3D printing the world: developing geophysical teaching materials and outreach packages

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Abstract

3D-printing techniques allow us to visualise geophysical concepts that are difficult to grasp, making them perfect for incorporation into teaching and outreach packages. Abstract models, often represented as 2D coloured maps, become more tactile when represented as 3D physical objects. In addition, new questions tend to be asked and different features noticed when handling such objects, while they also make outreach and education more inclusive to the visually impaired. Some of our most effective models are simply exaggerated planetary topography in 3D, including Earth, Mars and the Moon. The resulting globes provide a powerful way to explain the importance of plate tectonics in shaping a planet and linking surface features to deeper dynamic processes. In addition, we have developed a simple method for portraying abstract global models by 3D printing modified globes of surface topography, representing the parameter of interest as additional, exaggerated long-wavelength topography. This workflow has been applied to models of dynamic topography, the geoid and seismic tomography. In analogy to Russian nesting dolls, the resulting "seismic matryoshkas" have multiple layers that can be removed by the audience to explore the structures present deep within our planet and learn about the ongoing dynamic processes. While these 3D objects are easily printed on a cheap (<300 GBP, 400USD) desktop 3D-printer, the printing times still prohibit large-scale production. To ensure that there is sufficient material in a teaching setting, we have therefore also developed complementary paper equivalents. By projecting the coloured maps onto a dodecahedron, we developed cut-out-and-fold models to be handed out in a classroom setting to complement the 3D printed globes used for demonstration purposes. Together with animations, suggested questions and instructor "cheat-sheets", these materials form a complete teaching and outreach package that is both interactive and inclusive.

ED43B-1101: 3D printing the world: developing geophysical teaching materials and outreach packages

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3D printing allows us to visualise geophysical concepts that are difficult to grasp. However, printing times remain the limiting factor for large-scale production. Paper globe equivalents are a cheap alternative for classrooms. Together, these form a complete and inclusive teaching package.

3D printing methodology

1) Take scalar geophysical field with data in lat,lon,z
2) Combine with continental outlines and small-scale topography into composite greyscale image
3) Apply this "bump map" to the surface of a sphere using UV mapping in Blender and export as .stl
4) Halve and hollow out globes to speed up printing times
5) Slice for printing using Ultimaker Cura / Prucaslicer (or similar)

The process is illustrated here for dynamic topography.

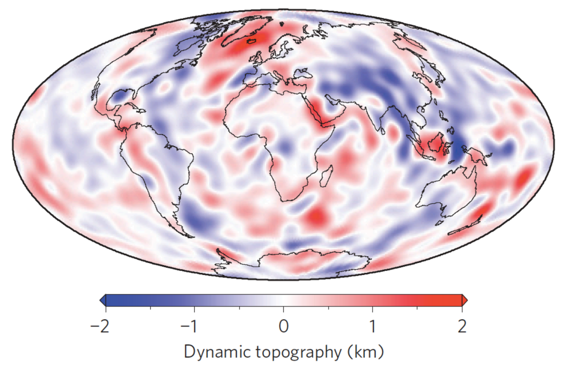
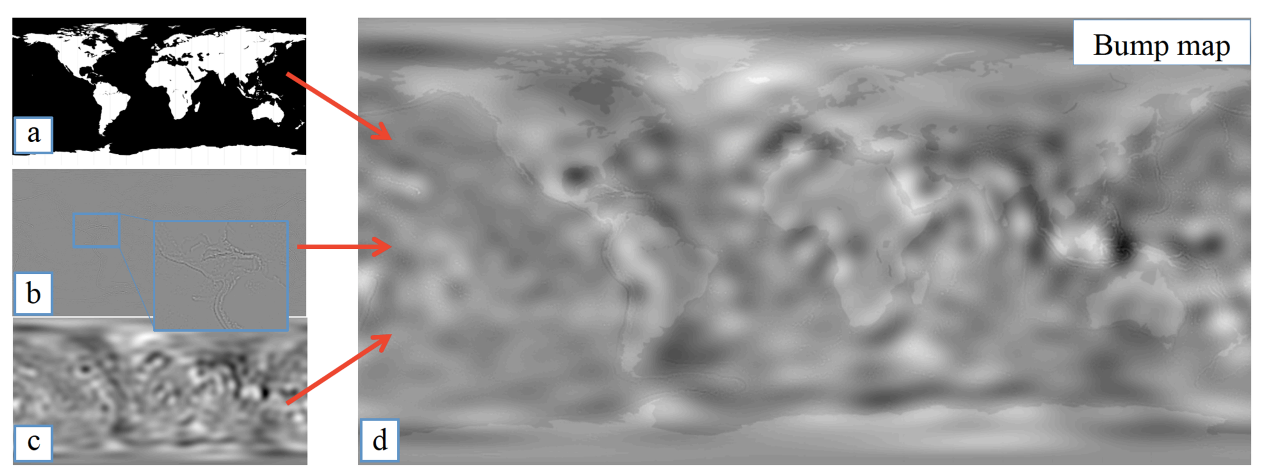


