IMAGING FOSSILS USING REFLECTANCE TRANSFORMATION AND INTERACTIVE MANIPULATION OF VIRTUAL LIGHT SOURCES

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ABSTRACT

Many fossils cannot be fully illustrated using a setting of physical light sources, and conventional photographic approaches are therefore insufficient. Polynomial texture mapping (PTM), a new technique for imaging surface relief using an ordinary digital camera and multiple light sources, offers an opportunity to resolve these difficulties. In PTM, a series of 50 pictures is taken with the specimen and camera in fixed positions, but with varying directions of incoming light. These pictures are converted digitally into a PTM file, incorporating information about the reflectance of each pixel under different lighting conditions. The number, position, and intensity of virtual light sources can then be manipulated, as can the reflectance properties of the imaged surface. In addition to bringing out low surface relief that may otherwise be difficult to illustrate, PTM also allows electronic transfer, storage, and publication of images, allowing users to manipulate virtual light sources interactively. Herein we test this technique using fossils with different types of preservation, including Cambrian fossils from the Burgess Shale and Chengjiang conservation lagerstätten, Cambrian fossils with 3D relief from dark shales of Norway, Carboniferous plant fossil impressions from England, Cambrian trace fossils in sandstone from Sweden, and Neoproterozoic impression fossils from the Ediacara lagerstätten of south Australia. Whereas not optimal for all types of fossil preservation, PTM enhancement techniques can provide noticeable improvement in the imaging of specimens with low color contrast and low but definite relief. The imaging of specimens with higher relief, although they can be easily photographed with traditional techniques, will still benefit from PTM because of the opportunity of interactive manipulation of light and reflectance.

INTRODUCTION

The photographic study and illustration of fossil specimens often involves enhancement of contrast. This contrast can be achieved with a number of photographic techniques such as oblique lighting, immersion in a liquid, and the use of polarized or ultraviolet light or high-contrast film (Howell 1977; Conway Morris 1985; Rayner 1992; Boyle 1992; Bengtson 2000). More recently, these techniques have been augmented by digital contrast-enhancement algorithms such as sharpening, filtering, and edge detection (Kirschvink et al. 1982; Ekdale and Jeong-Kyungwan 1996; Bengtson 2000). Digital image enhancement of paleontological photographs has so far involved the transformation of a single captured image. Such an image represents a blending of color, reflectance, and shading information in one two-dimensional image. The amount of enhancement possible is therefore severely limited. By combining a number of images made with different directions of incoming light, it is possible to record the luminance of each pixel under a variety of lighting situations. By converting this information through a suitable algorithm, a dynamic texture map can be rendered that allows the simulation of the surface being seen under all conceivable (and some inconceivable!) lighting conditions. The method, Polynomial Texture Mapping (PTM), allows the user to apply virtual light sources to a three-dimensional surface and to manipulate the color and reflectance properties of the surface (Malzbender et al. 2000, 2001).

This principle has been put to use in the study of partly effaced script on archeological artifacts and other objects (Malzbender et al. 2000, 2001; Brooks 2001), and a number of other applications are being tested. The study and illustration of fossil specimens appears to be a field where the method shows particular promise. In addition to the possibility of revealing subtle structures that may otherwise be difficult to illustrate, PTM lends itself nicely to interactive presentation, allowing manipulation of virtual light sources as well as surface properties. It therefore enables the production of images for electronic publication, allowing the reader to choose the optimal lighting and surface properties for studying different structures in the object.

We describe here the PTM method and explore its use for different kinds of fossils having varying relief, color and reflectance. As anticipated, some types of structures respond better than others to this kind of image manipulation, but in all cases visualization of fossils is enhanced by providing readers with the opportunity for interactive image manipulation.

