

Supplementary Material: The Antarctic crust and upper mantle

1 GEOLOGICAL SAMPLES

The spatial distribution of geological and geochemical samples available for Antarctica is uneven (Fig. S1).

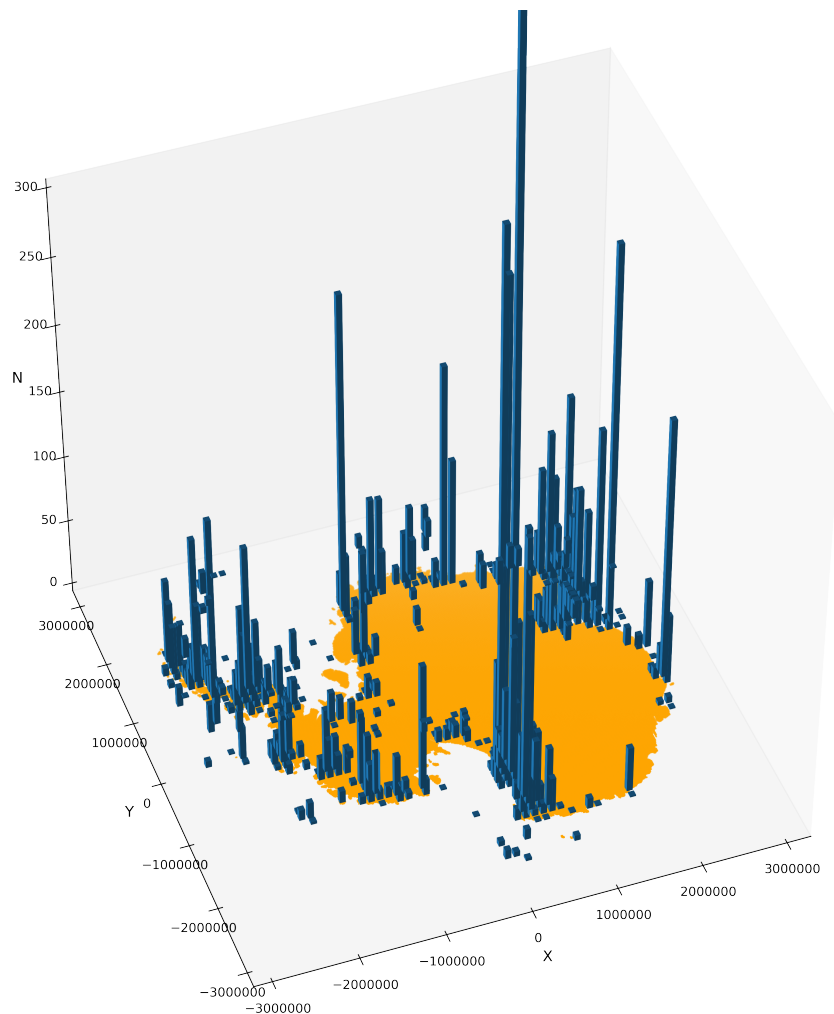


Figure S1. Number of samples per 100×100 km bin in the compilation of Gard et al. (2019).

