Interactive Gravity and Magnetic Application System

Documentation

IGMAS+ Team

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1. Welcome

Dear reader, thank you for choosing **IGMAS+** and welcome to the **IGMAS+** Online Documentation!

This website aims to enhance your understanding of the fundamental capabilities of the **IGMAS+** software and offer basic support. It provides a detailed explanation of how to fully utilize the powerful graphical interface of **IGMAS+**.

This documentation is the result of diligent and meticulous work carried out by the members of the **IGMAS+ Team** over the years. Their motivation stems from the high demand within the **IGMAS+** user community for an in-depth description of the software.

We encourage you to take your time to become familiar with **IGMAS+** and bear in mind that this documentation has been written by non-native English speakers.

We believe that **IGMAS+** will significantly contribute to your scientific endeavors, aiding in the integrated, interdisciplinary interpretation of complex geological structures at the macro-, meso-, and micro-scale.

> **Warning**
>
> This online documentation is under ongoing development: some parts can be missing and some materials can look incorrectly.

1.1 Download as PDF

This website can be downloaded as a standalone PDF file.

Download PDF

The former IGMAS+ User Manual is available here.

1.2 Quick links

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GFZ Helmholtz Centre Potsdam

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2. Workflows

Quote

Design isn't finished until somebody is using it.
— *Brenda Laurel*

2.1 Preface

In the "Workflows" chapter we break down the steps to make your **IGMAS+** project smoother.
You will learn here how to handle project parameters, explore different displays and visuals for a better view of your model, and discover seamless methods of importing model geometry, as well as easy ways to save and load your work.

Let's simplify the process of getting things done in **IGMAS+**!

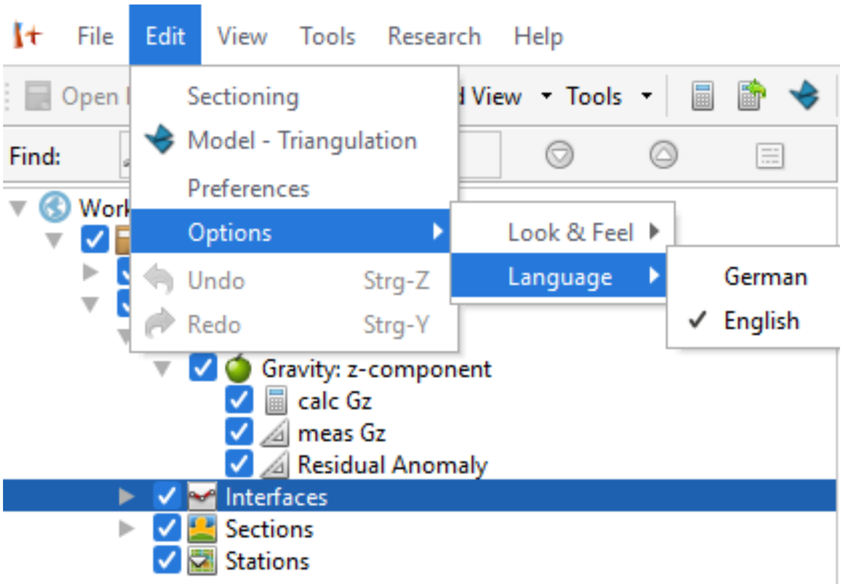
2.2 Setting up interface appearance

Before getting started, two more decisions related to the program interface can be made that is independent of the modelling process:

- the language of the interface
- the external appearance (interface theme).

2.2.1 Language

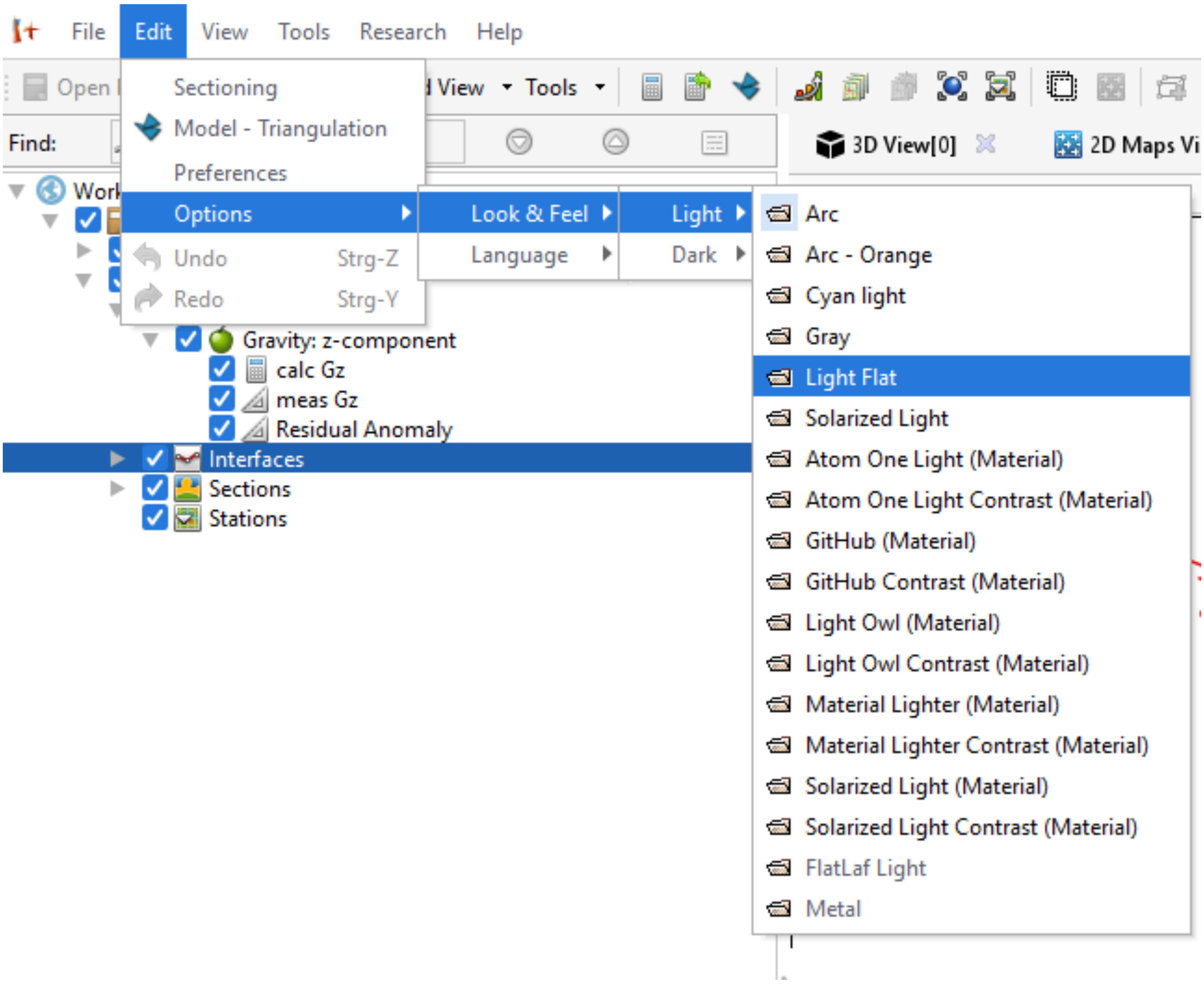
Click "Edit" in the **TITLE BAR** > select "Options" > and then "**Language**":