POLYNOMIAL TEXTURE MAPPING AND CONTRAST ENHANCEMENT

Polynomial Texture Mapping (Malzbender et al. 2001) refers to a set of computer graphics and image processing methods where each pixel in the image contains information about luminance as a function of the direction of incoming light. The light direction (l_x, l_y) is given as the x and y coordinates of the projection of the normalized light vector onto the image plane. The luminance function for each pixel is approximated by a biquadratic polynomial in l_x and l_y:
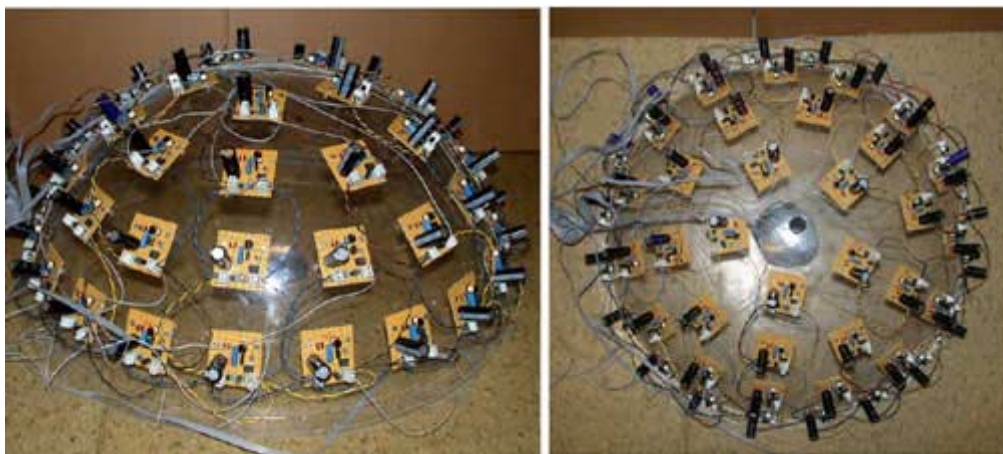
$$L = a_0 l_x^2 + a_1 l_y^2 + a_2 l_x l_y + a_3 l_x + a_4 l_y + a_5$$

The six coefficients $a_0 - a_5$ are stored in addition to the unscaled RGB (red/green/blue) values of the pixel. Alternatively, such a function can be used for the R, G, and B color channels separately in order to capture possible change in color as a function of the direction of incoming light.

By making a series of photographs with camera and specimen in fixed positions, but with varying directions of incoming light, the coefficients of the luminance polynomial for each pixel can be computed by a least-squares method (regression) using Singular Value Decomposition. Given this data set, the digital image can be interactively manipulated by moving virtual light sources on the computer screen, giving the illusion of moving one or several lamps around the real specimen. The luminance polynomial can also be extrapolated beyond the original range of lighting angles, simulating the effect of light sources in "impossible" positions almost parallel to, or even below, the surface of the specimen.

The surface-normal vector for each pixel can be estimated by finding the direction of maximal luminance. A new image can then be generated using any of the synthetic light reflection models known from computer graphics, such as Phong lighting (Phong 1975). The parameters of the synthetic reflection model can be freely manipulated, giving control of surface parameters such as the quantity of diffuse reflection, specular reflection (shininess), and the specular exponent. Perception of surface shape can be strongly enhanced by specular enhancement (Malzbender et al. 2000). A more subtle enhancement technique is to increase the curvature of the reflectance function in the space of light direction, reducing the range of light directions giving high luminance. This is referred to as diffuse gain (Malzbender et al. 2001). The techniques of specular enhancement and diffuse gain are examples of *reflectance transformation*.

Finally, one can try to estimate the true 3D relief from surface normals. This can be done by

Figure 1. Side and top view of the computer-controlled flash dome used for acquiring the set of 50 images. The digital camera is normally mounted at the top of the dome, pointing downwards. Diameter of dome is 40 cm.

converting the surface normals to partial derivatives (slopes) in the *x* and *y* directions, and finding a surface that minimizes least-squares deviations from the observed slopes. Using a variational approach, it can be shown that this optimization criterion leads to a Poisson equation which can be solved numerically with an iterative algorithm (Horn 1990). The resulting digital elevation map can be exaggerated vertically in order to amplify relief.

