3D-printed representations of global geophysical parameters for outreach and education

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Abstract

Measurements and models of global geophysical parameters such as potential fields, seismic velocity models and dynamic / residual topography are well represented as 2D coloured / contoured maps. However, as teaching aids and for outreach, they offer little impact. Modern 3D-printing techniques help to visualize these and other concepts that are difficult to grasp, such as the intangible structures in the deep Earth. We developed a simple method for portraying scalar fields by 3D printing modified globes of surface topography, representing the parameter of interest as additional, exaggerated topography. This is particularly effective for long-wavelength (>500 km) fields. The workflow uses only open source and free-to-use software, and the resulting models print easily and effectively on a cheap (<300 GBP, 400USD) desktop 3D-printer. We have printed 3D representations of different scalar fields, including models of the surface topography of rocky planets, which can be used in outreach events. These objects are powerful to explain the importance of plate tectonics in shaping a planet. The workflow was extended to 3D scalar fields by analogy to Russian nesting dolls, where the audience can remove shallower layers to see how structures change with depth. We applied this to global seismic tomography models resulting in prototypes of “seismic matryoshkas” (see Figure). The tactile nature of these objects ensures that anyone, including the visually impaired, can explore the structures present deep within our planet

3D printed representations of global geophysical scalar fields

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1. Introduction

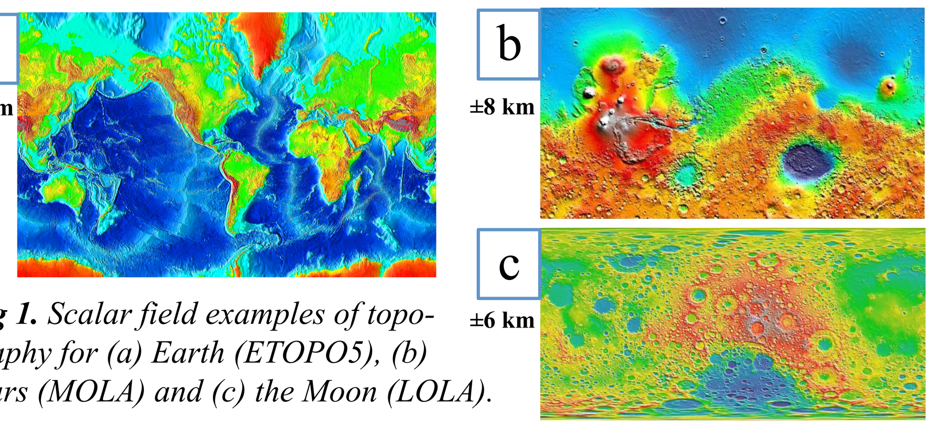


Fig 1. Scalar field examples of topography for (a) Earth (ETOPO5), (b) Mars (MOLA) and (c) the Moon (LOLA).

Global geophysical parameters (e.g. topography, seismic tomography, residual topography) are well represented as 2D colour maps (**Fig. 1**). However, they offer little impact as aids for teaching and outreach.

Here, we illustrate our method for portraying scalar fields using modern 3D-printing techniques. The resulting globes help to visualize difficult to grasp geophysical fields, such as seismic structures in the deep Earth.

The workflow uses only open-source and free-to-use software. The resulting models print easily and effectively on a cheap (<$400) desktop 3D-printer. Our models are free to use, hosted on the Thingiverse website.

2. Concept and methodology

We developed a simple method for portraying scalar fields by 3D printing modified globes of surface topography, with the parameter of interest as additional, exaggerated topography. We illustrate the procedure for a model of dynamic topography (**Fig. 2**), while other examples of planetary topography and seismic tomography are given on the right.

Since most accessible 3D printers are monochrome, i.e. use a single colour of plastic for the whole print, we add spatial and geological context by including familiar elements of topography and coastlines (**Fig. 3**).

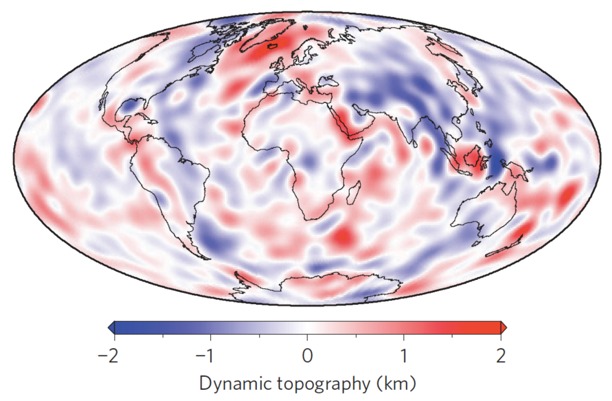


Fig 2. Global dynamic topography (data from Hoggard et. al, 2016).

