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ANAGLYPH STEREO IMAGING OF DINOSAUR TRACK MORPHOLOGY AND MICROTOPOGRAPHY

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ABSTRACT

Fossil tracks should be recorded by methods that foster detailed ichnological analysis. Although outline drawings remain the standard currency of footprint illustration, their simplicity entails a tremendous loss of information. By contrast, monocular photographs are highly detailed but often suffer from suboptimal lighting, which can cause misperceptions. Anaglyph stereo imaging offers a compact, scale-independent format for illustrating and presenting the complex three-dimensional (3-D) shape of dinosaur footprints. Using examples from the Upper Triassic Fleming Fjord Formation of East Greenland, we address the benefits of anaglyphs to the exploration and exposition of theropod tracks in both the field and laboratory. We find that the addition of stereopsis to other available depth cues (shading, cast shadows) maximizes the information content of a 2-D image while minimizing erroneous or ambiguous perceptions of shape.

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INTRODUCTION

Footprints record the dynamic interaction between an animal's limb and a malleable substrate (Baird 1957). As the foot penetrates and is extracted, nearby sediment is pushed, sheared, and dragged into a new configuration that variably records aspects of pedal anatomy and locomotor movement (Padian and Olsen 1984; Thulborn and Wade 1984, 1989; Gatesy et al. 1999; Gatesy 2003). This imperfect mold is further altered, if not

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completely destroyed, by pre-burial erosion, diagenesis, post-exposure weathering, collection, and preparation. A fossil track that survives these harsh filters can offer unique and valuable evidence of behavior in extinct taxa (e.g., Seilacher 1967). For ichnological analyses to be well founded, however, footprints must be documented by methods that minimize loss of information. Inaccurate representations of track morphology can distort or obscure potentially important data.

Compared to many other fossils, description of footprints can be particularly challenging. The most important distinction is that the internal morphology of bones, eggshells, and soft tissues are preserved when actual biological material serves as a template for mineral replacement. By contrast, tracks are purely sedimentary structures that only reflect a foot's external morphology and frequently lack discrete borders. Second, images of track surfaces are informative from a limited range of perspectives, whereas skeletal elements can often be figured from many viewpoints. Finally, many footprints are studied only in the field, rather than collected or cast. Even under controlled laboratory conditions, a track's three-dimensional contours and textures are notoriously difficult to quantify and illustrate, making these phases of analysis especially prone to inaccuracy or bias.

The human visual system is adept at determining the distance and orientation of surfaces. However, just as a camera compresses a 3-D world onto a planar CCD or film, depth information is lost when the environment is projected onto the 2-D receptor array in our retina (e.g., Palmer 1999). Our brain must therefore use a number of different signals to perceive spatial arrangement and resolve ambiguity. Some sources of information are intrinsically dynamic, such as the differential motion of objects at unequal distances (motion parallax). However, most other depth cues are static and potentially useful for extracting 3-D information from 2-D images on a monitor or in print (Palmer 1999; Ware 2004). These cues include occlusion (near overlaps far), perspective (convergence of parallel lines, position relative to the horizon, relative size, atmosphere), focus (depth of field), shading, cast shadows, and stereopsis. Unfortunately, tracks rarely show features with enough topography to benefit from occlusion, perspective, or depth of field. This leaves shading, cast shadows, and stereopsis as signals available for elucidating and communicating track geometry.

Stereopsis is the extraction of depth information from differences between images recorded by our two retinas (binocular disparity; e.g., Palmer 1999). Paleontologists have used stereophotographic techniques for more than 90 years (e.g., Hudson 1913, 1925) and the methodology is well described (Gott 1945; Evitt 1949; Feldman 1989; Knappertsbusch 2002). Yet, although several stereo pairs of tetrapod track photographs have been published (Sarjeant and Thulborn 1986; Ishigaki and Fujisaki 1989; McAllister 1989), this approach has been underutilized relative to the widespread use of stereophotography to illustrate skeletal fossils. There are drawbacks that make traditional stereo pairs less than ideal for publication and presentation (e.g., Evitt 1949). Printed figures are constrained to relatively small widths (less than ca. 8 cm), which preclude highly detailed images spanning a full page. At the same time, separate left and right images require at least twice the area of an individual plate. Traditional stereo pairs can only be projected before an audience using specialized polarizing or LCD equipment.

Anaglyph stereo imaging offers an alternative method of presentation that is scale-independent. An anaglyph is a color image formed by superimposing left and right members of a stereo pair. The two original images are color-converted so that each is invisible when viewed through a correspondingly colored gel. Inexpensive and widely available "3-D glasses" with different lenses (red-blue, red-green, or red-cyan) are worn to provide each eye with its appropriate image. Instructions for creating anaglyphs using imaging software such as Adobe Photoshop are available in Purnell (2003) and on many websites. Anaglyphs can be printed and projected at any size, making them ideal for journals, websites, museum displays, poster sessions, small seminars, and large conference halls. Sequential anaglyphs can be easily combined to create compelling stereo animations. Paleontologists have recently taken advantage of this technique by publishing static and animated anaglyphs of conodont and invertebrate microfossil material (Knappertsbusch 2002; Purnell 2003).