METHODS

The PTM images can be acquired with a single light source that is manually positioned for each exposure, but it is more practical to use a set of computer-controlled light sources in fixed positions. At the time of writing there are four such machines available, two of which have been used for this article. The original "flash dome" was described by Malzbender et al. (2001). A dome built at the Geological Museum in Oslo was based on the same design, with minor modifications. For the Oslo version (Fig. 1), 50 computer-controlled flashes were mounted on an acrylic dome (hemisphere) with a diameter of 40 cm. A Nikon Coolpix 995 digital camera was mounted at the top of the dome, pointing down onto the specimen, which is placed on a surface in the center of the dome. The flashes are synchronized with the camera exposures by using the flash synchronization output ("hot shoe") of the Coolpix camera. Custom-made software controls the flashes, the camera, and the transfer of images to the computer in an automated sequence. For the examples shown here (Figs 2–5), a relatively low resolution of 1600 x 1200 pixels was used (this is cropped to smaller size in the illustrations), but the system can handle higher resolutions at the cost of slower image transfer, image

processing, and interactive manipulation. The optical zoom range of the Coolpix 995 camera and the distance from specimen to the top of the dome allow visualization of specimens ranging in size from 50 to 300 mm across. Hence, this camera is not optimized for very small specimens. The light sensitivity of the camera chip was set to an equivalent of ISO 200, and the compression to "fine" (JPEG compression to 25% of original file size; as JPEG is a somewhat destructive compression, TIFF or equivalent is recommended if storage space allows).

The original "flash dome" (Malzbender et al. 2001), used for Figs 6–10, has a diameter of 64 cm and employs a Kodak DCS460 camera with a pixel resolution of 3060 x 2036 pixels and a Nikon ED AF Micro Nikkor 70-180 mm zoom lens. In order to minimize reflections from external objects, the dome is constructed of acrylic and the interior painted opaque matte black.

The 50 images were processed using software developed at HP Labs and available in the public domain:
HP Laboratories (latest version)
http://www.hpl.hp.com/ptm/ (latest version)
PE copy (version at time of writing)
http://palaeo-electronica/2002_1/fossils/ptm.htm

In a preliminary step, the program *ptmfitter* is used to combine the images into a single, compact PTM file containing the coefficients of the paraboloids approximating the brightness of each pixel as a function of the direction of incoming light. These data are then further processed by a viewing program (*ptmviewer*), allowing interactive control of image enhancement algorithms and the positions of virtual light sources.

Figure 2. PTM-reconstructed view of a *Marella* specimen from the Burgess Shale, Middle Cambrian, British Columbia. **2.1.** One virtual light source normal to shale surface. **2.2.** Oblique virtual light source from SE, inverted image. This image can be regarded as a "traditional" film-based photographic image for comparison with the enhanced versions. **2.3.** Specular enhancement. Note that color contrast is almost removed, whereas relief is enhanced. **2.4.** Addition (overlaying) of image 2.2 and 2.3.

