TEASING FOSSILS OUT OF SHALES WITH CAMERAS AND COMPUTERS

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ABSTRACT

Simple yet effective methods are available to enhance photographic images of low-contrast and low-relief specimens, such as fossils in shales, without manipulating or retouching the photographs. By applying polarizing filters to camera and light-source(s) in a way analogous to crossing nicols in a petrographic microscope, dramatic results can be achieved where there is a difference in reflectance between fossil and matrix, as with many coalified fossils. For example, this method is ideal for bringing out the shiny films representing soft tissues of Middle Cambrian Burgess Shale fossils. It is also useful in reducing reflections and increasing contrast in specimens that cannot be immersed in liquid (e.g., the Lower Cambrian Chengjiang fauna). Plants and graptolites in shales are other examples of suitable objects for this method. In addition, the use of digital imaging now makes it very easy to use interference between two versions to bring out differences. In this way, images of the same object taken with and without crossed nicols can be contrasted, as well as different colour channels. The result may be a dramatic improvement in the definition of hard-to-see or hard-to-image structures.

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Plain-language summary:

Fossils in shales can be difficult to see and photograph, because they are pressed flat and often do not differ much in colour or tone from the surrounding rock. Simple methods are available, however, that can improve the photographs dramatically. With the help of polarizing filters, such as are found in some sunglasses, directly reflected light can be filtered out. Skin doctors use this method to see and photograph injuries deep in the skin (such as acne), but it is also excellent for fossils that consist of shiny films in shale. Images of specimens from the famous Burgess Shale (containing preserved soft bodies of various animals from the Cambrian Period) show stunning results when processed by this method. The method is also very useful for fossils that are too delicate to be immersed in a liquid (otherwise a common method to reduce glare in photographs). Pictures taken with and without polarized light can also be combined to bring out structures that are invisible in the separate images. This can be done with traditional film techniques, but they are much more efficient when applied to digital images using an image-editing program. The same method can be used to bring out colour differences in a fossil.

INTRODUCTION

Figure 1 shows Cambrian chancelloriids from the Burgess Shale and Wheeler Shale. The specimen from the Burgess Shale (Figure 1A) is preserved both in its soft body and in the bristly exoskeleton consisting of spiny sclerites. The specimen from the Wheeler Shale (Figure 1B) is preserved as limonitic sclerites, without apparent remaining soft tissue. Figures $1A_1$ and $1B_1$ are taken in plain light. Although the specimens are flattened in the shales, the

Figure $1A_1$-B_1

Figure $1A_2$-B_2

images in figures $1A_2$ and $1B_2$ appear three-dimensional because of the photographic techniques used to maximize the contrast between the fossils and the surrounding matrix. These images have been produced by a combination of techniques that are generally available, but remarkably under-used in fossil photography. None of the techniques is new. The present article is intended to show their usefulness to palaeontologists and make them more widely known and applied. Parts of the procedures would be difficult to carry out without digit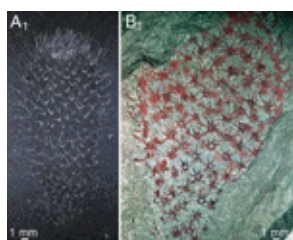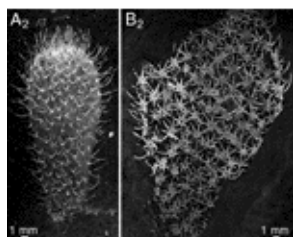ized images and graphic tools such as those included in Adobe Photoshop®, but the principles involved predate the invention of digital imaging.

Technical Note. The photographs in this article (except for Figure 9) were taken with a Leaf Microlumina™ digital camera equipped with a Nikon AF Micro Nikkor™ 60 mm macrophoto lens and extension bellows. Polarizing filters were applied to the lens and light sources as described later. For the originally captured raster images, the highest available resolution (3,380×2,700 pixels) was used. The images were processed on an Apple Macintosh® computer using Adobe Photoshop (version 5.0). Blending modes of layers and channels were applied as described for each picture; adjustment of input and output levels and application of the unsharp mask filter were performed in all cases to optimize the pictures, but the specific settings of these filters are not given for the individual pictures. (See Basic Concepts for a brief explanation of raster imaging, particularly as it applies to work in Adobe Photoshop.) No retouching was done on any of the images.

Museum number prefixes for the illustrated specimens are as follows: **NHM** = Natural History Museum (London) **ROM** = Royal Ontario Museum, Toronto; **USNM** = National Museum of Natural History, Washington, DC; **NIGPAS** = Nanjing Institute of Geology and Palaeontology, Academia Sinica; **NRM** = Swedish Museum of Natural History, Stockholm; **PMU** = Museum of Palaeontology, Uppsala University; and **LO** = Department of Historical Geology and Palaeontology, Lund University.

TECHNIQUES FOR IMPROVING PHOTOGRAPHS

Long before digital imaging had become feasible, various techniques had been developed to improve the quality of photographic recordings. Because the general goal of photography is to convert light from physical objects into permanent images, methods used to modify the quality of the images are extensions of the basic

photographic method itself. Every photograph is dependent on a number of choices by the photographer (which film or filters to use, which exposure, etc.). In that sense, no photograph is objective, and the various ways of improving photographic quality are part and parcel of photography.

The advent of digital imaging has expanded the possibilities of handling images, but has not changed anything in principle with regard to the non-objectivity of photographs. In fact, many techniques built into digital imaging systems are adopted from pre-digital techniques. For example, the much-used unsharp mask, an effective algorithm for increasing the apparent sharpness of digital images, stems from an ingenious nondigital technique (e.g., Malin 1993) by which a deliberately blurred positive copy of a negative is superimposed upon the original negative. Similar areas (i.e., those that are blurred in both original and copy) tend to cancel each other whereas the nonsimilar ones (i.e., sharp in original but blurred in copy) do not. The effect is that sharp areas in the original are enhanced, blurred subdued.

In many areas of science, image-improvement techniques are standard procedures to bring out visual detail in recordings from various types of devices. In fact, one could argue that every recording from an instrument, whether a camera or a seismograph, needs to be improved by various methods in order to be useful.

Clearly, however, digital techniques have also made radical image manipulation very easy, and so the question of the objectivity, or truthfulness, of a photograph has become even more vexing than was the case previously. The issue is now purely ethical, not technical. Manipulating an image with the intention to deceive is fraudulent, equivalent to fudging experimental data. Thus, as with experimental data, any deviation from standard procedure in obtaining an image must be accounted for. The recommendation by Hughes (1999) to include the original image alongside the processed images is well taken.

Based on the purpose behind the procedure, we may distinguish among restoration, enhancement, and manipulation of photographic images.

Restoration is intended to overcome the limitations of the recording device, to bring an image as close as possible to what was originally perceived by the eye, naked or through an instrument using visible light.

Enhancement is intended to bring out certain features of the image, in a way different from what the eye per-

ceives. Examples are false colours, edge accentuation, and retrodeformation.

Manipulation is intended to add information to an image that was not originally in it, for example by retouching, or drawing in of contours.

There is no distinct boundary between restoration and enhancement, but both may be said to employ objective procedures, acting equally upon the whole picture using some predetermined method or algorithm. Manipulation, in this context, implies that different parts of the images are treated differently as a result of ad hoc decisions by the operator.

A specific case is retrodeformation, restoring deformed fossils or sediments (e.g., Hughes 1999). Although such procedures technically amount to deformation of the photographic image, the algorithms employed are typically applied to whole images. Because the specific purpose is to visualize an earlier existing state of the object, this procedure is to be regarded as restoration or enhancement, rather than manipulation.

Techniques for image processing are today generally available with the common access to digital imaging programs, such as Adobe Photoshop, and more specific software for image enhancement and analysis. Restoring or enhancing images beyond the basic adjustment of brightness and contrast is still not common practice. However, the techniques now available to nearly all palaeontologists are very powerful for solving age-old imaging problems, such as how to bring out fossils with no appreciable relief or colour difference from the background.

The possibilities of transforming images using digital techniques are endless. Most applications of these techniques add nothing to the visible information content of the images, but rather amount to distortion. Except for their possible aesthetic value, they are of little interest for scientific imaging. The methods discussed here are intended to restore and enhance, not manipulate, the informative value of pictures of fossils.

A digital camera is not crucial to the techniques described here, because the images can also be digitized with the help of an ordinary flatbed scanner or slide scanner. However, in addition to providing a more direct path between object and picture, digital cameras help experimentation in that the results of each exposure are immediately visible.