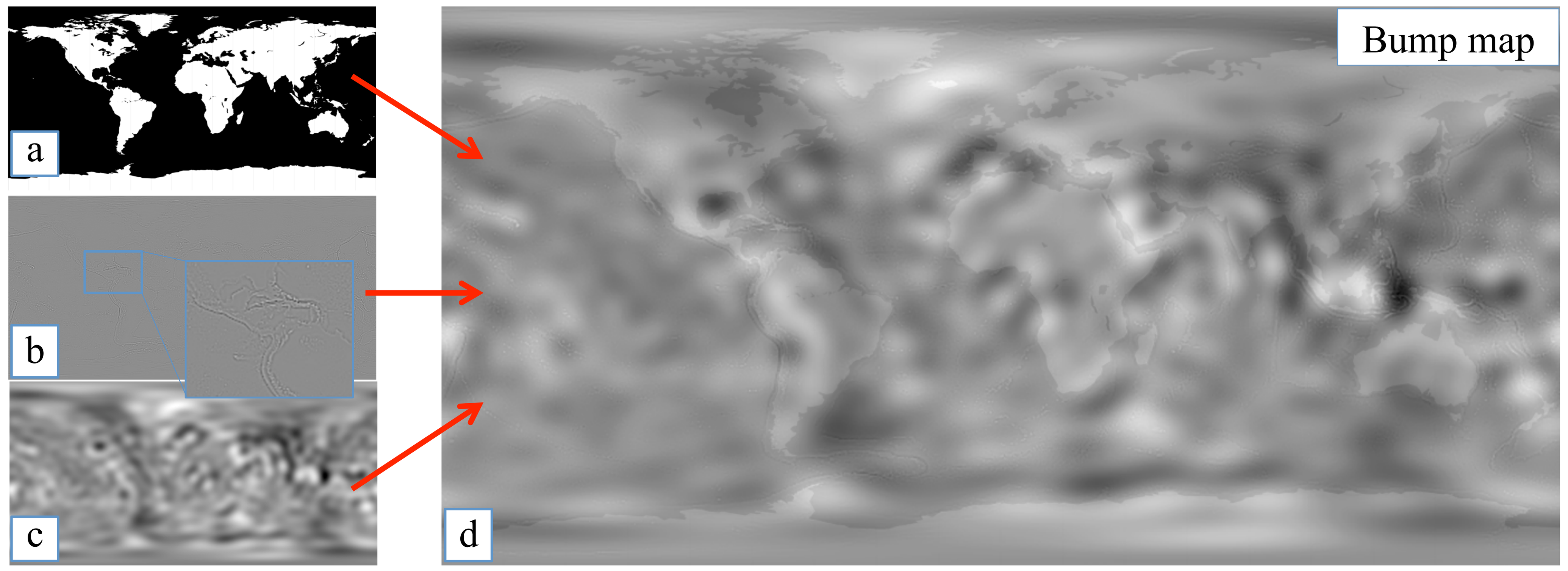


Fig 3. (a-c) Greyscale layers are composited to form the (d) bump map. Continental outlines (a) provide spatial reference and high pass filtered (<250 km) surface topography (b) provides geological features (mountains, trenches, seamounts etc.). Dynamic topography (c) provides the long wavelength component. Input images were generated using the Generic Mapping Tools (Wessel et al., 2013) and composited using ImageMagick.

To create the model, we apply a "bump map" to the surface of a sphere, using UV mapping with the open-source Blender software (**Fig. 4**). The bump map consists of a *plat carrée* projected greyscale image, unadorned, where white corresponds to the highest desired topographic point and black the lowest. Models can then be exported in the widely used STL format.

Models are sliced into northern and southern hemispheres and hollowed before printing – this minimises the amount of plastic and time required for printing. This can be accomplished in Blender prior to export, or afterwards using the more user-friendly Autodesk MeshMixer.

Models are sliced for printing by a desktop 3D printer using the Ultimaker Cura slicer, typically taking 6-8 hours to print using renewable PLA bio-plastic at high quality with material costs of $2-$8 per model.

