, as opposed to values that a given output device can represent, has long been known. Indeed, manual techniques that attempt to solve the same visual problems have been used with film cameras since the 1920s (Eismann 2004; Wyckoff 1972), although in an extremely time- and labor-intensive way. The initial use of HDR in computer imaging was to store the output of 3D rendering packages, but Debevec and Malik (1997) detailed a method for generating reality-based HDR values from multiple photographic exposures of the same base scene—the technique described in this paper. The resulting HDR files were initially used as a source for luminance data in 3D renderings, allowing the use of real-world lighting on rendered objects. This technique has become widespread in special effects and computer graphics, and a number of software packages now support HDR formats, including Adobe Photoshop CS2-4, the open source photo editor GNU Image Manipulation Program (GIMP, GNU Software Project, http://www.gimp.org/), and numerous specialized HDR packages. The initial HDR tool in common use—USC's HDRShop—was too complex for casual users, but HDR tools are now sufficiently simplified that even novice photographers can make use of the technique, and the process is straightforward and uncomplicated.

HDR files of real-world situations or environments are created by taking multiple exposures of a single photographic setup, with varying levels of light sensitivity (Figure 4). The photographs are then combined by software, which uses the varying pixel values and the exposure information to



#	LDR		HDR	
1	R	9	L	639.9
	G	9	R	777
	B	9	G	629
			B	290
2	R	255	L	2.18e+06
	G	255	R	2.20e
	B	255	G	2.18e
			B	2.08e
3	R	9	L	9512
	G	9	R	1.23e
	B	9	G	8925
			B	4654
4	R	255	L	6.97e+04
	G	255	R	8.65e
	B	255	G	6.57e
			B	4.53e
5	R	255	L	2.62e+06
	G	255	R	1.89e
	B	255	G	2.08e
			B	2.87e

FIGURE 2. TMP 1987.147.0001. Difference in representation of light values at particular positions in the image between 2.1, a conventional Low Dynamic Range image (LDR) and 2.2, simulated High Dynamic Range image (HDR). Note positions 1,3 and 2,4,5 have the same values in the LDR image, but differ in the HDR image.

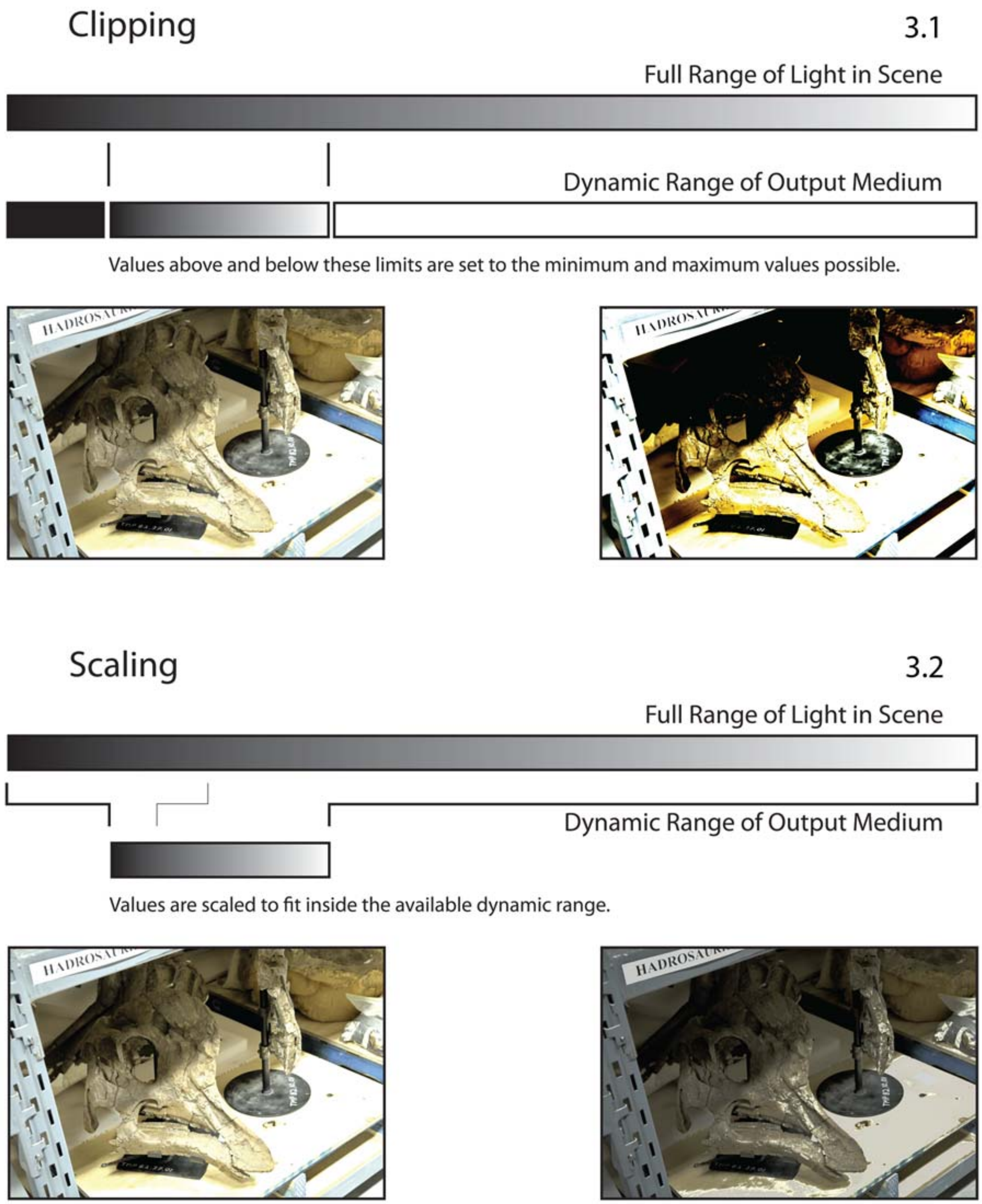


FIGURE 3. 3.1-3.9 Exposure bracket of TMP 82.37.01 over a +4EV/-4EV range, 3.10 resulting HDR simulated for display, 3.11 final tonemapped HDR image.

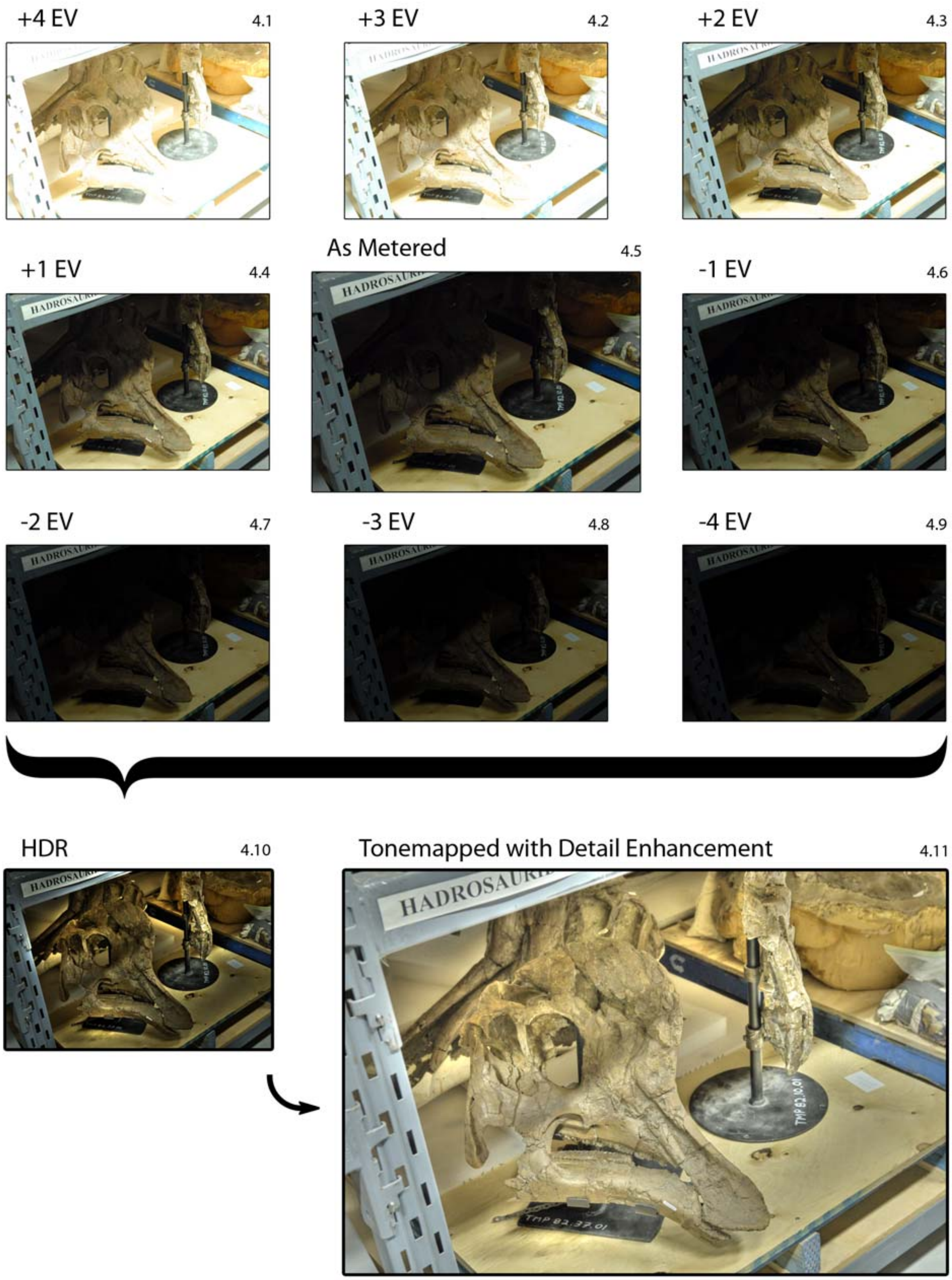


FIGURE 4. Two simple algorithms for tonemapping. 4.1 clipping, 4.2 scaling of the dynamic range.

deduce how much light was required to cause the camera sensor to react in that particular way across all the images. This information is then saved in a high dynamic range format, which must be processed further for actual use.

Why Use HDR?

HDR techniques solve several problems inherent in photography. The initial advantage of the method is that it moves much of the difficulty in choosing camera settings from the photographic session to the editing stage. That is, even if no other benefits of the technique are involved, the ability of an HDR file to store light levels with a more realistic dynamic range allows the photographer to virtually re-expose an image after the fact, instead of having to correctly expose the image at the start. This is not to say that care should not be taken to choose appropriate exposure settings and lighting when photographing, merely to say that the photographer is granted significant additional flexibility when processing (Bloch 2007).

More significantly, low dynamic range image formats are poorly designed for image processing purposes. Many image processing algorithms result in fractional values, values that are lost as a result of storing values as integers. Simply allowing the image format to retain information past the decimal point, as in Figure 2, even if the information is not immediately perceptible by the human eye, permits far more accurate image processing, and avoids banding and other errors that occur when images pass through multiple stages of image processing and the inevitable rounding that takes place when values are stored as integers. A brief example can show how this can cause difficulties: if a given grayscale pixel with a value of a hundred has its luminance reduced by a third, it should retain a value of 33.3, but it instead reduces to a plain 33, as do the adjacent pixels with values of 99 and 98. These pixels would change from a smooth three-pixel gradient of values to a solid region of one color. Additional operations can cause further errors of this sort, flattening out smooth gradients and subtle detail into patches of solid color; an overall loss of accuracy unacceptable in professional work.

Even in cases where the operation increases values, such as brightening an overly dark image, the rounding and truncation needed to fit low values into a restricted range of integers will cause an image acceptable at low levels to appear patchy and posterized when those values are increased (see Figure 5). Ten pixels, which have a single value at low levels, are likely to need ten different values at higher levels when brightened, but there is no way for the image processing application to produce those values. An image derived from an HDR file, even though it may not appear to have 10 different values when the image is displayed at a low brightness, is likely to retain those values, which can then be used by the image processing application (Figure 3).

HDR differs from other techniques that have been discussed for use with fossil specimens, and in some ways may complement them. Unlike many of the image enhancement techniques familiar to paleontologists (various sharpening and edge enhancement filters; Kirschvink et al. 1982; Ekdale and Jeong-Kyungwan 1996), HDR offers the advantage of providing additional detail captured from a specimen, not merely enhancement of the detail already present in a single exposure.

HDR imaging is similar in some respects to the methods outlined in Bengtson (2000) for using polarized light to enhance images of Burgess shale specimens and others with similar low-relief preservation. HDR imaging is easy to do in most cases and can be used in conjunction with polarizing filters to produce enhanced images. The combination of multiple exposures into an HDR is similar to Bengtson's use of image interference between two exposures to highlight anatomical details, but is simpler to perform, as HDR techniques have become widespread in software. Reflectance transformation techniques (Hammer et al. 2002) are based on the same principles as HDR, but require considerably more investment in time and equipment than HDR does.

Gatesy et al. (2005) tested the use of anaglyph stereo images to improve imaging of trackways and other low-relief impressions. Their methods, developed for work at very high latitudes, require waiting for situations with low even light. The HDR techniques outlined here could also be used to reduce the impact of varying lighting, since HDR images effectively create more even lighting. In addition, HDR images do not require 3D glasses for viewing, although anaglyphic stereo techniques do address one common issue with HDR—that minimizing the impact of shadows will inevitably flatten an image's appearance—and could therefore be profitably used in combination.

