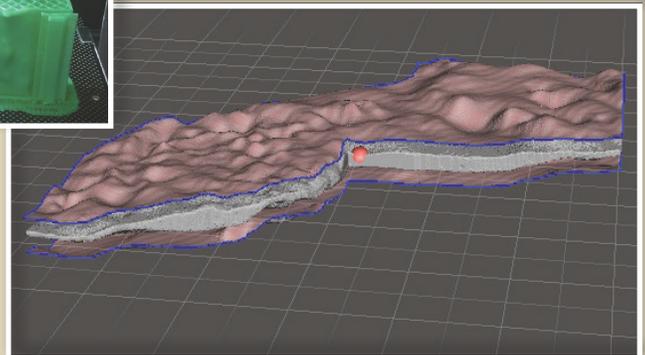
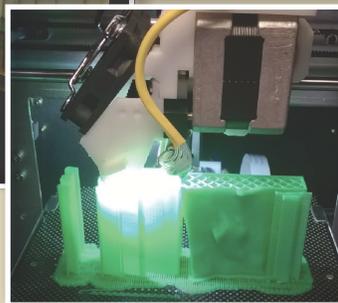
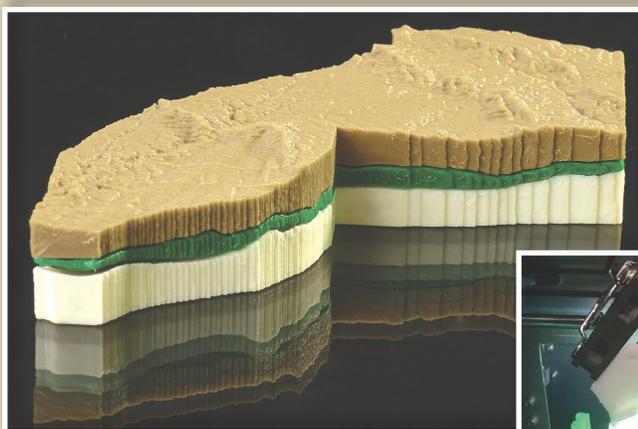


# Procedure for Three-Dimensional Printing of a Digital Hydrostratigraphic Model

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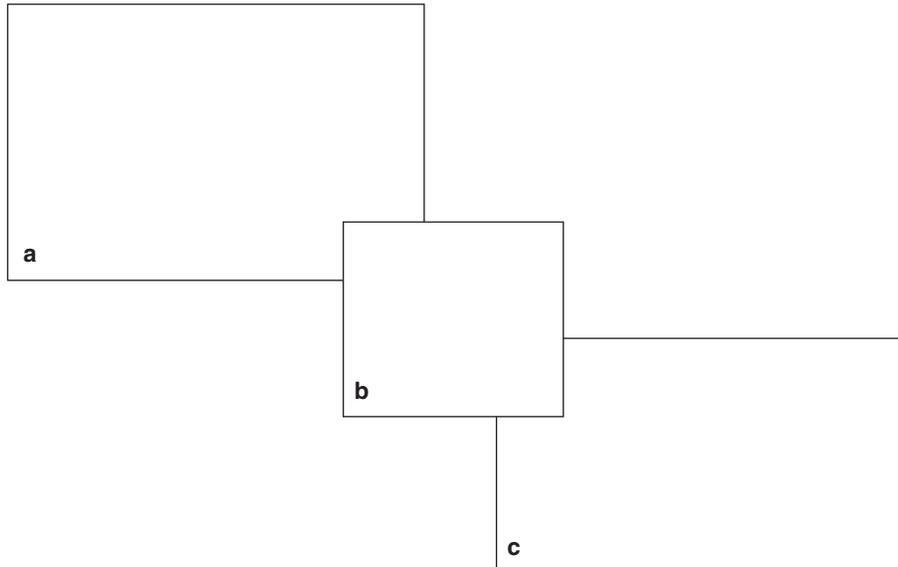


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**Front Cover:** (a) Three individually printed objects (with a 0.2-mm resolution) assembled to form the physical model. (Photograph by Joel M. Dexter.) (b) View of an extruded object from inside the 3-D printer. (Photograph by Yu-Feng Lin.) (c) Solid interpolated layer for the Mahomet aquifer constructed from the top and bottom surfaces in Meshmixer (<http://www.meshmixer.com/>), modeled at 20× vertical exaggeration based on 2-D layers of ArcGIS models.



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## ABSTRACT

Three-dimensional (3-D) printing provides the unique opportunity to transform models of theories, concepts, or measurements into physical objects. Many of these models are difficult to comprehend virtually. For the geosciences, 3-D printing is capable of representing complex geologic concepts or data. Here, we present a workflow for 3-D printing the physical representation of a hydrostratigraphic model that will assist others in using this technology. The hydrostratigraphic model presented for part of the Mahomet aquifer system in east-central Illinois was printed with a computer-guided 3-D printing system. The model contains three hydrogeologic or hydrostratigraphic units: the bedrock, the Mahomet aquifer, and the overlying strata.