Herein, we address the utility of anaglyph stereo imaging to the exploration and exposition of dinosaur tracks. Our examples are tracks attributable to small theropods that are preserved in the Late Triassic Fleming Fjord Formation of Jameson Land, East Greenland (Jenkins et al. 1994; Gatesy et al. 1999; Gatesy 2001, 2003). We present three case studies ranging from field to laboratory, from whole footprints to minute skin impressions, and across a range of imaging techniques. We include specific methods as part of each case study. Our goal is to focus on the benefits of anaglyphs for footprint studies in general, rather than on specific descriptions or interpretations of these specimens.

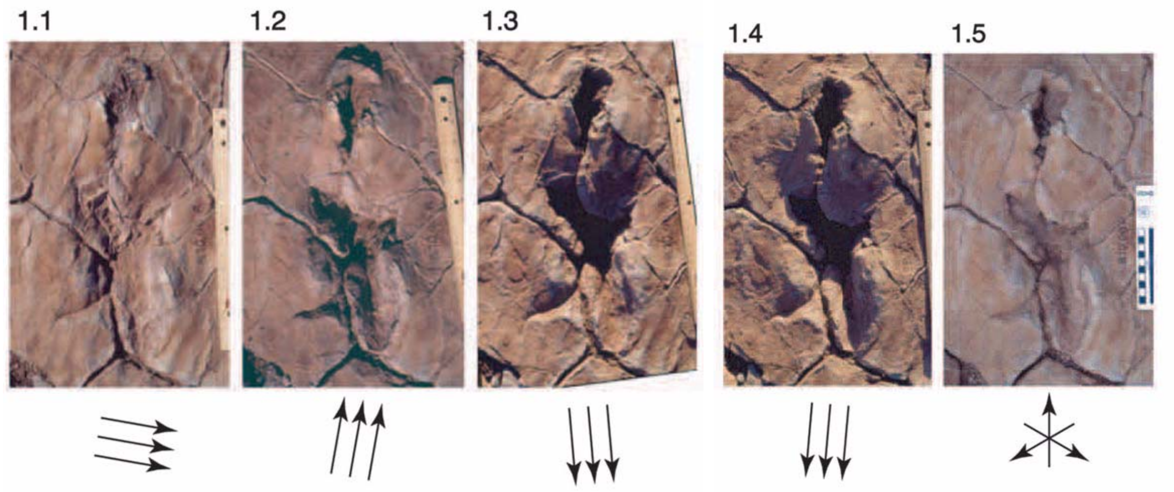

Figure 1. Five photographs of the same deep theropod track (MGUH VP 3391) in situ under different field lighting. Arrows depict primary direction of sunlight. Photograph 1.5 was taken under relatively uniform, ambient illumination on an overcast day. Infilling matrix was not yet removed when Figure 1.1 was taken. Scale bars equals 100 mm.

MATERIALS

Footprints are now known to be quite common in the Ørsted Dal Member of the uppermost Fleming Fjord Formation (Norian-Rhaetian; Clemmensen 1980; Clemmensen et al. 1998). Specimens described in this study were photographed and collected on the eastern slope of Wood Bjerg (71° 24.88´N, 22° 33.17´W) and the western slope of Tait Bjerg (71° 29.08´N, 22° 39.10´W). All collected material will be housed at the Geological Museum at the University of Copenhagen.

Anaglyphs were prepared for viewing with red-blue glasses (left eye red, right eye blue). Pairs of stereo photographs and micrographs were aligned and color converted in Adobe Photoshop 7.0. Full details on creating anaglyphs are available at websites such as The Southern California Earthquake Center (http://www.scec.org/geowall/makeanaglyph.html) and Mark Newbold (http://dogfeathers.com/3d/3dhowto.html#ps4). Additional tools for stereo, including anaglyphs, are available at VRex Stereoscopic 3 (http://www.vrex.com). An animated rotating track and spheres were created in Maya 6.0 (Alias). The animation was compressed with QuickTime Pro 6.5.1 (Apple).

RESULTS

During the short Greenlandic summer, track-bearing localities above the Arctic Circle offer the rare opportunity to photograph most footprints under sunlight 24 hours a day. Such freedom allows a single print to be naturally lit from all possible directions while still in situ (Figure 1). Despite this flexibility, many of our track photographs suffer from the commonly encountered flaws of excessive contrast (Figure 1.2-1.4), misleading or concealing shadows (Figure 1.3-1.4), confusing color artifacts, or morphological ambiguity due to uniform illumination (Figure 1.5). Even when multiple images are captured of the same track under different lighting conditions, the topology of the sediment's surface may not be obvious. Morphological description, artistic illustration, and scientific interpretation can be hampered by this variable fidelity, particularly if viewers are unfamiliar with the original material.