Select interface language: English or German

2.2.2 Theme

Click "Edit" in the **TITLE BAR** > select "Options" > and then "**Look & Feel**":



Select interface theme: selected one is "light"; in addition, there is a large number of colour shades for both “light” and “dark”.

2.3 Importing horizons

This Workflow is used if existing digital data define continuous horizons in the entire modelling area.
Several horizons are stacked, the physical parameters between the interfaces are assumed to be constant.
Users must use one file for each horizon.

Before we get started, here are a few tips to make sure the input works:

File formats
The following formats are possible: `*.xyz`, `*.csv` or Geosoft binary grid format `*.grd`, see Manual Section 6.3 on page 132. Preferred is the file format `*.csv`.

Point types
The points defining the horizons may be gridded or irregularly distributed. Points with identical location but different z-values will be averaged (there will be a notice).

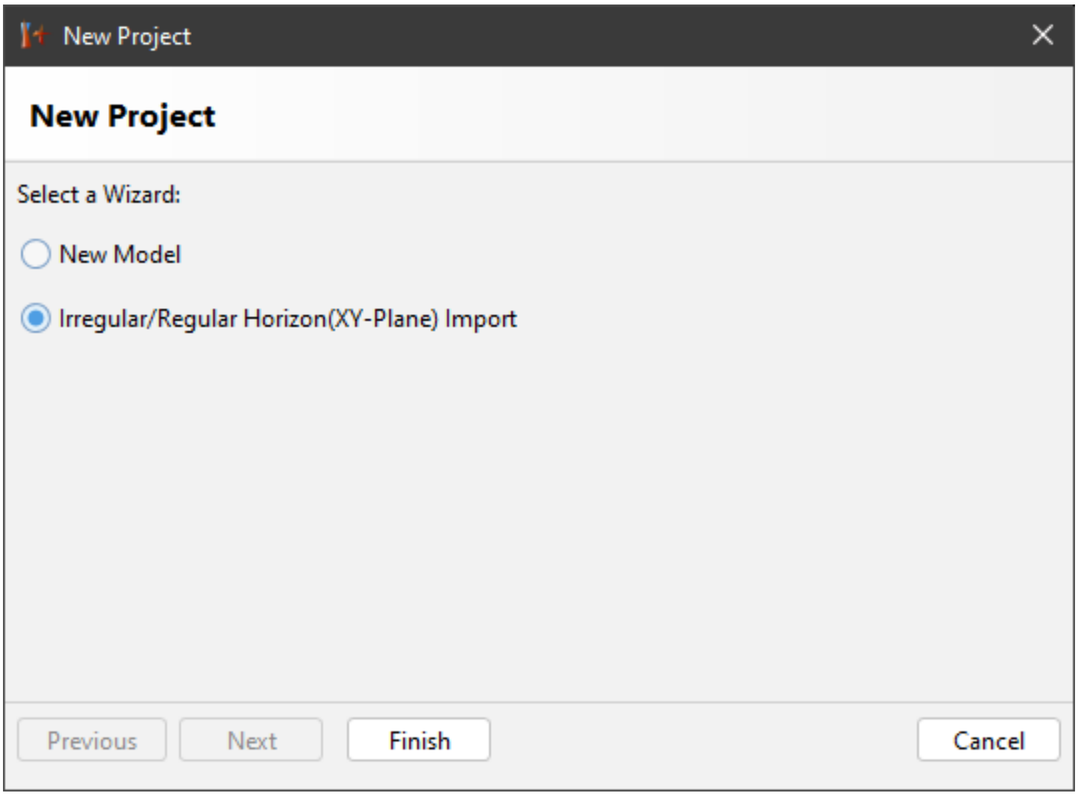
But beware:

- The points are interpreted to represent **point locations x, y, z**. They are not to be confused with **grid cells**, which are not used here, even in case of regularly gridded horizons.
- Make sure that the files are read in such a way that they always start with the top horizon. The order (from top to bottom) is very important, because it directly controls the triangulation. We will come back to this in a moment.
- Have you prepared the "correct gravity field"?
  That means, do you want to calculate with a FREE AIR or with a BOUGUER anomaly?
  In both cases a topography file must also be read in. Here you have to make sure that the model stations are NOT located inside the model masses - otherwise the mathematics behind everything will not work and the gravity will be calculated incorrectly.
- Make sure that the units are correct: give densities in kg/m^3, gravity in $mGal$ or $10^{-5} m/s^2$, depths and lengths in km or m.
- And finally: did you prepare your model data files for a plane gravity calculation (use UTM, Gauss-Krüger coordinates) or for a spherical calculation (use geographic coordinates with latitude and longitude)?

If all this is considered, it goes off, assuming that **IGMAS+** is installed correctly.