The results (Figs. 2–10) are presented here as PTM images, allowing the user full interactivity, including adjustment of the number, intensity, and positions of virtual light sources as well as manipulations of surface reflectance. For users who cannot run the *ptmviewer* software (it is currently only available in Windows, Linux, and HP-UX versions), simpler interaction can be achieved using the included QuickTime VR files (cf. Lyons and Head 1998), which require that the free QuickTime Player [link to http://www.apple.com/quicktime/] is installed on the computer. An even simpler format, clickable JPEG images, which only requires a browser, is also included for Figures 2 and 6. The QTVR and clickable JPEG formats only allow the user to select from a finite number of positions of a single light source and fail to provide interactive modification of surface reflectance parameters. However, they do provide a glimpse of the full interactivity provided by the PTM format. Finally, static images are given in a composite figure for each object, to illustrate the effects of a few selected manipulations of light source and reflectance on the specific object.
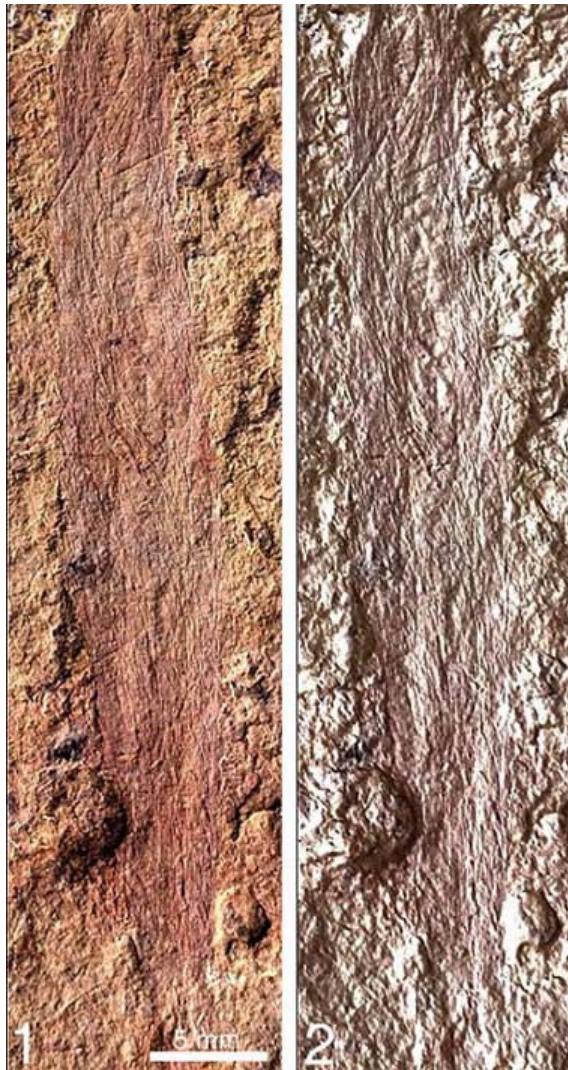
The fossils chosen for this study are deposited at the Palaeontological Museum, Oslo University (PMOU), the Swedish Museum of Natural History, Stockholm (SMNH), and the South Australian Museum, Adelaide (SAM). They cover a range of preservational modes. In order to take advantage of possible variation in surface reflectance with light angle, specimens were not whitened using ammonium chloride.
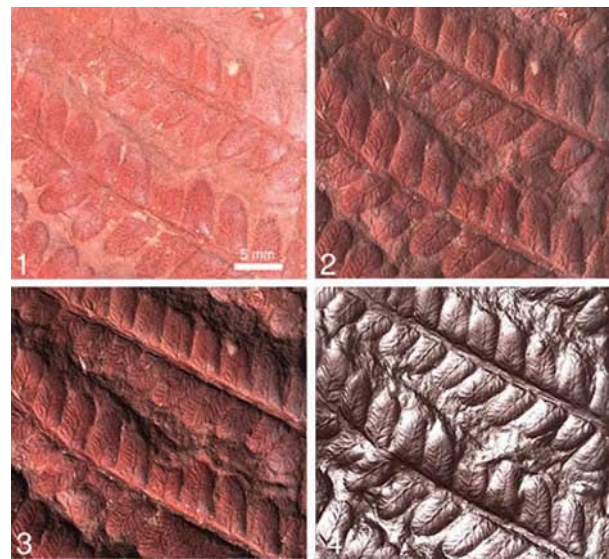
RESULTS

Middle Cambrian fossils from the Burgess Shale have traditionally been photographed in UV light (Conway Morris 1985). The use of polarizing filters to dampen directly reflected light has proven to be even more effective in bringing out details not otherwise visible (Boyle 1992; Bengtson 2000). The application of the reflectance transformation method on a *Marella* specimen, preserved mainly as a dark film on dark shale, was highly successful (Fig. 2). The image brightness drops to almost zero when using the low-angle lights, testifying to the very low relief of fossil features. The method of specular enhancement leads to a dramatic enhancement of relief, showing detailed anatomical and taphonomic structure in three dimensions (Fig. 2.3). However, the reduction of color contrast obscures the structures preserved as dark surface films. The best results were therefore obtained by combining (adding) the image obtained from specular enhancement with an inverted version of an unprocessed image made using low-angled virtual light.