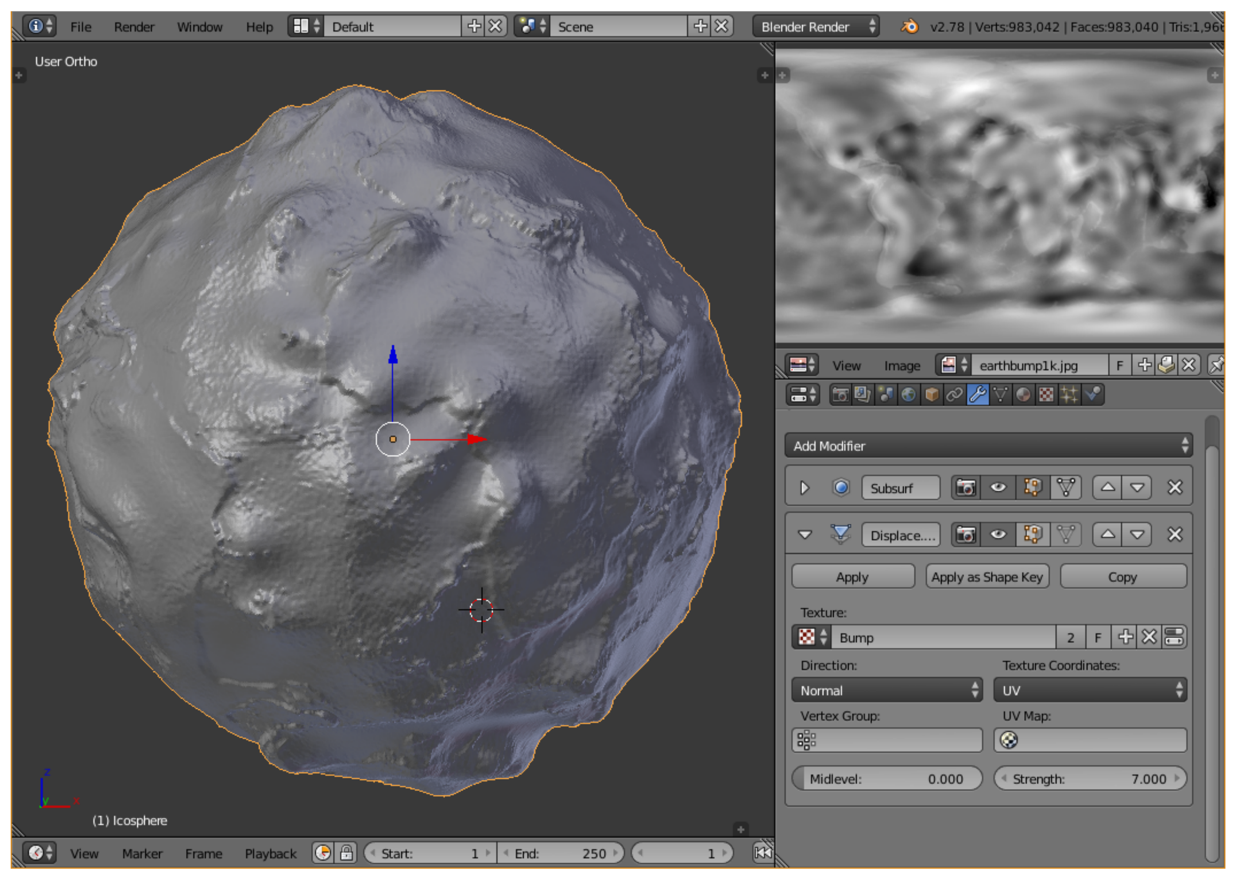


Fig. 4. Screenshot showing the application of the bump map in the Blender software.

