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Abstract

Geoscientists are some of most prolific producers of three-dimensional (3-D) data. These data do not belong in our computers—they belong in our hands. The power of computers to make accurate and speedy calculations on 3-D data sets is impossible for humans to match. Likewise, the power of the human mind and its sensory system to perceive qualitative aspects of physical objects is currently beyond computers. Three-dimensional printing, shorthand for a host of technologies more broadly described as “rapid prototyping,” is transforming how scientists, engineers, doctors, and artists interact with and understand 3-D data and models by allowing those data to be touched and viewed from any angle under real-world conditions. Importantly, 3-D printing produces tangible objects that are obviously intuitive to students, non-geoscientists, and decision makers.

Disciplines

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Making things geological: 3-D printing in the geosciences

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INTRODUCTION

Geoscientists are some of most prolific producers of three-dimensional (3-D) data. These data do not belong in our computers—they belong in our hands. The power of computers to make accurate and speedy calculations on 3-D data sets is impossible for humans to match. Likewise, the power of the human mind and its sensory system to perceive qualitative aspects of physical objects is currently beyond computers. Three-dimensional printing, shorthand for a host of technologies more broadly described as “rapid prototyping,” is transforming how scientists, engineers, doctors, and artists interact with and understand 3-D data and models by allowing those data to be touched and viewed from any angle under real-world conditions. Importantly, 3-D printing produces tangible objects that are obviously intuitive to students, non-geoscientists, and decision makers.

3-D PRINTING IS HERE

While some products result from a perfect mental vision, most manufacturing utilizes an iterative process. Human interaction with prototypes allows model qualities to be assessed in real-world situations. Computer-aided design (CAD) has yielded increasing design accuracy and has allowed design performance to be simulated computationally. However, the same fundamental need often still exists to validate models “in the *real* world.”

Rapid prototyping technologies have developed to meet this challenge. These consist of a family of methods for producing physical models from digital designs (cf. Pham and Gault, 1998). Most commonly, these systems are additive, building an object by fusing together feedstock (e.g., plastic, metal, mineral) delivered to the print area as a powder, liquid, film, bead, or thread. The combination of 3-D printing with any of the multitude of 3-D scanning technologies, like computed tomography (CT) or photogrammetry, creates a 3-D photocopier (e.g., Rengier et al., 2010).

Rapid prototyping is being put to such disparate uses as producing art installations, fabricating aircraft parts, designing jewelry, reproducing paleontological specimens, engineering bone implants, making textiles, creating edible foods, and fulfilling the human need for self-defense (i.e., making weapons). This transformative technology has been widely covered in the popular press, resulting in broad public awareness.

Among geoscientists, paleontologists have been early adopters of this technology (e.g., Bristowe et al., 2004; Balanoff and Rowe,

2002; Pouech et al., 2010; Hasiotis et al., 2011; Hyatt and Rosiene, 2013)—seeking to digitally extract fossils from stubborn matrices or reconstruct disarticulated specimens. Other geoscientific uses have been reported mainly through meeting abstracts: printing CT, LiDAR, and seismic data to understand morphology and stratigraphy (Reyes et al., 2008); printing extraterrestrial topography (Horowitz and Schultz, 2012); and visualizing earthquake distribution (Lindqvist et al., 2012).

3-D PRINTING IS EASY

Reliable desktop 3-D printers cost less than US\$3000, and feedstock is commodity priced (unlike 2-D printer ink). 3-D scanning has become easier and less-expensive as consumer-grade solutions have proliferated (e.g., Microsoft’s Kinect sensor and free smartphone apps that use cloud services to stitch multiple images into a 3-D model). Free online services (e.g., thingiverse.com, tinkercad.com, 123Dapp.com) allow basic CAD modeling with options to export printable files or have a printing service deliver a completed model. These services provide free platforms for the distribution of models, often including social media and metrics for tracking views and downloads (i.e., impact). While academic and government institutions provide online warehouses of 3-D data and models (cf. DigiMorph.org, GB3D), a peer-review mechanism is sorely needed to ensure uniform standards of accuracy and printability while providing easy access and citability.