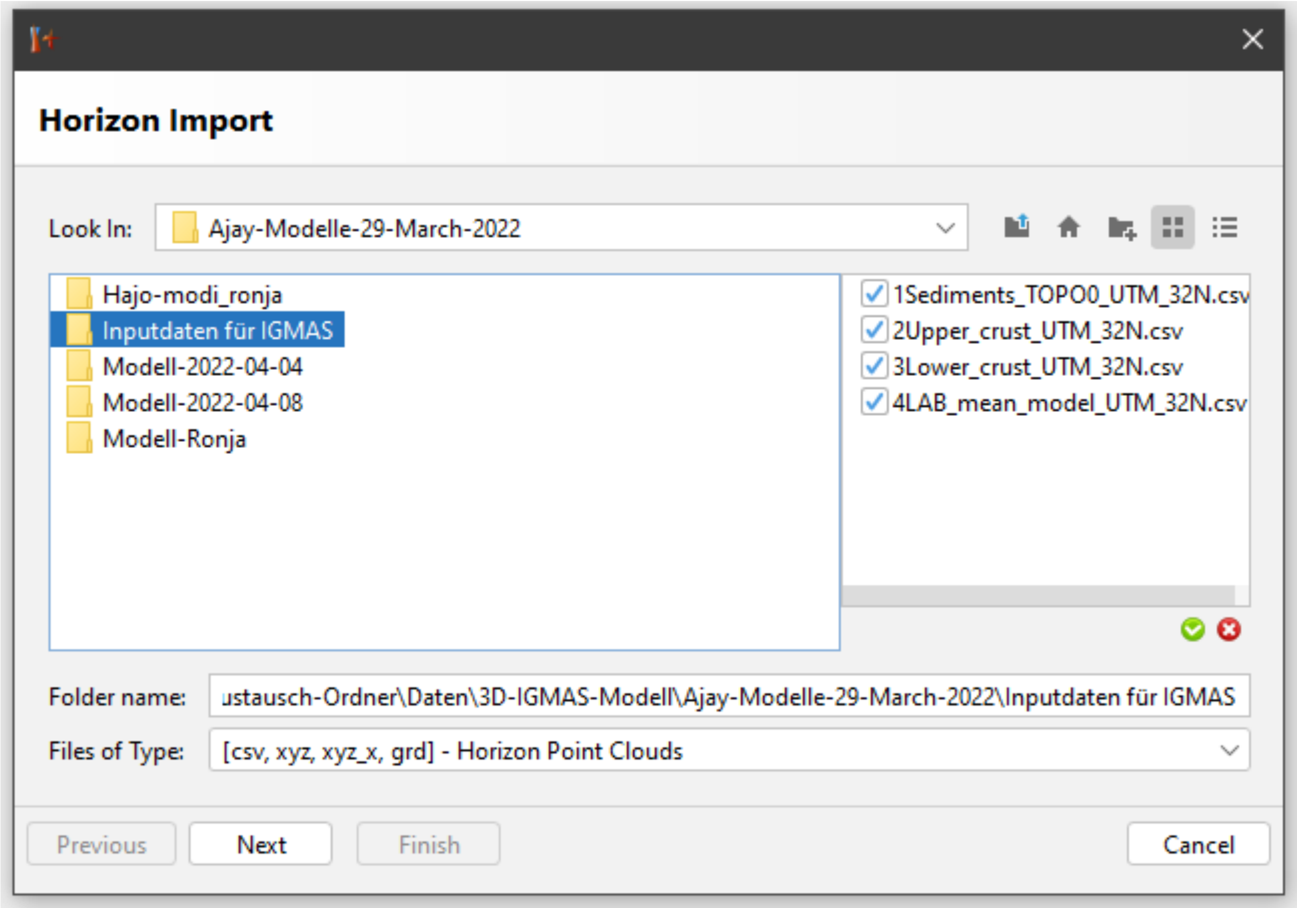
2.3.1 How to import model geometry?

Choose **File > New Project > Irregular/Regular Horizon (XY-Plane) Import.** Choose the directory and the file(s) to be imported. Make sure to select all files for the model to be built, as later inclusion of additional horizons is not possible. This is how it looks like:



Press Finish 

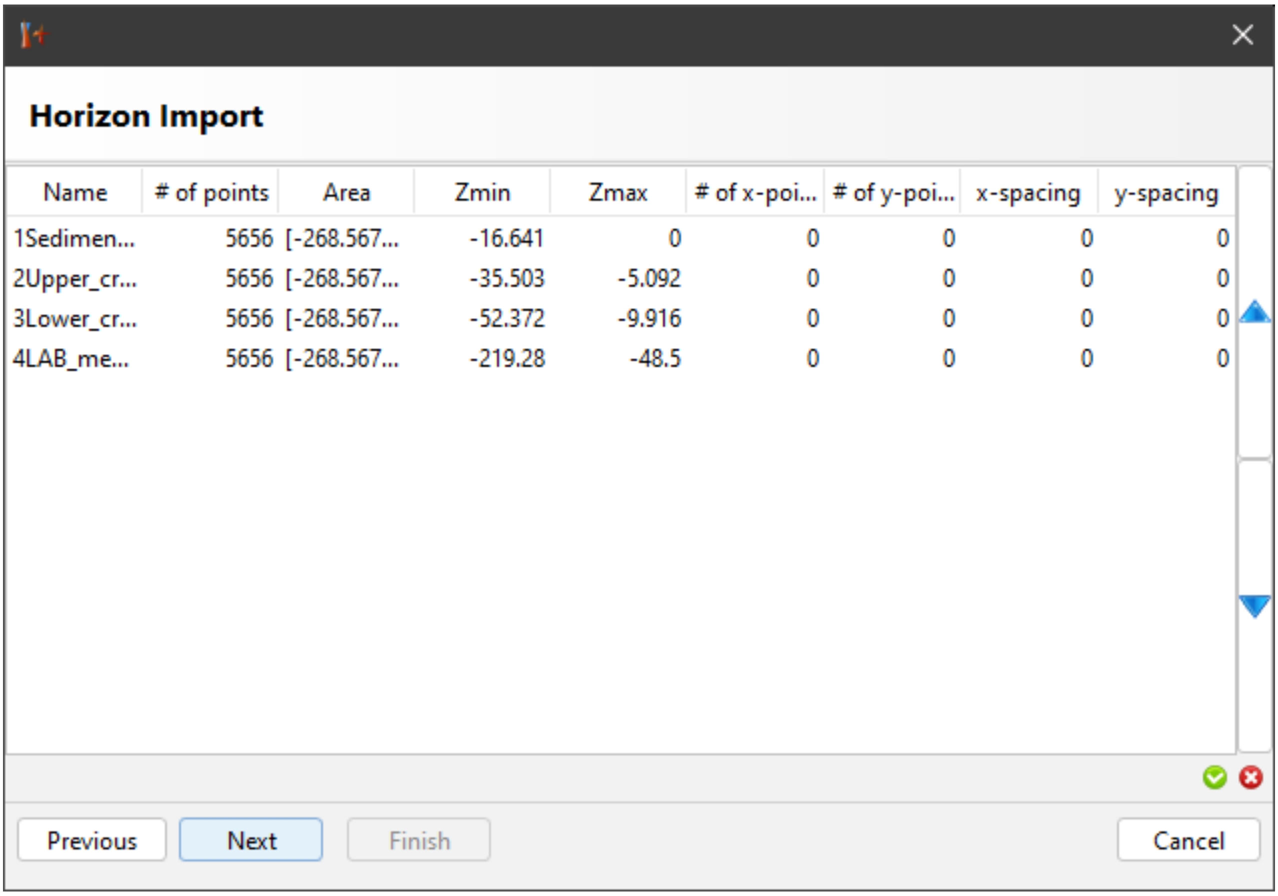
Now you see the following mask:



On the right, the input files are listed with the horizons from top to bottom. Below that the "Folder name" is displayed and below that the file type.

Press Next

Der “import wizard” lists all imported horizons (files) and orders them from top to bottom according to the value **Zmin**. Make sure, that the list corresponds to the stratigraphic column / layering in your modelling area. We had already pointed this out above. If necessary, change the order using the arrows on the right hand of the wizard.



From left to right, the following information is displayed:

Name This name will be used as the name of the body **below** the corresponding horizon. Can be changed later.

# of points Number of points to be read from file (for information only).

Area Minimum x-coordinate, minimum y-coordinate, size in x-direction, size in y-direction (for information only).

Zmin Minimum depth of the horizon (for information only, the value is used to define the layer order.

Zmax Maximum depth of the horizon (for information only).

# of x-points, # of y-points This value is used to apply averaging of horizon vertices on regularly spaced locations. Default is 0 for irregular points and original number of points for grids (no averaging). All three coordinates (X, Y and Z) will be averaged using the block average method (see Section 6.1.4 on page 124). Alternatively, user can use **x-spacing** and **y-spacing** to set up the grid for averaging (see below).

x-spacing, y-spacing Instead of setting number of points one can set desired spacing and corresponding number of points will be automatically recalculated.

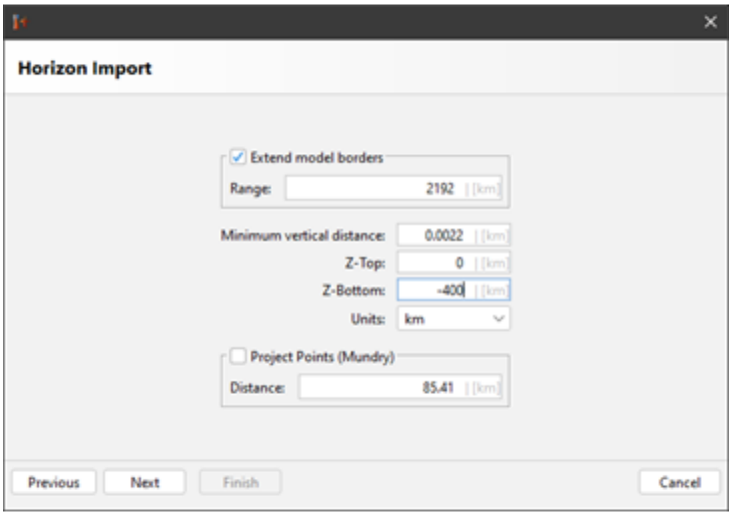
Hint:

The last four columns can be used for filtering of highly oversampled horizons. Sometimes seismologists provide Moho depths data in a resolution of 100 m x 100 m ;-)

Press Next

The next wizard defines the general model parameters:

You see:



Extend model borders. Check, if the model should be extended laterally, and specify the model extension (**Range**). Refer to Section 5.10 on page 121 to read more about the model extension.

Minimum vertical distance. Minimum thickness of bodies. It is used only if the imported vertices have identical horizontal positions throughout all horizons or if the vertices are interpolated regularly on the sections (see **Project Points (Mundry)** below). *In our example it is 2.2 m.*

Z-Top. Depth of the upper limit of the model (plane, horizontal). Default 0, if no topography is given, otherwise maximum **Zmin** of all horizons. *In the example input file, there is no topography in the model.*