Creating HDR Images

There are three steps to generate an HDR image: image aquisition, image assembly, and tonemapping. The equipment requirements for

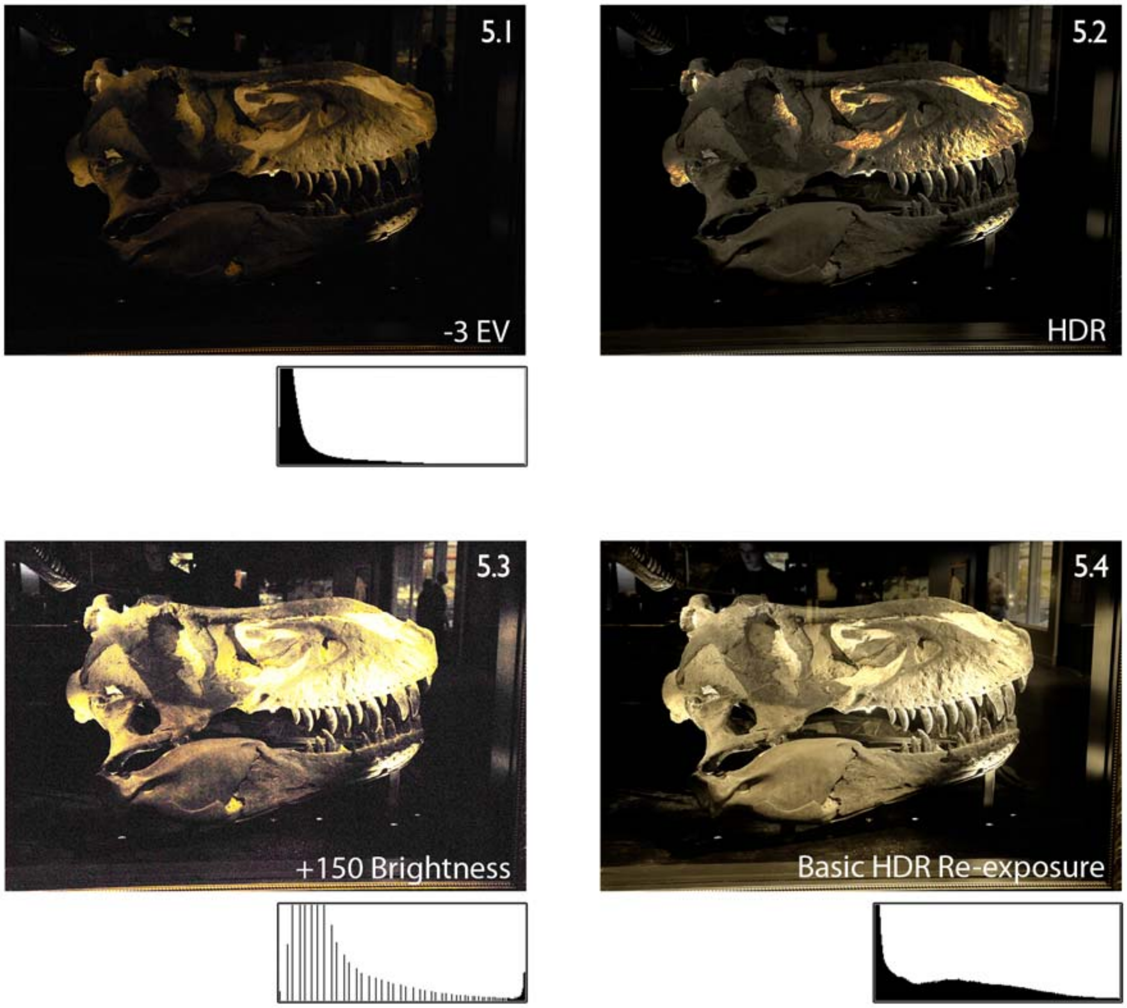


FIGURE 5. TMP 1981.006.0001, *Tyrannosaurus rex*, "Black Beauty". Increasing brightness in an LDR image and a HDR image. 6.1 specimen as photographed in the exhibit space at -3EV, 6.2 simulated HDR exposure. Histograms show total number of pixels at a given light level in the image. Both images processed to increase brightness of the image to roughly equal levels in 6.3 (LDR) and 6.4 (HDR). Note the lack of detail present in the histogram in 6.3, where the increase in brightness only moves the values present in the darker image, without making additional detail visible. Added information present in the HDR image allows values not differentiable at low levels to show additional information when brightened.

using HDR are minimal: a camera capable of incrementally varying the exposure, a mechanism for stabilizing the camera (camera stand, tripod, microscope mount), and a computer with appropriate software.

Image acquisition. A minimum of three shots of the same subject at different exposures bracketing +/- 3-4 exposure values (EV, a combination of aperture and shutter speed that provides a measure of the amount of light reaching the sensor) are needed, with all other settings held constant and the camera as stable as possible, with the goal being to vary the amount of light received by the camera's sensor while holding other settings constant. Exposure bracketing should be performed using changes in shutter speed to change the EV, because varying the aperture will alter depth of field between shots, and varying the ISO setting will introduce noise into some of the images. Shutter speed variation can create problems in capturing motion using HDR, but this issue is not significant for specimen photography. More than three shots can be used to create the HDR image, and in general the great the number used, the smoother the result will be. Using multiple images will also reduce the impact of brackets that are too widely spaced, where a given pixel may lack useful information because it is either under- or over-exposed in the source images. Using multiple images, however, can produce unwanted softness in the resulting image (Bloch 2007) if the camera is not tightly locked down. Better results are obtained by shooting more bracketing shots over a wider range of EVs.

The input files can be TIFF, JPEG, or RAW (an unprocessed format recording camera data directly, which must be processed by a RAW interpreter specific to the camera). On the whole, image size does not appear to be an issue, and the user is free to select a convenient size. Images with pixel dimensions of 3872x2592 images were routinely processed for this paper on a 2.5 gHz Mac Pro with 2 GB of RAM.

If using TIFF or JPEG formats, no compression or other in-camera image processing should be performed. White balance and focus should be adjusted manually, although in some situations autofocus may be acceptable.

Two issues complicate handheld shooting. Camera motion while the shutter is open will cause blurring of the image, with increasing blur for longer exposure times. Shots taken from different locations will have different viewpoints, making inter-frame alignment challenging or impossible. Of the applications we tested, only Hydra was consistently able to cope adequately with handheld shooting at the ranges used for specimen photography (Figures 5, 6). Even Hydra could not produce a usable file from a handheld bracket shot in a dark room (thus requiring long shutter speeds, Figure 7). The success rate of handheld shooting improves dramatically with brighter lights and greater distances to the subject.

If available, a remote trigger should be used, as this will prevent the user from adding vibration to the camera body during shooting.

As discussed below, many issues of exposure, shadows, and overall lighting can be addressed in processing. Of the traditional difficulties in photography, only focus problems cannot be mitigated or eliminated in the computer processing stage. Although wherever possible controlled lighting should be used, many of the images in this paper were shot in collection ranges without additional lighting, a common situation for paleontologists studying large or fragile specimens. It is important to repeat that this technique does require a significantly larger amount of data storage than traditional methods, as multiple exposures are needed to generate a single final image.

Image Assembly. After acquisition, it is necessary to take the RAW or TIFF files generated and assemble them into HDR files, whether .HDR (Radiance) or .EXR (OpenEXR) files. In general, this process is straightforward, assuming that the camera has included exposure data in the metadata of each generated file. If a specific camera does not automatically indicate, at least the relative EV of a given shot to the metered exposure, this value must be entered manually. Depending on the application, other settings having to do with how motion is handled and which images to take information from may be set as well, but overall, this stage can be as simple as passing all shots having to do with a given image to the assembly program. Currently, this stage is somewhat time-intensive, but as technology advances, and more image processing is offloaded onto graphics-specific processors, the time investment for this stage should fall rapidly.

Images assembled in this manner also usually have reduced noise, as a single pixel is the result of combining multiple exposures, compared to single images.

Tonemapping. HDR files can be thought of as unexposed film; they contain an impressive amount of information that cannot, as yet, be directly seen by the end user. As no monitor or paper can display the full range of dark through light that the file can contain, the files are difficult to deal with in their entirety. The file must be developed, as it were, before it can be used; it must be processed to convert the values that are stored in the file into values that fit with the dynamic range of the output medium, a process that is generally referred to as “Tonemapping.” Tonemapping is not restricted to HDR techniques; digital photography inherently requires it, as the electrical impulses generated by a digital camera’s sensor, which are stored mostly unprocessed when saved as a RAW file, must be tonemapped to be displayed. (RAW files can, in a sense, be thought of as a form of HDR file, as camera sensors frequently have a greater dynamic range than necessary to generate a print, although this dynamic range is usually less than that of a purpose-composed HDR file.)

Any set of rules that govern how a value is turned into something that can be displayed can be considered as tonemapping. Even the most basic process, where values above a certain level are set to white and those below set to black, is a valid tonemapping algorithm. There exist many algo-

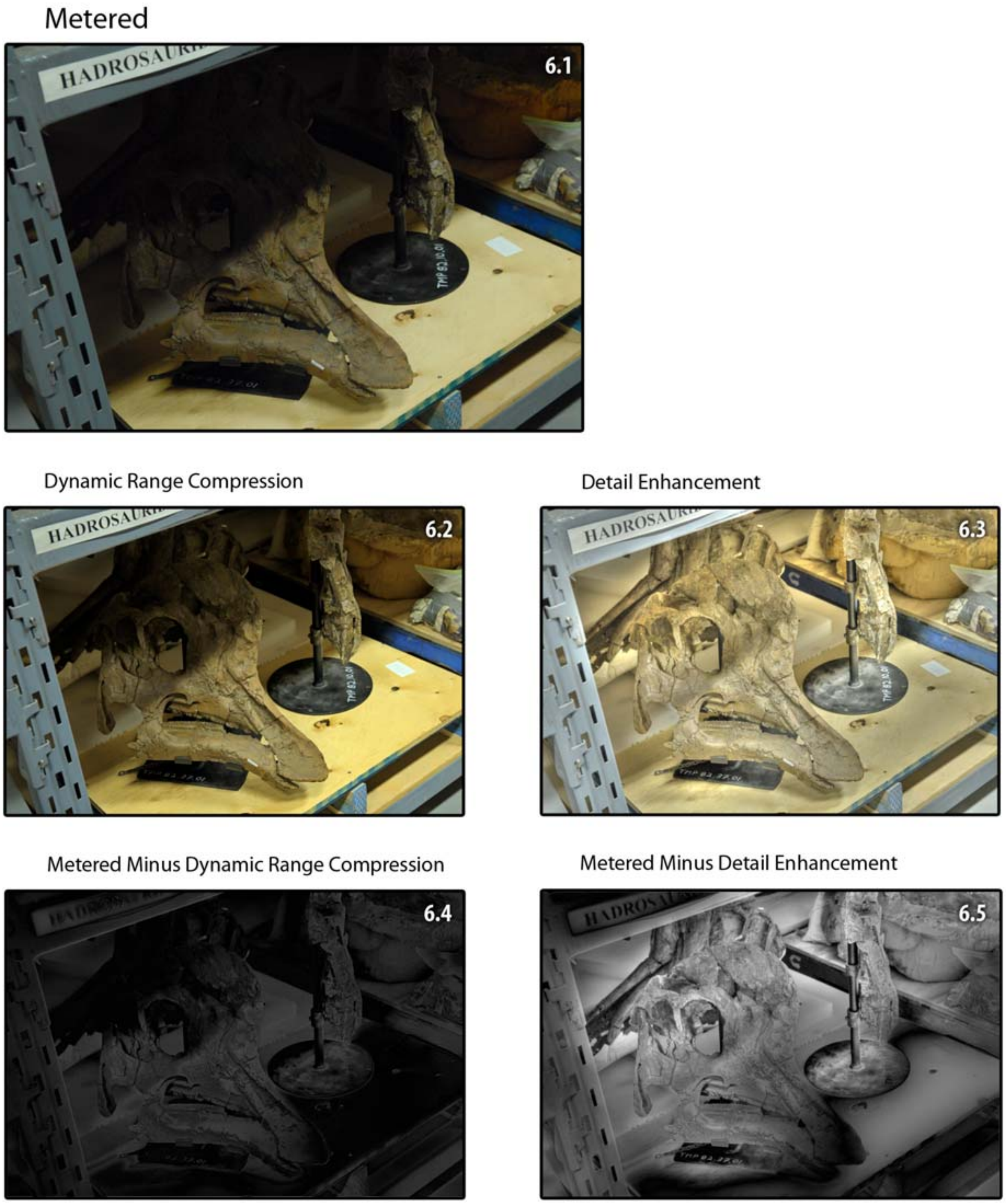


FIGURE 6. Comparison of two tonemapping algorithms. 5.1 original metered exposure, 5.2 HDR image after tonemapping using dynamic range compression, 5.3 HDR image after tonemapping using a detail enhancement algorithm, 5.4 the difference between dynamic range compression tonemapped HDR image and metered exposure, 5.5 difference between detail enhancement tonemapped HDR image and metered exposure. In the two difference maps (5.4 and 5.5), dark regions show little difference, lighter regions show greater differences between two images.