The printing process began by determining the export file type that would allow grids of elevations corresponding to the top surface of the hydrostratigraphic units, which had been made with a geographic information system (GIS), to be imported into the 3-D printing software. Three processes were key to converting the GIS data to a file format that would be readable by the printer. We found that the triangulated irregular network (TIN) format could be translated efficiently into the stereolithography (STL) format to be 3-D printing ready. First, two-dimensional surfaces in TIN format were constructed to represent the top and bottom elevations of each unit. The TIN files were then exported to virtual reality modeling language files (WRL format) by using ESRI ArcScene software. The WRL files were next converted to STL-formatted files to construct a 3-D solid object model with the free software programs netfabb (<http://www.netfabb.com>) and Meshmixer (<http://www.meshmixer.com>).

Through iterative testing, we found that printing the model in different orientations had a significant impact on the printed resolution as well as on the stability of the model during the printing process. The prototype 3-D model of the Mahomet aquifer system was printed on its side (i.e., along the horizontal axis), with the east side aligned along the base of the printer. Thus, with the proper

workflow and setup, the 3-D printer was able to produce a physical object that very closely resembled the computer-generated digital model at a low cost and in a short time frame.

## INTRODUCTION

Three-dimensional (3-D) printing is a technology that provides a unique opportunity to study geological strata by transforming digital data into physical objects. Although widely used in manufacturing, the health sciences, and the fine arts, 3-D printing has only been utilized by geoscientists over the last decade, primarily to reproduce paleontological specimens or unique structures (Balanoff and Rowe 2002), create physical models of landscapes (Hasiuk and Harding 2016), and duplicate the microstructure and pore spaces of geologic materials (Head and Vanorio 2016). In addition, creating physical objects has allowed visually impaired geoscientists the opportunity to interact with their field or laboratory data (Horowitz and Schultz, 2014). In the last few years, the cost of 3-D printers and their associated software has decreased significantly, making these reproductions more affordable.

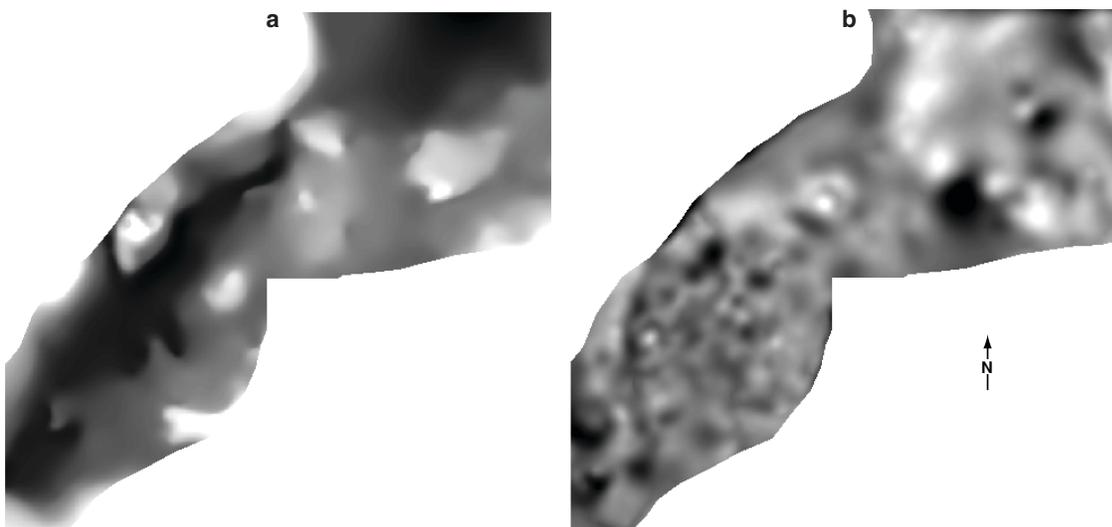
Three-dimensional printing is a revolutionary manufacturing technology in which a 3-D object is created by successively superimposing multiple two-dimensional (2-D) layers of material. It is also known as rapid prototyping or additive manufacturing. It is a mechanized method by which 3-D objects are made quickly on a reasonably sized machine connected to a computer that contains blueprints of the object. The 3-D printing process has wide appeal in the area of custom manufacturing. Three-dimensional printing can transform conceptual or empirical models into physical realizations.