***Fig 1.** Global dynamic topography (data from Hoggard et. al, 2016).*



White = up (bump), black = down (dent)

***Fig 2.** (a-c) Greyscale layers are composited to form a (d) bump map. Continent outlines (a) provide spatial reference, while high pass filtered surface topography (b) provides geological features. Dynamic topography (c) provides the long wavelength component here. Input images were generated using the Generic Mapping Tools (Wessel et al., 2013) and composited using Python.*

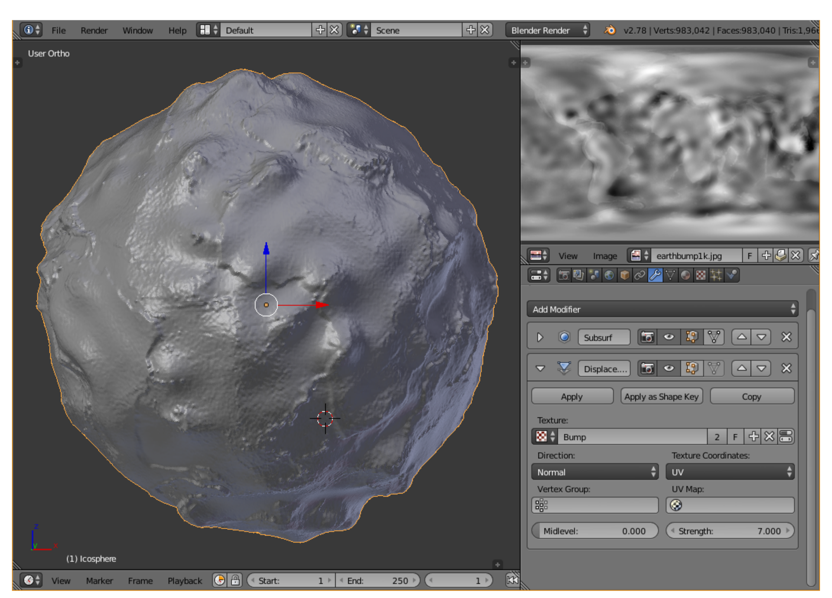
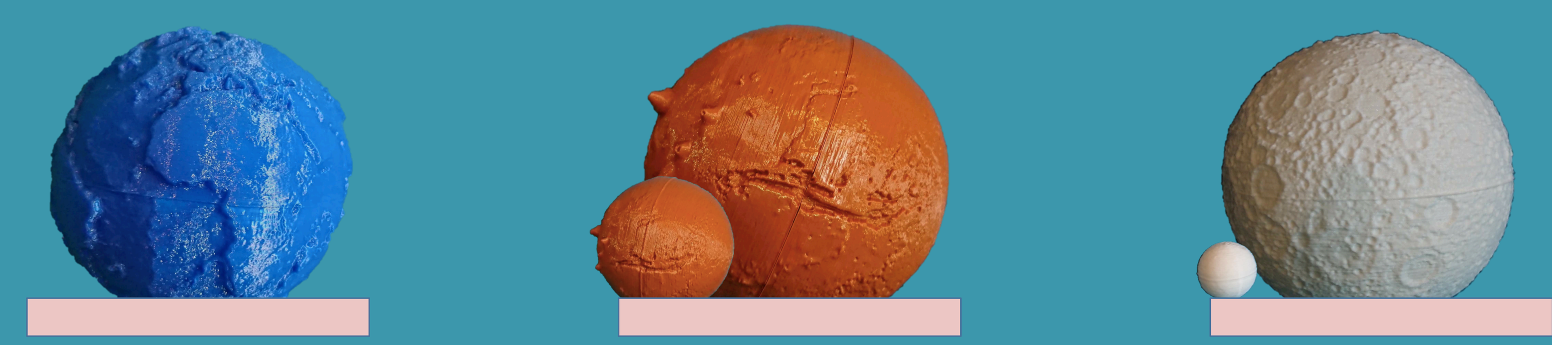