Over the last 10 years, we have documented tracks in the field by taking sets of two to five photographs from slightly different perspectives. To avoid bulky hardware, we use a simple 35 mm single lens reflex camera with a zoom lens rather than specialized cameras or multi-camera configurations. Exposure, focus, and focal length are set manually and kept constant throughout a series. In lieu of a tripod, which casts undesirable shadows, the camera is hand-held using our legs and body to maintain a constant height above the track. We orient the specimen's anteroposterior axis along the width of the film frame, typically by standing to the side of the track furthest away from the sun to keep our own shadow out of the field. The first picture is taken while leaning forward (weight on toes) with the camera approximately 10 cm past a position directly above the center of the track. One to four additional pictures are then taken in quick succession before the cloud cover can appreciably change. We keep our feet planted, but progressively shift weight to our heels to move the camera backward in ca. 10 cm increments. Before each

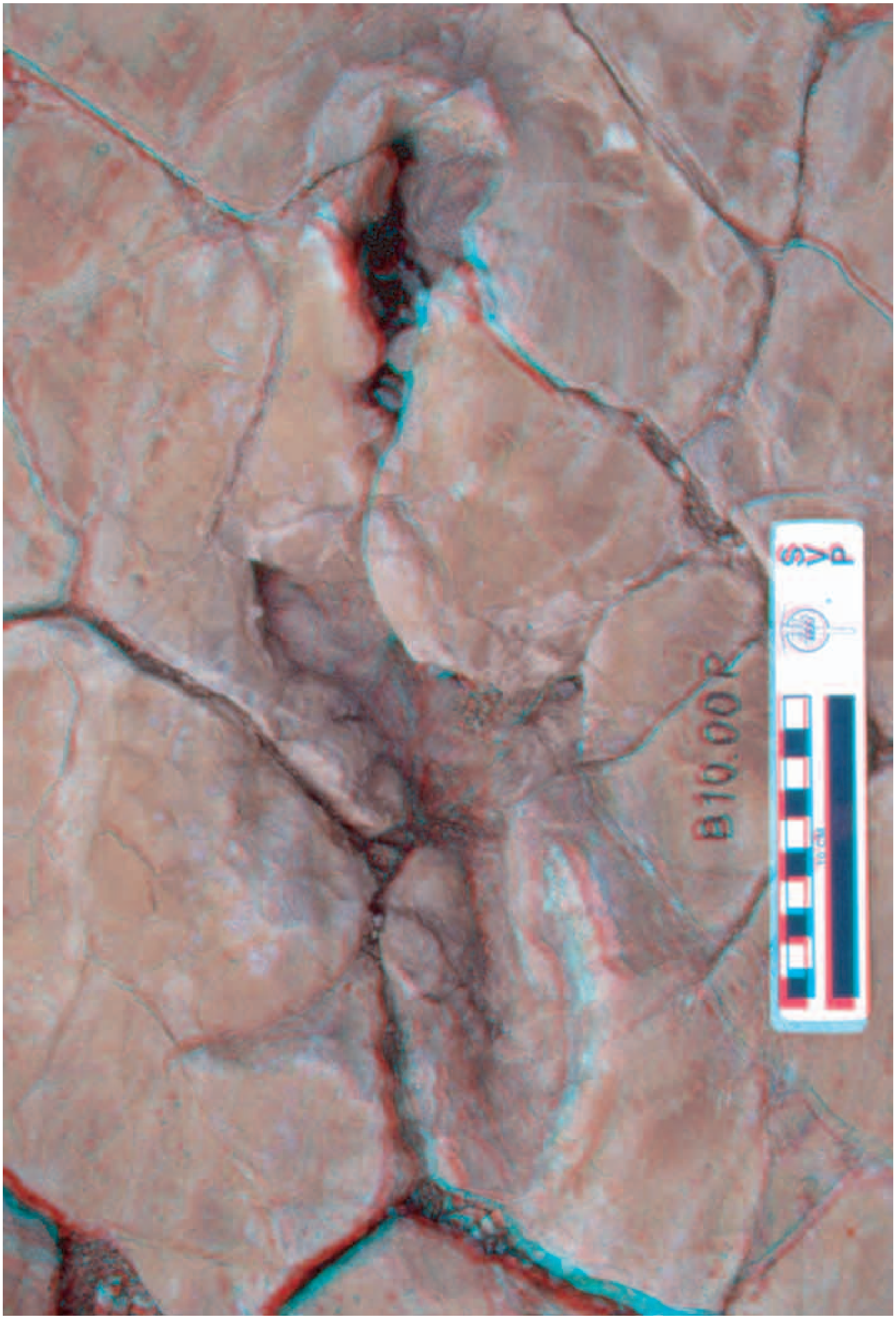

Figure 2. Red-blue anaglyph made from two photographs of a deep theropod track (MGUH VP 3391) under relatively even lighting as in Figure 1.5. Scale bar equals 100 mm.