The 3-D printing technology can provide important benefits in many fields. *Time* magazine reported that 3-D printing was one of the “Five Best Ideas of the Day” (The Aspen Institute 2014a,b). The technology was first developed by Charles Hull in 1984 to print physical 3-D objects from digital data. Hull later patented the technique, termed stereolithography, in 1986 (Hull 1986, 2015). After 30 years

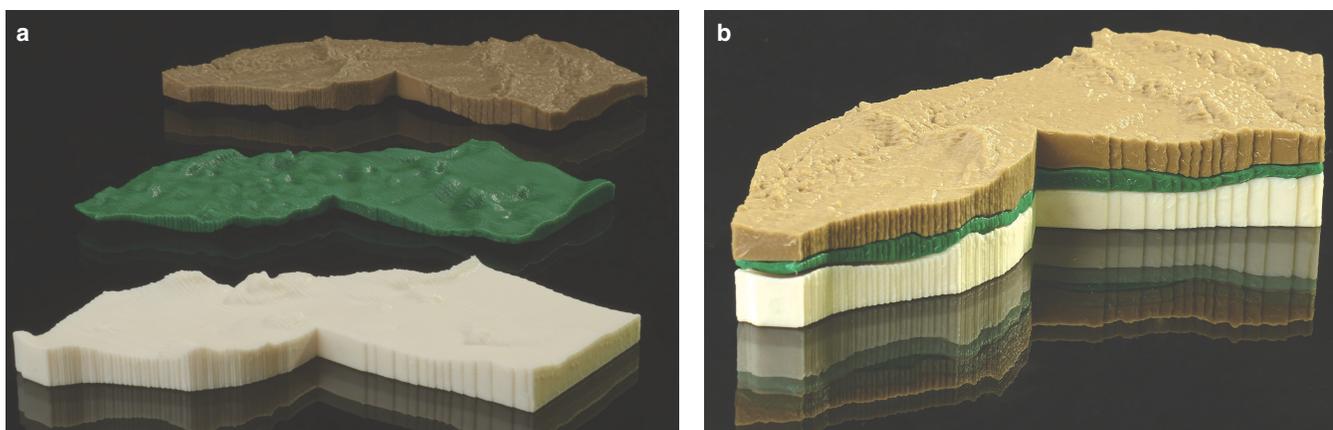
of development, 3-D printing is now being applied in many different fields. In medicine, the access to 3-D printed organs and limbs has helped physicians treat patients and save lives. This technology is now commonly utilized for medical diagnosis (e.g., Halterman 2015). Customized prosthetics allow the disabled to move freely (O’Toole 2014). In aerospace, NASA recently shipped a 3-D printer to the International Space Station, which allowed astronauts in space to print tools and parts remotely that otherwise would have taken months to acquire (Temperton 2014). In the fine arts, performers have collaborated with engineers to transform vibrations created by a sound or musical arrangement into 3-D printed ceramic objects (Koslow 2016).

In the geosciences, institutions such as the Department of Geology and Geoscience at Cedarville University, the first academic institution to expand the use of 3-D printers, have accurately reproduced fossils, landscape models, and internal rock structures. These objects are widely used in the university’s teaching and research programs (e.g., McKeivitt et al. 2015). In the future, 3-D printing technology could be used to create objects that are tested to validate geologic interpretations and processes. In hydrogeology, being able to print physical models of the hydrostratigraphy or hydrofacies could provide a better understanding of their spatial complexity and continuity and would allow accurate testing of hydraulic parameters in the laboratory. By comparison, interactive geological models compiled digitally on computer screens still cannot offer the same benefits as interacting with physical objects.

In this paper, we present a comprehensive workflow for building a physical representation of a hydrostratigraphic model developed for part of the groundwater system in east-central Illinois (Stumpf and Dey 2012; Figure 1). The strong public interest in studying and protecting the Mahomet aquifer makes it a good prototype for an experiment in which this technology is integrated into educational programs. The elevation data of the land surface and the top and bottom surfaces of the Mahomet aquifer were used to print the three



**Figure 1** Example of the hydrostratigraphic units as ESRI grids in raster format. (a) Elevations of the bottom of the Mahomet aquifer [grayscale at 475–340 feet above mean sea level (msl)]. (b) Elevations of the surface of the Mahomet aquifer (grayscale at 578–406 feet msl).



**Figure 2** The printed model represents, respectively, the surface topography and thickness of the deposits (mostly glacial till) lying above the Mahomet aquifer (brown layer); the Mahomet aquifer, a glacial sand and gravel aquifer (green layer); and the bedrock (white layer). (a) The three hydrostratigraphic units are printed as individual objects. (b) The three individually printed objects (with a 0.2-mm resolution) can then be assembled to form the physical model. (Photographs by Joel M. Dexter.)

layers (Figure 2), representing (from bottom to top) the bedrock (in white), the Mahomet aquifer (in green), and the overlying aquifers and aquitards (in brown). The objective of this report is to help future users adapt any newly available 3-D printing software and hardware for geologic applications as the technology advances. Therefore, this report is focusing on the conceptual processes and workflow. Complete details on particular operational commands

and specific tools are available in the software user manuals.