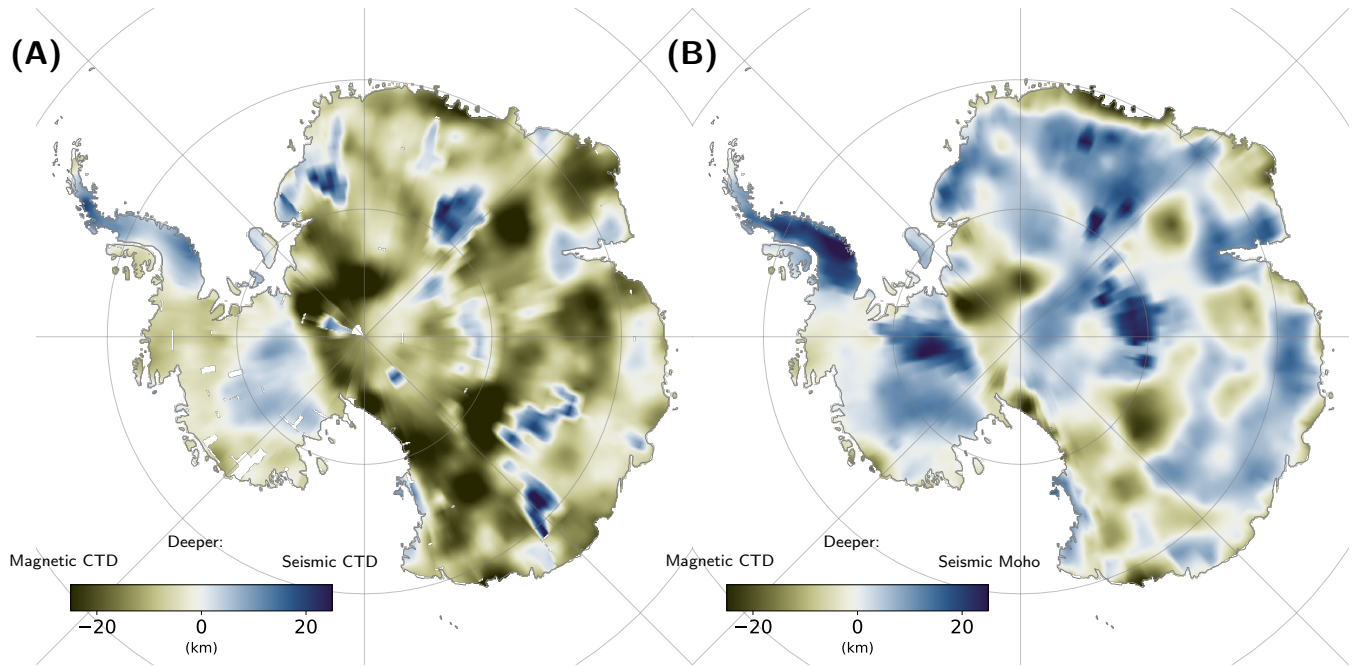


Figure S2. Illustration of framework capability to compare and appraise different models: (A) Comparison of Curie temperature depth (CTD) from magnetic and seismic studies; CTD derived from seismic study (An et al., 2015a) minus CTD from magnetic study (Martos et al., 2017). Magnetic CTD is deeper at negative values (green), and seismic CTD is deeper at positive values (blue). (B) Comparison of CTD from magnetic study and seismic tomography derived Moho, constrained by receiver function studies; Moho depth (An et al., 2015b) minus magnetic CTD (Martos et al., 2017). Magnetic CTD is deeper at negative values (green), the Moho is deeper at positive values (blue).

2 MOHO AND CURIE TEMPERATURE DEPTH

Figure S2A shows the difference between a Curie temperature depth (CTD) derived from seismic constraints (An et al., 2015a) and a magnetic derived estimate (Martos et al., 2017). When expressed in kilometres, we see that the larger disagreements occur in East Antarctica. In the green colored areas, as for the Transantarctic Mountains, the magnetic model suggests a deeper isotherm. This can either indicate overestimated temperatures from the seismic model, or an overestimation of the CTD in the magnetic study. In blue areas, the seismic CTD is deeper than the magnetically derived isotherm. This is caused either by the temperature in the seismic model being underestimated, or the magnetic derived isotherm being too shallow. Figure S2B similarly shows the difference between the seismic Moho (An et al., 2015a) and the CTD from magnetic constraints, 'the magnetic Moho' (Martos et al., 2017). Notably, we have generally a closer agreement, and the pattern is different from figure S2A. This suggests that the magnetic method is sensitive to the seismic Moho rather than the temperature isotherm, as the Curie temperature isotherm has no direct impact on elastic properties.

3 TERNARY MAPS

We demonstrate the capability to visualise multivariate data through the construction and use of ternary images from three colour renderings. Such renderings can assist in segmentation of the crust and pattern recognition, and suggest a highly heterogeneous Antarctic interior, more complex than suggested in many previous studies.

Three-colour renderings are produced using RGB channels, with each band (RGB) representing a dataset. Three examples are provided. The values are not directly meaningful, but the color representation can reveal contrasts in lithospheric properties.