Figure 3. QuickTime^{TM} animation of a shallow theropod footprint. As the image rotates or is stopped in different positions, the appearance of the track and surrounding mudcracks can shift from concave (actual) to convex and back again. This flipping illusion primarily depends on the direction of sunlight with respect to the observer, but the effect can vary among viewers and over time. Click to run movie.

shot we center the camera on the same point in the track and maintain a correct focal distance by fine-tuning camera height until the target is focused crisply in the viewfinder.

We organize our 35 mm slides on a light table using a stereo viewer. Slides are lined up from leftmost to rightmost and labeled sequentially. We then choose the two most effective pictures to create a stereo pair, keeping the lowest numbered slide on the left at all times. Typically these are the images shot most orthogonally and an adjacent slide, but different pairs can be substituted if needed. Slides are scanned into a computer at 2400 dpi. Digital files are aligned and cropped to form stereo pairs and anaglyphs in Adobe Photoshop (Figure 2).

Following ichnological tradition, we initially tried to photograph only under relatively cloud-free conditions so that a track's shape would be well defined by the primary light source. However, as examples in Figure 1 show, direct sun frequently creates harsh contrast that conceals portions of the track. Ripple marks that are clearly discernable in some situations (Figure 1.1, 1.3) seem to disappear when lighting parallels crests and troughs (Figure 1.2, 1.4). Even relatively minor differences in sun position (compare Figure 1.3 and Figure 1.4) can have a dramatic effect on cast shadows, which may obscure or overly emphasize specific areas. The sun's elevation is also important. Tracks in the Fleming Fjord Formation of Greenland typically exhibit features elevated well above the bedding plane. When incident light strikes a track at a very low angle, even small surface irregularities can cast long, distracting shadows. These mounds and crests can eclipse large portions of the track and surrounding rock (Figure 1.2-1.4). In some circumstances, strong directional lighting creates shading cues that cause concave structures to appear convex and vice versa (Figure 3).

At the other extreme, photographs taken under overcast or hazy skies are particularly difficult to interpret as monocular images (Figure 1.5). But when viewed in pairs, the relatively shadow-free illumination produces superior anaglyphs (Figure 2). We now prefer to collect images on days with relatively uniform, ambient lighting, even if the track's structure appears indistinct when seen through the camera's viewfinder and as a single slide.

Anaglyph Microscopy of Tracks in the Laboratory

Our Greenlandic track collection includes over three dozen specimens preserving skin impressions in the form of dimples, pimples, ridges, valleys, and striations (Gatesy 2001; Gatesy et al. 2003). Such minute, finely detailed textures are quite shallow (ca. 0.2 mm or less), making them extremely difficult to photograph in the field.

Under laboratory conditions, accurately documenting skin impressions presents two main chal-

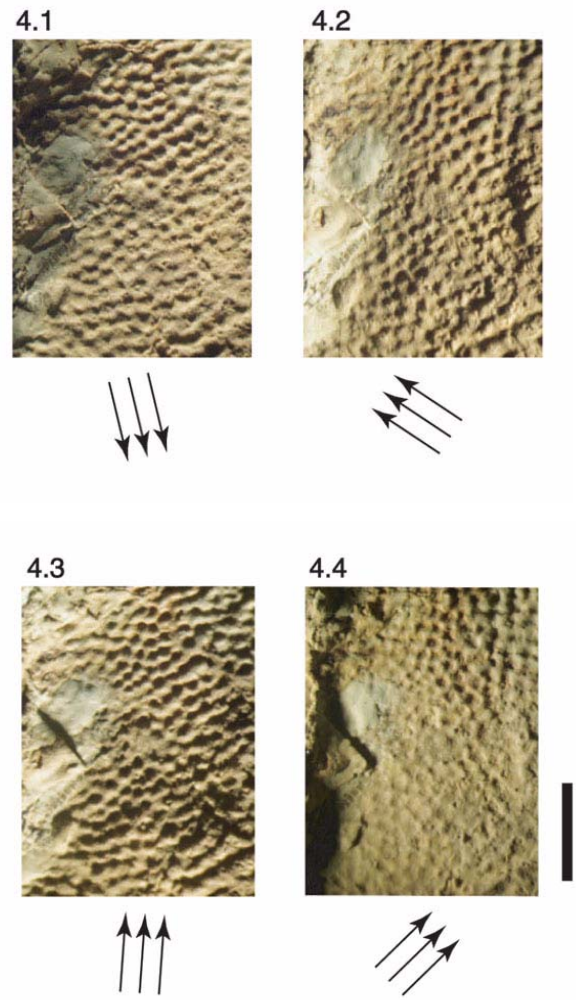

Figure 4. Four micrographs of skin impressions in a shallow theropod track under different laboratory lighting. Arrows depict direction of fiber-optic illumination. Note the uneven illumination, particularly in Figure 4.4. Dimple patterns within a single region appear to vary significantly depending on the positioning of the lamp. In some images, particularly Figure 4.4, these dimples may appear as convex "pimples." Scale bar equals 5 mm.