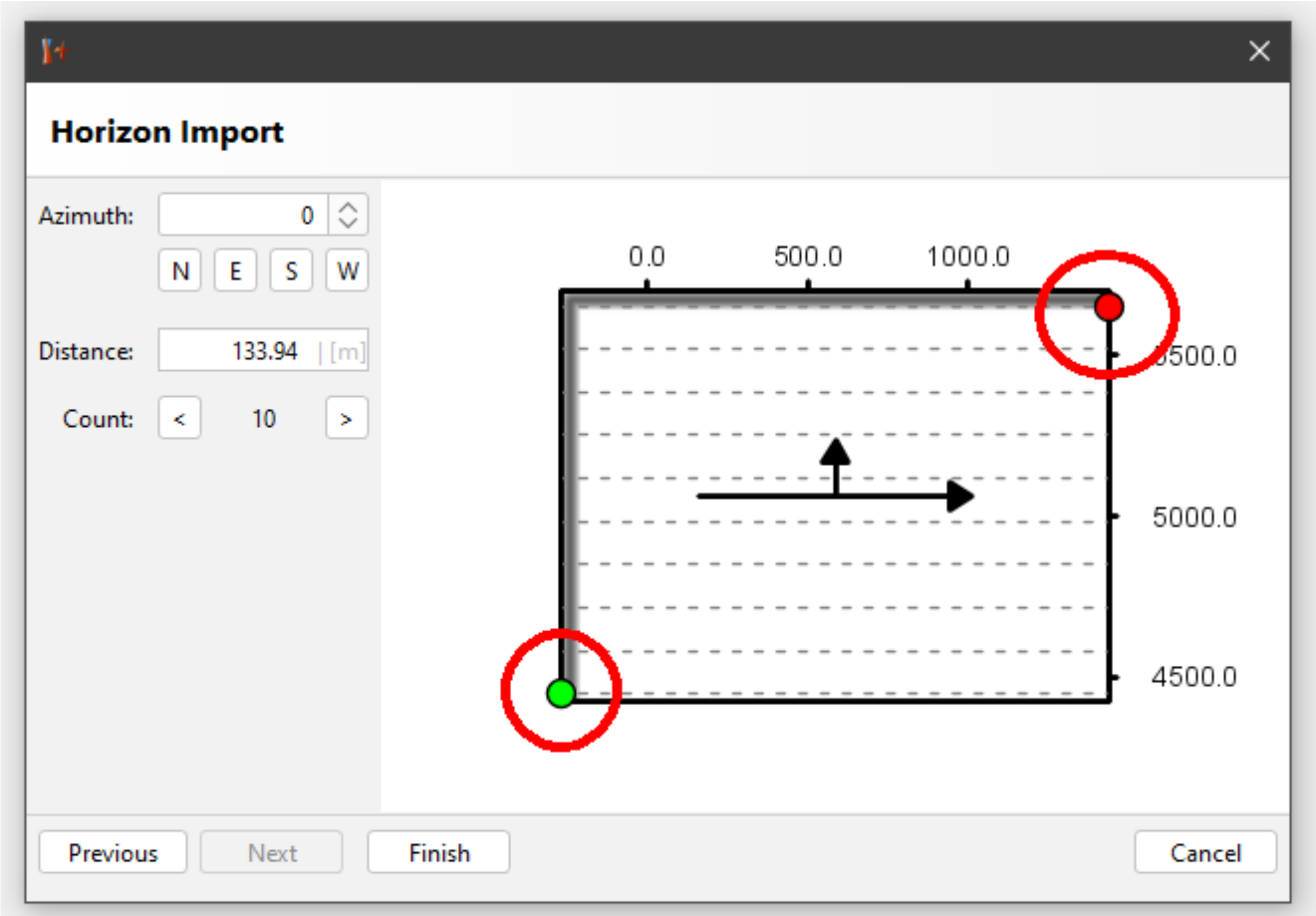
Z-Button. Depth of the lower limit of the model (plane, horizontal). Default: minimum **Zmin** value of all horizons. The biggest depth is 400 km (upper mantle); this is the bottom of the density model – *set by the user.*

Units. Make your choice depending on the data entered (depths, distances, grid spacing, etc.). *Here we used "km".*

Project Points (Mundry). Interpolate irregularly spaced horizon vertices on the sections to be build. Default is: **no**.

In our model, we wanted to re-interpolate the data ("even" grid spacing). For this purpose a procedure according to Mundry is used.

Press Next



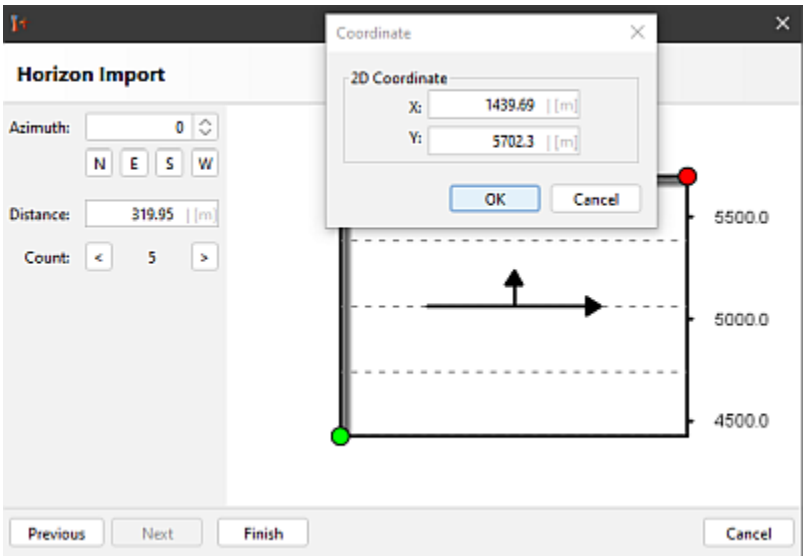
Almost done: In this last wizard we are able to specify the area to be modelled and the position of the vertical sections.

By default, the modelling area is the maximum area, which is covered by all horizons - indicated by a grey rectangle. Five vertical model layers are given *by default*. The first and fifth/last are hidden by the frame. They will be visible in the next image. The numbers at the border indicate the coordinates - in the example these are UTM coordinates.