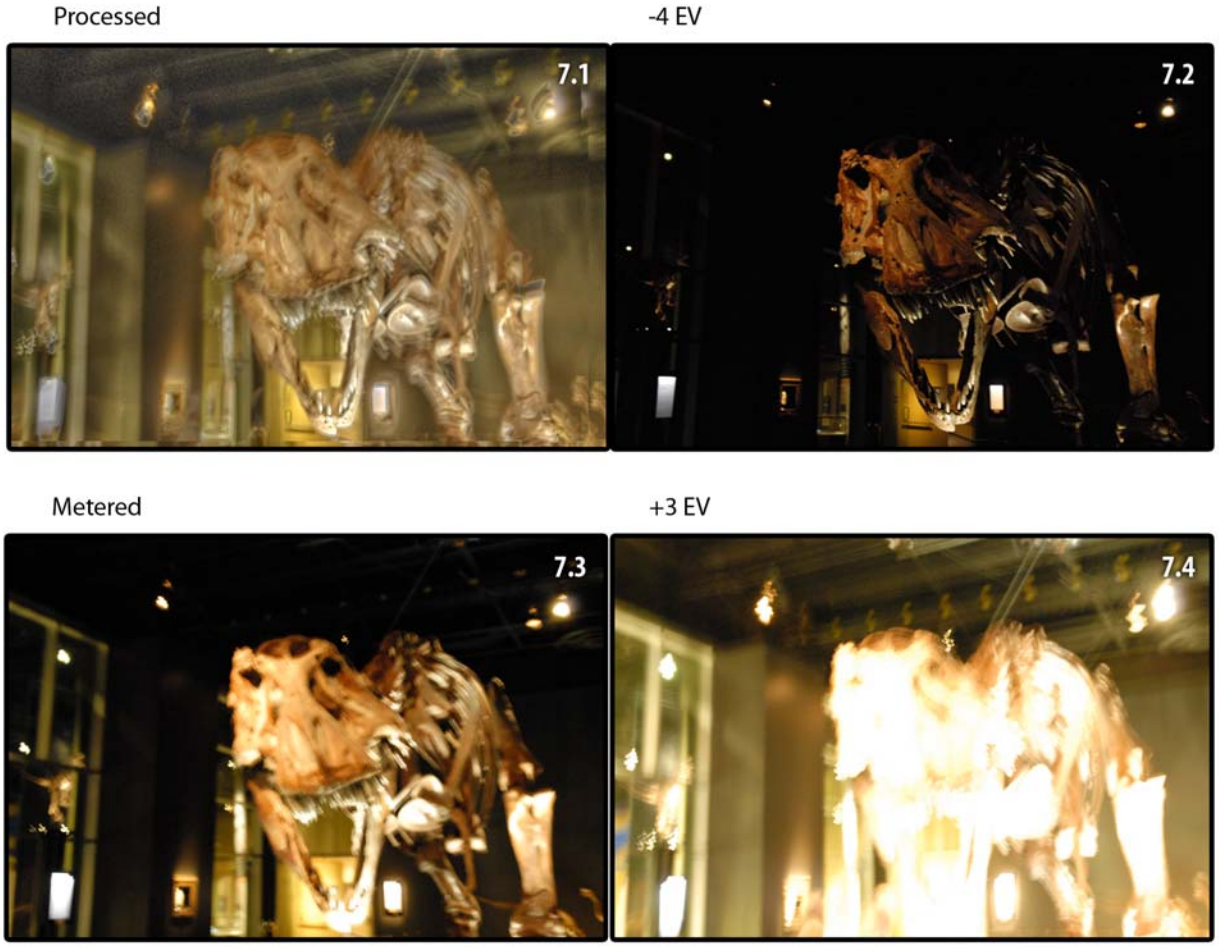


FIGURE 7. TMP 82.37.01, poor results from use of a handheld camera at low light levels.

rithms for tonemapping (Reinhard et al. 2005), including ones that allow the user to process an HDR file so that the output appears as if it was a photo shot at a given F-stop, even if such a photograph was never taken. Another such algorithm is analogous to Photoshop's "Auto Contrast" command, which will set the brightest value in the image to white, and the darkest to black, with the remainder of values distributed in between (See Figure 4).

Other algorithms exist, and some are of particular interest to the paleontologist. These algorithms fall into two main groups that can be called global and local operators. Generally, the global operators apply a given conversion uniformly across the image, while local operators take small sections of the image and process each one differently in order to emphasize particular traits rather than consistency across the image. Local processing is typically used for detail enhancement, intelligently adjusting contrast and brightness to preserve or emphasize fine detail while maintaining overall luminance continuity across the image. In reasonable conditions, local operators allow the reduction or elimination of shadow, the preservation of color and detail in brightly lit areas, and the ability to emphasize fine surface detail too subtle for integer-based file formats to support. Each program discussed in this paper has at least one global and one local operator.

In no case do any of these operators add information to the image; they make visual data, which might be difficult to see via a given output device, more apparent. Figure 6 shows the difference between a global operator's output (Photomatix Pro's Tone Compressor, an implementation of the aforementioned equivalent of Auto Contrast), and a local detail enhancement operator (FDRTools's Compressor). The applications discussed below each have roughly comparable functions, but the exact details of each program's operation vary, making direct comparison between particular functions difficult. Once a given image has been tonemapped, it may be treated as a normal, low-dynamic-range image.

METHODS

Except where noted, all images were shot using a Nikon D200 Digital Single Lens Reflex (DSLR) camera, using either a Nikkor 17-55mm lens or a Micro Nikkor 105mm lens. Camera Control Pro software (Nikon) was used to emulate a cable release - but a dedicated cable release or self-timer can achieve the same end. We used Polaroid UV filters and a tripod, but no additional lighting in all but one test case. All images were shot using an automatic bracket sequence of 9 shots taken at 1.0 EV steps above and below the metered exposure, varying the shutter-speed. Images were saved to both Nikon's NEF format (a version of the RAW format) and high quality JPEG files, in sequence of underexposed, metered, and overexposed. Each set of 9 images was processed using Photomatix Pro (HDRSoft), Hydra 1.5 (Creaceed Software), FDRTools (AGS Technik) and Adobe Photoshop CS3, running under Mac OS X 10.5.3. Each HDR image was saved in a floating-point, high-dynamic range format, as either a Radiance file (.HDR) or OpenEXR (.EXR). The HDR images were then tonemapped using Photomatix Pro's Detail Enhancement mode, and FDRTools's Compressor mode. Selected images were also processed with Hydra and Photoshop for comparison purposes. The settings while using the Photomatix Detail Enhancement mode were: strength 100%; colour saturation to 50%; light smoothing set to 3 levels: very low, medium and very high. Settings used using the FDRTools Compressor mode were compression and contrast set to 10, and smoothing set to 5. Hydra's Local Adaptation mode produced images nearly or only slightly below Photomatix Pro in quality, but user interface and stability prevented significant testing, while Photoshop's Local Adaptation mode generated very high-quality tonemapping, at the expense of a more involved process.

After tonemapping, images were saved as TIFF files. Comparison images were generated by taking the two images to be compared (usually the metered exposure and the resulting tonemapped output), by loading the images into Photoshop, converting them to grayscale, and combining them in two layers in a single document. We then set the uppermost layer to the Difference layer mode. This results in a grayscale image where darker regions indicate areas of little change between documents, and lighter areas indicating more significant differences. In cases where the camera moved between shots, the image presented in the tonemapped TIFF file was shifted relative to the metered exposure. In those situations, the tonemapped image was manually aligned with the metered image, which leaves uncompared areas along the edges of the comparison image. These uncompared regions were left in the resulting figures to preserve the size relationship between the difference image and the original.

RESULTS

Our results show that HDR processing and tonemapping can be used to compensate for challenging environments for specimen photography, such as those often encountered when working with large or fragile specimens, as tested here. We did not test extensively in the laboratory with better control of lighting, but even in good photographic conditions, HDR methods should reduce noise, preserve visual information and allow more flexibility in image processing.

Collections ranges

Collections are challenging to the specimen photographer—while they tend to be adequately lit, the lighting is overhead and usually blocked by tall shelving with narrow aisles. Many collections ranges complicate the issue by lacking useful work areas with even lighting or power sources nearby.

Figure 8 shows the surface texture of a crocodilian skull in considerably more detail in the HDR image (Figure 8.2) than can be seen in the metered exposure (Figure 8.1), demonstrated by the image difference (Figure 8.3). HDR can be used to reduce unneeded contrast, as in cases where specimens are on shelving and may be difficult or impractical to move (Figures 9, 10), making conventional photography impossible. Extreme contrast adjustments are often unable to recover detail in shadowed areas in a single metered exposure. Using HDR the impact of shadows is reduced and anatomic detail can be recovered from specimens that are too delicate or heavy to be moved off of shelving units for photography (Figure 11), while preserving or emphasizing contrast in fine details through the software's local adaptation tonemapping algorithm.

In testing, collection ranges proved to be suitable environments for handheld photography, assuming large specimens; all tested ranges featured sufficiently bright light to make fast shutter speeds possible, and simply bracing the elbow

FIGURE 8. TMP 86.61.01, crocodilian skull. 8.1 original metered exposure, 8.2 processed tonemapped HDR image, 8.3 difference map as in Figure 6. Additional detail in 8.2 resulting from adjusting one control in the FDR-Tools software, no manual retouching or additional brightness/contrast adjustments.

supporting the camera on a shelf or leaning against a support pillar provided adequate stabilization to shoot specimens such as hadrosaur skulls. Smaller fossils still required a tripod for successful image acquisition.

Exhibits

Galleries are often are dramatically lit, creating complex shadows absent in a more evenly lit space. Where specimens are behind glass, HDR can allow image capture that shows more than simply the reflection of the photographer in the glass—while far from perfect, Figure 12 shows that HDR recovers information about the anatomy behind the glare. Figure 13 shows both improvement in detail in shadowed areas and in reduced glare from the glass case. Figure 14 illustrates a worst case scenario: a dark specimen, dramatically lit, and behind glass. Using HDR allowed the omission of flash lighting that would have increased glare from the glass, and evened out the lighting and contrast to highlight additional detail (though, in this case, a polarizing filter aided in glare reduction).

Even in open mounts the specimens themselves may cast inconvenient shadows. Figure 15, a skeleton on display, shows the improvement in shadows in the HDR version, allowing pelvic structures that are in shadow in the metered exposure to be seen. In particularly well-lit exhibit spaces, detail enhancement tonemapping does not seem to add significant value to the images, although added emphasis may be placed on surface texture, such as in Figure 16, and overall image noise may be reduced.

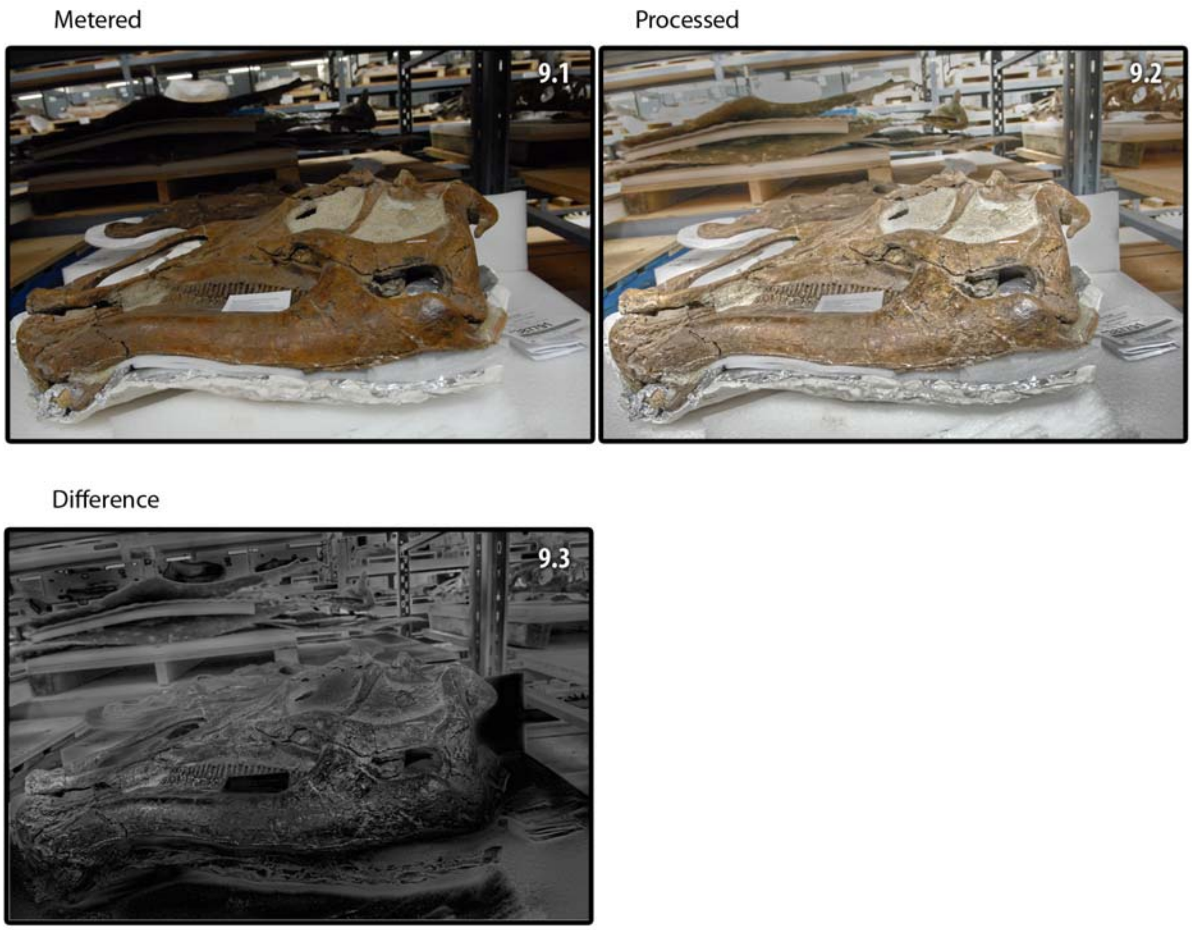


FIGURE 9. TMP 1980.022.0001, hadrosaur skull. 9.1 original metered exposure, 9.2 processed tonemapped HDR image, 9.3 difference map as in Figure 6.