## FILE FORMAT

Understanding the type of data format of the import and export files is important for successful 3-D printing. The source data for this test were in raster format (as ESRI 2-D grids) or vector format (as triangulated irregular network [TIN] files). Both formats can easily be converted

using ESRI ArcGIS software. However, the 3-D printing operation requires specific input formats, such as stereolithography (STL) files, a data format that is not presently supported by common geographic information system (GIS) software applications. Thus, the 3-D printing process began by determining the correct export file type that would allow raster or TIN formats to be converted into file formats usable by the 3-D printing software and hardware.

Stereolithography files are in ASCII format, native to the stereolithography CAD (computer-aided design) software (Chua et al. 1997). When drawn, an STL file shows triangular representations of surface elevations that are arranged to build a 3-D model. Each surface is tessellated, or broken down logically, into a series of small triangles (facets). Each facet is described by a perpendicular direction and three points representing the vertices (corners) of the triangle. An STL file contains a list of facet data. Each facet is uniquely identified by a unit normal (a line perpendicular to the triangle and with a length of 1.0) and by the three vertices (Burns 1989). The orientation of a facet is determined by the direction of the unit normal and the order in which the vertices are listed. The facets define the surface of the 3-D object. A slicing algorithm is then used on the data to determine cross sections of the 3-D shape to be built; the 3-D model is created by successively superimposing multiple 2-D layers of material from the printer.

It is possible to convert a TIN format file to an STL format file because their triangular mesh structures are compatible. Both file formats can be converted to virtual reality modeling language (VRML) in a WRL file format. Therefore, VRML (or the WRL file) is the bridge file format needed to run the conversion between TIN and STL using the available software, such as ESRI ArcScene software. Furthermore, VRML is a 3-D navigation specification that enables the creation of interactive 3-D websites. With VRML, users can take virtual tours through 3-D digital models (e.g., buildings or cars) and view 3-D virtual reality interactively by using web browsers (The VRML Consortium Inc. 1997).

## WORKFLOW

Digital 3-D modeling in hydrogeology is an evolving field (Bajc and Newton 2005; Turner 2006; Kessler et al. 2009; Atkinson et al. 2014). Universities, governments, and private companies use a number of software packages, such as ArcGIS, GOCAD, GeoScene3D, RockWorks, and GSI3D, to create digital 3-D models (e.g., Berg et al. 2011). Although each software package has its own

native file format, typically, data representing the modeled surfaces can also be stored in vector format (TIN) or as a gridded array with a raster data structure. Therefore, the general procedure we describe can be applied to other input data formats that can be exported to WRL format. At present, the standard practice is to use software such as Tinkercad, 3D Slash, 123D Design, or Meshmixer to create the 3-D printed objects. The procedure represented in this workflow is certainly replicable with other software. After several tests to print the example hydrostratigraphic model, we determined that two associated file formats (STL and WRL) and three software packages (ArcGIS, <https://www.arcgis.com/features/index.html>; netfabb, <http://www.netfabb.com>; and Meshmixer, <http://www.meshmixer.com/>) were required to optimize the workflow (Figure 3).

Below, we provide the three-step process used to produce an STL file from the hydrostratigraphic data:

1. The ESRI raster data sets were converted to TIN format by using the Conversion Toolset function in the 3D Analyst Toolbox available in ArcGIS. The example hydrostratigraphic model was vertically exaggerated 20× so that the units could be shown with enough detail. The TIN files representing the surface elevations of each hydrostratigraphic unit were then converted to WRL files by using ArcScene.
2. The virtual reality models (WRL files) of the top and bottom surfaces of each hydrostratigraphic unit were converted to STL files by using the netfabb program. The conversion, shown in Figure 4, was necessary to construct a solid 3-D object for each unit, making them ready for 3-D printing.
3. In the final process, Meshmixer software was used to construct each hydrostratigraphic unit by integrating the top and bottom surfaces. Several tools (e.g., Extrude, Make Solid, and Attract) were used to refine the 3-D physical structure of the STL files, further optimizing the printing process.

As shown in Figure 5, the void space between the top and bottom surfaces was filled after potential weaknesses in the support structure were examined and fixed during the printing process. Each hydrostratigraphic unit was then ready for 3-D printing.

