VIRTUAL PALEONTOLOGY: COMPUTER-AIDED ANALYSIS OF FOSSIL FORM AND FUNCTION

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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.

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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.

Technique	**Data collected**	**Destructive?**	**Interior visualized?**	**Acquisition time**	**Region of interest**	**Maximum resolution**	**Best suited to which fossil groups**	**Best suited to which preservation types***	**Notes**
Serial-grinding tomography	Optical images	Yes	Yes	Days to weeks	>1 mm	10 µm	Vertebrates, invertebrates, plants, trace fossils	Altered, cast/mold, permineralized	Should be last resort as destroys specimen
Focused ion beam tomography	SEM images	Yes	Yes	Hours to days	1 µm–1 mm	50 nm	Microfossils	Original	Best for small, exceptionally preserved specimens
Micro-CT	X-ray attenuation images	No	Yes	Minutes to hours	1–250 mm	1 µm	Vertebrates, invertebrates, plants, microfossils, trace fossils	Altered, cast/mold, original, permineralized	Useful for most specimens; requires X-ray attenuation contrast
Industrial CT	X-ray attenuation images	No	Yes	Minutes to hours	>200 mm	100 µm	Vertebrates, trace fossils	Altered, cast/mold, original, permineralized	Best for larger specimens; requires X-ray attenuation contrast
Synchrotron CT	X-ray attenuation/ X-ray phase images	No	Yes	Minutes	50 µm–600 mm	200 nm	Vertebrates, invertebrates, plants, microfossils	Altered, cast/mold, original, permineralized	Best for smaller specimens; phase contrast useful if low X-ray attenuation contrast
Neutron tomography	Neutron attenuation images	No	Yes	Minutes to hours	2–300 mm	30 µm	Vertebrates, plants	Altered, cast/mold, original, permineralized	Useful for large and dense specimens; requires neutron attenuation contrast
Magnetic Resonance Imaging	Distribution of light elements	No	Yes	Minutes to days	<1 m	10 µm	Vertebrates, invertebrates, plants	Cast/mold, original, permineralized	Best for samples with high hydrogen content
Confocal laser scanning microscopy	Optical/ fluorescence images	No	Yes	Minutes to hours	10–250 µm	300 nm	Invertebrates, plants, microfossils	Original, permineralized	Requires translucent fossil/matrix (e.g., amber)
Laser scanning	Surface images	No	No	Minutes to hours	1 mm–1 m	50 µm	Vertebrates, invertebrates, plants, trace fossils	Altered, cast/mold, original, permineralized	Useful for imaging in the field
Photogram-metry	Surface images	No	No	Minutes to hours	Any	N/A	Vertebrates, invertebrates, plants, microfossils, trace fossils	Altered, cast/mold, original, permineralized	Uses photography or SEM. No theoretical limit to resolution

*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.