lenges. First, adjacent regions of impressions may appear different because of uneven lighting. Microstructural features are best seen under a binocular dissecting microscope using low-angle, grazing illumination. Unfortunately, skin impressions are most often found lining the concave or undulating depressions made by the digital pads. Such areas are impossible to light uniformly even with flexible-necked fiber-optic lamps, resulting in apparent textural variation across any non-planar surface (Figure 4). Second, the same region of skin impressions can appear quite different under the binocular microscope as the angle of incident light is altered. For example, a small patch of skin impression may look like an array of concave dimples when lit from one direction (lower region of Figure 4.2) but shift in appearance to valleys of interconnected dimples when lit from another (Figure 4.1, 4.3). This raises the question of whether a single primary light source is the best method for revealing track microtopography. As with whole tracks lit by the sun on a clear day, strong directional lighting from a single lamp casts crisp shadows that make textures stand out, but these high-contrast patterns may be misleading about surface geometry. As with whole tracks, concave structures can sometimes flip to appear convex (Figure 4.4), and vice versa.

We capture pairs of images for anaglyphs by mounting a digital camera (Olympus Camedia C-50) on a tripod and then sequentially positioning its lens in front of the microscope's left and right eyepieces. Shutter speeds are set manually to achieve the proper exposure. Specimens are lit with four arms from two fiber-optic lamps to provide a relatively diffuse illumination without strong shadows. Digital JPEG files are brought directly into Adobe Photoshop and combined into anaglyphs (Figure 5).

If the region of interest is relatively inaccessible to viewing and/or illumination, we make silicone peels. Peels offer more freedom for lighting, reduce the risk of damaging original material, and provide a homogeneous color that accentuates shape. We cast small areas of skin impression using silicone putty (Knead-A-Mold, A2Z Solutions) that does not require a separator. After thorough mixing, we smear small (ca. 1 mm diameter) balls of putty into the cleaned rock surface to minimize the possibility of entrapping air bubbles, gradually building up layers to create a peel 2-3 mm thick. Before the putty hardens we mark the back of each peel with the specimen number, digit number, and orientation with respect to the track's main axis.

Peels can be trimmed and mounted for viewing at higher magnifications by Scanning Electron Microscopy (SEM). We used a Hitachi 2700 SEM to collect images at magnifications of ca. 50X. Despite the high resolution, we found that microtopography was sometimes ambiguous in monocular images. In particular, our interpretation of an SEM image of a silicone peel often changes from concave to convex, or vice versa, if the image is reoriented on the page (Figure 6). Such ambiguity can be avoided by using stereopsis to resolve visual conflicts caused by directional illumination. Capturing multiple images of the same region while incrementally tilting the stage allows us to assemble anaglyphs quite easily. Figure 7.1 shows the true