USING POLARIZED LIGHT

Light reflected from a surface is differently polarized depending on the angle of incidence, the optical properties of the material, and the topography of the surface. If polarized light is used for illumination, changes in the polarization of the returned light can be analyzed using an additional polarization filter in front of the detecting

device. This is the principle of epi-polarizing microscopes and other similar instruments. The ability of such devices to separate directly reflected light from backscattered light is used, for example, in ophthalmology (Fariza et al. 1989) and dermatology (Philip et al. 1988; Anderson 1991; Phillips et al. 1997).

The principle is eminently useful for fossil photography as well. Rayner (1992) used it to obtain high-contrast images of coalified fossils in dark shales, and Boyle (1992) applied it to Burgess Shale fossils. The technique is simple. In the setup used here, the camera lens is fitted with a regular polarizing filter, and spot lamps used for the illumination are also provided with polarizing filters that can be rotated in front of the lamps (filters of the appropriate size can be cut from commercially available gelatin filters). The filter at each of the light sources is then rotated individually so as to obtain maximum extinction of reflections from the object (or a reflecting object temporarily inserted in front of the camera lens); this is most easily done if the other light sources are covered or put out when the filter of one source is adjusted. The procedure is analogous to crossing the nicols in a petrographic microscope and will consequently be referred to here as *crossed nicols* (the term *nicol* in current usage refers not only to a Nicol prism, but to any filter that polarizes light). Further practical considerations are discussed by Rayner (1992) and Boyle (1992).

With this setup, dramatic contrasts may be obtained from otherwise very low-contrasting material, depending on whether the light at reflection keeps its original polarization or becomes more or less strongly repolarized. Also, because direct reflections are repressed, the effect is similar to that obtained when a specimen is immersed in water or some other clear fluid. Both these effects are very useful when photographing fossils from two of the classic Cambrian preservation lagerstätten, the Burgess Shale and the Maotianshan mudstone (with the Chengjiang fauna), as well as other fossils, such as graptolites and plants, preserved in shales or mudstones.

Burgess Shale

The Middle Cambrian Burgess Shale in British Columbia is not only famous for its exquisitely preserved fossils, but also infamous for the difficulties it presents to the photographer. The fossils are generally preserved in a shiny film that differs only slightly in colour from the surrounding rock. Commonly interpreted as an aluminosilicate film (Conway Morris 1977; Whittington 1985; Conway Morris 1990; Towe 1996; Orr et al. 1998), its reflectant matter appears to consist mainly of thermally altered organic carbon (Butterfield 1996). The reflectance of this film makes it possible to photograph the fossils by tilting them so that the directly reflected light (ultraviolet light is commonly used for

increased contrast) falls into the camera lens (Conway Morris 1985). The same property, however, also allows us to make use of polarized light to increase the contrast between fossils and shale (Boyle 1992).

Figure 2A.

Figure 2B.

In Figure 2, a specimen of *Waptia* (cf. Briggs et al. 1994, pp. 157–158) from the Burgess Shale has been immersed in water and photographed without (Figure 2A) and with (Figure 2B) crossed nicols. The image taken without crossed nicols shows the low contrast between the dark shale and the films representing the fossil soft parts. When crossed nicols are applied (Figure 2B), the improvement is dramatic: the outlines of the soft parts are now clearly visible against the shale surface.

Figure 3A.   **Figure 3B.**

The same procedures were applied to the images in Figure 3, showing the sponge *Vauxia* (cf. Rigby 1986) from the Burgess Shale. The details of the organic skeleton are considerably enhanced under crossed nicols (Figure 3B).

Figure 4A.   **Figure 4B.**

Figure 4 and Figure 5 show grey-scale images of two more Burgess Shale fossils, *Marrella* (cf. Whittington 1971) and *Burgessia* (cf. Hughes 1975). In Figure 4A and Figure 5A, the specimens have been immersed in water and photographed without crossed nicols. (The dark irregular patch in Figure 4 is squeezed-out internal fluids and/or decomposed body tissues, a common occurrence with *Marrella*.) In Figures 4B and 5B, the specimens are photographed with crossed nicols. All four pictures represent a single colour channel.

Figure 5A.   **Figure 5B.**

A number of high-quality photographs of Burgess Shale fossils have been produced throughout the years; see, for example, the photograph of *Thaumaptilon* by

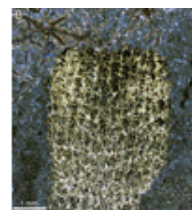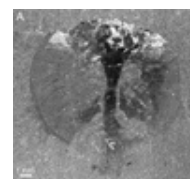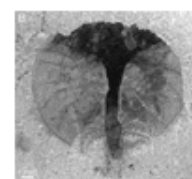B.K. Harvey in Conway Morris (1993), figures 1–2, the suite of photographs by C. Clark in Briggs et al. (1994), the ctenophore images by several photographers (including B. Boyle) in Conway Morris and Collins (1996), or the figures of *Alalcomenaeus* in Briggs and Collins (1999). These have been taken using various methods, including ultraviolet radiation, direct reflections, low-angle lighting, water immersion, and crossed nicols.

Chengjiang

The early Cambrian Maotianshan mudstone in south China, containing the exquisitely preserved Chengjiang fauna (e.g., Hou and Bergström 1997), represents a different problem for photography than the Burgess Shale. Although flattened, the fossils are preserved in considerably higher relief than those of the Burgess Shale. Consequently, low-angle light can bring out good details. Also, there is commonly a colour difference between fossils and matrix, brought out by iron-rich red films representing part of the soft bodies. The main problem in photographing them is, instead, that the mudstone is very friable and cannot be immersed in a fluid without breaking apart. Thus the common technique of photographing fossils immersed in water, glycerin or some other suitable liquid to remove reflections and increase contrast cannot be used. This is where the

Figure 6A.   **Figure 6B.**

technique of polarizing the light comes in useful. (The red colour of the Chengjiang fossils also makes them suitable for photography with orthochromatic films, which are insensitive to red, as shown in the photographs by U. Samuelsson in Hou and Bergström 1997.)

Figure 6 shows a specimen of *Yunnanozoon* from the Chengjiang mudstone (cf. Hou et al. 1991; Chen et al. 1995; Dzik 1995; Shu et al. 1996). Figure 6A is taken without, and Figure 6B with, crossed nicols. The difference in result is less dramatic than in the case of the Burgess Shale fossils; however, the use of crossed nicols has an effect similar to that of immersing the specimen in liquid, namely to reduce reflections and enhance contrasts.

Other carbonized fossils

The effects of using polarized light for the photography thus will range from good to spectacular, depending on the differences in reflectance of the objects. Only experimentation will tell how useful the method is in any particular case, but carbonized fossils seem consistently to yield fine results, as noted by Rayner (1992).

Two further examples of such fossils are given here. Figure 7 shows a Tertiary leaf from Spitsbergen. In this case, the surface topography of the leaf comes out best in unpolarized light (Figure 7A), whereas the use of crossed nicols brings out the contrast with the matrix as well as the colour differences within the leaf (Figure 7B). Figure 8 shows graptolites from Ordovician grey shales of Scania, Sweden. Although there is a colour difference between fossils and matrix that comes out without crossed nicols (Figure 8A), a clear contrast is not obtained until crossed nicols are applied (Figure 8B
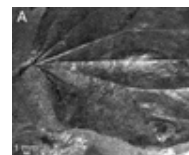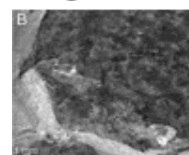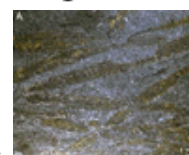

Figure 7A.

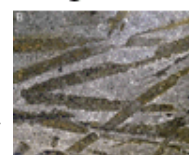**Figure 7B.**

Figure 8A.

Figure 8B.

A SECRET OF TWO PICTURES

The technique with polarized light is often useful in itself; further enhancements may be unnecessary. However, much as in the case of the unsharp mask, interference between two similar but not identical images may bring out information that is not obvious from any one of the single images. Figure 9 is constructed to illustrate the principle. The left and middle images appear identical to the eye, but they are not. In the middle image, the *Palaeontologia Electronica* logo has been superimposed on the original picture and given an opacity value of 1% (i.e., it is so transparent as to be practically invisible). When the middle image is subtracted from the left one and the levels are adjusted, the logo appears again (right image), as an expression of the

Figure 9.

areas in which the two images differ ever so slightly. Note that the third image can only be recovered when the first two, imperceptibly different images are combined to interfere with each other; thus the third image can be regarded as being embedded in both, not just one, of the first two.