Exhibit spaces were, as seen in Figure 7, not always suitable for handheld use. While many specimens found in the exhibit spaces we tested were large enough that the motion of the camera was insignificant in comparison to the distance to the specimen, in dark environments, the blur caused by camera motion was too great to ignore, even with Hydra's better support for handheld imagery. In well-lit spaces, particularly ones where furniture or other assets exist to brace the camera on, handheld shooting may work.

Ichnofossils

We briefly explored the use of HDR to enhance images of trackways. The Dinosaur State Park trackways (Figure 17) are dramatically lit from low angles to highlight the tracks in the display space. HDR techniques showed that areas that appeared flat in the metered exposure (Figure 17.1) show considerably more surface details (Figure 17.2) in the processed HDR image. The difference image shows there is more detail within the deeper tracks that was hidden in shadow in the metered exposure. The processed image also shows a reduction in large-scale contrast, making fine detail easier to compare.

Surface Texture

Bone (Figure 18), plant material (Figure 19) and invertebrate fossils (Figure 20) were all optimized for surface detail. This level of detail was achieved quickly with little user input, in contrast to the larger amount of time needed to produce similar results in Photoshop working from a single LDR image.

Field photography

Our tests in field situations were limited, but Figure 21 shows considerable enhancement of detail in strata as compared with Photoshop manipulations of the metered exposure. We suspect that HDR may prove useful in documenting stratigraphic sections and sedimentary structures, especially the early morning or late afternoon, when the

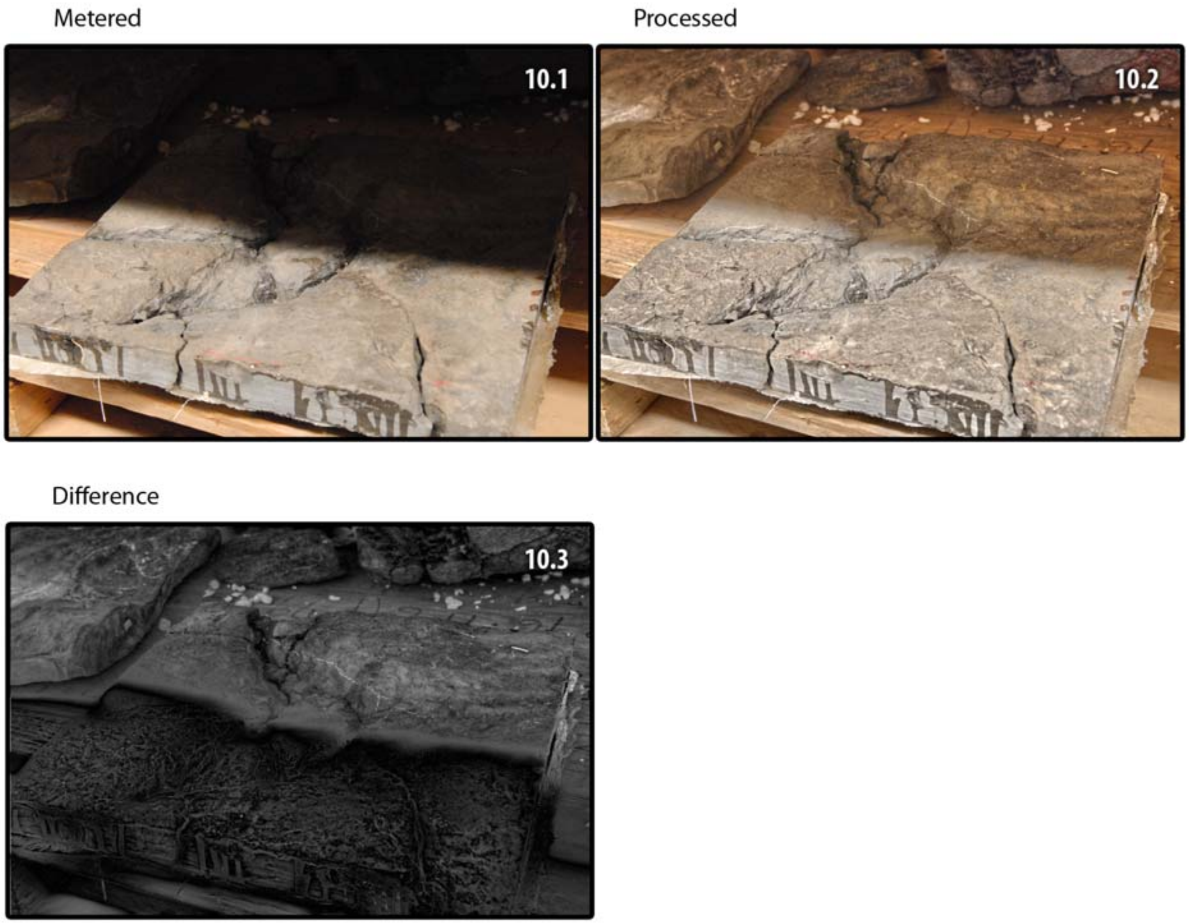


FIGURE 10. TMP 1979.023.0063, dinosaur footprint, shot on the shelf in the collections range. High contrast from nearby light source. HDR processing reduces extreme contrast. 10.1 original metered exposure, 10.2 processed tonemapped HDR image, 10.3 difference map as in Figure 6.

lighting angles cause more extreme contrast, but were unable to test this.

Optical microscopy

Our tests show that HDR processing is of significant use. Microscopic subjects are frequently poorly lit, and subtle coloration or fine detail may be impossible to effectively emphasize through physical means. Extensive use of HDR-based imaging in microwear studies have shown promise (Fraser, personal commun. 2008).

Microscopic HDR has proven to be extremely susceptible to vibration-related issues, as the low light levels present call for slower shutter speeds. In our tests, we discovered that the vibration caused by a fiber-optic light source's fan on the same work surface caused the specimen under the microscope to move while the shutter was open, causing the images to exhibit motion blurring. More than any other application, microscopic work calls for the camera to use slow automatic shooting speeds, remote operation through software or camera releases, and mirror lock-up (SLR and DSLR cameras use a mirror to provide the viewfinder image, and the swing of the mirror out of the way to expose the sensor causes vibration, which can be prevented by setting the camera to "lock up" the mirror, blocking the viewfinder and leaving the shutter exposed).

We anticipate that extended depth of field techniques (e. g. Knappertsbusch et al. 2006) can be combined with HDR processing, but have not tested this.

Comparison of software packages tested

The four software packages used in this paper are not, by any means, the only HDR-capable packages on the market. Many other programs are available, ranging from the simple to the complex. As a complete survey of the market is beyond the

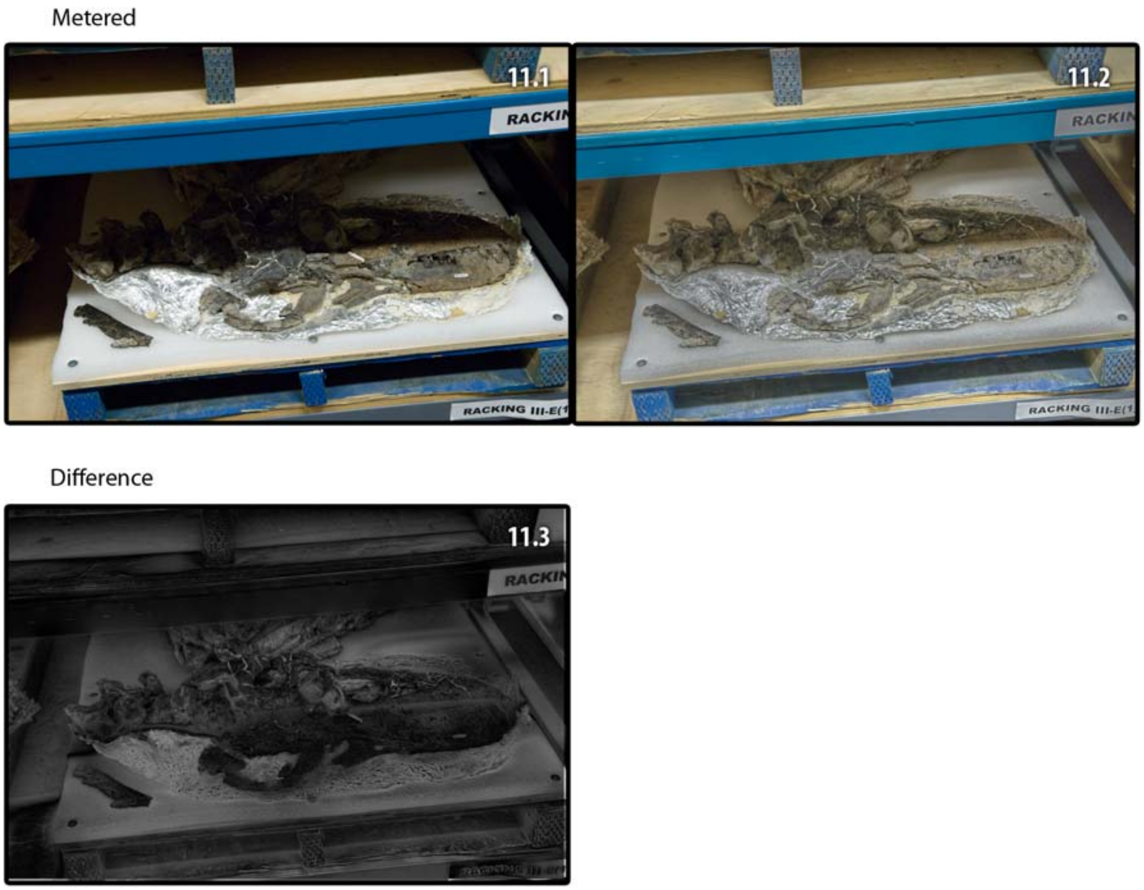


FIGURE 11.TMP 86.64.01, very fragile tyrannosaurid specimen, photographed under the same lighting conditions as Figure 10. 11.1 original metered, 11.2 shows the processed tonemapped HDR image, 11.3 difference map as in Figure 6.

scope of this paper, we decided to limit coverage. Photoshop was chosen due to its ubiquity, Photomatix Pro and FDRTools are popular in the online HDR community, and Hydra's ability to process handheld images fit with our goal of analyzing HDR techniques in terms of speed and convenience to the paleontological community.

All of the software tested can generate a usable HDR file, have dynamic range compression and detail enhancement tonemapping algorithms, and can be adjusted to give reasonably similar output. Figure 22 shows the result of passing the same nine JPEG files through the complete HDR processing pipeline in each application. As there are two distinct stages—assembly and tonemapping—to the processing workflow, we also tonemapped the same HDR file, generated in FDRTools, in all four applications, as seen in Figure 23.

Table 1 summarizes our findings when comparing the software applications tested.

FDRTools places more emphasis on the HDR assembly process than the other three applications. It has three different methods for merging images, and allows the user to include or exclude files or parts of files interactively. As a result, its HDR assembly output seems to preserve slightly more image detail than the others, more cleanly, with an apparently simpler alignment tool. Its detail enhancement algorithm exposes significantly fewer controls than Photomatix Pro's, but generates equivalent or slightly superior output for most uses. On our test system, however, it took the longest time to process a given HDR and tonemap. This is mitigated by its interactive preview and batch features, which allow the user to configure multiple sets to process before doing final processing. FDRTools does not include automatic folder crawling; each assembly must be configured by the user prior to start.

Photomatix Pro's interface is conceptually simple, even if at times it overwhelms the user with

TABLE 1. Comparison of software packages tested.

Operation	Photoshop	Photomatix Pro	FDRTools	Hydra
Image selection	Interactive selection with CS4, basic selection in CS3.	Basic selection	Interactive selection of images and dynamic ranges	Crashed with use of more than 4 exposures
Image alignment	Automatic alignment with some manual adjustment available	Two options for automatic detection	Automatic alignment, with some manual adjustment available	Powerful automatic alignment, with extensive manual correction support; allows use of handheld brackets
Batch processing	Powerful tools but not well integrated with HDR functions	Will automatically process images in a folder with the bracket number specified	Extensive support but not as simple to use as Photomatix	Not available but available as Aperture (Apple Corp.) plugin
Tonemapping preview	Automatic update, likely to change in CS4 version	Fixed size real-time preview	Flexible sized automatic update preview, not real-time	Real-time preview available but buggy
Operating system	Windows, Mac OS X	Windows, Mac OS X	Windows, Mac OS X, Linux (under development)	Mac OS X
Cost at time of writing (educational version)	$300 USD	$40 USD	29 Euros	$30 USD
Preview version	30-day trial announced but not released as of this writing for CS4	Available	Available	Available