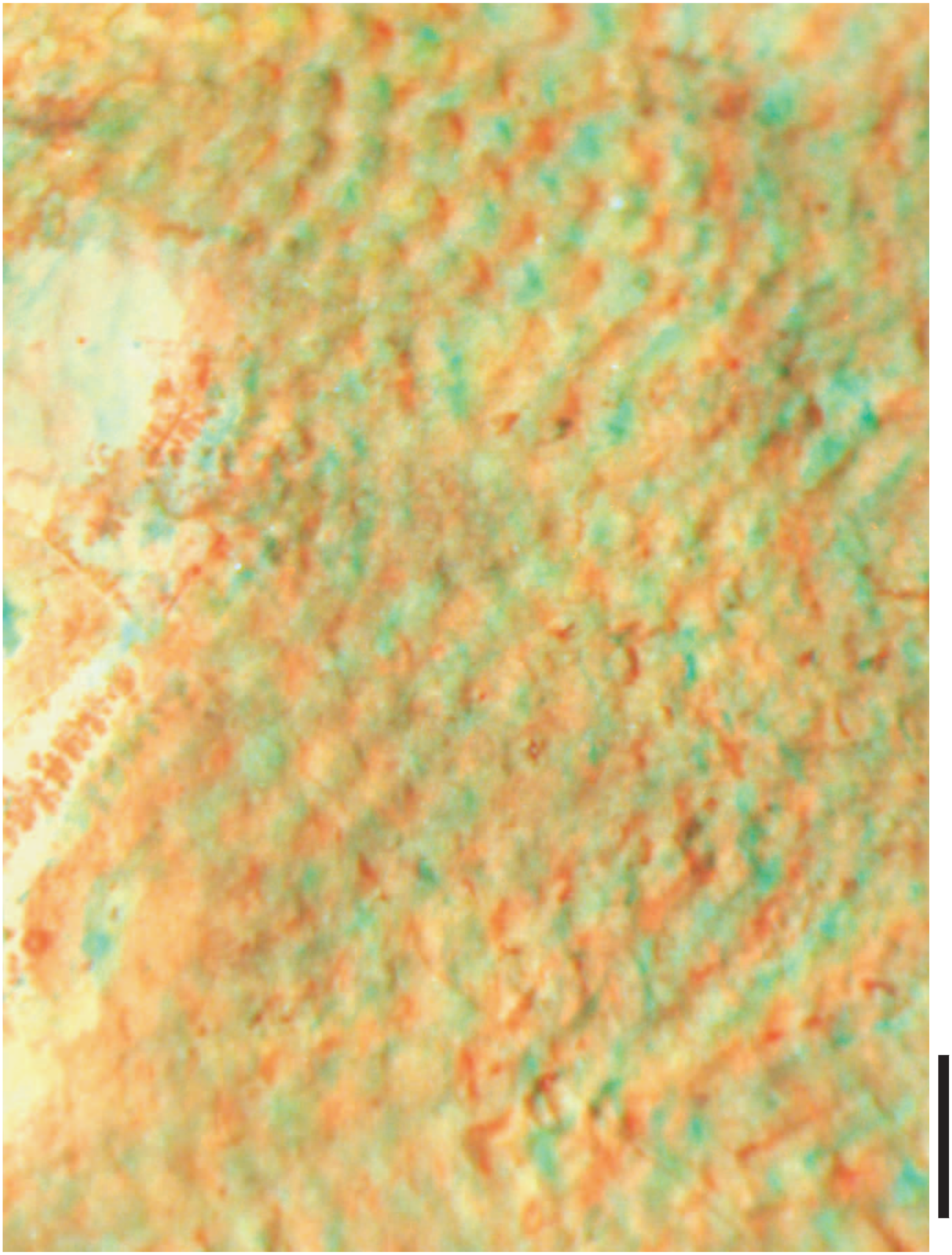

Figure 5. Red-blue anaglyph produced from two micrographs of the region of skin impressions shown in Figure 4. Relatively even illumination was used to avoid confusing or misleading shadows. Scale bar equals 2 mm.

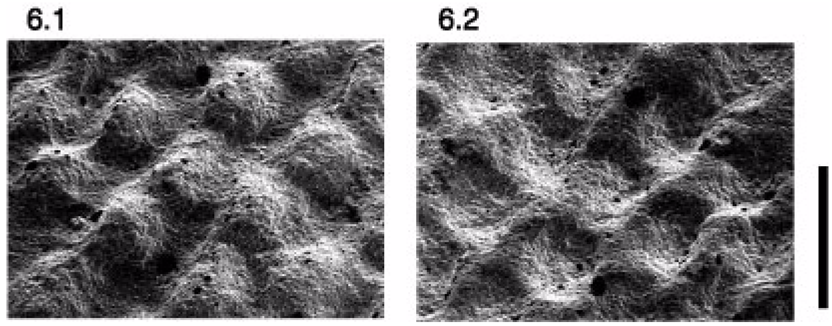

Figure 6. SEM images of silicone peels made from theropod skin impressions are also prone to error. The hill-like structures appear convex in Figure 6.1, but can flip to be perceived as concave hollows when the image is rotated 180 degrees as in Figure 6.2. Scale bar in this slightly oblique view equals ca. 1 mm.

orientation of the peel, with hill-like pimples. However, we can intentionally reverse the illusion of depth by rotating the completed anaglyph about a vertical axis. In Figure 7.2 these convexities now appear concave. Such "virtual" casts of silicone molds foster direct comparison with the original footprint.

DISCUSSION

Information about a track's surface morphology needs to be collected and distributed as objectively as possible because these raw data form the foundation of ichnological analysis. Interpretive drawings should be made to highlight aspects of interest, but such representations are most effective when presented in conjunction with less subjective records of the original material. The need for accurate documentation is particularly intense for specimens that remain in the field beyond easy access by other workers. Anaglyphs have the potential to record and transmit a track's morphology with high fidelity.

Anaglyphs are by no means perfect. Special glasses are required to view relatively large color