Lower Cambrian fossils from the Chengjiang deposit in the Maotianshan Shale of China (Chen

Figure 4. *Pecopteris* spp. Coal Measures, Upper Carboniferous, Forest of Dean, England. **4.1.** One virtual light source normal to surface. **4.2.** Oblique virtual light source from NE, comparable with traditional photograph. **4.3.** Diffuse gain, providing subtle improvement in some regions but not in others. **4.4.** Specular enhancement. Note "whitening" effect.

Figure 3. The sponge *Paraleptomitella dictyodroma* from the Cambrian Maotianshan Shale of Chenjiang, China. **3.1.** Oblique virtual lighting from PTM reconstruction, comparable with a traditional photograph. **3.2.** Specular enhancement.

et al. 1997), preserved with low relief on a light-colored shale, might be expected to be a good target for PTM imaging. Figure 3 shows a specimen 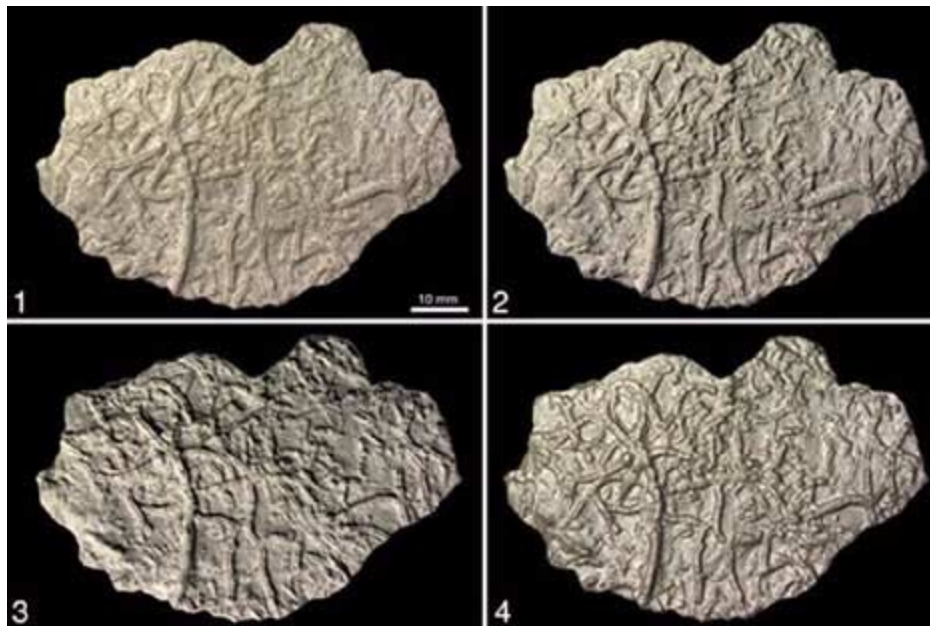of the sponge *Paraleptomitella dictyodroma* with different enhancement techniques. Whereas oblique lighting enhances low-relief spicules, specular enhancement does not seem to offer any improvement in this case.