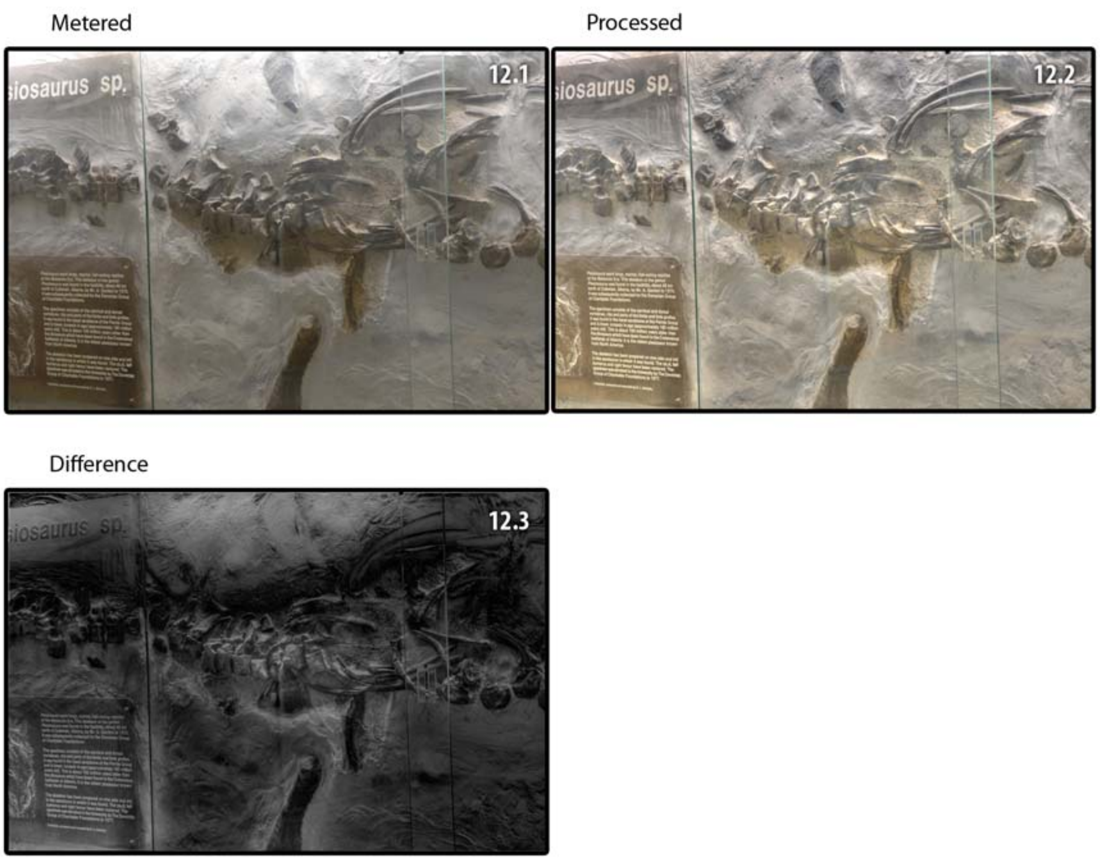


FIGURE 12. A plesiosaur, UCMZ(VP) 1978.001, on display behind glass at the University of Calgary. Note additional detail and correction for glare and oblique lighting in HDR image. 12.1 original metered exposure, 12.2 processed tonemapped HDR image, 12.3 difference map as in Figure 6.

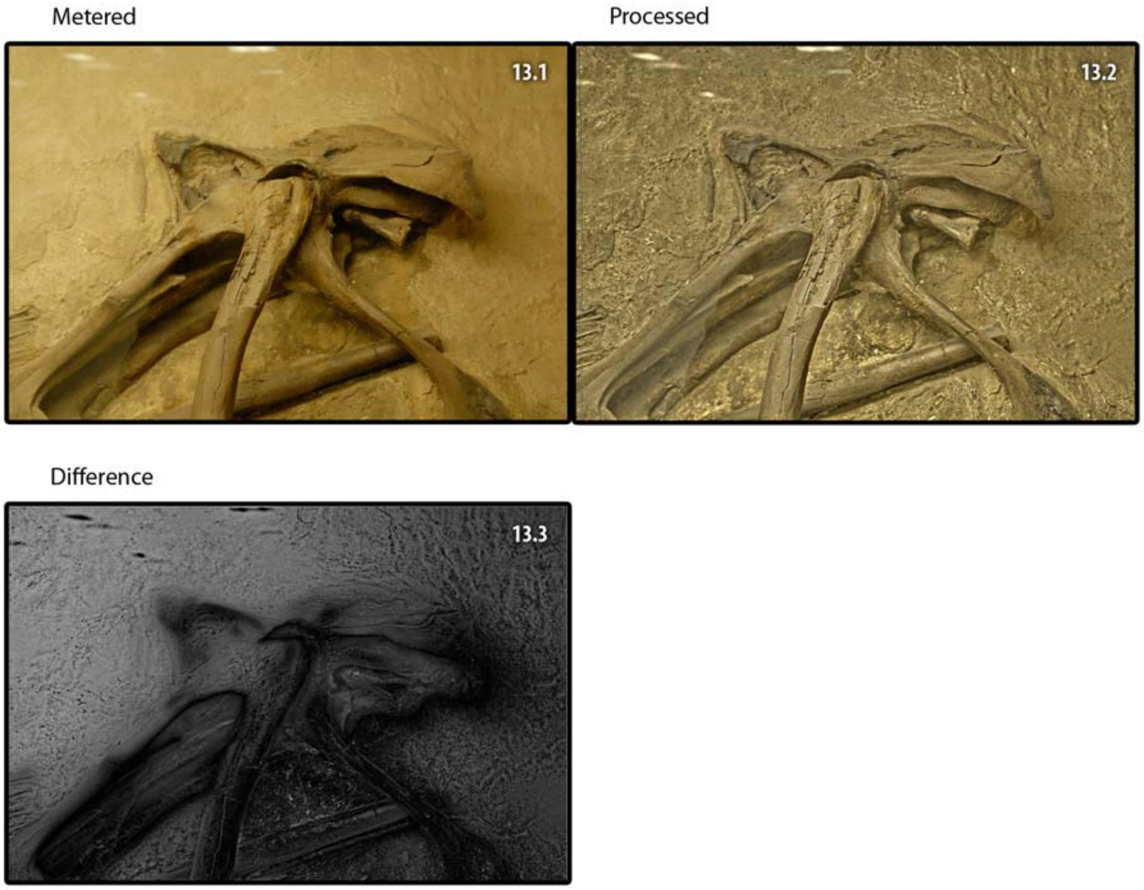


FIGURE 13. An ornithomimid pelvis, UCMZ(VP) 1980.1, on display behind glass at the University of Calgary. Note improved surface detail and decreased shadows in the HDR processed image. 13.1 original metered exposure, 13.2 processed tonemapped HDR image, 13.3 difference map as in Figure 6.

choices. The HDR assembly process exposes fewer controls than FDRTools, but has an alignment choice and an explicit option for dealing with motion in the image. It does not include per-image weighting, nor the additional assembly methods that FDRTools uses. The tonemapping interface, however, has the most controls of the four, allowing a considerable amount of image processing to be done directly in the tonemapping process. Photomatix Pro was more sensitive to noise than the other applications, and had, as of version 3.0.2, trouble reading some of our RAW images, generating distorted or sheared images. Typically, restarting the program solved the problem, but Photomatix Pro handled scenes with noise or grain with less fidelity than the other applications tested.

Photomatix Pro includes a batch processor that will crawl through a folder, processing specified numbers of source images into HDR format and tonemapping them automatically (unlike FDRTools, all sets must be processed with the same settings.) This is made considerably easier by properly organizing the source images in the first place. Photomatix Pro will process filenames in numerical order; however, as our workflow involved shooting a single identifying image of the specimen's label prior to shooting the bracket sequence, we could not simply download the camera to a single folder and unleash Photomatix's batch processor. Having the file preview in order from darkest to lightest made it simpler to locate each set of nine images using the operating system's icon-based previews than would otherwise be the case. The need to move and rename files manually is less intrusive in the workflow than the equivalent process in FDRTools or Photoshop.

Both Photomatix Pro and FDRTools have a preview loupe that allow the user to examine small sections of the HDR image with an automatically updated exposure. This allows the user to see fine detail in small areas without tonemapping, which may be useful.

Photoshop is, of course, the most capable image processor of the four, but its very power

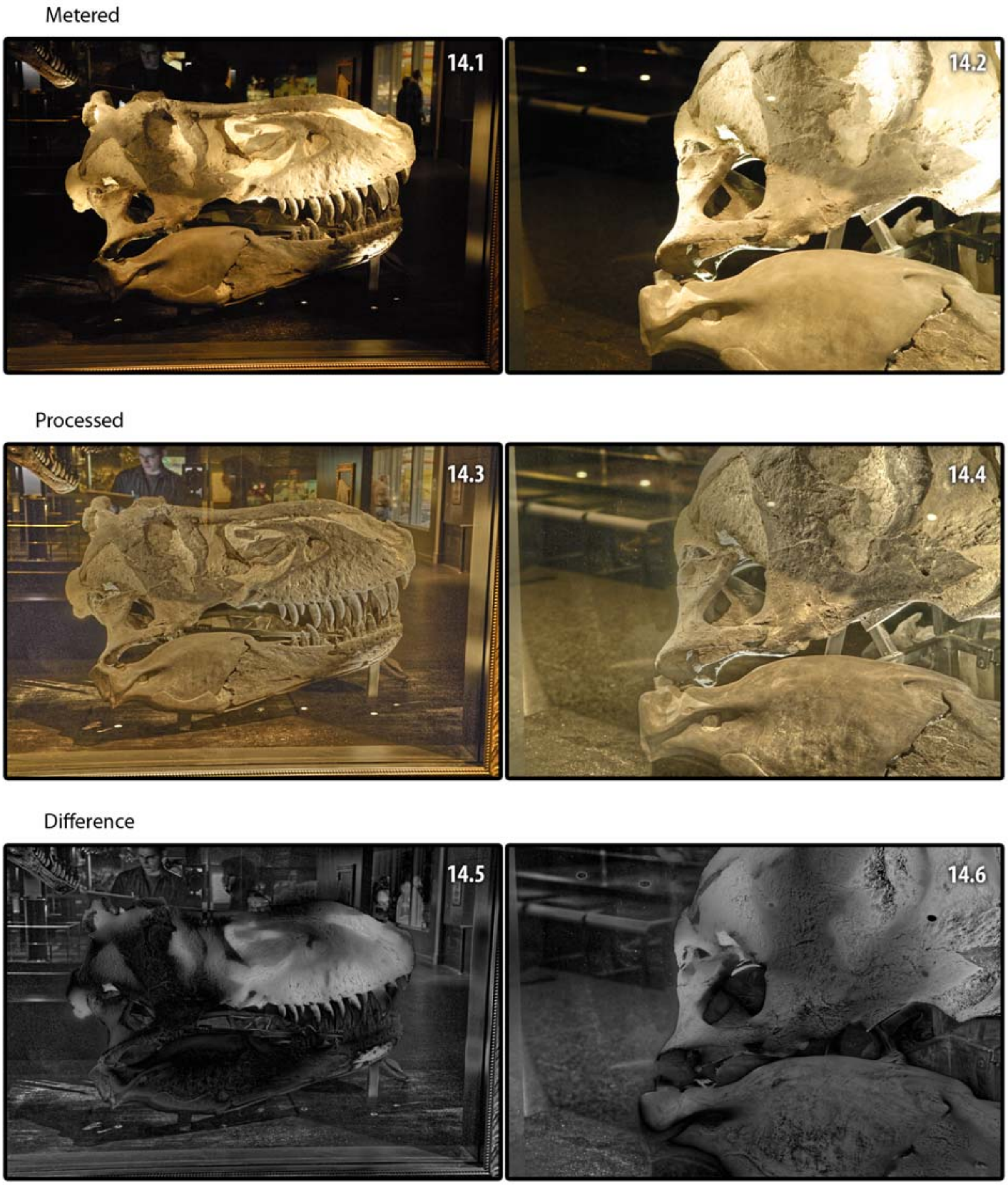


FIGURE 14. TMP 1981.006.0001, *Tyrannosaurus rex*, "Black Beauty". Dramatically lit exhibit with high contrast, behind glass, showing the ability of HDR processing to create a properly exposed image in a poor lighting situation. 14.1 and 14.2 original metered exposures, 14.3 and 14.4 processed tonemapped HDR images, 14.5 and 14.6 difference map as in Figure 6.

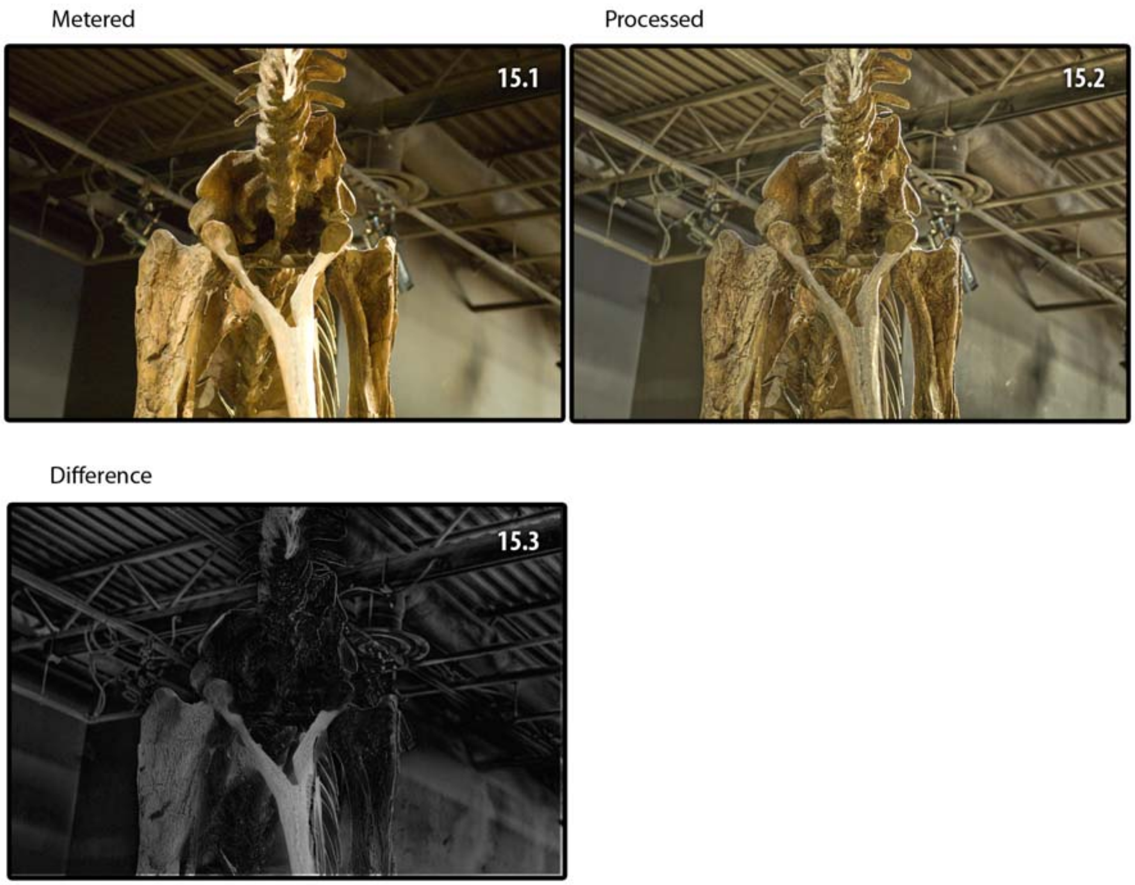


FIGURE 15. Cast of *Lambeosaurus* on exhibit at Dinosaur Provincial Park Field Station. Note additional detail of the pelvis in HDR hidden by shadows in original exposure. 15.1 original metered exposure, 15.2 processed tonemapped HDR image, 15.3 difference map as in Figure 6.

means that it requires marginally more user attention than the other applications. Its detail enhancement operator requires, to get equivalent output to the previous two applications, manipulation of a curve rather than a simple numeric setting. Its HDR assembly as of Photoshop CS3 Extended is perfectly acceptable, albeit as slow as FDRTools. Photoshop CS4 Extended should be significantly faster on well-equipped computers, as much of the image processing load has been offloaded to the graphics processing unit (GPU).