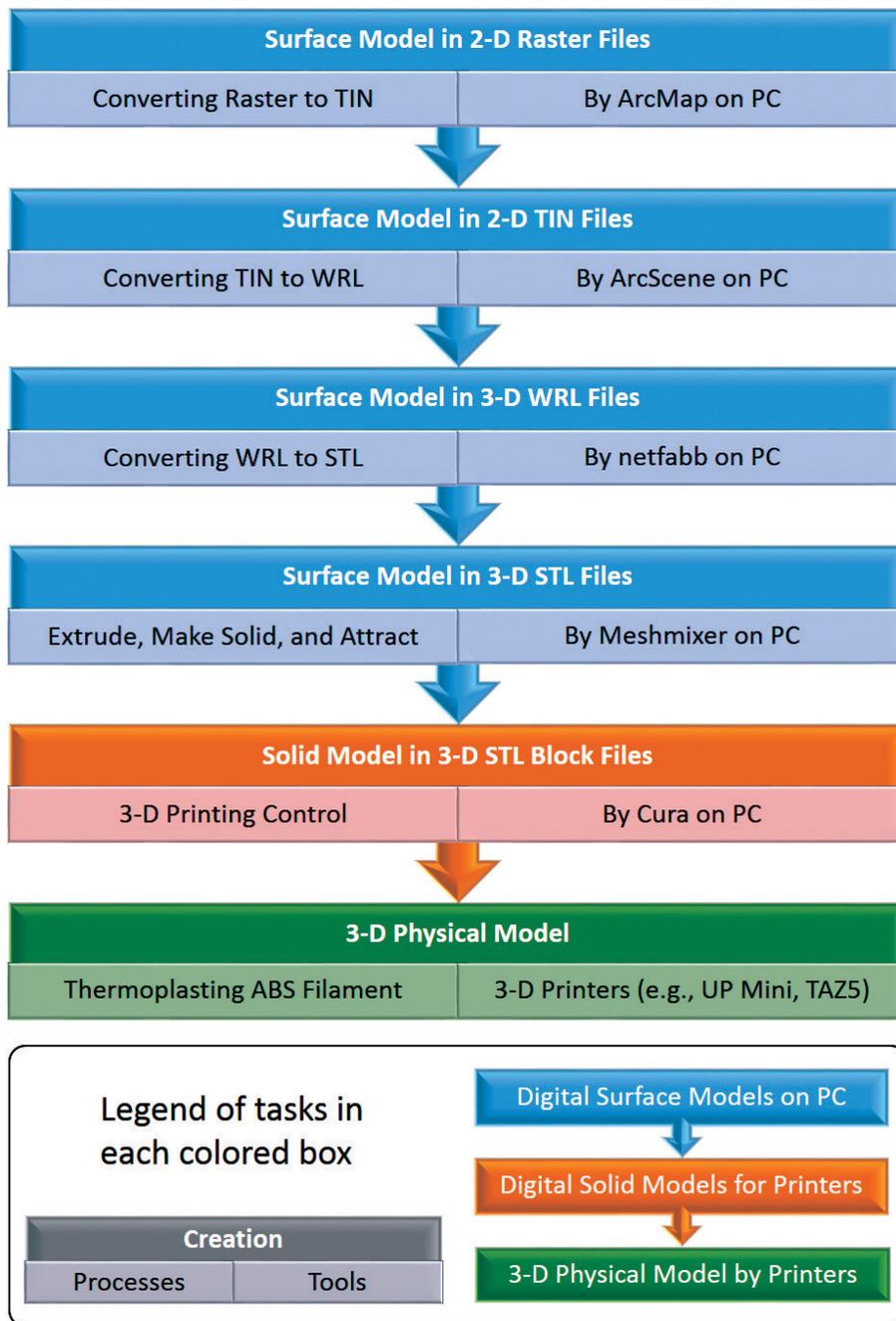
Cura software (version 2.1.2), developed by Ultimaker B.V. (<https://ultimaker.com/en/products/cura-software>), was used to prepare the 3-D file for printing. Cura is free open-source software released through an AGPLv3 (Affero General Public) license, and is one of the most commonly used software packages for maintaining a seamless integration between the hardware, software, and extruded materials. The software can easily be used by both novice and advanced users, and its functionality is further enhanced through contributions from the user community.