Low-relief fern impressions in claystone from the Carboniferous Coal Measures of the Forest of Dean, Gloucestershire, England, are devoid of color contrast, and can be difficult to photograph and study with conventional techniques. Figure 4 shows some results from applying PTM techniques. The 3D reconstruction from surface normals (Fig. 11) does not add significant information.
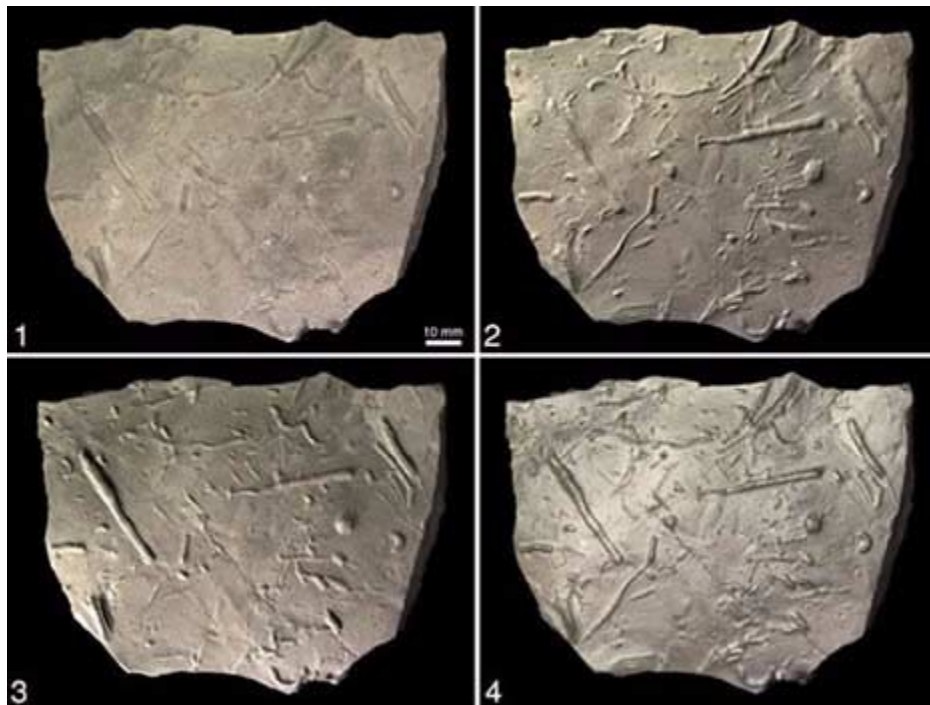
Late Neoproterozoic Ediacaran fossils are commonly preserved in low relief on the soles or tops of sandstone beds. Imaging them usually employs whitening in combination with very low-angle lighting. The two examples illustrated here
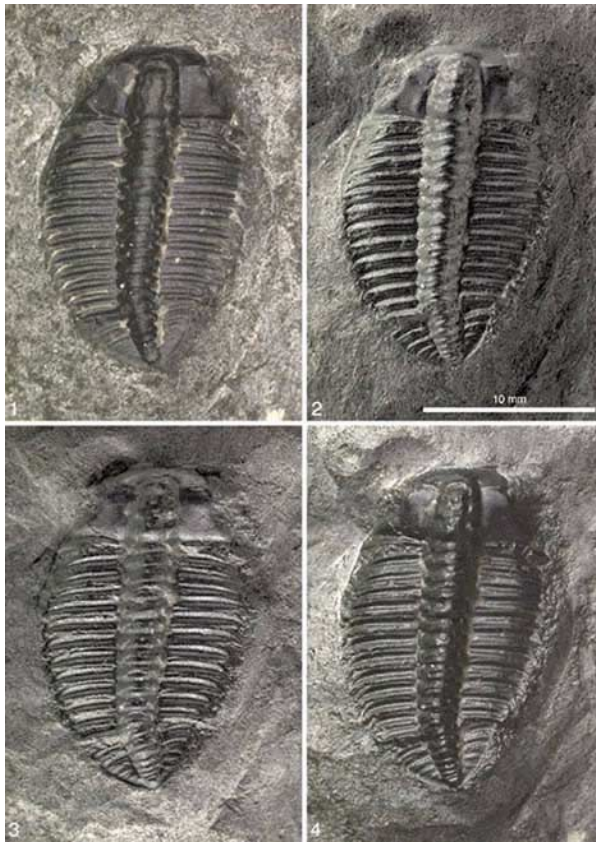

Figure 5. Hyolithids and trilobite fragments (*Paradoxides forchhammeri*) from the Cambrian Alum Shale of Krekling, Norway. **5.1**. Oblique virtual lighting. **5.2**. Diffuse gain. **5.3**. Specular enhancement.