Each dataset (D) is standardised:

$$D_S = \frac{D - \bar{D}}{s(D)} \quad (S1)$$

Where \bar{D} is the average value and $s(D)$ is the standard deviation for D . D_S is the standardised data set. To enhance the visualisation, the dataset is clipped at the 5% percentile and 95% percentile of the standardised values. Missing data in one of the three datasets are removed from all three to provide a consistent color rendering.

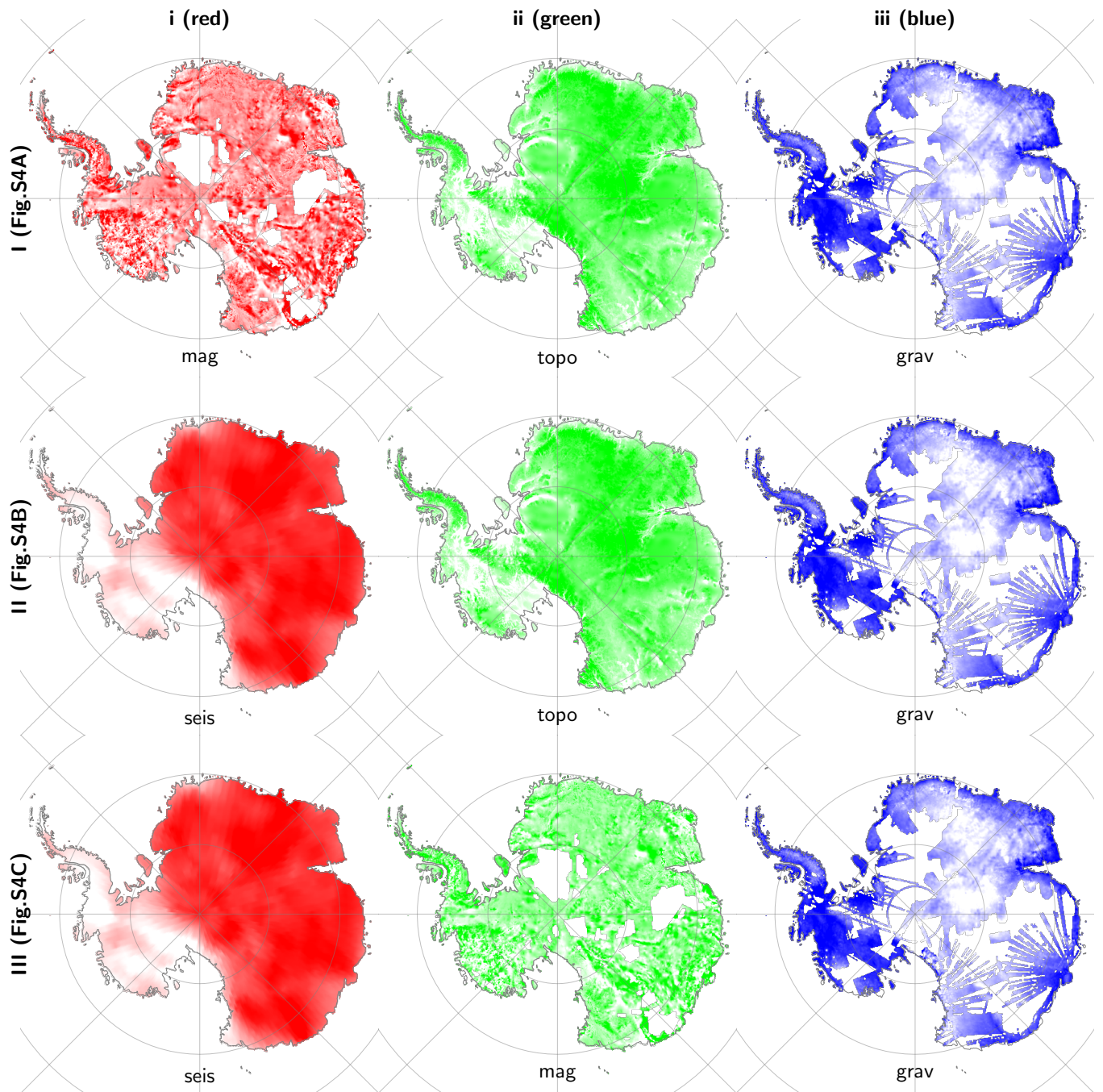


Figure S3. (Caption next page.)