This case is constructed, but the principle can often be profitably applied to palaeontological imaging. If different parts of the object reflect light differently, in frequency or polarization, two or more recordings can be made to interfere with one another so as to bring out the regions in which they differ. In this way, a picture taken in plain light can be pitched against one taken with crossed nicols. Another pos-

IMAGE INTERFERENCE IN DIGITAL SYSTEMS

Although image interference can be performed with traditional photographic films, digital techniques speed up the procedure considerably and allow for controlled experimentation and exact repeatability. The options available in the blending modes of Adobe Photoshop, although they do not allow total control of the settings, are eminently useful for this purpose.

The blending modes can be used with different drawing tools, but for the present purpose they only need to be used from the "Layers" palette or from the "Calculations" option on the "Edit" menu. The options that are most useful are "Difference" and "Subtract." They work in similar ways, by subtracting the pixels value of one layer from that of the other. See "Basic Concepts" for an explanation of some terminology of digital images as used in Adobe Photoshop.

The blending modes in Adobe Photoshop act by calculating a new value for each pixel based on the values of the corresponding pixels in the two original images (which must have a one-to-one pixel correspondence). "Difference" and "Subtract" both calculate the numerical difference between the two values, but "Difference" returns negative numbers as positive, whereas "Subtract" returns them as 0.

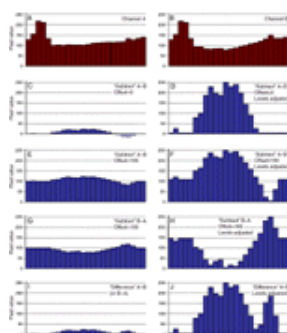The results of the two blending modes is shown diagrammatically in Figure 10, which represents a cor-

Figure 10.

responding row of pixels in two versions (A–B) of a simplified grey-scale image. The blue diagrams (C–J) show three applications of "Subtract" and one of "Difference," with levels not adjusted (left column) and adjusted (right column). "Subtract" renders negative resulting values (light blue in C) as 0, thus losing part of the information, but this may be countered by using an "Offset" setting that will bring all values above 0 (E, G). Switching the order of subtraction (from A – B to B – A) creates images that are each other's negatives (E–F vs. G–H), provided that no subtraction values are negative.

Because "Difference" makes no difference between positive and negative results (I–J), it does not matter which image is subtracted from which; this method may therefore create artifacts, such as pits in the surface being rendered light (cf. F and J). "Difference" is, however, more flexible to use in Adobe Photoshop than "Subtract", because it can be simultaneously applied to multiple channels (e.g., colour pictures). Further, because it can be applied from the "Layers" palette, it allows one to view continuously the effects of adjustments of highlights, shadows, and midtones of the two original images. One may therefore use the slide controls in the levels adjustment to obtain maximum contrast visually.

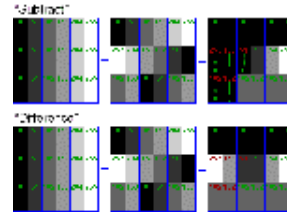Figure 11 shows the effect of the two blending modes on a chart having different shades of grey.

Figure 11.

APPLICATIONS OF IMAGE INTERFERENCE

Although the information brought out by image interference between lighting modes, colour channels, and so on is often significant and useful, the application of these techniques must be done with care. Visual artifacts may be created, not only because Adobe Photoshop's "Difference" blending mode, as mentioned, renders all subtraction results of pixel values positive, but also because the signal intensity in each image results from interactions of a number of factors (colour, morphology, reflectance, spectrum and angle of incident light, etc.). When several complex signals are combined the results become more difficult to interpret.

Nonetheless, when the difference between the images is pronounced and due to only one or a few factors, image interference may yield spectacular results. Figure 12 shows an assemblage of fossils, two chancelloriids and one sponge from the Burgess Shale, photographed under water without (Figure 12A) and with (Figure 12B) crossed nicols. The chancelloriids have three distinct types of tissue preservation: sclerites preserved in pyrite (bright in both Figures 12A and 12B), sclerites preserved as a shiny film (semibright in Figure 12A, dark

Figure 12A.

Figure 12B.

Figure 12C.

Figure 12D.

in Figure 12B), and integument preserved as a nonshiny film (same colour as matrix in Figure 12A, darker than the matrix in Figure 12B). When Figure 12B (with its darker fossil relative to the matrix) is subtracted from
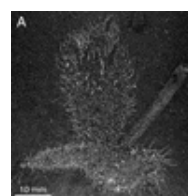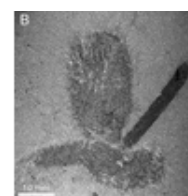
Figure 12A (with its lighter fossil), the brightness gap between the films (most sclerites and integument; the pyritized sclerites acquire a brightness intermediate between matrix and films) comes out in bright pixels, contrasting sharply with the dark matrix (Figure 12C; cf. also Figure 10A–B, E–F, in which the central part of the picture acquires higher pixel values after the subtraction).

Subtracting channel A from B, the inverse picture is obtained (Figure 12D; cf. Figure 10E–F vs. G–H). Such a negative image is most easily produced directly through the "Inverse" command in Adobe Photoshop and may turn up to be better for viewing details than the positive image (compare the frequent use of negative images in astronomy).

An Adobe Photoshop PSD file (1.8 MB), containing the original colour images (in reduced resolution) for Figure 12, is enclosed to enable the reader to experiment with layer and channel interference.

Another example of the same image interference technique is between colour channels of one colour picture. Figure 13A shows a specimen of *Chancelloria* from the Middle Cambrian Wheeler Shale of Utah. The sclerites are spectacularly preserved in limonite (presumably arising from the weathering of pyrite) and would seem to need no enhancement. Crossed nicols are often applied with advantage on this material, as in this picture, because the rock is a friable mudstone that often does not survive immersion in liquid. Nonetheless, the sclerites form an intricate meshwork, and many rays are indistinct because they are somewhat buried and lie under a very thin layer of matrix. By subtracting the green channel
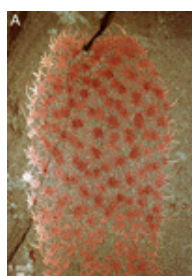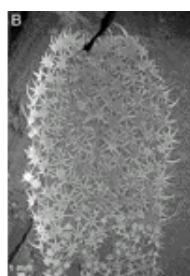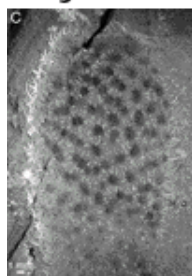

Figure 13A.

Figure 13B.

Figure 13C.

Figure 13D.

(Figure 13C) from the red one (Figure 13B), we achieve a highly enhanced contrast between sclerites and matrix, making the bright sclerites appear as if they were suspended over a black background (Figure 13D). The uneven colouring of the central versus peripheral sclerites in the original picture (Figure 13A) has disappeared in the final image, because the procedure singles out spectral colour differences rather than differences in intensity. As the sclerites lie in several layers, a three-dimensional effect obtains. The result could not have been achieved simply by enhancing the contrast of the red channel.

Whenever a colour difference exists in a picture, it may be enhanced by this procedure. The picture of *Yunnanozoon* (Figure 6), in addition to the typical reddish tint, has bluish areas marking out the tissues surrounding the gut. By subtracting the blue channel from the green one, the bluish areas were enhanced by darkening; the resulting channel was then blended with the original colour image (using Adobe Photoshop's "Multiply" mode, which has the same effect as superimposing the images upon each other) to get back to a more natural-looking image (Figure 14).

In the case of the graptolite image in Figure 8, subtraction of the green channel of the image taken under crossed nicols (Figure 8B) from that of the unpolarized image (Figure 8A) enhances the carbonized structures of the graptolite rhabdosomes and brings out features that were obscure in the original image (Figure 15). Subtracting the green channel of the original picture of *Burgessia* (Figure 5A) from the red one in the image taken under crossed nicols (Figure 5B) simultaneously brings out structures in the darkest and the lighter parts of the original images (Figure 16).
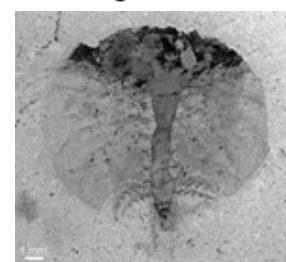

Figure 14.

Figure 15.

Figure 16.

FURTHER CONSIDERATIONS

The results of the methods described here are not always easy to predict; experiments are necessary for each particular case of preservation. For example, some preservational modes of Burgess Shale fossils do not yield higher contrast using crossed nicols. Dark graptolitic shales are sometimes disappointing because both fossils and matrix extinguish almost completely under crossed nicols, yielding poorer contrast than without polarization of the light. Conversely, some plant fossils to which I have applied this method yielded such high

contrasts that the digital camera captured practically only outlines; in such cases the use of photographic film, with its higher tonal range, may be advantageous.