***Fig. 3.** Screenshot showing the application of the bump map in the Blender software.*

3D printing the world

PLANETARY TOPOGRAPHY

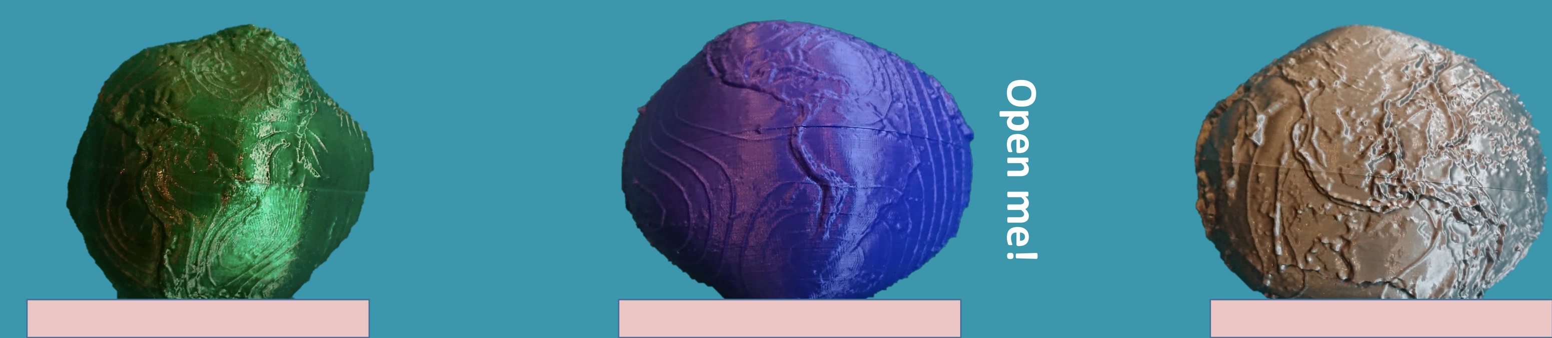


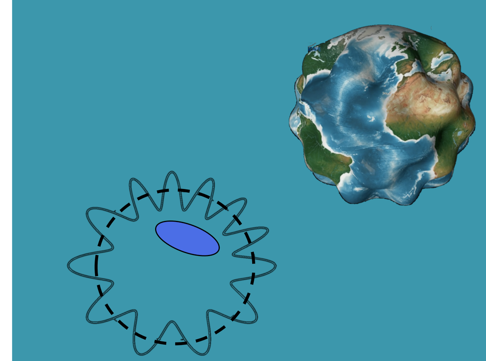
EARTH	
Data:	ETOPO1
True diameter:	12,742 km
Vertical exagg.:	50 : 1
Relative size:	1 : 1

MARS	
Data:	MOLA
True diameter:	6,779 km
Vertical exagg.:	20 : 1
Relative size:	1 : 1.9

MOON	
Data:	LOLA
True diameter:	3,747 km
Vertical exagg.:	14 : 1
Relative size:	1 : 3.4

STANDING WAVE FREQUENCY VARIATIONS



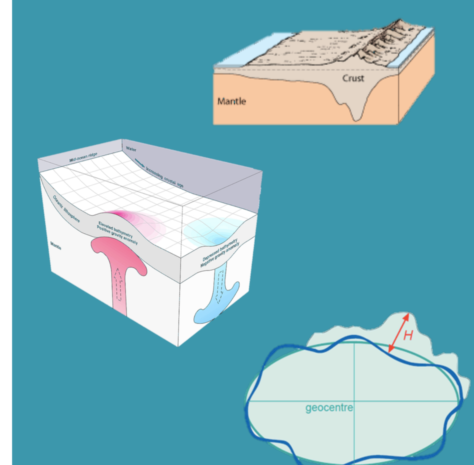


MODE $_0S_{26}$	
Data:	KDR13
Centre frequency:	3.45 mHz
Max freq variation:	27.6 µHz
Sensitive to:	Upper mantle

MODE $_2S_{16}$	
Data:	KDR13
Centre frequency:	3.44 mHz
Max freq variation:	27.3 µHz
Sensitive to:	Lower mantle