Figure 6. Trace fossils (*Cruziana tenella*), positive hyporelief, Lower Cambrian Mickwitzia Sandstone, Västergötland, Sweden. SMNH X3527. **6.1.** No enhancement; virtual light from NW. **6.2.** Diffuse gain; virtual light from NW. **6.3.** Diffuse gain; virtual light from SW. **6.4.** Specular enhancement; virtual light from NW. Note how, in contrast to the more naturalistic lighting in 6.2 and 6.3, specular enhancement brings out all structures irrespective of their orientation in the bedding plane.

Figure 7. Trace fossils (*Helminthoidichnites tenuis*), positive hyporelief, Lower Cambrian Mickwitzia Sandstone, Västergötland, Sweden. SMNH X3528. **7.1.** No enhancement; virtual light normal to bedding. **7.2.** No enhancement; virtual light from NW. **7.3.** No enhancement; virtual light from SW. **7.4.** Specular enhancement; virtual light from NW. Note how, in contrast to the more naturalistic lighting in 7.2 and 7.3, specular enhancement brings out all structures irrespective of their orientation in the bedding plane.
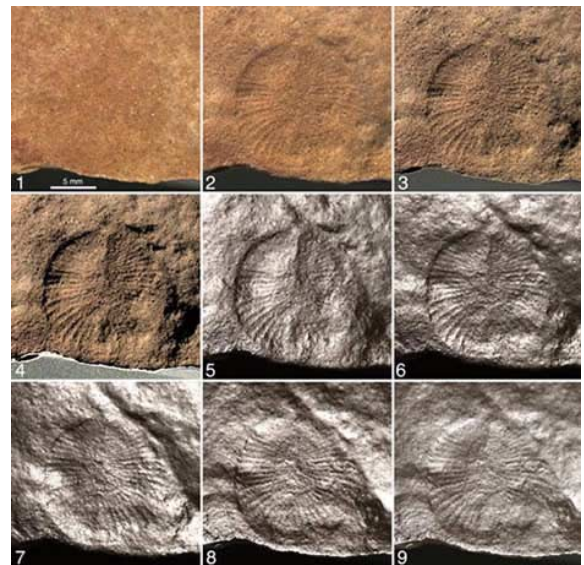
Figure 8. Olenid trilobite, Upper Cambrian Alum Shale, Närke, Sweden. SMNH Ar59484. **8.1.** No enhancement; virtual light normal to bedding. **8.2**. No enhancement; extrapolated PTM space; virtual light from +NW. 8.3. No enhancement; extrapolated PTM space; virtual light from +S. 8.4. Specular enhancement; virtual light from NW.

Figure 9. *Dickinsonia*, negative hyporelief, Neoproterozoic Rawnsley Quartzite, Flinders Ranges, South Australia. SAM P 39886. **9.1.** No enhancement; virtual light from above. **9.2.** No enhancement; virtual light from NW. **9.3.** No enhancement; extrapolated PTM space; virtual light from +NW. **9.4.** Diffuse gain; virtual light from NW. 9.5–9. Specular enhancement; virtual light from various directions.

(Figs. 9, 10) from the Rawnsley Quartzite of South Australia show that the physically impossibly low position of the virtual light source through extrapolation of PTM space may help to bring out faint structures (Figs. 9.3; 10.3, 10.4); also that specular enhancement may bring out details that are otherwise obscured by the granularity of the sandstone (Fig. 9.5–9.9).

PTM imaging of a slab of Cambrian shelly fragments (hyolithids and trilobites) in a dark shale of the Alum Shale Formation of Krekling, Norway, illustrates the use of specular enhancement for amplifying relief and substituting for physical whitening of the specimen (Fig. 5.3).