In the examples of image interference given here, only a few methods (light polarization and colour separation) have been used to produce the alternative images. Obviously, other methods can be used to produce pairs suitable for image interference, such as different frequencies of lighting, different filters, and different detectors in an instrument (for example, secondary-electron versus backscattered-electron or cathodoluminescence detectors in a scanning electron microscope).

Finally, a number of systems for computerized image processing and analysis are available, some of them without charge (e.g., NIH Image). Using computer algorithms to find edges, select areas of certain colour or shape, filter out certain frequencies of noise, and so on, goes one step beyond the application of simple calculations uniformly across an image as demonstrated here, and so it may be seen as pattern analysis rather than imaging. At any rate, the discussion of such techniques would be the object of an entirely different article.

ACKNOWLEDGEMENTS

BASIC CONCEPTS

Adobe Photoshop works with *raster images,* such as those acquired from a scanner or a digital camera.

The smallest element in a raster image is a *pixel* (picture element). Pixels are rendered square, as in a chess board. Adobe Photoshop stores grey-scales as 8-bit images; they are said to have a pixel depth of 8 bits. A bit can have one of two values (0 or 1), which means that an 8-bit pixel can have $2^8 = 256$ different values, corresponding to 254 shades of grey (1–254) plus black (0) and white (255).

In colour pictures, there are three (the additive complementary colours red, green, and blue; RGB, used for screen displays) or four (the subtractive complementary colours cyan, magenta, and yellow plus black; CMYK, used for printing) separate pictures, stored in separate 8-bit *channels*. Each channel has the appearance of a grey-scale picture taken through a colour filter; displayed in its proper colour together with the other ones, it will give the right colour blend.

Adobe Photoshop also allows the storing of several image *layers* in each file. A layer may consist of one of more channels.

Brightness and contrast of an image can be modified in several ways in Adobe Photoshop, through adjustment of *levels* or *curves*. In the levels control, the pixel values of an image are represented by a histogram, in which the height of each of the 256 bars represents the number of pixels with that value in the image. In the curves control, the user can adjust the shape of a curve defining how each original pixel value of an image is to be translated into a new value. Whereas the curves control allows more flexibility, the levels control is more intuitive and can be recommended for most practical purposes.

The resolution of the image is determined by the original image quality and the pixel frequency. There is no point in increasing the *pixel frequency* beyond what the actual resolution of the image justifies (except to adjust the magnification of an item in a composite raster image), but the pixel frequency can profitably be adjusted *downwards* to provide optimal file size. Here are some rules of thumb. For images to be printed with a halftone screen (consisting of black dots with varying sizes; this is the usual mode of printing to paper), the frequency of pixels should be 1.5-2 times that of the screen. For a 150 lpi (lines per inch) halftone screen, the image should then have a resolution of 225-300 ppi (pixels per inch; with respect to the intended final size). Computer screens and web browsers optimally display images with a 1:1 correspondance between image pixels and screen dots. Thus an image intended to take up half the width of an ordinary 640×480 dpi (dots per inch) computer screen should be 320 pixels wide.

The *unsharp mask* filter is used to restore sharpness to images that have been blurred during the photographic process. It should be applied sparingly, after any necessary transformation of the image (such as resampling of pixels during nonorthogonal rotation or a change of resolution) has been performed. The filter identifies pixels that differ from surrounding ones by more than a specified *threshold* value, and it increases the contrast by a specified *amount*. In addition to threshold and amount, the radius of sampled pixels used for the comparison can also be set. Normal values are 1-2 pixels *radius* and 50-200% amount. Threshold values should be set depending on the nature of the figure; for example, the value can be selected so as to avoid accentuating the grain of the matrix surrounding a fossil.

The effects of using the unsharp mask will typically be more pronounced in a computer screen display than when printed to paper because the halftone screen used for printing will have a lower frequency than the raster image. Thus, when the image is intended for printing, the threshold and amount settings may be set somewhat higher than for screen display.

