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‘Virtual paleontology’ entails the use of computational methods to assist in the three-dimensional (3-D) visualization and analysis of fossils, and has emerged as a powerful approach for research on the history of life. 3-D imaging techniques allow poorly understood or previously unknown anatomies of fossil plants, invertebrates, and vertebrates, as well as microfossils and trace fossils, to be described in much greater detail than formerly possible, and are applicable to a wide range of preservation types and specimen sizes (Table 1). These methods include non-destructive high-resolution scanning technologies such as conventional X-ray micro-tomography and synchrotron-based X-ray tomography. In addition, form and function can be rigorously investigated through quantitative analysis of computer models, for example finite-element analysis.

In 2012, we co-chaired a topical session on Virtual paleontology: computer-aided analysis of fossil form and function at the Annual Meeting of the Geological Society of America in Charlotte, North Carolina. In this special issue, we offer a collection of 12 papers arising from this session, 10 of which are based on talks and posters given at the meeting.
These contributions introduce some of the state-of-the-art techniques for virtual paleontology, illustrate the variety of fossils and preservation types that can be examined, and present important paleontological findings arising from the application of these methods.

Several papers focus on the application of X-ray computed tomography (CT) to fossils of various vertebrates and plants. This includes work using high-resolution X-ray micro-tomography (micro-CT or µCT) to visualize the endocranial anatomy of early ray-finned fishes (Giles and Friedman, 2014) and a new fossil porpoise (Racicot and Rowe, 2014). Fisher et al. (2014) use an industrial CT scanner to image two mammoth calf mummies, obtaining insights into their morphology, development, and taphonomy. In addition, two studies illustrate the value of synchrotron radiation X-ray tomographic microscopy (SRXTM) for studying very fine-scale features, such as the development of the vertebrate skeleton (Rücklin et al., 2014) and the systematically important anatomical details of Cretaceous fossil plant material (Friis et al., 2014).

Although CT is the most widely used imaging method in virtual paleontology, other approaches have also proven valuable for studying fossils in 3D. Dawson et al. (2014) present images of plant fossils obtained using neutron tomography, which were superior to X-ray-based images for their material. Moreover, destructive methods can reveal details that would otherwise have been hidden, as shown by Schemm-Gregory (2014), who uses serial grinding to study fossil brachiopods, and by Juarez Rivera and Sumner (2014), who unravel the structure of Archean microbialites with the aid of serial sectioning.

Finally, four papers outline modern approaches for the visualization and quantitative analysis of fossil specimens. Lautenschlager and Rücklin (2014) discuss alternative strategies for presenting 3-D digital data, while Garwood and Dunlop (2014) explain how Blender can be used by paleontologists to bring their fossils back to life. Lehane and Ekdale (2014) introduce a suite of analytical tools for quantifying the morphology of trace fossils. Bright
(2014) reviews finite-element analysis (FEA), a method that can be used to quantify function in extinct species, and comments specifically on the validity of paleontological models.

All of the papers in this special issue make use of cutting-edge computational methods that can provide new insights into fossils and the history of life. These contributions also serve to illustrate the variety of approaches that are available to paleontologists (Table 1). In all cases, methods were carefully chosen according to the properties of the material under investigation (i.e. size and composition), as well as the particular research questions being asked; selection of the most appropriate approach is an important step in any virtual paleontological investigation. If applied correctly, virtual techniques have the potential to transform the study of ancient organisms, and can hence be expected to form an integral part of the science of paleontology in the coming years.

ACKNOWLEDGEMENTS

We thank the contributors to this special issue and all of the presenters at the associated topical session. We are very grateful to Kathleen Huber, Steve Hageman and Brian Pratt for their help preparing this special issue, and also to the many reviewers whose critical comments improved the quality of the included papers. The session at the 2012 Geological Society of America Annual Meeting was supported by the Paleontological Society, the Palaeontological Association, and the Geobiology and Geomicrobiology Division of the Geological Society of America.

REFERENCES


TABLE 1—Comparison of 3-D imaging techniques applicable to fossils, with some notes on their suitability for different material. See Sutton et al. (2014) for a comprehensive review of the techniques.