MODE $_{13}S_6$	
Data:	DRH13
Centre frequency:	6.16 mHz
Max freq variation:	16.1 µHz
Sensitive to:	Inner core

GENERAL GEOPHYSICS

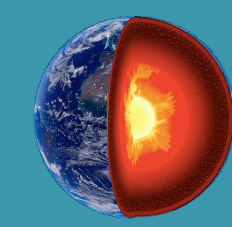


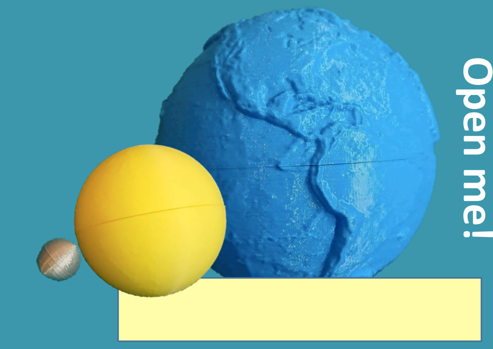
CRUSTAL THICKNESS	
Data:	ETOPO1 / CRUST1.0
True diameter:	6,371 km
Vertical exagg.:	50 : 1
Information on:	Isostasy

DYNAMIC TOPOGRAPHY	
Data:	Hetal16
True diameter:	6,371 km
Vertical exagg.:	300 : 1
Information on:	Mantle flow

GEOID	
Data:	GGM05C
True diameter:	6,371 km
Vertical exagg.:	10,000: 1
Information on:	Density

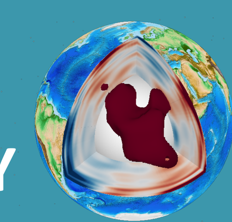
EARTH INTERIOR





SURFACE, OUTER CORE & INNER CORE	
Data:	ETOPO1 / PREM
True radii:	6,371 km
	3,481 km
	1,221 km
Vertical exagg.:	50 : 1
Relative size:	1 : 1

SEISMIC TOMOGRAPHY



50, 660 & 2850 KM DEPTH	
Data:	SP12RTS
True radii:	6,321 km
	5,711 km
	3,521 km
Max velocity variation / contour level:	3.3 / 0.50 %
	1.3 / 0.25 %
	1.4 / 0.25 %

Take a picture for a link to 3D-printing designs

Acknowledgements: PK is funded by a Royal Society University Research Fellowship (URF\R1\180377) and gratefully acknowledges their support. Outreach funding is provided by an Enhancement Award (RGF\EA\181029).
Models: Script to make dodecahedrons can be downloaded from https://github.com/renaud71/dodecahedron (Toussaint, 2018, doi:10.5281/zenodo.2531114). 3D-printed designsare available at https://www.thingiverse.com/jeffwinterbourne/designs.
Data used in 3D printing: Earth topography: ETOPO1 (https://www.ngdc.noaa.gov/mgg/global/). Mars topography: MOLA (https://attic.gsfc.nasa.gov/mola/). Moon topography: LOLA (https://lola.gsfc.nasa.gov/). Seismic tomography: SP12RTS (Koelemeijer et al., GJI, 2016). Splitting functions: KDR13 & DRH13 (Koelemeijer et al., GRL, 2013; Deuss et al., GJI, 2013). Crustal thickness: CRUST1 (Laske & Masters, Geophys. Res. Abs, 2013). Geoid: GGM05C (Ries et al., CSR-16-02, 2016). Dynamic topography: Hetal16 (Hoggard et al., Nature Geosc, 2016).
Software: GMT (Wessel & Smith, EOS Trans, 2013), Blender (https://www.blender.org/), Autodesk MeshMixer (www.meshmixer.com/), Ultimaker Cura (https://ultimaker.com/en/products/ultimaker-cura-software), PrucaSlicer (https://www.prusa3d.com/prusaslicer/).

DEEPSCAPE

ROYAL HOLLOWAY UNIVERSITY OF LONDON

Ecole et Observatoire des Sciences de la Terre

Paper globe equivalents

Printing full-size globes takes roughly 6-8 hours on a cheap desktop 3D printer and cost $2-3 each in materials, prohibiting large-scale production. To ensure availability of sufficient material in a teaching session, we have developed complementary paper equivalents, which have the added advantage of being full-color.