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FIGURE 1. Images of Middle Cambrian chancelloriids. A. *Allonnia*, Burgess Shale, British Columbia (ROM 49601A). Immersed in water. A_1. Plain light. A_2. Red channel of image taken with crossed nicols subtracted from green channel of image in unpolarized light, using Adobe Photoshop's "Subtract" blending mode (settings: Opacity = 100, Offset = 75, Scale = 1). Levels subsequently adjusted. B. *Chancelloria*, Wheeler Shale, Utah (USNM 509795). B_1. Crossed nicols. B_2. Red channel subtracted from green channel, using Adobe Photoshop's "Difference" blending mode and adjustment of levels.Click on image to toggle between A_1, B_1 and A_2, B_2.
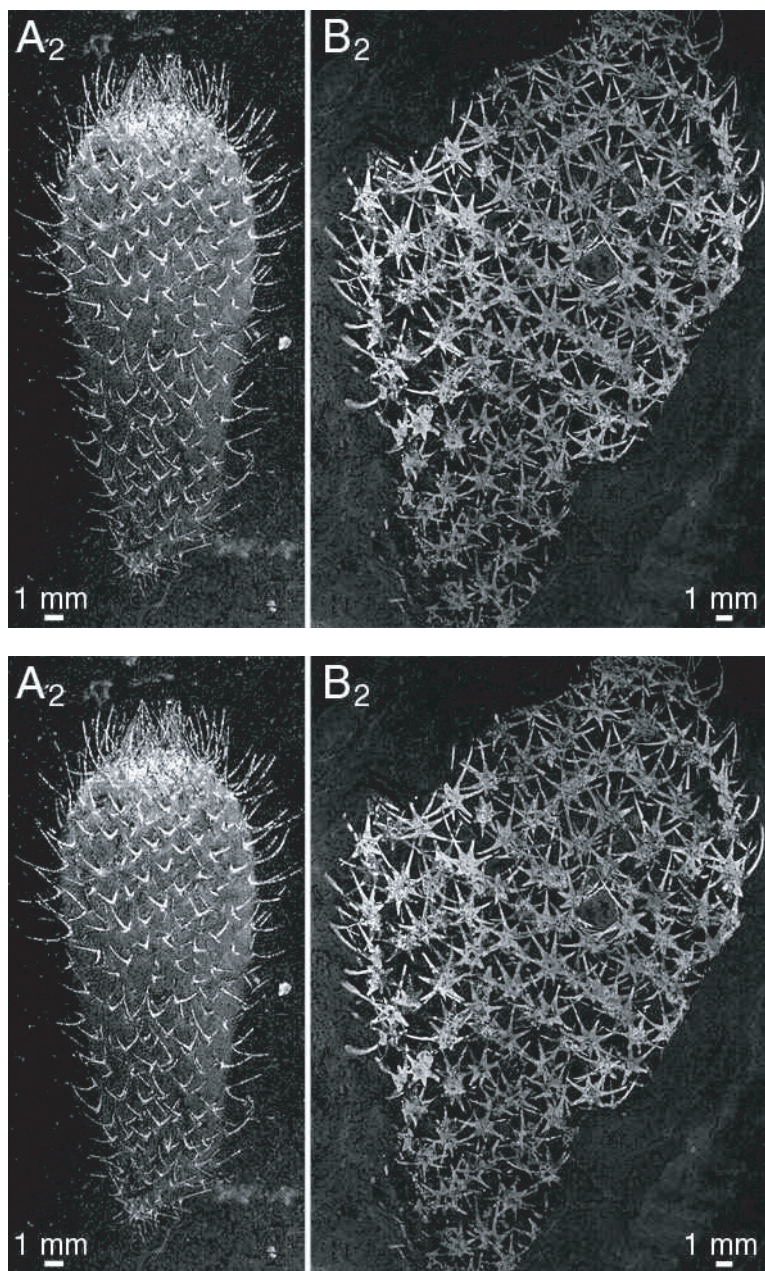
FIGURE 2. A specimen of *Waptia* from the Burgess Shale, British Columbia (PMU Ca1). Immersed in water. A. Without crossed nicols. B. With crossed nicols. (Click on the picture to toggle between different views.)
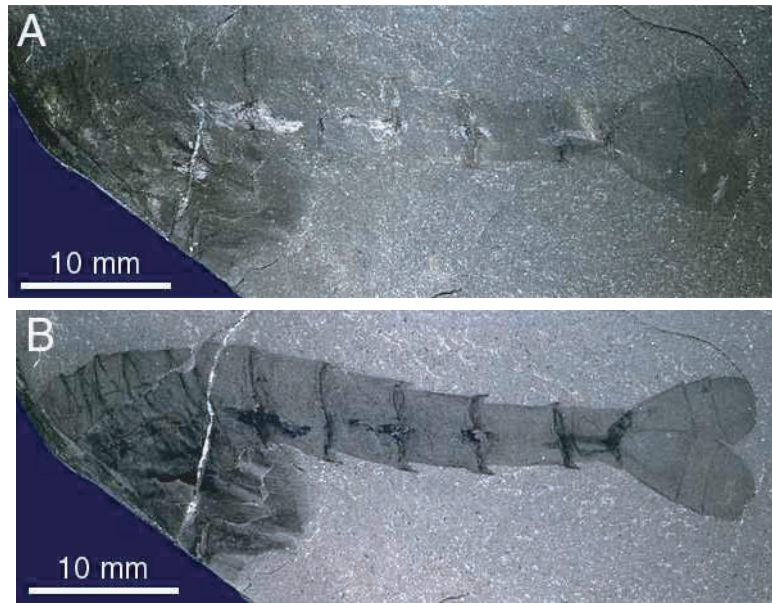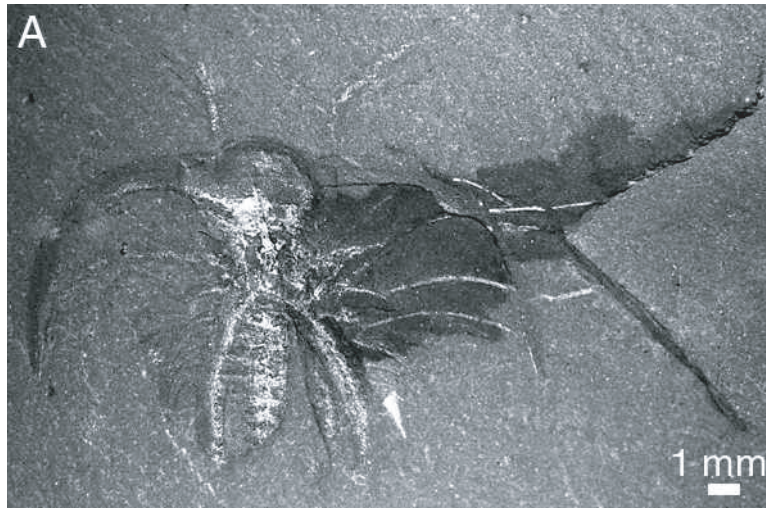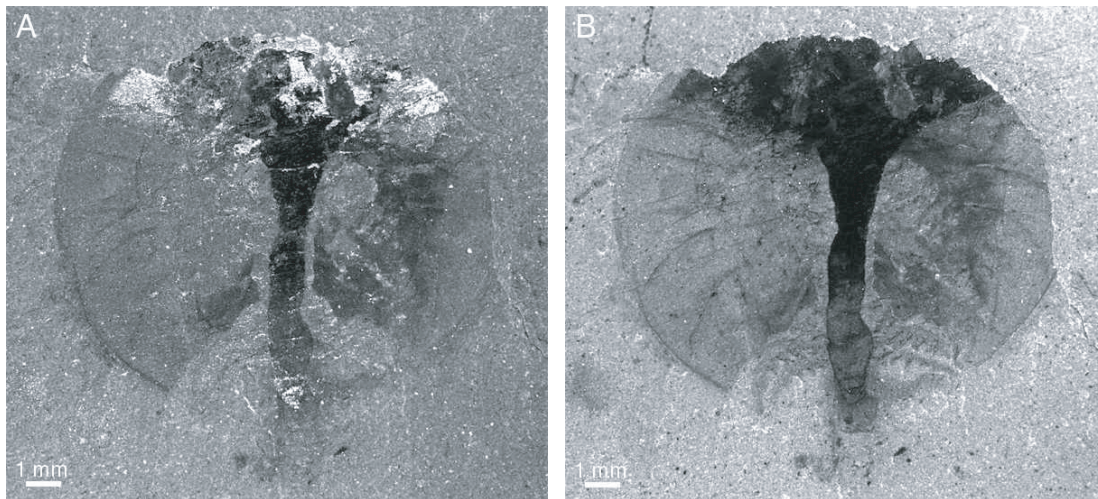
FIGURE 3. A specimen of **Vauxia** from the Burgess Shale, British Columbia (ROM49599A). Immersed in water. A. Without crossed nicols. B. With crossed nicols. (Click on the picture to toggle between different views.)
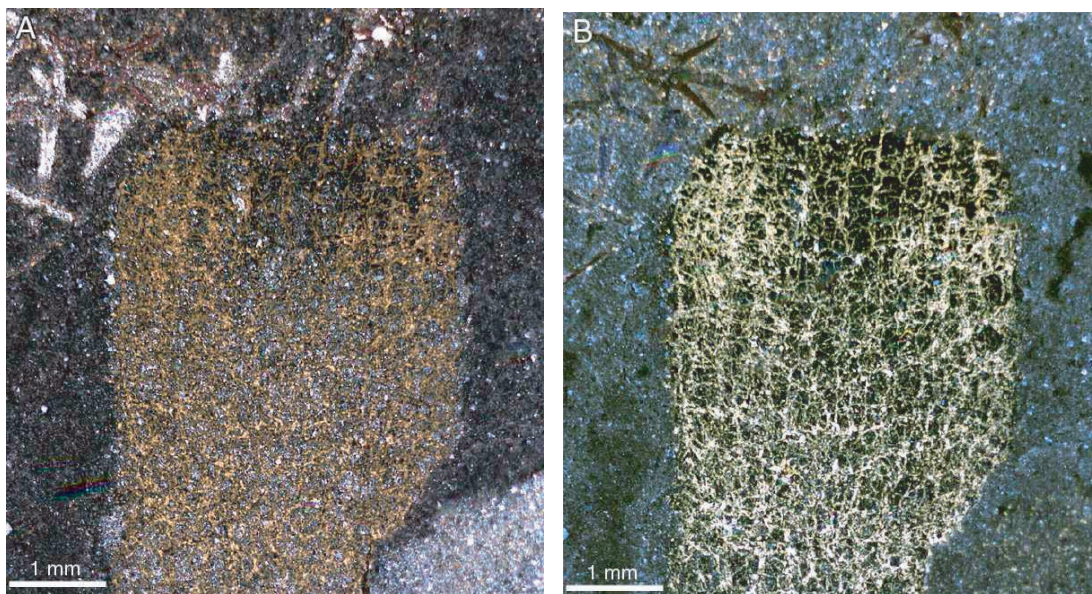
**FIGURE 4.** A specimen of *Marrella* from the Burgess Shale, British Columbia (LO8101t). Immersed in water. A. Without crossed nicols; blue channel. B. With crossed nicols; red channel. (Click on the picture to toggle between different views.)

FIGURE 5. A specimen of *Burgessia* from the Burgess Shale, British Columbia (LO8103t). Immersed in water. A. Without crossed nicols; green channel. B. With crossed nicols; red channel. (Click on the picture to toggle between different views.)