<table>
<thead>
<tr>
<th>Technique</th>
<th>Data collected</th>
<th>Destructive?</th>
<th>Interior visualized?</th>
<th>Acquisition time</th>
<th>Region of interest</th>
<th>Maximum resolution</th>
<th>Best suited to which fossil groups</th>
<th>Best suited to which preservation types*</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Serial-grinding tomography</td>
<td>Optical images</td>
<td>Yes</td>
<td>Yes</td>
<td>Days to weeks</td>
<td>&gt;1 mm</td>
<td>10 µm</td>
<td>Vertebrates, invertebrates, plants, trace fossils</td>
<td>Altered, cast/mold, permineralized</td>
<td>Should be last resort as destroys specimen</td>
</tr>
<tr>
<td>Focused ion beam tomography</td>
<td>SEM images</td>
<td>Yes</td>
<td>Yes</td>
<td>Hours to days</td>
<td>1 µm–1 mm</td>
<td>50 nm</td>
<td>Microfossils</td>
<td>Original</td>
<td>Best for small, exceptionally preserved specimens</td>
</tr>
<tr>
<td>Micro-CT</td>
<td>X-ray attenuation images</td>
<td>No</td>
<td>Yes</td>
<td>Minutes to hours</td>
<td>1–250 mm</td>
<td>1 µm</td>
<td>Vertebrates, invertebrates, plants, microfossils, trace fossils</td>
<td>Altered, cast/mold, original, permineralized</td>
<td>Useful for most specimens; requires X-ray attenuation contrast</td>
</tr>
<tr>
<td>Industrial CT</td>
<td>X-ray attenuation images</td>
<td>No</td>
<td>Yes</td>
<td>Minutes to hours</td>
<td>&gt;200 mm</td>
<td>100 µm</td>
<td>Vertebrates, trace fossils</td>
<td>Altered, cast/mold, original, permineralized</td>
<td>Best for larger specimens; requires X-ray attenuation contrast</td>
</tr>
<tr>
<td>Synchrotron CT</td>
<td>X-ray attenuation/ X-ray phase images</td>
<td>No</td>
<td>Yes</td>
<td>Minutes</td>
<td>50 µm–600 mm</td>
<td>200 nm</td>
<td>Vertebrates, invertebrates, plants, microfossils</td>
<td>Altered, cast/mold, original, permineralized</td>
<td>Best for smaller specimens; phase contrast useful if low X-ray attenuation contrast</td>
</tr>
<tr>
<td>Neutron tomography</td>
<td>Neutron attenuation images</td>
<td>No</td>
<td>Yes</td>
<td>Minutes to hours</td>
<td>2–300 mm</td>
<td>30 µm</td>
<td>Vertebrates, plants</td>
<td>Altered, cast/mold, original, permineralized</td>
<td>Useful for large and dense specimens; requires neutron attenuation contrast</td>
</tr>
<tr>
<td>Magnetic Resonance Imaging</td>
<td>Distribution of light elements</td>
<td>No</td>
<td>Yes</td>
<td>Minutes to days</td>
<td>&lt;1 m</td>
<td>10 µm</td>
<td>Vertebrates, invertebrates, plants</td>
<td>Cast/mold, original, permineralized</td>
<td>Best for samples with high hydrogen content</td>
</tr>
<tr>
<td>Confocal laser scanning microscopy</td>
<td>Optical/fluorescence images</td>
<td>No</td>
<td>Yes</td>
<td>Minutes to hours</td>
<td>10–250 µm</td>
<td>300 nm</td>
<td>Invertebrates, plants, microfossils</td>
<td>Original, permineralized</td>
<td>Requires translucent fossil/matrix (e.g., amber)</td>
</tr>
<tr>
<td>Laser scanning</td>
<td>Surface images</td>
<td>No</td>
<td>No</td>
<td>Minutes to hours</td>
<td>1 mm–1 m</td>
<td>50 µm</td>
<td>Vertebrates, invertebrates, plants, trace fossils</td>
<td>Altered, cast/mold, original, permineralized</td>
<td>Useful for imaging in the field</td>
</tr>
<tr>
<td>Photogrammetry</td>
<td>Surface images</td>
<td>No</td>
<td>No</td>
<td>Minutes to hours</td>
<td>Any</td>
<td>N/A</td>
<td>Vertebrates, invertebrates, plants, microfossils, trace fossils</td>
<td>Altered, cast/mold, original, permineralized</td>
<td>Uses photography or SEM. No theoretical limit to resolution</td>
</tr>
</tbody>
</table>
We define four different preservation types as follows. Altered encompasses fossils where the original material of the organism has been replaced by another mineral. Cast/mold encompasses fossils where the original material of the organism has dissolved away and, sometimes, been filled with sediment or minerals. Original encompasses fossils where the original material of the organism is preserved unaltered (e.g., amber, pollen). Permineralized encompasses fossils where the original material of the organism remains but is encased in a mineral matrix.