Figure S3. Illustration of framework capability to visualise multivariate data. Three-colour rendering of input data for fig. C2. The rows represent the sub-figures (fig. S3: A, B, and C), and the columns (i, ii, iii) represent the datasets used. Shown standardized and clipped, as described in text. Upper row: input to fig. S3A, Magnetic-Topography-Gravity. (i) Total magnetic intensity (Golynsky et al., 2017) in red, (ii) Subglacial topography (Fretwell et al., 2012) in green, (iii) Bouguer gravity (Scheinert et al., 2016) in blue. Middle row: input to fig. S3B, Seismic-Topography-Gravity. (i) Seismic wave speed at 100km depth (An et al., 2015b) in red, (ii) Subglacial topography (Fretwell et al., 2012) in green, (iii) Bouguer gravity (Scheinert et al., 2016) in blue. Lower row: input to fig. S3C, Seismic-Magnetic-Gravity. (i) Seismic wave speed at 100km depth (An et al., 2015b) in red, (ii) Total magnetic intensity (Golynsky et al., 2017) in green, (iii) Bouguer gravity (Scheinert et al., 2016) in blue.

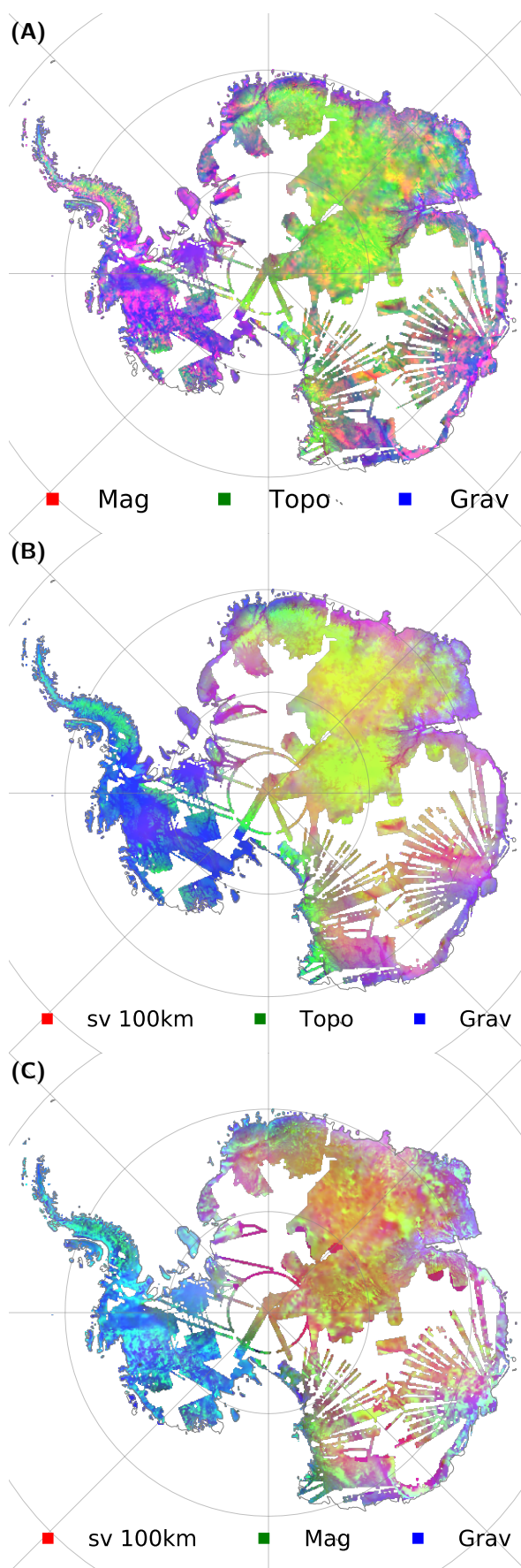


Figure S4. (Caption next page.)