It is important to note at this point that Photomatix Pro tonemapping appears to produce higher-quality results in low-magnification microscopy use than FDRTools at this point, possibly due to it exposing more controls dealing with fine details in the tonemapping stage. Similarly, FDRTools's greater control over the assembly stage permits optimization of the HDR file for this purpose. While further testing is warranted, it appears that microscopic HDR benefits from using FDRTools for assembly and Photomatix Pro for tonemapping.

Hydra is, unfortunately, still something of a work in progress. Its image alignment tools are, as its advertising indicates, extremely powerful. In our testing, it managed to assemble useful HDRs from handheld brackets that the other applications were unable to handle. However, its interface as a standalone application is badly designed, with no way to save a HDR or tonemapped file with a user-specified filename. Some buttons in the interface do not do anything, and, in general, the program seems to be only half-finished. Stability issues were also present, with crashes happening more frequently than the other three applications combined. It has tight integration with Apple's Aperture software, and in situations where its unique abilities are required, it has no competition among the four we tested.

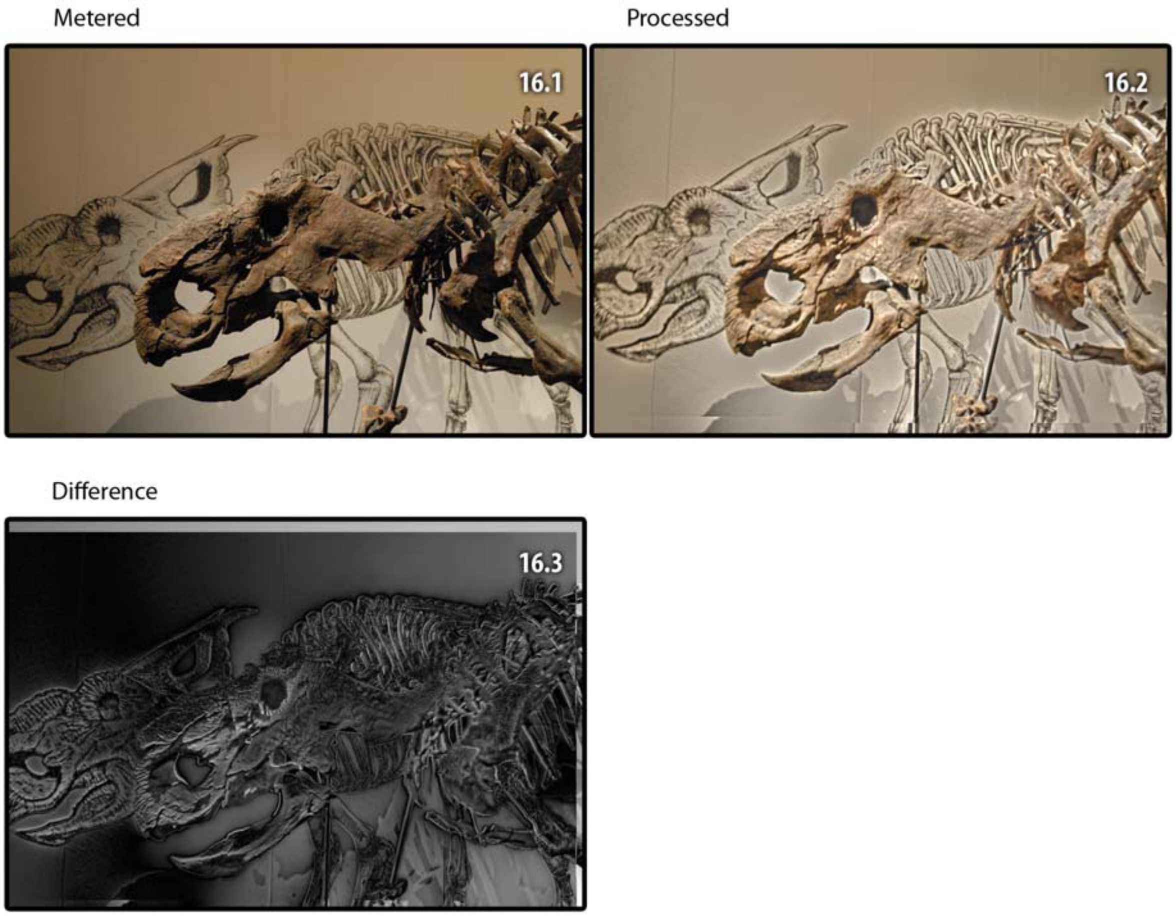


FIGURE 16. TMP 2002.076.0001, *Pachyrhinosaurus*. Shot using a handheld camera, shows improved surface detail and reduced contrast. 16.1 original metered exposure, 16.2 processed tonemapped HDR image, 16.3 difference map as in Figure 6.

Hydra aside, the other three applications are all usable as a primary HDR assembly and tonemapping application. Photoshop's ubiquity makes it the likely first HDR application many users will have access to, but we recommend testing the other two applications as well, as Photoshop is the slowest to use from a user interface standpoint (as opposed to its processing speed, which is comparable to the others). Both Photomatix Pro and FDRTools have downloadable demo versions. FDRTools will likely remain our default HDR assembly application for the time being, and its resistance to the noise issues that trouble Photomatix Pro means that we will likely use it to tonemap as well. However, Photomatix Pro's greater configurability will keep it in our toolbox. We cannot recommend the current version of Hydra with an entirely clear conscience, but if the ability to shoot handheld is a requirement, then it is worth evaluating Hydra, as updates are frequent.

Problems And Limitations

The HDR shooting process, as simple as it can be, does involve several areas that can create additional problems in the final image. The virtual ISO rating of the DSLR should be set as low as possible for the lighting situation. As can be seen in Figure 24, a high ISO rating, chosen in that figure to reduce the length of time the shutter needed to be open, adds unwanted noise to the image. A complete bracket, one that surrounds the dynamic range of the scene completely, can reduce the appearance of noise considerably, but if the ISO rating is too high, even the redundant visual information provided by the bracket may not be able to eliminate noise or grain.

Motion complicates effective HDR image acquisition, both in the camera and in the scene. Software, particularly Hydra, can cope with a moving camera; as long as the shutter speed is fast

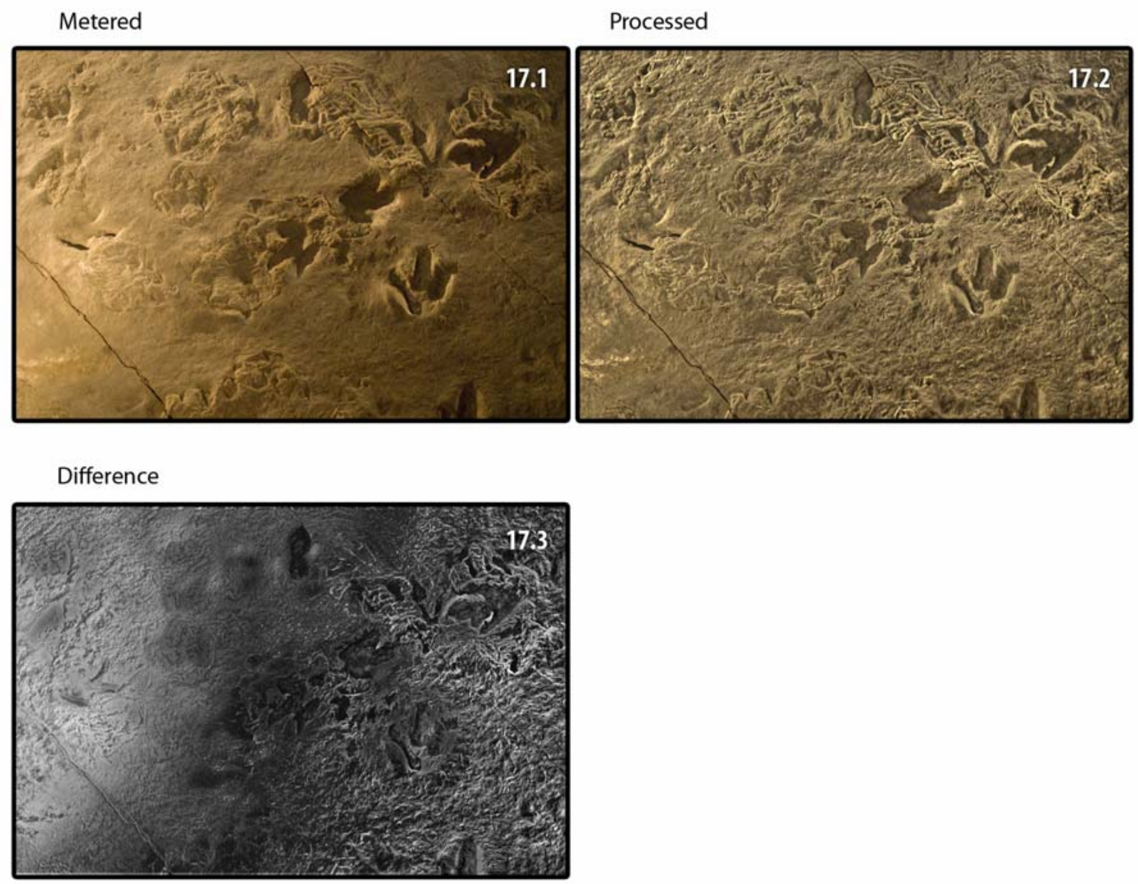


FIGURE 17. Dinosaur trackways on display at Dinosaur State Park, CT. Tracks are lit from a low oblique angle, causing extreme shadows. HDR processing increases detail within tracks and on the surface, reducing large area contrast. 17.1 original metered exposure, 17.2 processed tonemapped HDR image, 17.3 difference map as in Figure 6.

enough that motion blur is imperceptible. Handheld shooting is possible, but in darker areas, or with too low an ISO setting, the shutter may remain open during the higher EV bracketing shots long enough for blur to be recorded. HDR processing cannot restore detail to an image that was not recorded in the first place, and the blurring caused by a moving camera body is frequently best repaired by leaving a particularly blurred image out of the HDR assembly. If the camera moves too much through the bracket, as in Figure 7, the image may not be recoverable at all. However, if the camera is not adding blur to the scene, software can reduce or eliminate the impact of motion in the background, as long as the subject of the shot is immobile.

Care must be taken when using detail enhancement operators in tonemapping. The reduction or elimination of shadows can cause an unwanted flattening of the image, as the human eye tends to use shadows as cues to determine shape in photographs. For particular purposes, highlighting of surface detail at the expense of flattened topology may be desired, but this effect can be minimized by the settings used for local operators or the use of global operators for tonemapping.

Colors may be increased in apparent saturation during processing. Even though the resulting colors may, in fact, be mathematically accurate, it may be necessary to reduce the saturation of the resulting image to produce a more "realistic" appearance.

Lastly, we made, during the production of images for this paper, the discovery that autofocus, particularly in areas where one is shooting specimens behind glass, can be problematic. It is often better to manually focus on the object of interest, as the autofocus will often focus on the nearest object, as in Figure 25, where the autofocus helped us produce a very in-focus reflection on the glass, and a very out-of-focus specimen.