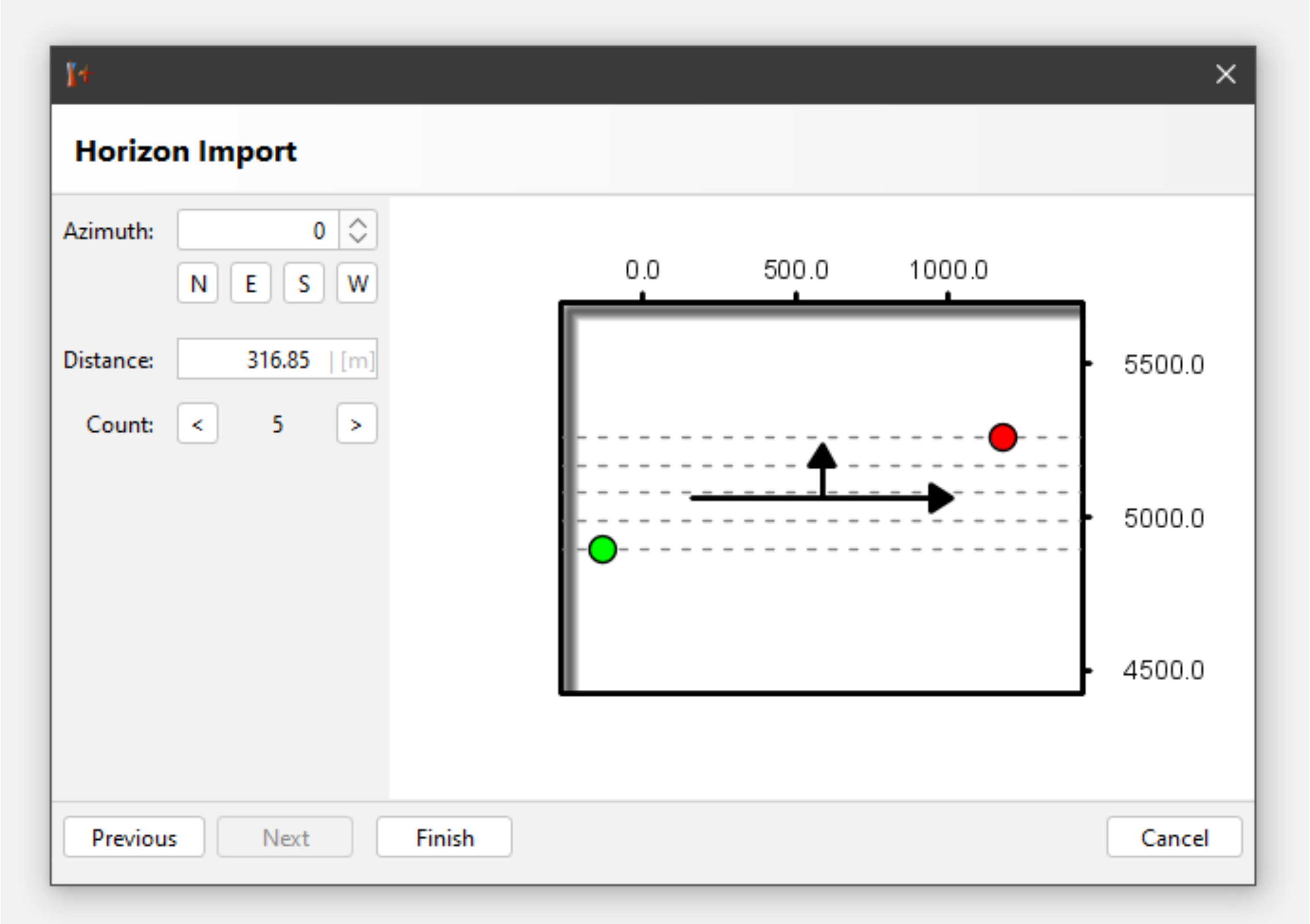
Green dot___Defines the max. south-west corner of the modelling area.

Red dot_____Defines the max. north-east corner of the modelling area.

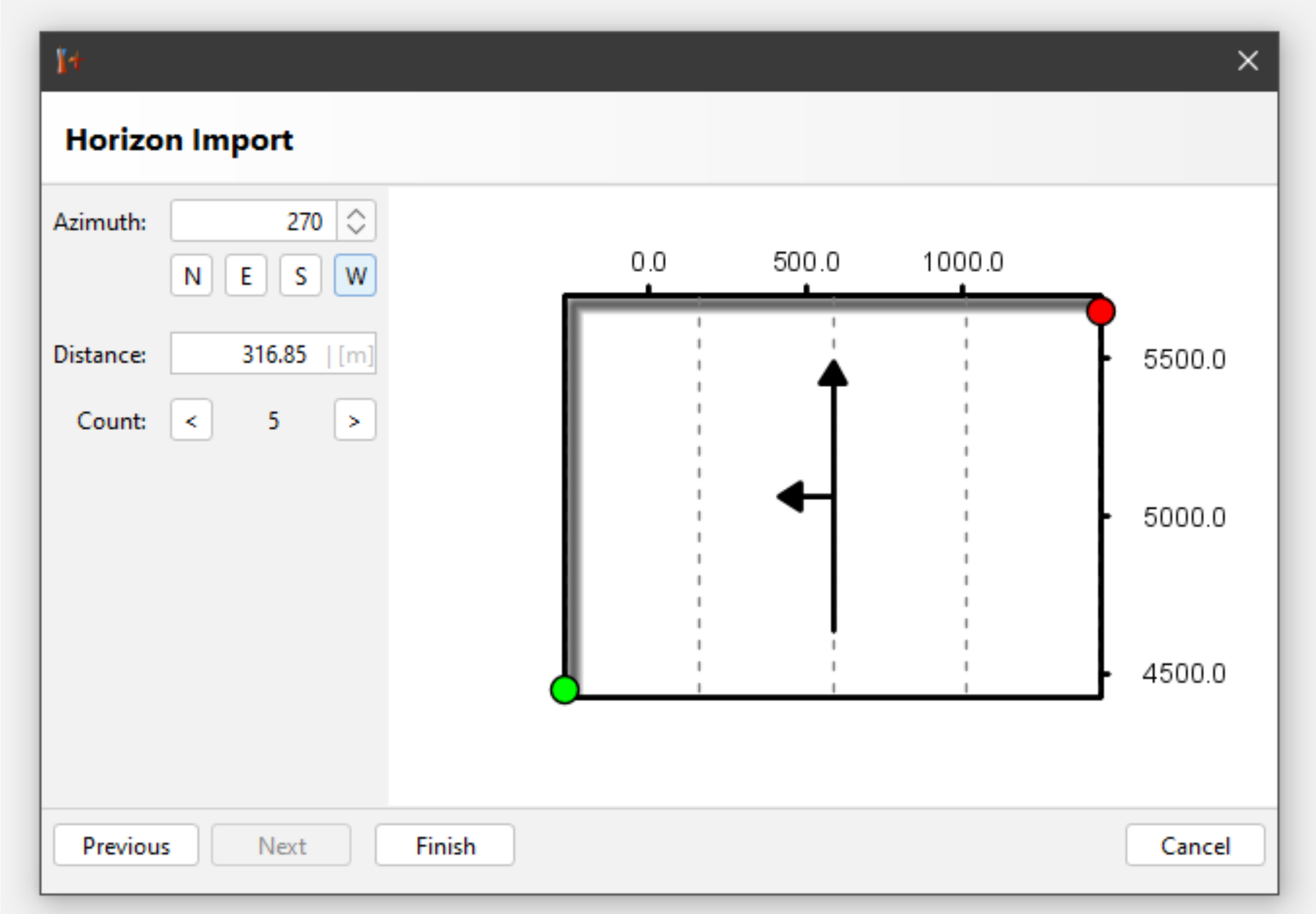
You may change the position of the circles by either clicking with the **right mouse button** on them (alphanumeric input); (an example for the coordinate input of the red point you can see here):