## 3-D PRINTER

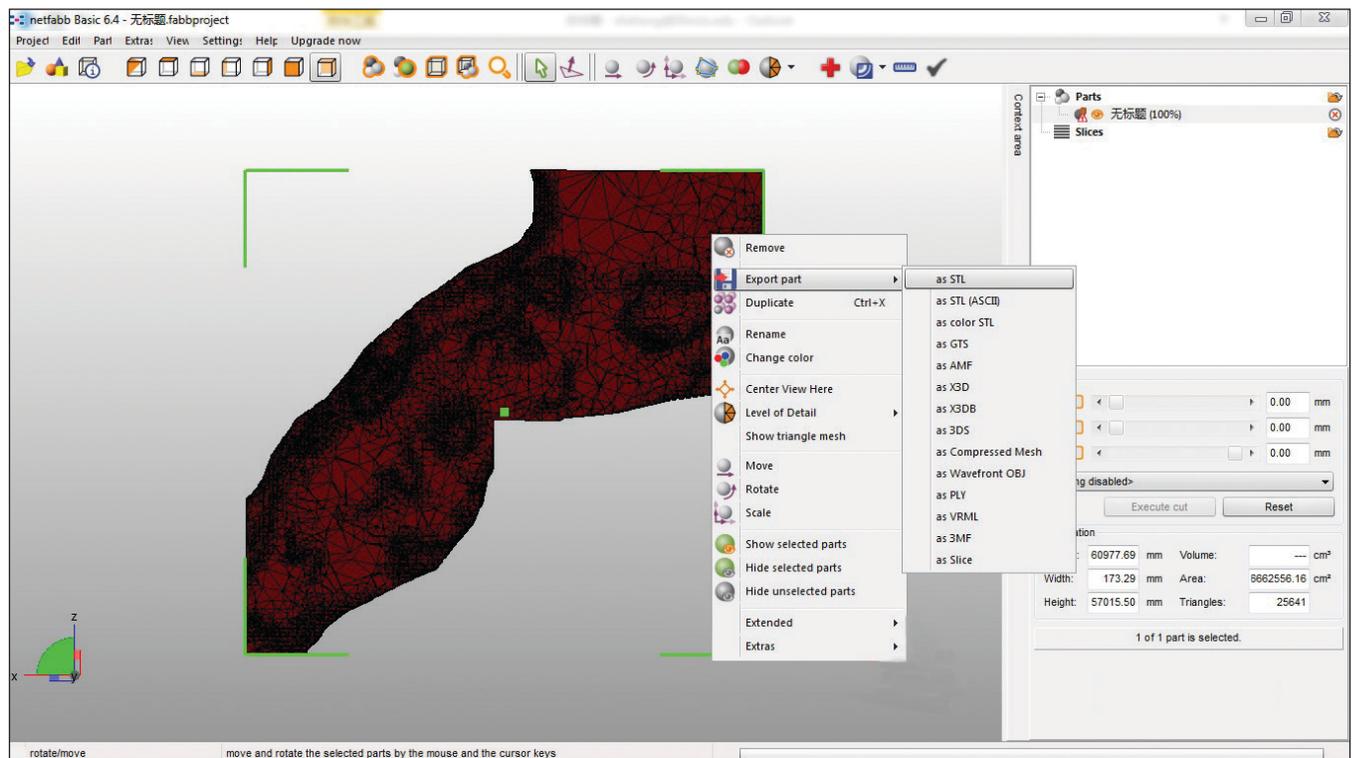
A prototype of the physical model was printed at the Champaign-Urbana Community Fab Lab (<http://cucfablab.org/>). A UP Mini 3-D printer manufactured by UP3D (<https://www.up3d.com/?r=mini>) was used. The printer is capable of fabricating objects stored in STL files by using acrylonitrile butadiene styrene or polylactic acid thermoplastic filament for one color at a time. The maximum printed dimensions are 12 cm for each of the axes (*x*, *y*, and *z*). The vertical resolution of the printer (*z*-axis quality) is 0.2 mm. The higher resolution of the *z*-axis was achieved by printing the model in a vertical printing position (i.e., with the model oriented on its side), rather than printing it from the bottom to top (Figure 6). For printing more complicated models, the UP Mini automatically prints extra temporary and disposable objects that provide balance and support but are not part of the final product.