Figure S4. Ternary plots as an illustration of framework capability to visualise multivariate data. (A) Three colour rendering of the relation between the total magnetic intensity (Golynsky et al., 2017) in red, subglacial topography (Fretwell et al., 2012) in green with isostatic correction (figure and discussion in main article), and Bouguer gravity (Scheinert et al., 2016) in blue. (B) Three colour rendering of the relation between the seismic wave speed at 100km depth (An et al., 2015b) in red, subglacial topography (Fretwell et al., 2012) in green and Bouguer gravity (Scheinert et al., 2016) in blue. (C) Three colour rendering of the relation between the seismic wave speed at 100km depth (An et al., 2015b) in red, magnetic intensity (Golynsky et al., 2017) in green and Bouguer gravity (Scheinert et al., 2016) in blue. All datasets are individually standardised and clipped as described in text.

REFERENCES

- An, M., Wiens, D. A., Zhao, Y., Feng, M., Nyblade, A., Kanao, M., et al. (2015a). Temperature, lithosphere-asthenosphere boundary, and heat flux beneath the Antarctic Plate inferred from seismic velocities. *Journal of Geophysical Research: Solid Earth* 120, 8720–8742. doi:10.1002/2015JB011917
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- Scheinert, M., Ferraccioli, F., Schwabe, J., Bell, R., Studinger, M., Damaske, D., et al. (2016). New Antarctic gravity anomaly grid for enhanced geodetic and geophysical studies in Antarctica. *Geophysical Research Letters* 43, 600–610. doi:10.1002/2015GL067439
- Stål, T. and Reading, A. M. (2020). A Grid for Multidimensional and Multivariate Spatial Representation and Data Processing. *Journal of Open Research Software* 8. doi:10.5334/jors.287

4 SHORT USER GUIDE TO AGRID

In this supplementary section, we provide a short user guide to *agrid*. We provide a synthetic example to introduce the basic use of the software.

4.1 Installation

There are many options to access the code:

1. Download the module directly from GitHub and incorporate in your project with a relative path to the module used. Alternatively, a subset of the provided methods can be copied into a project:

```
https://github.com/TobbeTripitaka/agrid/tree/master/agrid
```

2. Clone the Git repository:

```
$ git clone https://github.com/tobbetripitaka/agrid
```

3. Install with PIP:

```
$ pip install agrid
```

4. Conda users can also use anaconda installer (presently only OSX):

```
$ conda install -c tobbetripitaka agrid
```

5. Use the Docker container provided

```
link/to/docker
```

6. Use the Virtual Machine provided

```
link/to/vm
```

Now, we can test the installation by setting up a grid model, of e.g. Antarctica:

```
# Python 3
from agrid.grid import Grid
from agrid.acc import download

km = 1000
ant = Grid(crs=3031, res = [25*km, 25*km],
           left = -3100*km, up=3100*km,
           right = 3100*km, down = -3100*km)
print('Number of cells in X, Y, Z directions:', ant.nnn)
```

We have now defined a Grid object that contains variable that defines or model. E.g. `ant.nn` returns a tuple of the horizontal size of the grid. `ant.nx` returns the number of cells along x-axis.

We also generated a dataset `ant.ds`, that is used to contain arrays and metadata. It also contains coordinates and dimension data:

```
print(ant.ds)
```

```
<xarray.Dataset>
```

```
Dimensions:  (RGB: 3, X: 248, X_edge: 249, Y: 248, Y_edge: 249, Z: 5, Z_edge:
```

```
Coordinates:
```

```
* X          (X) float32 -3100000.0 -3074898.8 ... 3074898.8 3100000.0
```

```

* Y      (Y) float32 -3100000.0 -3074898.8 ... 3074898.8 3100000.0
* Z      (Z) float32 0.0 8000.0 16000.0 40000.0 350000.0
* X_edge (X_edge) float32 -3112500.0 -3087399.2 ... 3087399.2 3112500.0
* Y_edge (Y_edge) float32 -3112500.0 -3087399.2 ... 3087399.2 3112500.0
* Z_edge (Z_edge) float64 -4e+03 4e+03 1.2e+04 2.8e+04 1.95e+05 5.05e+05
* RGB    (RGB) <U1 'R' 'G' 'B'
  XV     (Y, X) float32 -3100000.0 -3074898.8 ... 3074898.8 3100000.0
  YV     (Y, X) float32 -3100000.0 -3100000.0 ... 3100000.0 3100000.0
  lat    (Y, X) float32 -51.15066 -51.296318 ... -51.296318 -51.15066
  lon    (Y, X) float32 -135.0 -135.23291 -135.46771 ... 44.76709 45.0
Data variables:
*empty*