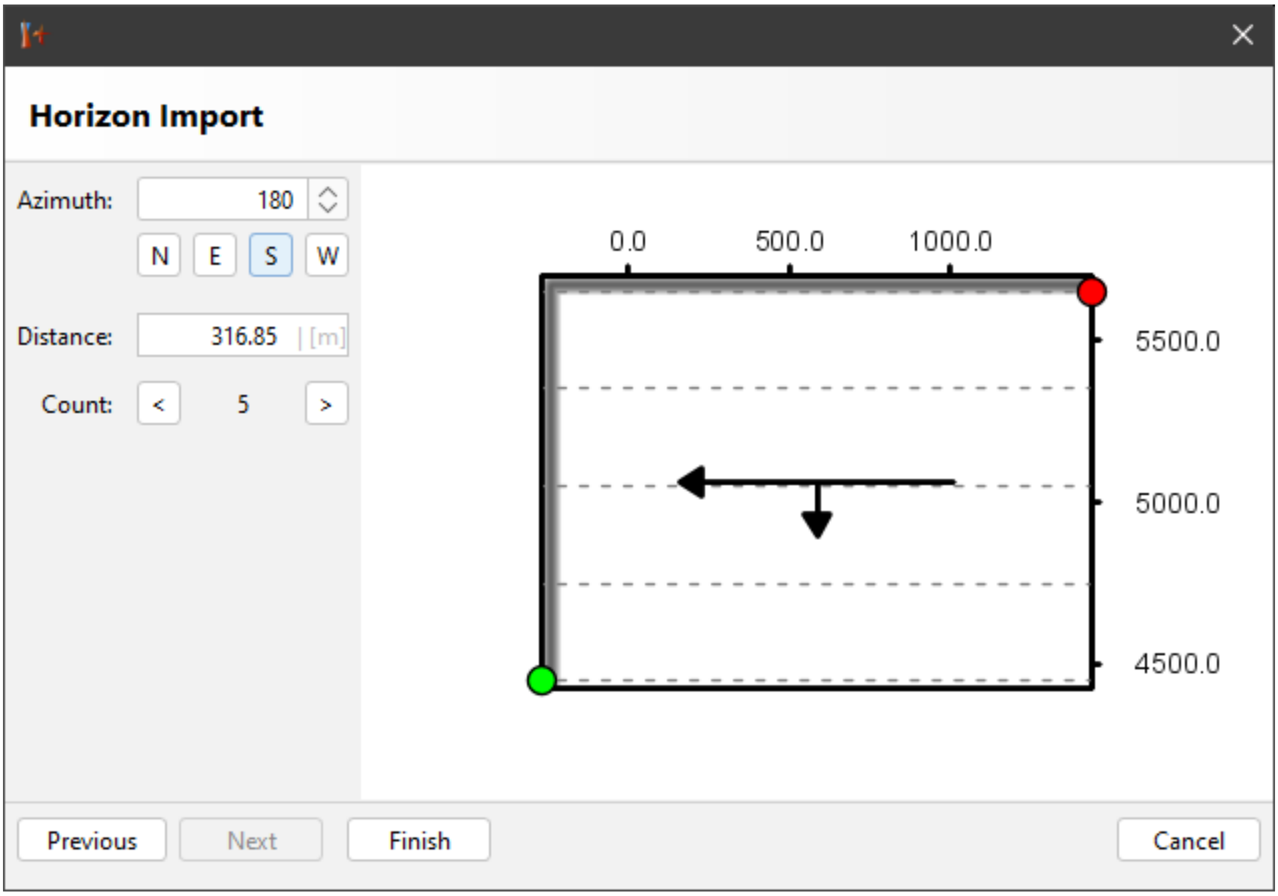
or just dragging them. Both input options redefine the model boundaries, also change the spacing of the five specified vertical planes (dashed lines in the window between the coloured points.



Azimuth, N – E – S - W. Sometimes the horizontal direction of the vertical sections must be adapted to the gravity field to be examined, because the modeling should ideally always be as perpendicular as possible to the main strike of the anomaly - this ensures the greatest possible model gravity effect. You have the possibility to set a first rough adjustment of the direction via **N**orth - **S**outh - **E**ast - **W**est.



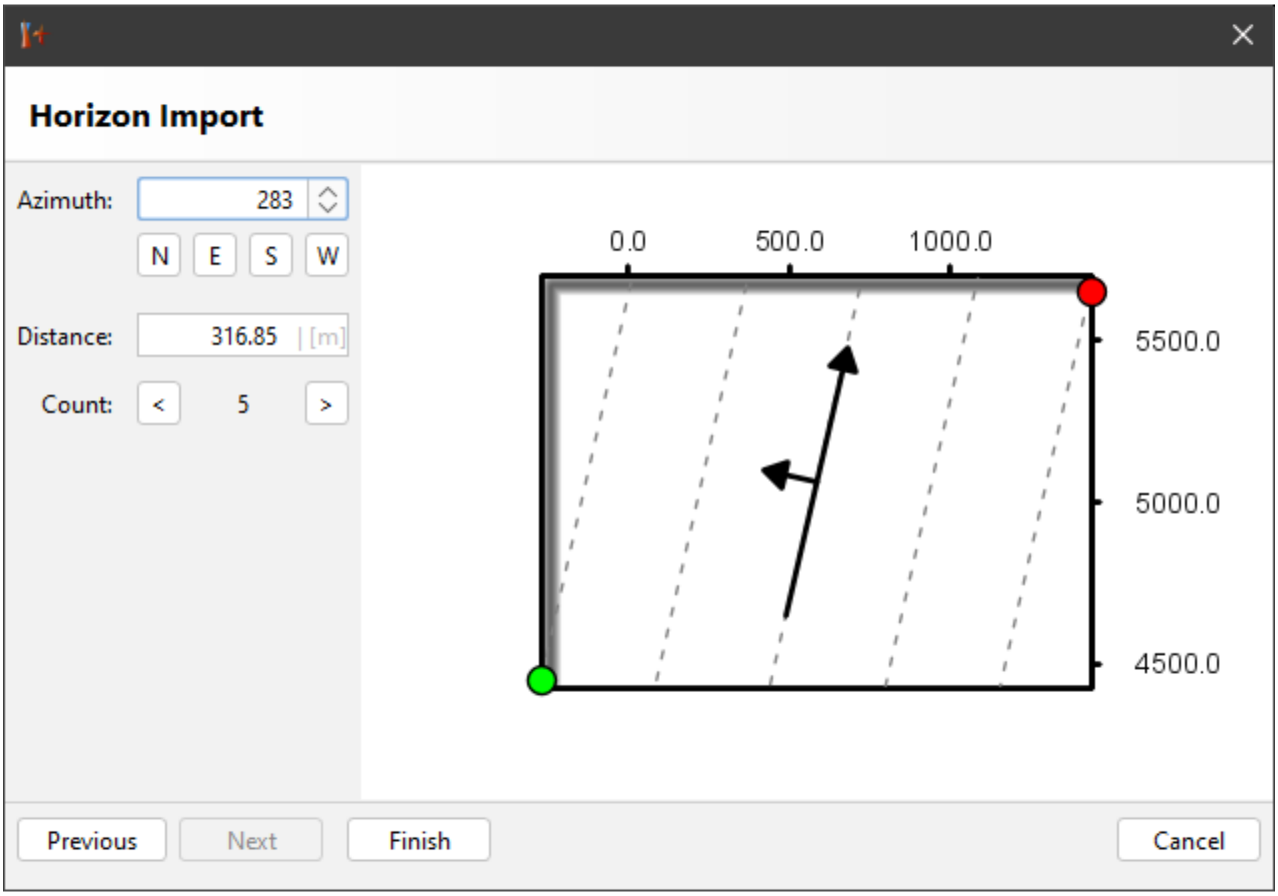
West: the vertical sections run in N-S-direction