3a. Dynamic topography

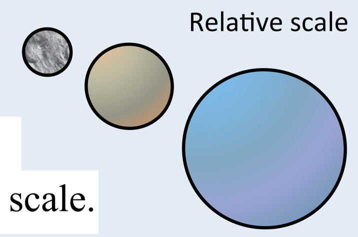
"Dynamic topography" is caused by density variations and flow in the convecting mantle. As the convective state of the mantle changes, surface topography of ±1 km is generated at wavelengths between 500-10,000 km

Data:	Hoggard et al. (2016)
Vertical exaggeration:	~ 300 : 1

Notable dynamic topographic highs are found at hotspots (e.g. Iceland, Hawaii) and lows include the Gulf of Mexico and the Argentine abyssal plain.

www.thingiverse.com/thing:3253664

3b. Topography of the rocky planets

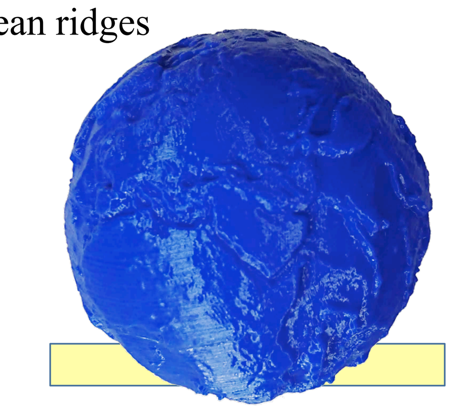


Detailed topographic models of the rocky planets are made available (Earth by us, Mars and Moon by others) and serve as excellent teaching material. Note that the printed examples are not at relative scale.

Earth

Data:	ETOPO5
True planet diameter:	12,742 km
Vertical exaggeration:	50 : 1
Relative size to Earth:	1 : 1

Recognisable features:
- Mountain belts and deep trenches at convergent plate boundaries
- Bend in Hawaiian volcanic chain
- Plate subsidence away from mid-ocean ridges

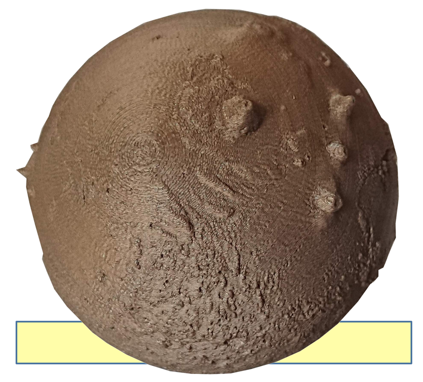


www.thingiverse.com/thing:2237721

Mars

Data:	MOLA
True planet diameter:	6,779 km
Vertical exaggeration:	20 : 1
Relative size to Earth:	1 : 1.9

Recognisable features:
- Hemispherical dichotomy of northern plains vs. southern highlands
- Olympic Mons (25 km tall)
- Valles Marineris canyon system

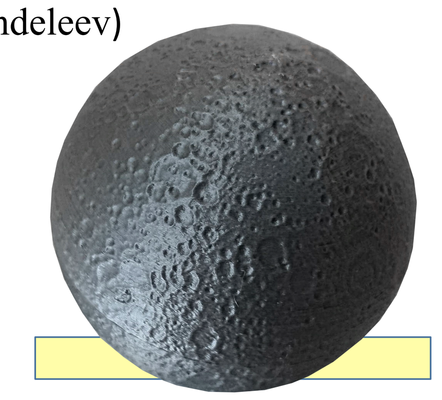


www.thingiverse.com/thing:403244 (user GlobeMaker)

Moon

Data:	LOLA
True moon diameter:	3,747 km
Vertical exaggeration:	14 : 1
Relative size to Earth:	1 : 3.4

Recognisable features:
- Flat maria on the lunar near side
- Giant far side South Pole Aitken impact basin (13 km deep)
- Double rimmed craters (e.g. Marth, Mendeleev)

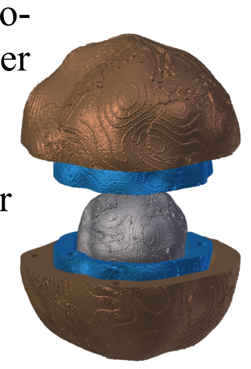


www.thingiverse.com/thing:1924845 (user chhu)

3c. Seismic tomography "Matryoshkas"

Global tomographic models of seismic velocity provide crucial information about our planet's interior. We represent S-wave velocity variations such that elevated regions indicate low velocities and fast velocities show up as depressions (**Fig. 5 & 6**).

Globes were hollowed out in Blender using boolean operations and recessed holes for magnets added to allow the globes to close.



To capture the depth variations of seismic velocities, globes can be opened up to reveal deeper layers, analogous to Russian nesting dolls (Matryoshkas).