```

X, Y are coordinates to center points of grid cells. _edge are the corners between the cells. XV, YV are 2D grids that contain coordinates for each cell in used projection. Similarly, lat and lon contains geographical coordinates for each grid cell. There are no data variables yet.

Numpy arrays can be assigned to the grid:

```

import numpy as np
checkerboard = np.kron([[1, 0] * 4, [0, 1] * 4] * 4,
                       np.ones(np.array(ant.nn)//8))
ant.ds['CHESS'] = (('Y', 'X'), checkerboard)
ant.map_grid(checkerboard, save_name='chess.pdf')

```

Note that the grid data array is defined in order Y, X, as the coordinates refers to rows and columns of e.g. 2D arrays.

Online data sources can be linked to the grid, and are only downloaded once, unless specified. The meta_dict variable adds meta data to the array. The assign_shape method assigns polygon vector data file to the grid, using attribute data. Here, we generate a Boolean map:

```

url_land_polygon = ('https://www.naturalearthdata.com/'
                    'http://www.naturalearthdata.com/'
                    'download/10m/physical/ne_10m_land.zip')
download(url_land_polygon,
         'ne_10m_land.zip',
         meta_dict={'Type' : 'Land Polygons'})
ant.ds['LAND'] = (('Y', 'X'),
                 -1 < ant.assign_shape('ne_10m_land.shp', 'scalerank') )
ant.ds['LAND'] = ant.ds['LAND'].where(ant.ds['LAND']) # Assigns not a number

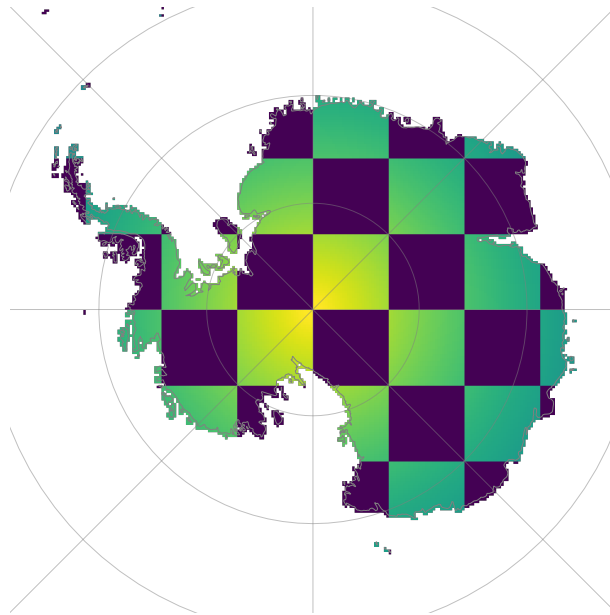
```

The framework allows computations to be defined with just a few lines of code:

```

example = ant.ds['LAND']*ant.ds['CHESS']*ant.ds.coords['lat']
ant.map_grid(example, cmap='viridis',
              vmin = -90, vmax=-60,
              save_name='fig/quick_guide.pdf')

```



4.2 Further resources

- Software paper in Journal of Open Research Software (Stål and Reading, 2020).
- Tutorials at <https://github.com/TobbeTripitaka/agrid/tree/master/tutorials>
- Code to reproduce this paper and additional links at https://github.com/TobbeTripitaka/ant_lithosphere

4.3 Version compatibility.

This short guide refers to version 0.3.x. Complete backward compatibility might not be supported in future releases, however v. 0.3.x will be kept and maintained.