FIGURE 6. *Yunnanozoon* from Chengjiang, South China (NIGPAS 115437). A. Without crossed nicols. B. With crossed nicols. (Click on the picture to toggle between different views.)
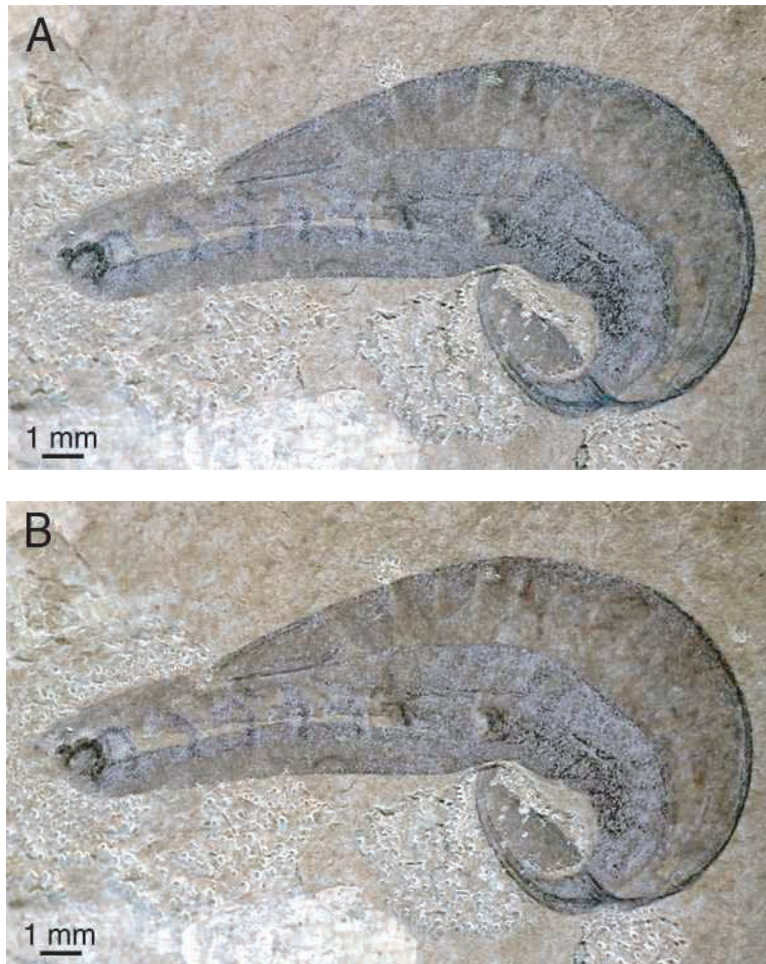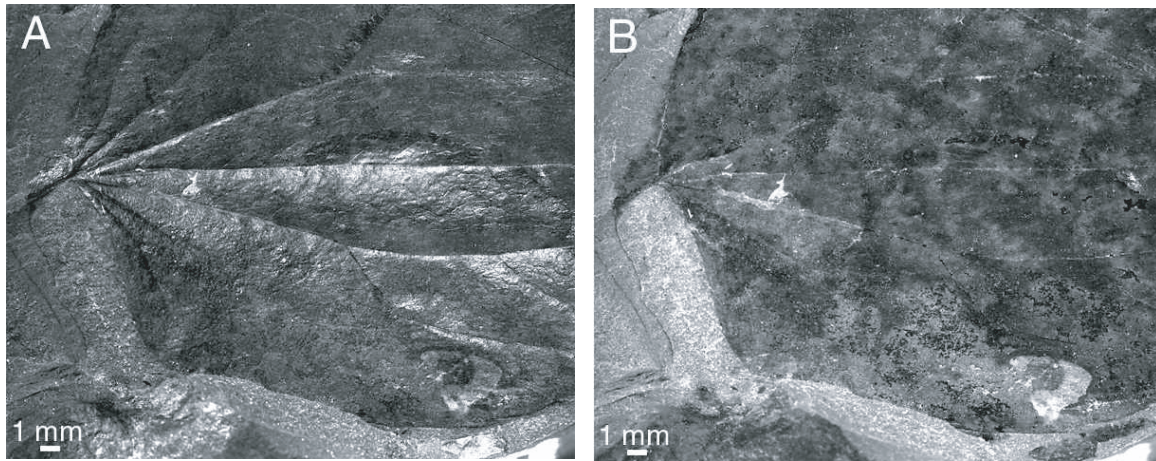
FIGURE 7. Leaf of *Trochodendroides* (Cercidiphyllaceae), Lower Paleocene, Firkanten Formation, Kolfjellet, Spitsbergen (NRM S051710). Red channel. A. Without crossed nicols. B. With crossed nicols. (Click on the picture to toggle between different views.)
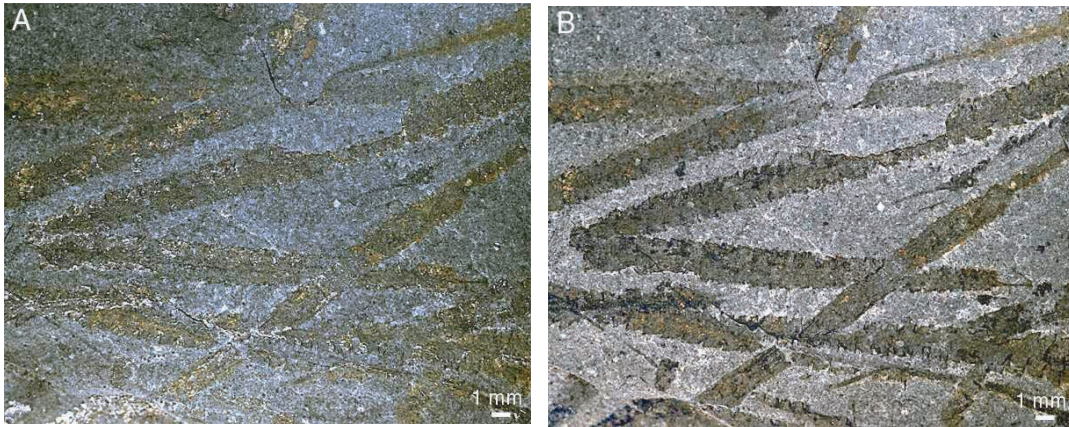
FIGURE 8. *Graptolites* (Climacograptus), Upper Ordovician, Sularps Kvarn, Fågelsången, Scania (NRM Cn 54044). Immersed in water. A. Without crossed nicols. B. With crossed nicols. (Click on the picture to toggle between different views.)

FIGURE 9. Two imperceptibly different images (left and centre) give the image to the right when the difference of their pixel values is calculated using Adobe Photoshop's "Difference" blending mode (levels subsequently adjusted). Note that this operation will not work on the file used for screen display, because the JPEG compression destroys the information subtly hidden in the images. To repeat the operation, use the uncompressed file in TIFF format (720 kB). Copyright of photograph: The Natural History Museum, London 1999 (Specimen image no: NHM PP DI 00075). Copyright of logo: Coquina Press 1998.