SP12RTS

Data:	Koelemeijer et al. (2016)
Slices:	50, 660 & 2850km depth
Contours:	- 0.50 % (50km)
	- 0.25 % (660 / 2850km)

www.thingiverse.com/thing:3254056

The 3D print of SP12RTS at 2850km has an ellipsoidal shape due to elevated topography under the Pacific / Africa, where we see large-low-velocity-provinces (Fig. 5).

Fig. 5

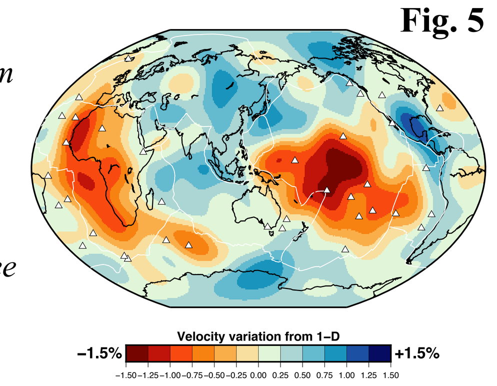
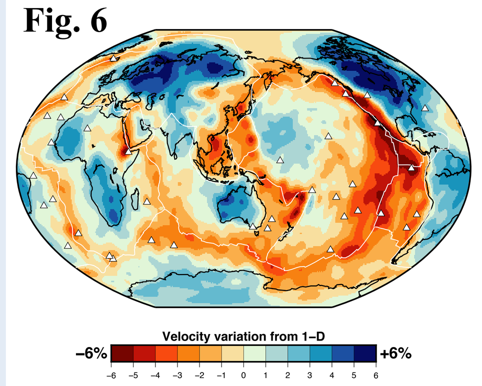


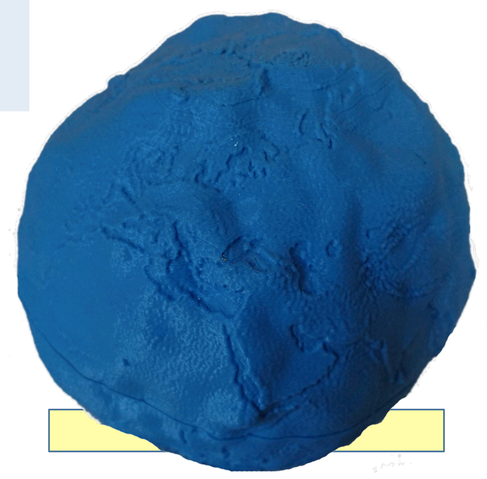
Fig. 6



The 3D print of S40RTS at 100km shows elevated areas at mid-ocean ridges due to low velocities (hot regions) and depressed areas in continental cratons due to high velocities - cold material (Fig. 6).

S40RTS

Data:	Ritsema et al. (2011)
Slices:	100 & 2850km
Relative radii to scale	



www.thingiverse.com/thing:3258477

4. Education and impact

The tactile nature of 3D printed objects makes them inclusive teaching material, supporting pupils with visual impairments.

3D-printed globes of Earth, Mars and the Moon can be used to discuss the effect of plate tectonics on planetary topography. Earth shows primarily tectonic features; the Moon is shaped by impact craters; and Mars shows a mixture.

Seismic "matryoshkas" allow students to literally peel away different Earth layers and to discover how seismic structures change with depth. These structures can be linked to mantle convection patterns and planetary evolution. While these objects are relevant to various aspects of the science curriculum, they also spark an interest in studying Earth Sciences.

References:

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- Hoggard, M.J., N. White & D. Al-Attar, *Nature Geosc.,* **9**, 456, 2016.
- Koelemeijer, P., A. Deuss, J. Ritsema et al., *Geophys. J. Int.,* **204**, 1024-1039, 2016.
- LOLA: Lunar Orbital Laser Altimetry (https://sos.noaa.gov/datasets/moon-topography/).
- MOLA: Mars Orbital Laser Altimetry (https://sos.noaa.gov/datasets/mars-topography/).
- Ritsema, J., A. Deuss, H.-J. van Heijst et al., *Geophys. J. Int*., **184**, 1223–1236, 2011.
- Wessel, P., W. H. F. Smith, R. Scharroo, et al., *EOS Trans. AGU*, **94**, 409-410, 2013.

Software:

ImageMagick (www.imagemagick.org), Blender (https://www.blender.org/), Autodesk MeshMixer (www.meshmixer.com/), Ultimaker Cura (https://ultimaker.com/en/products/ultimaker-cura-software).

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