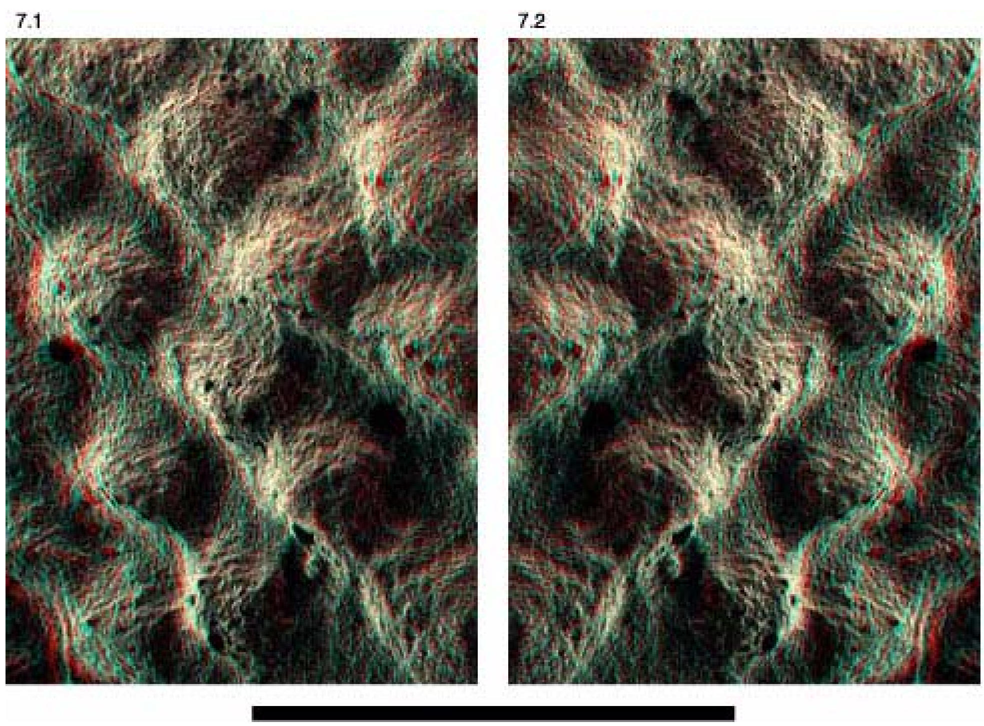

Figure 7. Red-blue anaglyph made from two scanning electron micrographs of a silicone peel of theropod skin impressions shown in Figure 6. Figure 7.1 shows the correct relief of the peel. In Figure 7.2 the anaglyph has been intentionally rotated about a vertical axis to reverse the stereoscopic effect and recreate the dimpled surface of the original specimen. Scale bar in this slightly oblique view equals ca. 2 mm.

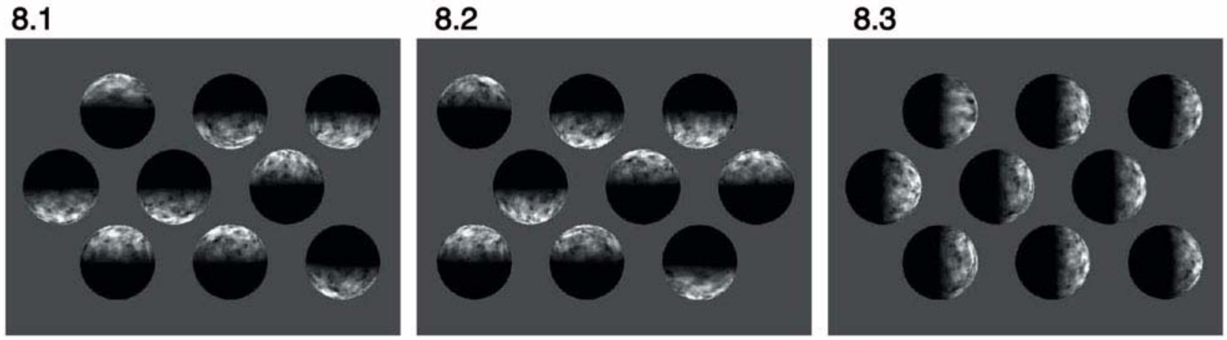

Figure 8. Erroneous or ambiguous interpretations of depth can arise when lighting does not meet our expectations. In Figure 8.1, computer-rendered spheres lit from different directions are perceived as either convex "pimples" or concave "dimples" (after Ramachandran 1988). Spheres lit from above tend to be interpreted as protruding, whereas those lit from below are seen as hollow. Figure 8.2 shows the same pattern rotated 180 degrees. Spheres previously seen as convex appear concave, and vice versa. Such flipping occurs with photographs of dinosaur footprints. Spheres lit from the side as in Figure 8.3 remain ambiguous.

image files. Another concern is variation in color output, which can lead to ghosting artifacts when a gel does not completely filter out the image meant for the opposite eye. Low quality glasses can significantly darken an anaglyph, which already suffers from loss of saturation and true color balance. Finally, new methods are needed to standardize camera positioning in the field. Our hand-held technique is fast and flexible, but intraocular distances vary and image pairs frequently require minor rotation, translation, and rescaling in order to align. Despite these drawbacks, anaglyphs hold promise for efficiently maximizing the amount of data that might be extracted by faithfully recording a track's 3-D geometry.

Alternative Imaging Formats

Relative to anaglyphs, most other formats entail additional subjectivity, information loss, or optical illusion. For example, simple outline drawings are the most commonly used method of portraying the general size, shape, and placement of tracks in published studies. Although silhouettes can be generated quickly and cheaply, they are notoriously subjective because a continuous surface must be reduced to a single edge (e.g., Thulborn 1990). More importantly, information about depth and texture is excluded (e.g., Moratalla et al. 1997). Internal and external track features are sometimes represented by additional lines, stippling, and shading (e.g., Hitchcock 1858; Currie et al. 1991; Farlow and Chapman 1997), but artistic bias remains a concern (Baird 1952; Thulborn 1990).