FIGURE 10. Diagram showing the principles of the channel (or layer) blending modes "Subtract" and "Difference" in Adobe Photoshop. Each bar in the histograms represents one pixel in an image, the height of the bar corresponding to the pixel value, from 0 (black) to 255 (white). The right-hand column of the blue diagrams (D, F, H, J) shows the result of a level adjustment to extend the range of values from 5 (near-black) to 250 (near-white). A–B. Two versions of an image, with slight nuance differences, mainly in the central part. C–D. "Subtract" mode, with no offset. Note negative values in C, representing an area where B is brighter than A, which will be rendered as 0 (5 after level adjustment in D). E–F. Same as C–D, except that offset value (the value added to the result of the subtraction) has been set to 100. Note that the negative values in C are now positive, and the information in that part of the pictures will be retained. G–H. Same as E–F, but with A subtracted from B rather than the opposite. Note that the resulting curves are negatives of those in E–F. I–J. "Difference" mode. Note that the valley (dark) in F is now rendered as a peak (bright).
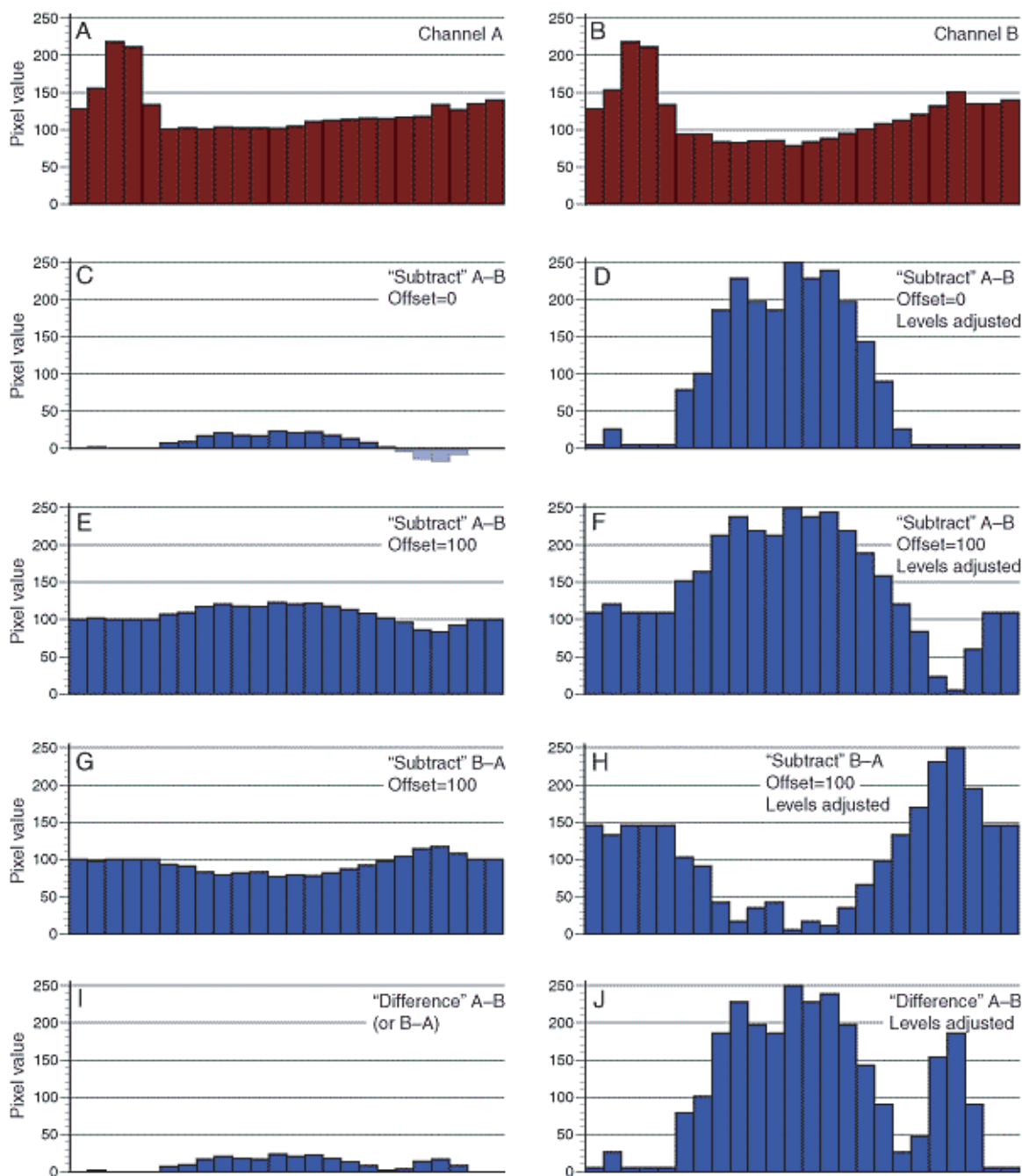
FIGURE 11. The effect of the Adobe Photoshop channel (or layer) blending modes "Subtract" (Offset = 0) and "Difference" on various shades of grey. The two left charts in each row represent the two layers to be blended; the right one the result. Pixel values are given for each field; for negative subtraction results the value is in red. Diagram showing the principles of the channel (or layer) blending modes "Subtract" and "Difference" in Adobe Photoshop. Each bar in the histograms represents one pixel in an image, the height of the bar corresponding to the pixel value, from 0 (black) to 255 (white). The right-hand column of the blue diagrams (D, F, H, J) shows the result of a level adjustment to extend the range of values from 5 (near-black) to 250 (near-white). A–B. Two versions of an image, with slight nuance differences, mainly in the central part. C–D. "Subtract" mode, with no offset. Note negative values in C, representing an area where B is brighter than A, which will be rendered as 0 (5 after level adjustment in D). E–F. Same as C–D, except that offset value (the value added to the result of the subtraction) has been set to 100. Note that the negative values in C are now positive, and the information in that part of the pictures will be retained. G–H. Same as E–F, but with A subtracted from B rather than the opposite. Note that the resulting curves are negatives of those in E–F. I–J. "Difference" mode. Note that the valley (dark) in F is now rendered as a peak (bright).
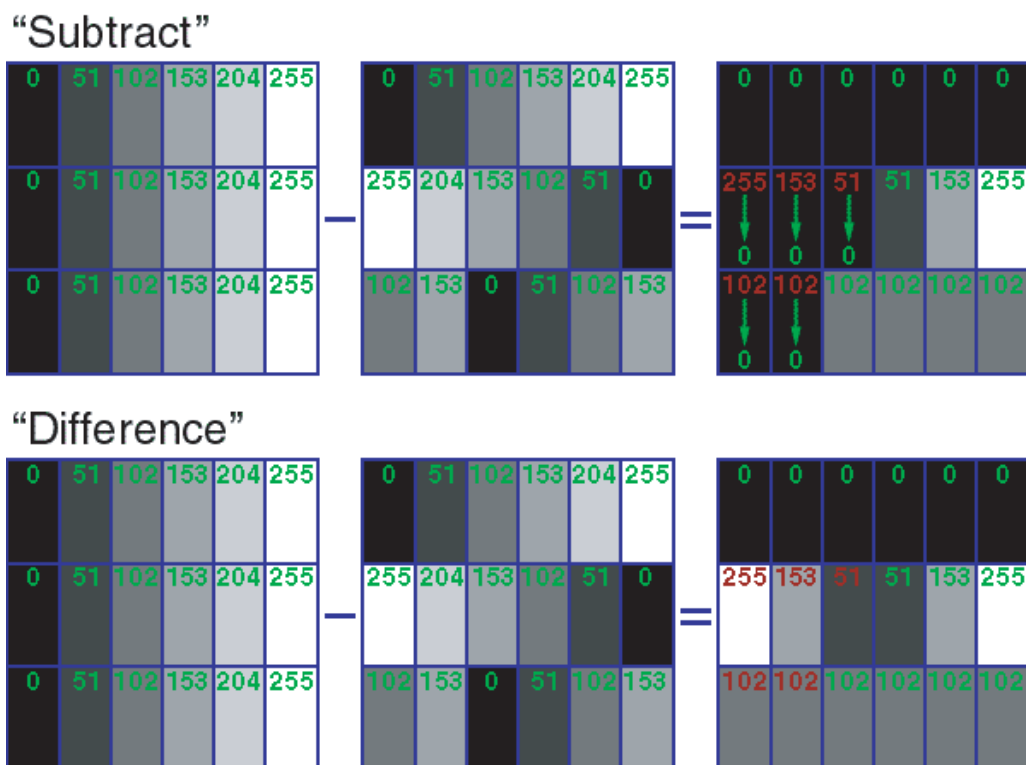
FIGURE 12. Two specimens of *Chancelloria* and one of the sponge *Vauxia* from the Burgess Shale, British Columbia (ROM 49605). Immersed in water. A. Without crossed nicols; green channel. B. With crossed nicols; green channel. C. Image obtained by subtracting the pixel values of B from those of A, using the Adobe Photoshop "Subtract" blending mode (settings: Opacity = 100, Offset = 100, Scale = 1) and subsequently adjusting the levels in the combined channel. D. Image obtained as in C, except that values of A are subtracted from those of B (this has the same effect as inverting the values of C). (Click on the picture to toggle between different views, or select one of the following links: A, B, C, D.)
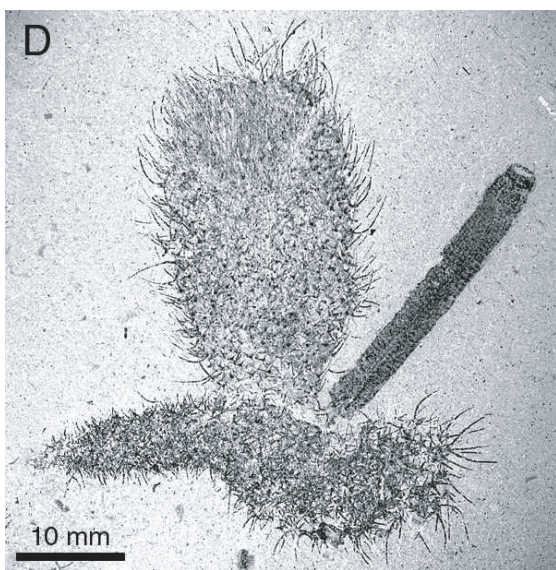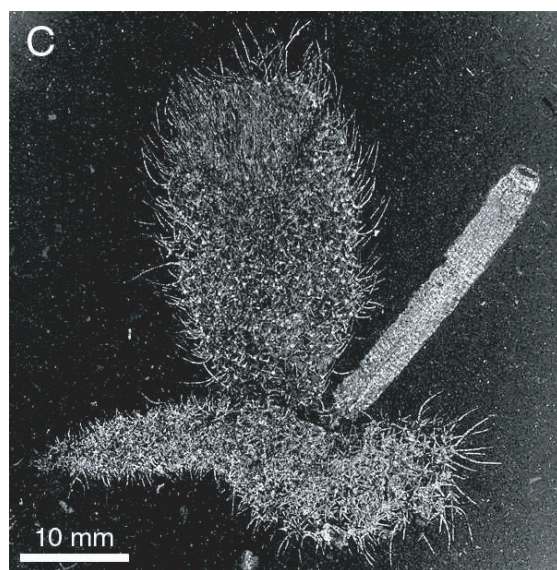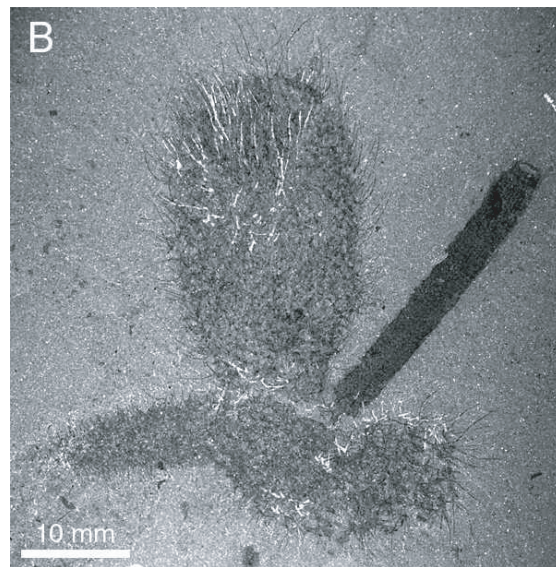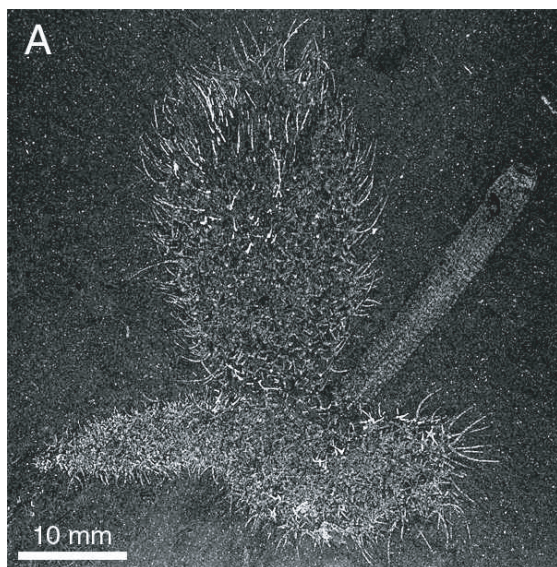
FIGURE 13. *Chancelloria* from the Middle Cambrian Wheeler Shale, Wheeler Amphitheater, Utah (USNM 509794). A. With crossed nicols. B. Red channel. C. Green channel. D. Image obtained by subtracting the pixel values of C from those of B, using the Adobe Photoshop "Difference" blending mode, adjusting the levels of the B channel for optimal contrast, and subsequently adjusting the levels in the combined channel. (Click on the picture to toggle between different views, or select one of the following links: A, B, C, D.)
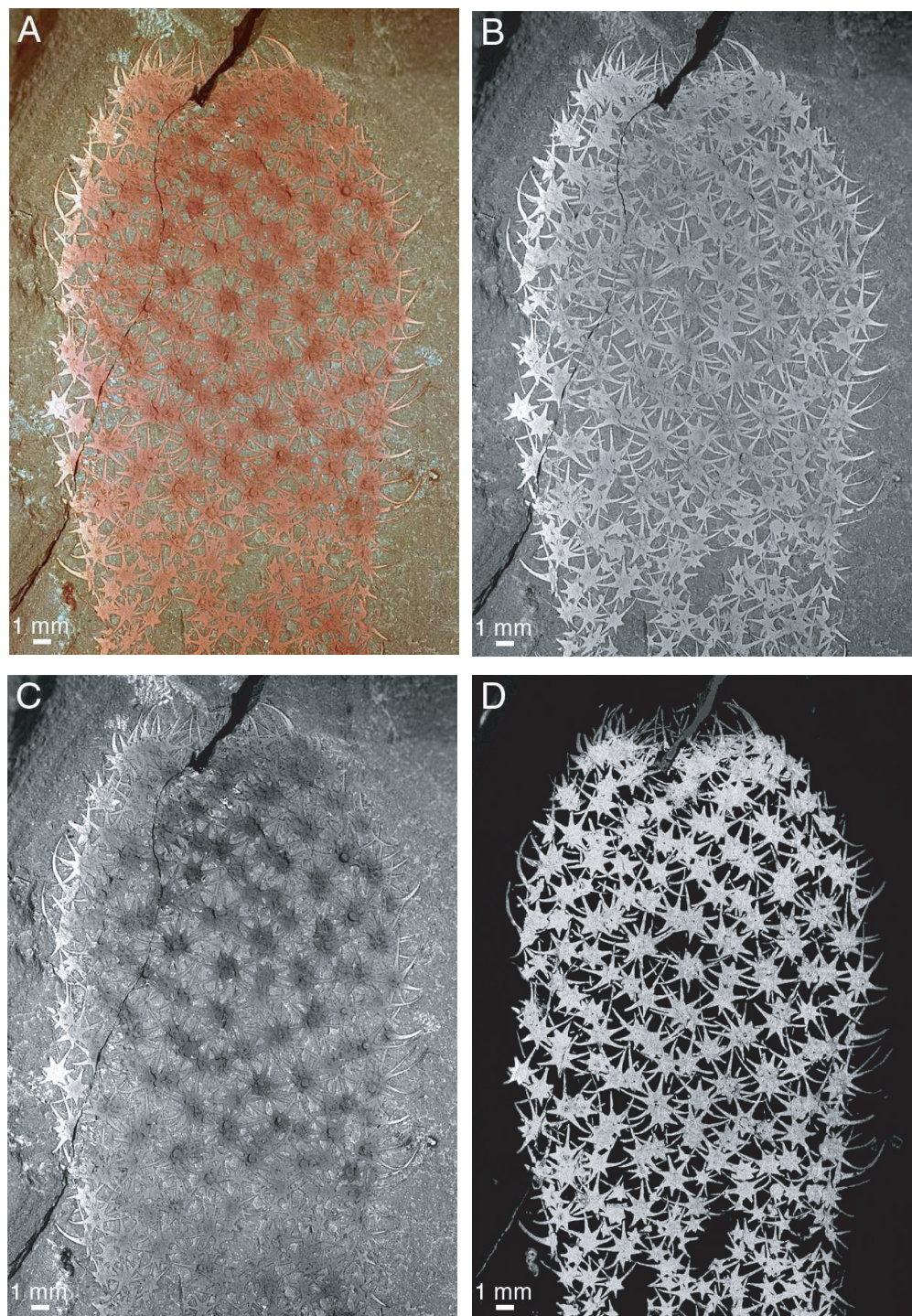
FIGURE 14. *Yunnanozoon* from Chengjiang, South China. Image produced from Figure 6B by subtracting the blue from the green channel using Adobe Photoshop's "Subtract" mode (settings: Opacity = 100; Offset = 75; Scale = 1), adjusting the levels, and blending the resulting channel with the original colour image using the "Multiply" mode. (Click on the picture to toggle between this figure and the original Figure 6B.)