Fossils of high relief are generally easier to photograph than those of low relief. Here, traditional photographic methods usually produce good results using a proper choice of lighting in combination with surface treatment. The Cambrian trilobite in Fig. 8, from the Alum Shale Formation of
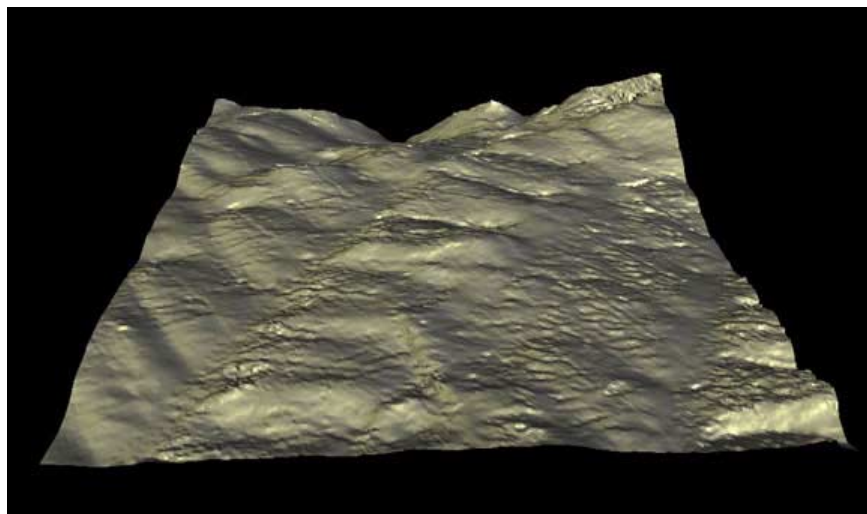
Närke, Sweden is a classic object for palaeontological photography. The different orientations of the virtual light in Fig. 8.2 and 8.3 serve to illustrate the importance of light directions for the understanding of the morphology; the full effect is best seen in the interactive models. As with the specimen in Fig. 5, specular enhancement may substitute for physical whitening in producing a more even surface color (Fig. 8.4).

A promising application of PTM imaging is in trace fossils, where the structures are often faint and oriented in many different directions so that a single lighting mode cannot capture the full morphology. Figures 6 and 7 show two slabs of Lower Cambrian trace fossils in "neutral" virtual lighting (1), and with two directions of the virtual light to demonstrate how differently oriented structures are picked up in other ways (2, 3). Interestingly, specular enhancement serves to outline all structures independently of their orientation because of the strong differences in tone between surfaces nearly parallel to the main plane and those nearly normal to it (4).

These experiments indicate that reflectance transformation techniques offer significant improvement over non-transformed images in some cases, whereas in others the improvement, if any, is marginal compared with traditional techniques. However, in all cases the possibility of

Figure 10. *Spriggina*, negative hyporelief, Neoproterozoic Rawnsley Quartizite, Flinders Ranges, South Australia. SAM P 39887 **10.1.** No enhancement; virtual light from above. **10.2.** No enhancement; virtual light from NW. **10.3.** No enhancement; extrapolated PTM space; virtual light from +NW. **10.4.** No enhancement; extrapolated PTM space; virtual light from +SSW.

Figure 11. Three-dimensional surface of specimen in Fig. 4, reconstructed 2.5 cm across.

interactive manipulation of virtual light in PTM images adds a new dimension to the electronic illustration of fossil specimens.

CONCLUSION

An alternative approach for illustration of low-contrast fossils with minor surface relief is to use a high-precision laser scanner (Lyons et al. 2000). Using such a technique, the elevation data from the scanner can be amplified or surface normals estimated for the purpose of specular enhancement or diffuse gain. However, for small surface relief and high image resolution, a very sophisticated and expensive scanner is needed. In contrast, the photographic apparatus necessary for the PTM technique can be constructed for less than 2000 US dollars. Spatial resolution is also compromised by using a laser scanning system, because the computation of geometric surface normals requires convolution with a kernel having spatial

extent. In the case of PTM , normal estimation for each pixel is performed independently.

In addition to image enhancement, the PTM technique involves an efficient set of acquisition techniques and a file format for the electronic publishing of fossil images where virtual lighting can be freely manipulated. Considering how morphological features of a single fossil specimen are differentially enhanced in a dramatic way depending on lighting, this has the potential of greatly increasing the information content of paleontological images.

The PTM technology is a relatively simple and inexpensive new tool for paleontological illustration, to be used in addition to or in combination with existing photographic techniques. Compared with other methods, it provides the best results for specimens with little color contrast and small but definite relief, but its interactiveness is useful for all types of specimens.

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