3-D PRINTING IS USEFUL

In the geosciences, we struggle with a fundamental problem—we love nature, but its aspects can be truly enormous or fantastically miniscule, very far away or exceedingly rare. Our burden is to overcome these conditions and communicate effectively about nature. With equal ease, 3-D printing can make hand-samples out of subduction zones and foraminifera, Martian topography, and seismic data.

Such models are immediately useful because much of what we need to communicate concerns shape and form (Fig. 1). For these purposes, we can produce inexpensive teaching models on demand, saving acquisition costs while bringing unique specimens to broader audiences. Three-dimensional printing makes the natural specimen the starting point. Digital models can be transformed (e.g., scaled, mirrored, distorted) by an instructor or a student to explore concepts like morphology, vertical exaggeration, or strain. With a little CAD work, we can make *flexible fossils* to more effectively communicate how organisms, extinct and extant, locomote.

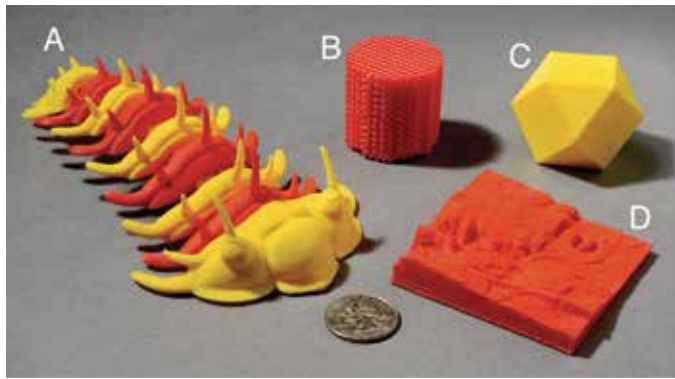


Figure 1. 3-D printed geological things. (A) Flexible fossil (“*Comura articulatum*,” thingiverse.com). (B) “Artificial reservoir rock” with through-going porosity (GeoFabLab). (C) Crystal model (rhombic dodecahedron, 3Dlapidary.com). (D) Topography of Ames, Iowa, USA, near the football stadium (GeoFabLab). Models were printed in ABS (acrylonitrile butadiene styrene) plastic, the same material used to make LEGO®. Photograph by Bob Elbert.

Students might more easily develop a sense of scale from a *touchable topography*—that they themselves choose and print—that combines local elevation data showing natural and human features. By printing in multiple colors, geological attributes (like geologic formations or geophysical measurements) can be printed over elevation data as a way to better understand a new field area or check field results. Medical researchers already 3-D print hydroxyapatite for bone implants (e.g., Dorozhkin, 2010), and some researchers have 3-D printed using silica, marble, and gypsum feedstocks.

Destructive testing yields valuable information at the expense of repeatability. *Geo-cloning* uses 3-D scanning or computational methods to create a digital model of a specimen that can be 3-D printed for analysis with traditional laboratory methods. Three-dimensionally printed river cobbles have been used to investigate weathering processes (Bourke et al., 2008). Others have used CT scanning and 3-D printing to reproduce pore networks (Otten et al., 2012). *Recombinant geology* involves modifying the intermediate digital model to test hypotheses about the original specimen. For example, parametrically modeled pelecypod shells have been 3-D printed to assess their burrowing functionality (Germann et al., 2014).

3-D PRINTING IS INCLUSIVE

Perhaps the most compelling reason to adopt 3-D printing into your teaching and research philosophies is that it will help you communicate more effectively. Some people do not “get” 3-D data on a computer screen, even with 3-D glasses or in 3-D visualization rooms. By printing 3-D data sets, we can interact with them in a more intuitive, more *human* way. Microfossils and pore networks can be scaled up to sizes more easily explored. A tangible model can help make the most of the short amount of time with a key decision maker at your company or funding agency. Visually impaired geoscientists may benefit greatly from having the opportunity to touch their data (Horowitz and Schultz, 2012).

With 3-D printers in our classrooms and laboratories, by taking them to conferences and K–12 science nights, we can help cement geoscience in the public’s perception as a high-tech field and career. Students watch 3-D printers with a fervor usually reserved

for athletic events. Let’s capitalize on this passion and use 3-D printers in the same way we have used dinosaurs to sneak into young hearts and minds, making them more engaged with the geosciences and more aware of how much fun we have.

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