FIGURE 15. Graptolites (*Climacograptus*), Upper Ordovician, Sularps Kvarn, Fågelsången, Scania (NRM Cn 54044). Image produced from Figure 8B by subtracting the green channel of B from that of A, using Adobe Photoshop's "Subtract" mode (settings: Opacity = 100; Offset = 100; Scale = 1) and subsequently adjusting the levels. (Click on the picture to toggle between this figure and the original Figure 8A and 8B.)
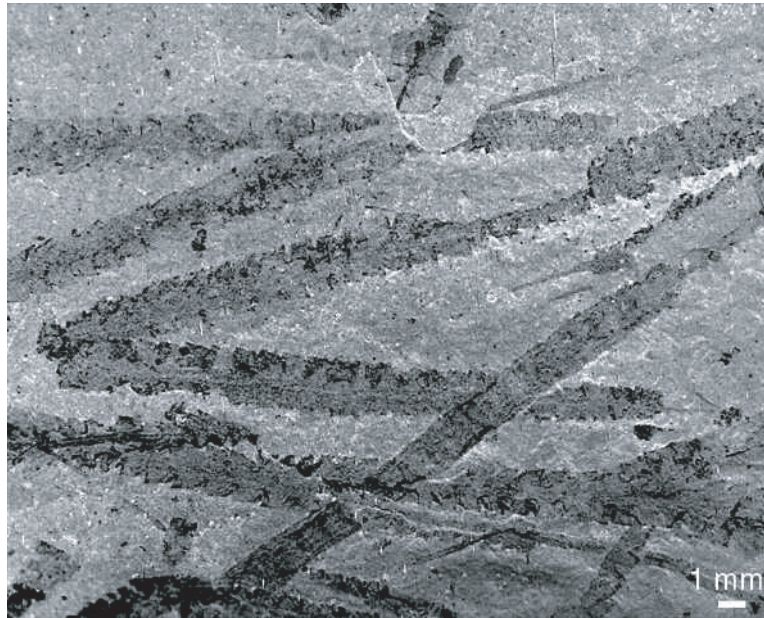
FIGURE 16. *Burgessia* from the Burgess Shale, British Columbia (LO8103t). Immersed in water. Image produced from Figure 5 by subtracting the green channel of A from the red channel of B, using Adobe Photoshop's "Subtract" mode (settings: Opacity = 100; Offset = 100; Scale = 1) and subsequently adjusting the levels. (Click on the picture to toggle between this figure and the original Figure 5A and 5B.)