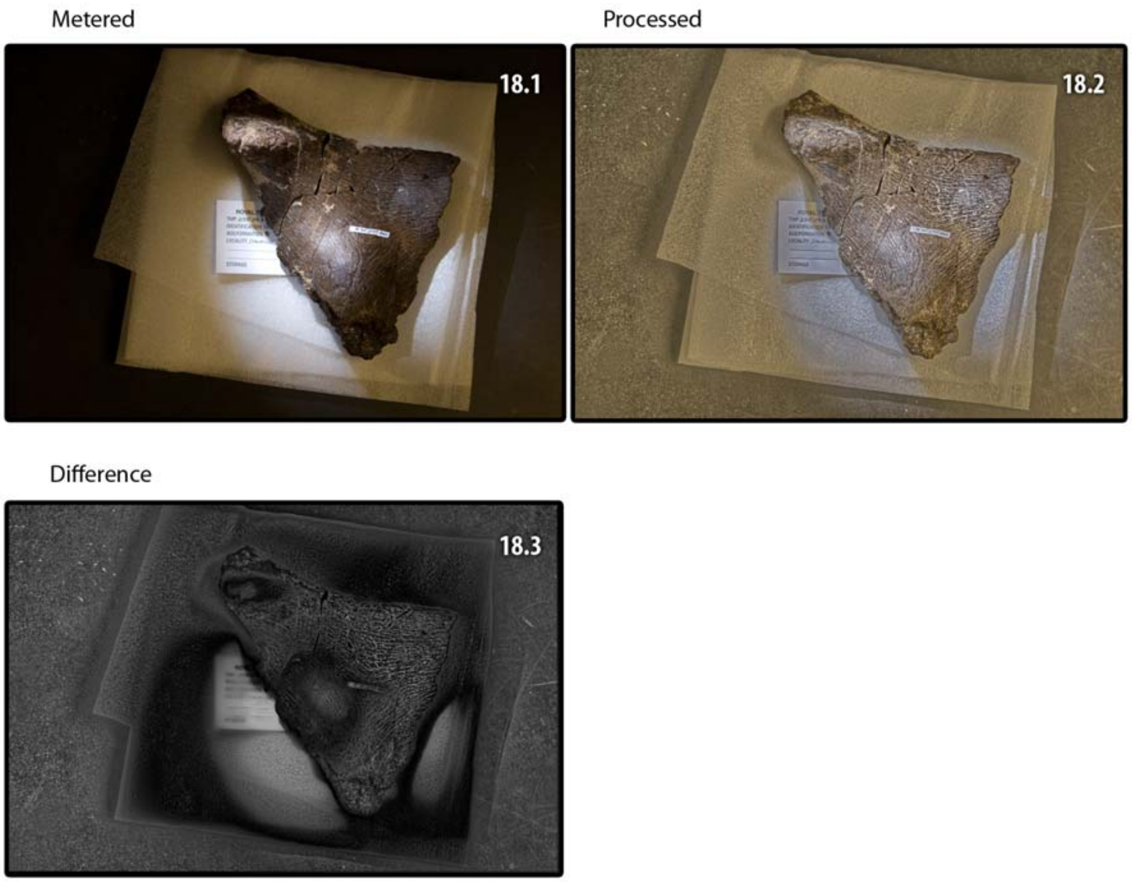


FIGURE 18. TMP 2005.09.81, ceratopsian parietal. Note improvement in details of surface texture, reduction in glare. 18.1 original metered exposure, 18.2 processed tonemapped HDR image, 18.3 difference map as in Figure 6.

DISCUSSION

A major advantage to using HDR techniques is the speed with which a researcher can ensure that they capture needed information in different lighting conditions, without investing time in minute adjustments of lights. While it is always preferable to create specimen photos in controlled settings with good lighting, HDR methods can be especially useful when specimens are mounted or otherwise difficult to move into better-lit conditions, such as large, fragile objects on shelving. It is also useful for any specimen or landscape where surface detail is important, and should be easy to carry out in field situations. In situations where speed is required, HDR techniques may make the difference between obtaining ten usable shots, or one traditionally well-lit shot.

It is important to note that, though HDR processing and detail enhancement tonemapping might not directly improve an image over the metered exposure, the added precision and workflow changes can be useful in any case. A HDR file can be virtually reexposed to produce exactly the exposure needed after the fact, and many image processing operations produce more accurate output when performed on floating point pixels. The simple act of shooting a bracket increases the likelihood of getting a usable image, even if no HDR assembly is done.

Furthermore, properly processed HDR-derived images show dramatically reduced noise and grain. As with the traditional photographic exposure blending technique, the random noise introduced by the photographic medium in one image will be overwhelmed by values from the other images. It is therefore sometimes worthwhile to shoot a bracket and generate a HDR image simply to re-expose it to the original EV value in software. If the additional detail recovered through HDR processing is not necessary, most HDR software also includes a pure exposure blending mode, which takes advantage of the software's alignment capabilities.

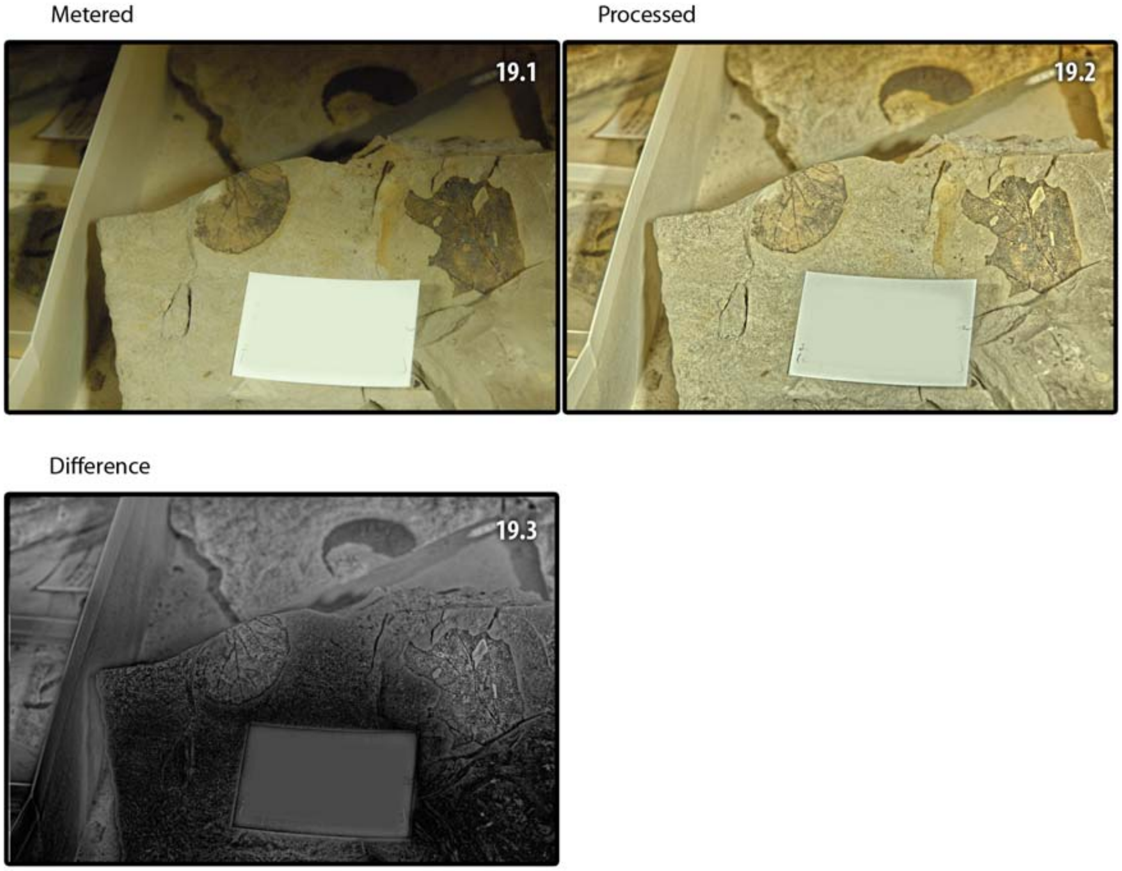


FIGURE 19. TMP95.98.232, plant specimen. 19.1 original metered exposure, 19.2 processed tonemapped HDR image, 19.3 difference map as in Figure 6.

Shooting for HDR requires less equipment to be carried in field or museum settings, as the only required equipment is a camera, tripod or other stabilizer, and a larger than usual number of memory cards. The processing is relatively straightforward using the tools we tested, all of which are inexpensive. Much of the detail enhancement available in the software is automated, so refining the image is much simpler than a complex series of enhancements to a single exposure in Photoshop. With modern cameras, in addition, the shooting process is constant, regardless of illumination, and the researcher is able to get into an efficient rhythm.

Lastly, HDR processing reduces the number of irrevocable decisions that must be made when taking specimen photographs. The camera can be set up, and shots taken as quickly as the specimen can be repositioned. In exhibit spaces, usable images can be shot almost at walking speed, without inconveniencing museum visitors or staff.

However, for specimen photography that, by convention, has a specified direction of light to show particular features (more common in invertebrate paleontology), HDR cannot be used to add that directional light in processing. Any needed directional lighting should be added at the time of shooting the bracket.

For reference photos to accompany notes taken on museum visits, in field situations, or even for publication (depending on requirements), HDR can provide a significant visual advantage. In less constrained situations where copy stands, lights, and time are available, conventional single exposures can yield similar results to an HDR image—but the HDR image still has significant advantages, due to the greater post-processing flexibility and accuracy inherent in the format.

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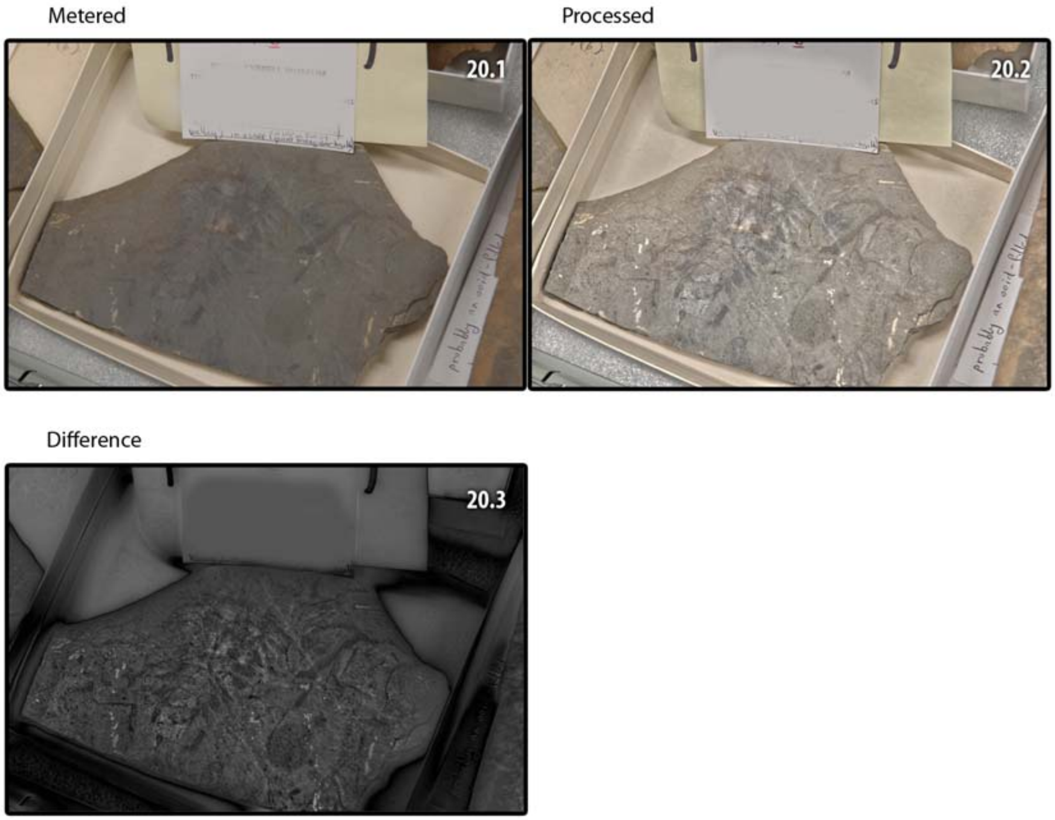

FIGURE 20. TMP 2008.024.0235, *Sidneyia*. Note improved detail highlighting chisel marks from preparation. 20.1 original metered exposure, 20.2 processed tonemapped HDR image, 20.3 difference map as in Figure 6.

early version of this work. Dr. Craig Scott, Dr. Nick Longrich, Caleb Brown, Patrick Wise, Danielle Fraser and Dr. A. P. Russell provided access to specimens in their keeping, and made many valuable suggestions.