## EXAMPLE HYDROSTRATIGRAPHIC MODEL

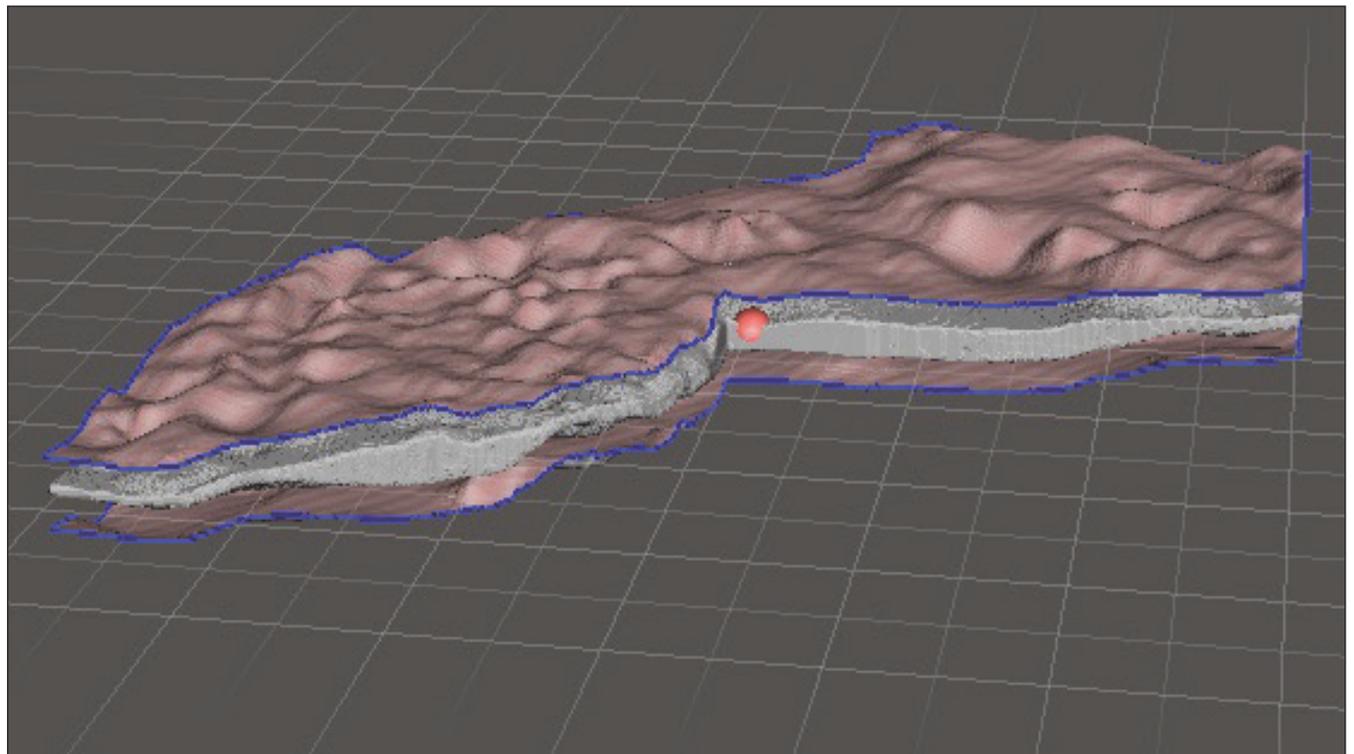
The Mahomet aquifer, an important glacial sand and gravel aquifer in east-central Illinois (Herzog et al. 1995; Soller et al. 1999), is the main source of



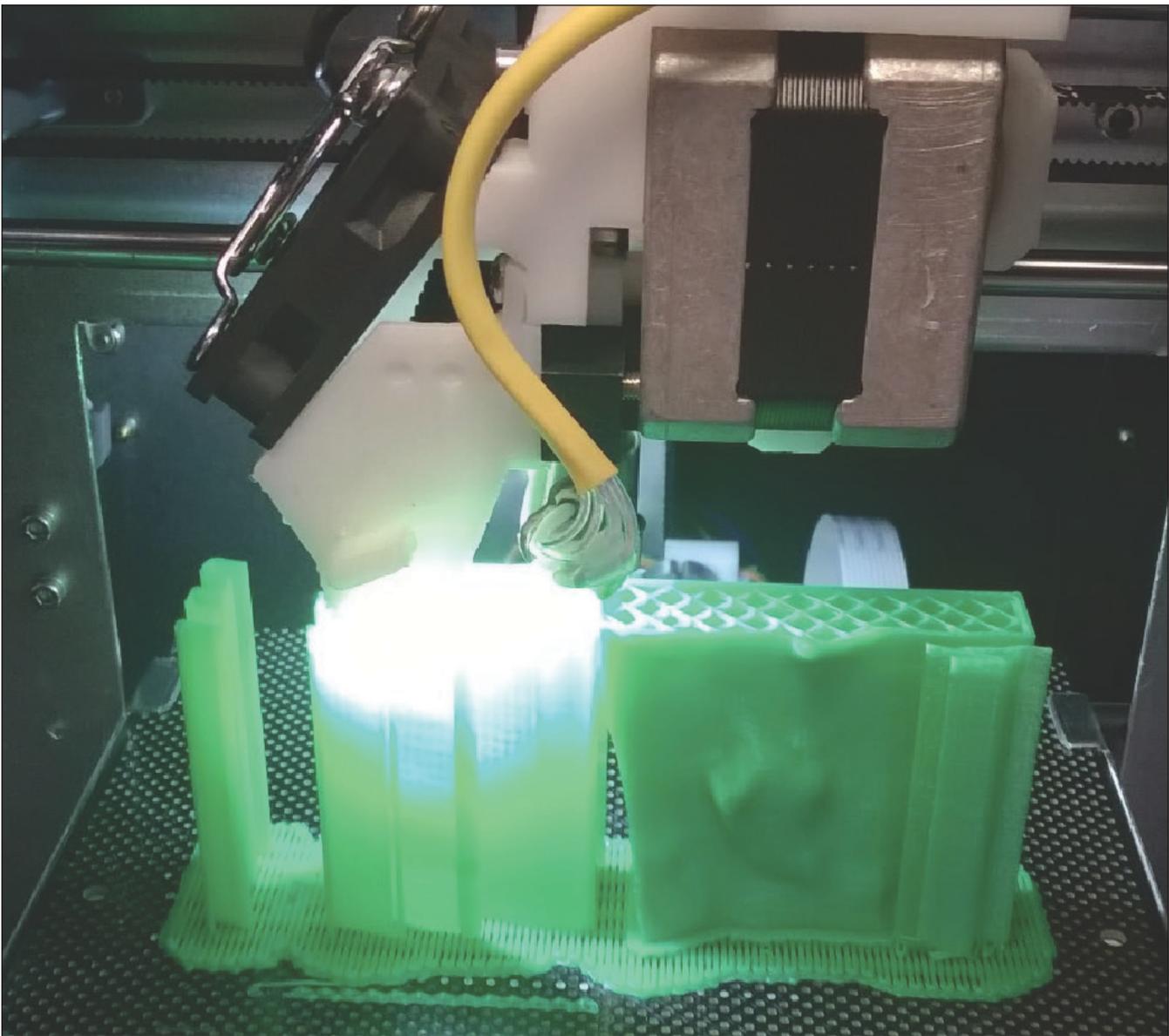
**Figure 3** Workflow used to create the 3-D printed model from the hydrostratigraphic data. TIN, triangulated irregular network; STL, sterolithography; ABS, acrylonitrile butadiene styrene.