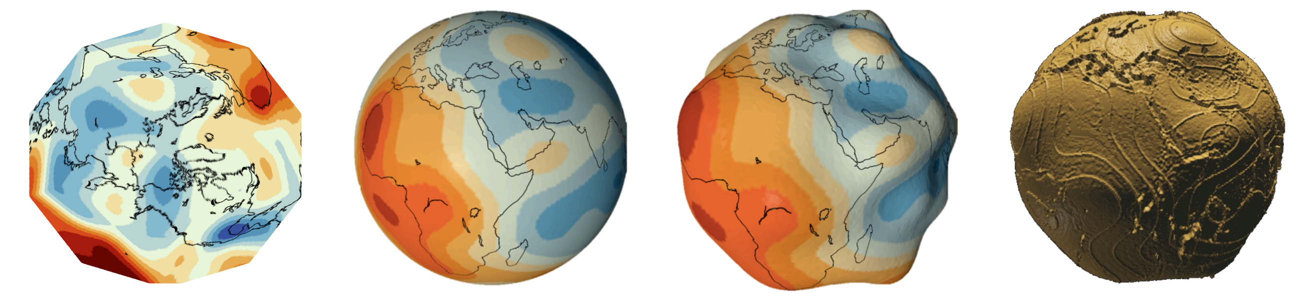
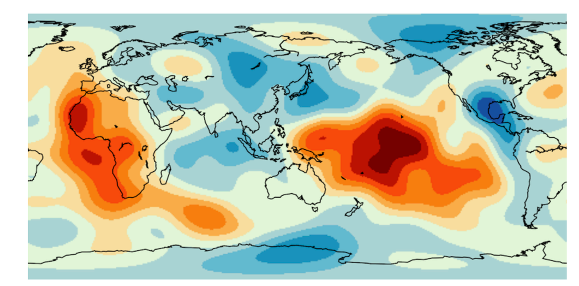


***Fig 4.** Different representations of the same scalar geophysical field (here seismic tomography at 2850 km depth), showing the relationship between a paper dodecahedron (left) and 3D-printed globe (right).*

Paper globe methodology

1) Plot scalar geophysical field in Cartesian projection
2) Project the image onto faces of dodecahedron
3) Flatten the dodecahedron faces onto sheet of paper



This process is illustrated here for seismic tomography at 2850 km depth.

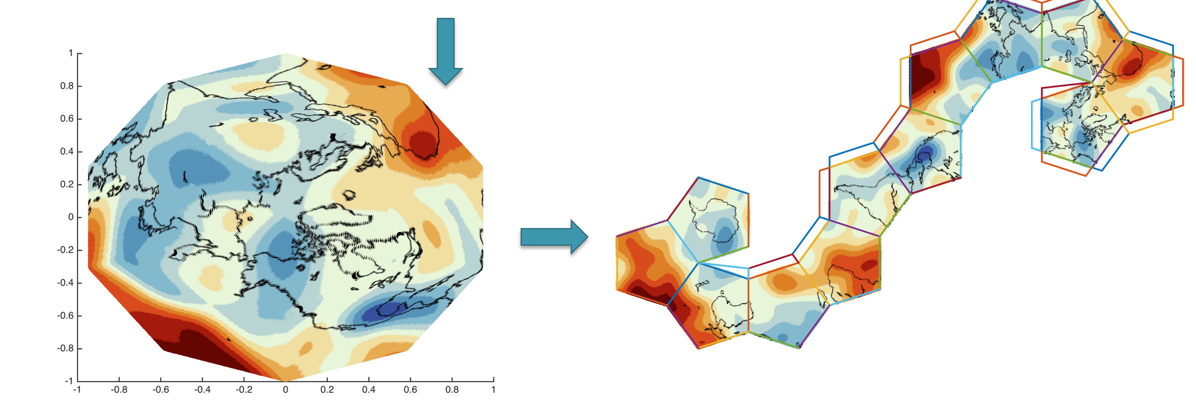


***Fig 5.** Illustration of the process to create a dodecahedron globe. A Cartesian image is created of the data (1 deg = 1 map unit), which is projected onto the faces of the dodecahedron.*

Use in outreach and teaching settings

The 3D-printed globes and paper equivalents, together with animations, suggested questions and instructor cheat-sheets form a complete package that is both interactive and inclusive.

***Fig 6.** Pictures of an outreach session, where 3D-printed globes were used together with paper equivalents and animations to discuss various concepts in the Earth Sciences.*