Isoheight contour maps (Lim et al. 1989; Farlow and Lockley 1993; Graham et al. 1996; Farlow and Chapman 1997; Rasskin-Gutman et al. 1997) and moiré topography (Ishigaki and Fujisaki 1989) record internal shape information, but at a relatively low resolution. Neither takes advantage of the shading or cast shadow mechanisms of spatial perception. True depth must be represented numerically, because the absolute inter-contour spacing is not apparent from the lines themselves. Nor is either method easily amenable to specimens in the field, although scanning of in situ surfaces is likely to become viable in the near future. Computer renderings of tracks as distorted wire-mesh grids (Farlow and Chapman 1997; Rasskin-Gutman et al. 1997) provide more complete depth information, but must be viewed from an oblique perspective, which hides some features and hinders comparison among tracks. Other workers have used stipple density or tones of gray to depict relative depth (Harris et al. 1996; Gatesy et al. 1999; Gatesy 2001), but such illustrations have never been executed with any quantitative control.

Photography would appear to offer the simplest and most objective solution to illustrating footprints, but snapshots can fall short as well (Figures 1, 3, 4, 6). As discussed earlier, conditions in the field are often unsuitable for faithfully capturing a track's shape. A surface may be indiscernible in the ambient illumination provided by the bright haze of fog, gray overcast of clouds, or permanent shade under an overhang. Under clear skies the contrast may be too high, obscuring details in both the brightest and darkest areas. Waiting for better weather or shooting at a different time of day is not always possible. More commonly, the sun is simply too high, too low, or at an unfavorable direction to produce ideal shading and shadows, which can cause these cues to be confusing or incomplete.

In monocular photographs, directional illumination can create misleading shading cues that cause depth reversal. Although images of whole tracks can be affected (Figure 3), the dimple-like skin impressions of theropod dinosaurs, in particular, are strikingly similar to the spheres used by Ramachandran (1988) to explore this phenomenon of human perception. For example, Figure 8.1 is a computer rendering of nine shaded spheres. The four lit from above are perceived as convex “pimples” rising out of the page, whereas the five lit from below are seen as concave “dimples” (Ramachandran 1988). The viewer-dependent nature of this illusion can be demonstrated by rotating Figure 8.1 by 180 degrees, as in Figure 8.2. Spheres previously perceived as convex are now seen as concave, and vice versa. Spheres lit from the side remain ambiguous (Figure 8.3). Our brain is accustomed to seeing objects lit from above by a single light source (Ramachandran 1988; Palmer 1999; Ware 2004), so we subconsciously expect a photograph of a track to follow this pattern. Since tracks are traditionally presented vertically as if walking up the page, lighting from an anterior direction fits our implicit assumption, and we can frequently, if not always, interpret the shape correctly from shading and shadows. Photographs of tracks lit from their posterior aspect appear to be illuminated from a source at the bottom of the page, which can cause confusion (Figure 4.4). Orienting all photographs to a consistent lighting direction could alleviate this visual conflict, but would clearly hamper morphological comparison among tracks. A reference object such as a small cube helps document the position of the light source but may not remove the flipping artifact.

When merged as stereopairs, many of the shortcomings of monocular photographs, including lighting from below, can be overcome. Information from binocular disparity ensures that a viewer will perceive the correct surface orientation. In the same way, an anaglyph can make the most of two photographs taken under less than ideal conditions by combining them into a stereoscopic whole greater than the sum of its parts.

SUMMARY

Outline drawings remain the standard currency of footprint illustration, but their simplicity entails a tremendous loss of information. Analyses based on such interpretive drawings, no matter how sophisticated, will always bear the risk of reaching conclusions that cannot be substantiated from the original material. Footprints of dinosaurs and other tetrapods warrant illustration, recording, and analysis with all the detail that current technology allows. Only when tracks can be captured in their entirety with minimal distortion can we expect to synthesize meaningful interpretations of the morphology, movement, and sedimentary interaction that created them. Anaglyphs offer a compact, scale-independent format for combining the strengths of each of the three available perceptual depth cues, and represent a step toward taking paleoichnology away from its 2-D past and into the third dimension.

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In presenting anaglyphs of theropod footprints, we remember with great affection a friend and colleague who devoted his professional life to promoting the exploration of the vertebrate fossil record throughout the world. Will Downs joined us in the deserts of American southwest, in the foothills of the Atlas Mountains of North Africa, and across the vast landscapes of Arctic Greenland. With little money and few possessions, he carried with him an indefatigable spirit of curiosity and seemingly relentless energy. The techniques described in this paper would have appealed to Will, for he was always keen to try new approaches and eager to experience new ways of seeing the world. We affectionately dedicate our contribution to his memory.

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