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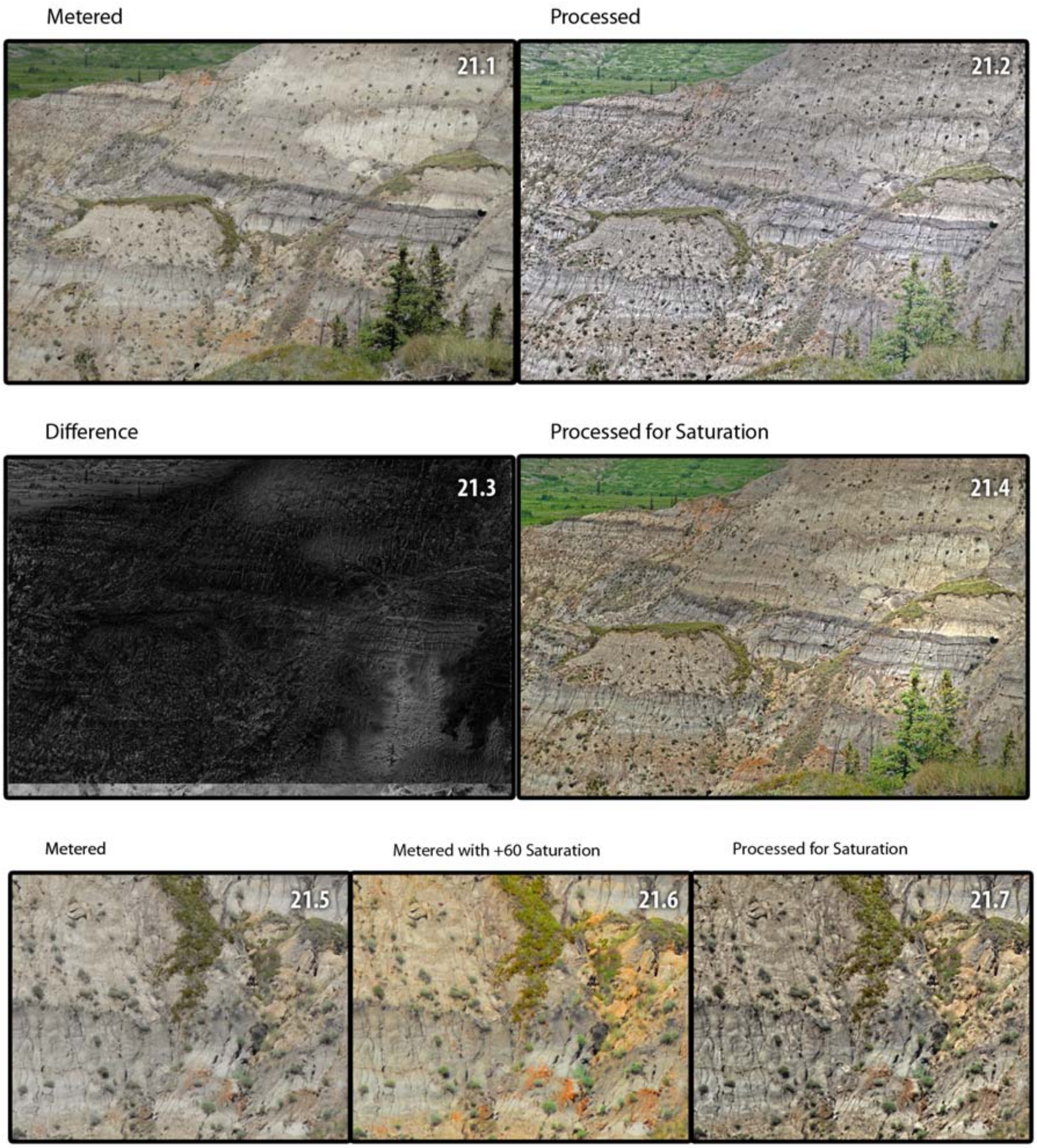

FIGURE 21. Field images of exposures of the Scollard Fm., AB. Note increased detail in the HDR processed image in 21.2, and superior enhancement of color detail in 21.4. 21.1 original metered exposure, 21.2 tonemapped HDR image with increased detail. 21.3 difference map as in Figure 6. 21.5 and 21.7, magnified sections of 21.1 and 21.4, respectively. 21.6 increased color representation using the LDR metered exposure as a source image. Note preservation of color detail in 21.7 compared to 21.6.

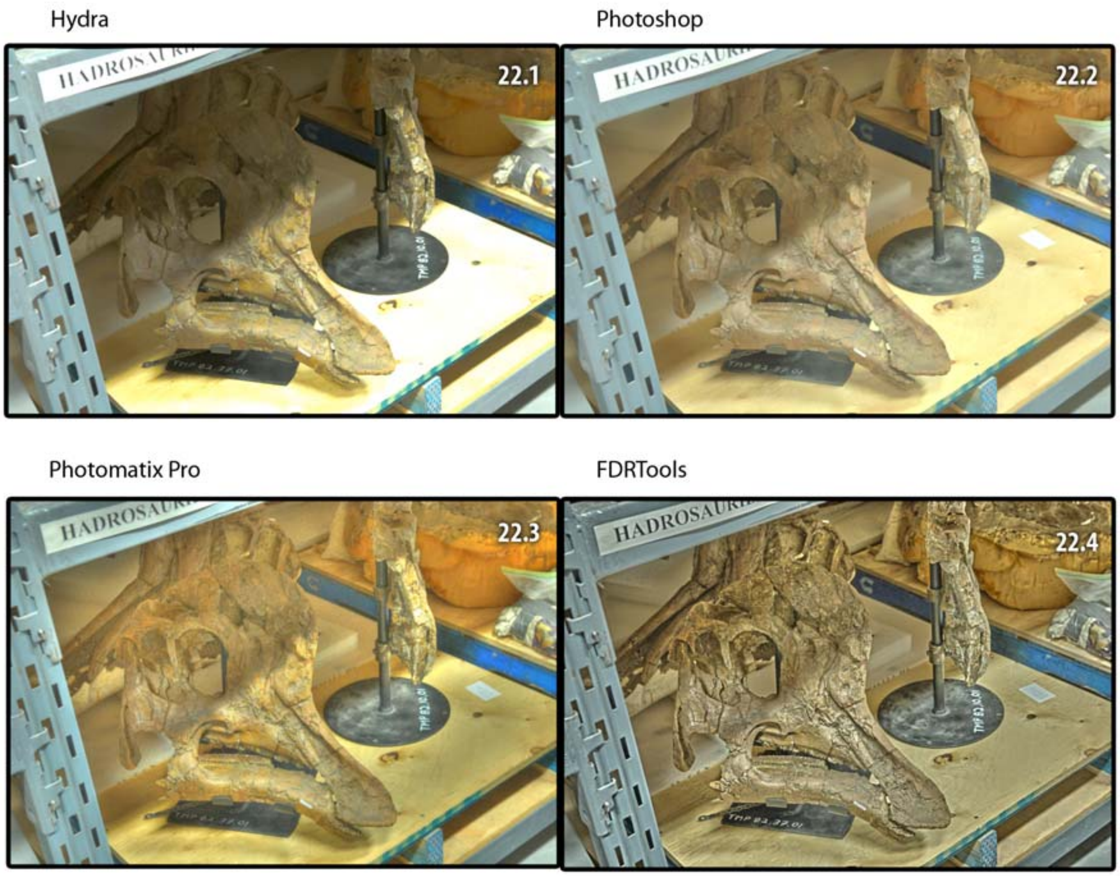

FIGURE 22. TMP 82.37.01, processed using each HDR software package tested. Both HDR assembly and tonemapping done in one application per image.

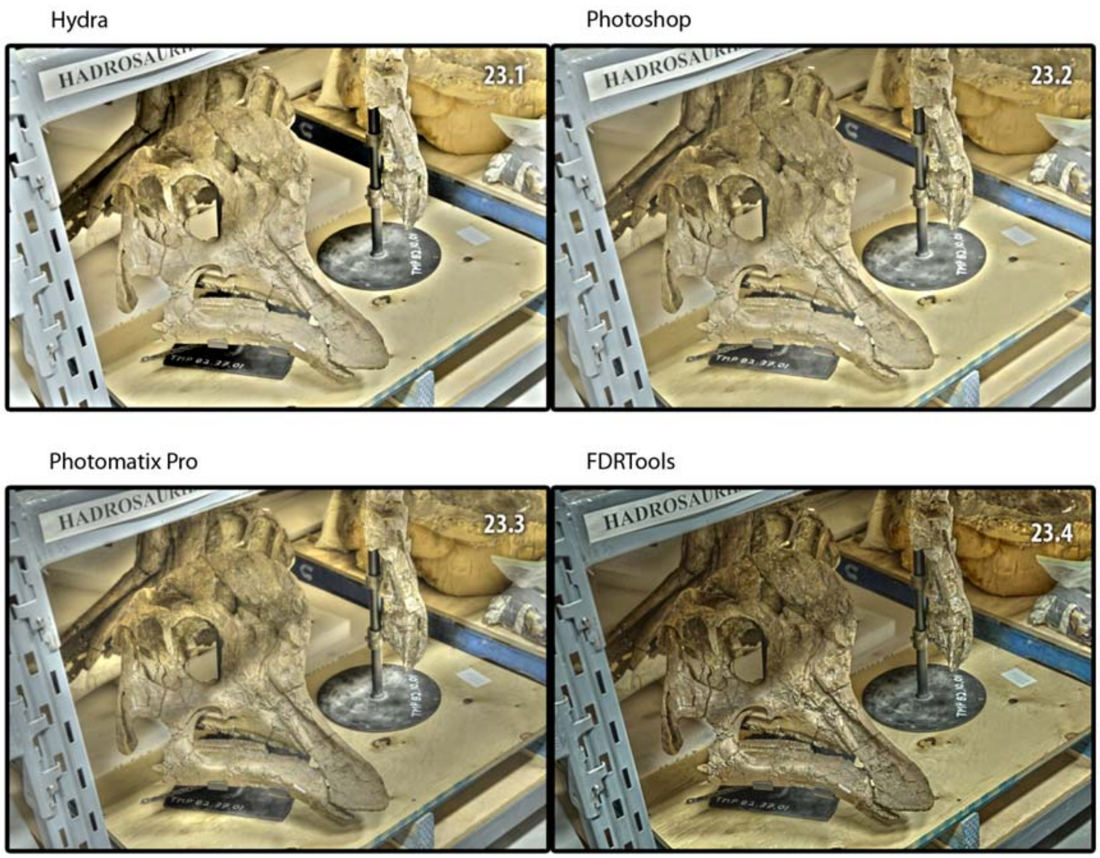

FIGURE 23. TMP 82.37.01, same source files as Figure 22. HDR assembly done using FDRTools, tonemapping performed in each software package tested.

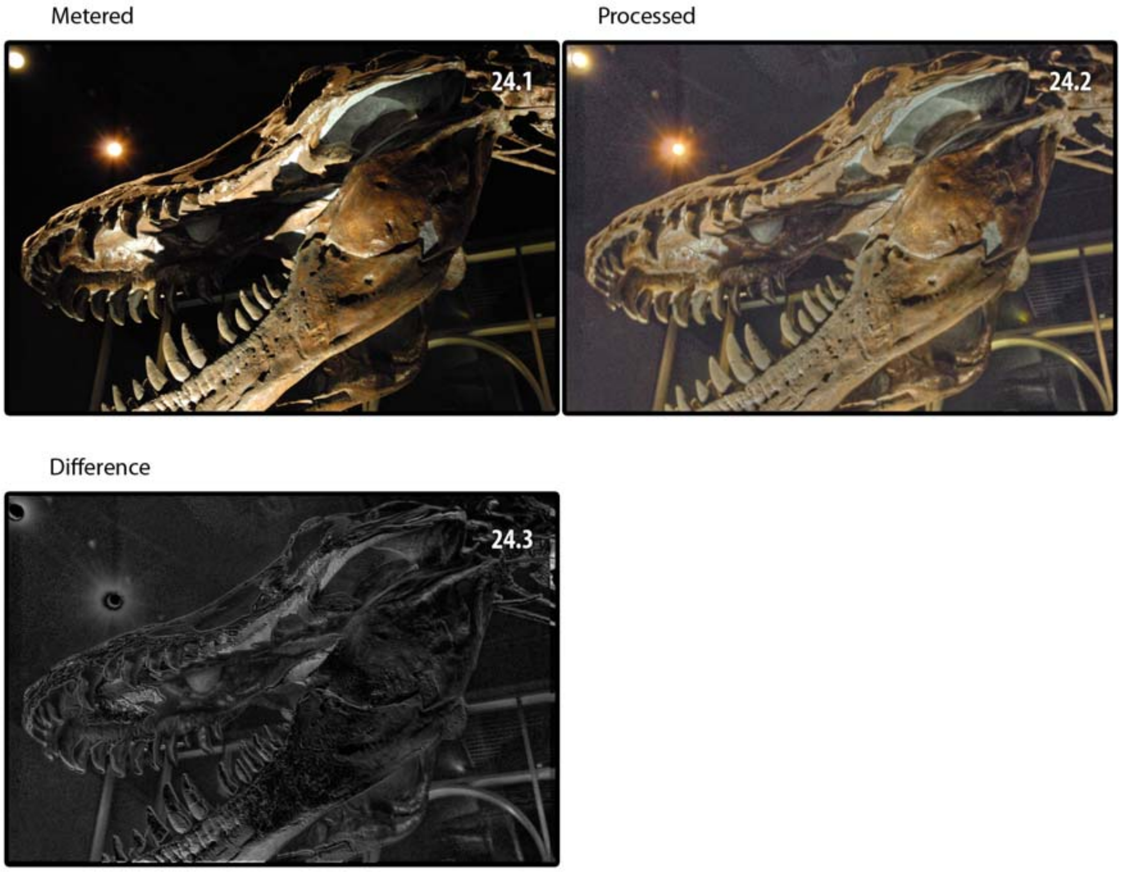

FIGURE 24. High ISO noise in low light. 24.1 original metered exposure, 24.2 tonemapped HDR image, 24.3 difference map as in Figure 6.

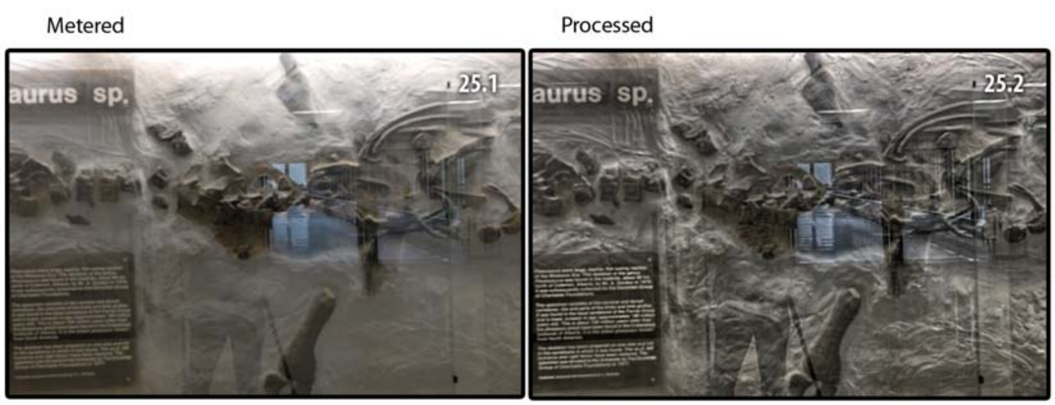

FIGURE 25. Problems using autofocus when shooting through glass. 25.1 original metered exposure, 25.2 processed tonemapped HDR image.