**Figure 4** Screen shot of the WRL file converted to stereolithography (STL) format in netfabb (<http://www.netfabb.com>). The triangulated irregular network (TIN) for the top surface of the Mahomet aquifer is shown.



**Figure 5** The solid interpolated layer for the Mahomet aquifer is constructed from the top and bottom surfaces in Meshmixer (<http://www.meshmixer.com/>). The unit is shown at 20x vertical exaggeration.



**Figure 6** View of an extruded object from inside the 3-D printer. The model layers were printed while positioned vertically, which is from east to west in geographic coordinates. The x-axis (eastern edge of the model; see Figure 1) lies along the bottom of the printer platform. The inner support structure is shown at the top right. The supporting material (left of the spotlight) will support the west part of the model, to be printed later. (Photograph by Yu-Feng Lin.)

groundwater for more than 800,000 residents in the region (Roadcap et al. 2011). The Mahomet aquifer forms part of the Mahomet aquifer system, a hydrologic system that was recently designated as a “sole source aquifer” by the U.S. Environmental Protection Agency (2015). Empirical hydrostratigraphic models have been constructed for the aquifer system to illustrate the spatial distribu-

tion and continuity of hydrogeologic or hydrostratigraphic units in the subsurface (e.g., Herzog et al. 2003). Hydrostratigraphic units are assigned “based on their inherent mappable hydraulic properties and attributes” (see Seaber 1986, p. 9); hydrostratigraphic units are related to the geologic framework, which is based on lithologic characteristics and stratigraphic relationships (Seaber 1988).

The hydrostratigraphic model used for the 3-D printing process was developed from newly acquired data, including detailed descriptions of sediment and bedrock core collected from boreholes (Stumpf and Dey 2012). The modeling process also included analyses of newly collected geophysical and hydrogeological information and existing geologic logs. Methodologies for the data compilation, analysis, and interpolation

processes have been established by scientists and professionals at the Illinois State Geological Survey and Illinois State Water Survey (e.g., Berg et al. 2016). The example hydrostratigraphic model has been used at several scientific presentations and public meetings to illustrate these research efforts effectively.

## CONCLUSIONS

This prototype printed object included only three layers, so the hydrostratigraphic model of the Mahomet aquifer system could be reproduced relatively quickly and cost effectively. Because of the physical dimensions of the modeled area, printing it at a larger scale would have been cost prohibitive. Subsequent versions of the model will include additional layers representing other aquifer and aquitard units from the upper hydrostratigraphic unit, which for this test are not subdivided out.

Since the prototype object was printed, presentations have been made at several public meetings to illustrate the subsurface geometry of units composing the Mahomet aquifer system and explain the 3-D printing process. We foresee 3-D printing as a tool that will eventually be integrated into research programs, education, and outreach efforts in the geosciences. With the increasing availability of 3-D printers, extremely realistic models of fossils, fractured rocks, and planetary bodies could be printed remotely from shared digital design files (Hasiuk 2014; Horowitz and Schultz 2014; Rosen 2014). Using these models, scientists could test and analyze specific processes and systems with precise replicas of geologic materials and structures having different characteristics and properties, including porosity and permeability (Rangel et al. 2013; Ishutov et al. 2015; Hasiuk and Harding 2016).

At this point, the resolution (i.e., feature size and layer thickness) is the major constraint on the types of features or structures that can be printed. Nevertheless, many scientists expect that smaller scale geologic and hydrogeologic features, for example, pore spaces and crystal structure, will eventually be duplicated as the technology advances further (Hasiuk et al. 2016). Utilizing

3-D printers to create so-called “smart rocks” with synthetic porous structures and micro sensors (Heriot-Watt University 2016) could lead to new technological advances and improve the efficiency of current mineral and petroleum extraction and monitoring.

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