South: the vertical sections run E-W-direction.

☞ In our example from the beginning, the vertical sections are aligned in the west-east direction and count from south to north.

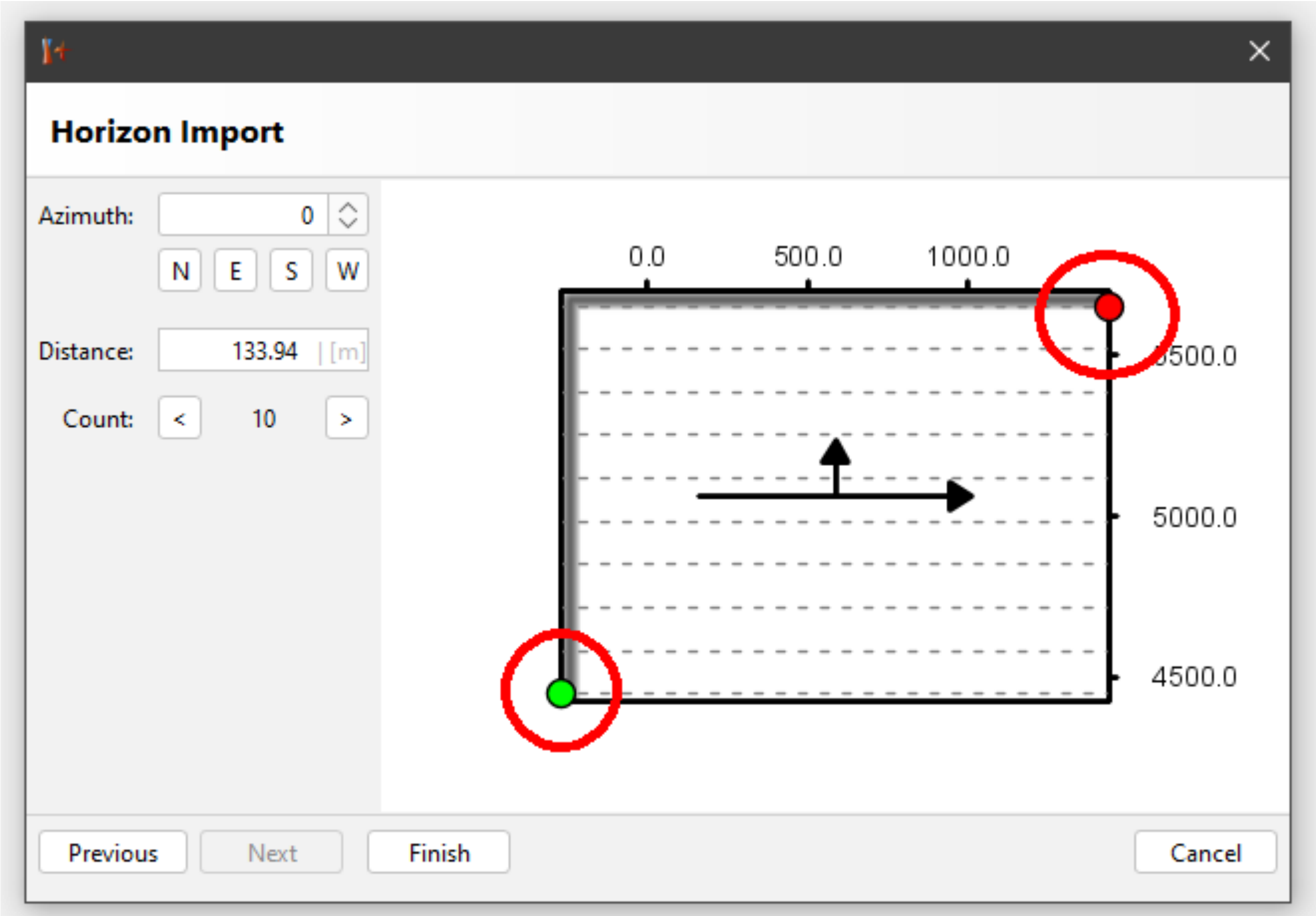
If you want to rotate it even more precisely, use the alphanumeric input in the azimuth window of the setting. In the example in the next figure, 283 (270 + 13) deg. has been used.



Distance. The vertical sections to be created are indicated by dashed lines. Use the alpha-numeric input to modify the distance between the vertical sections. Specification in km (as defined above for the input units). In the example, this would be approx. 317 km (316.85 km).

Count: Use the \< and > characters to decrease or increase the number of layers.

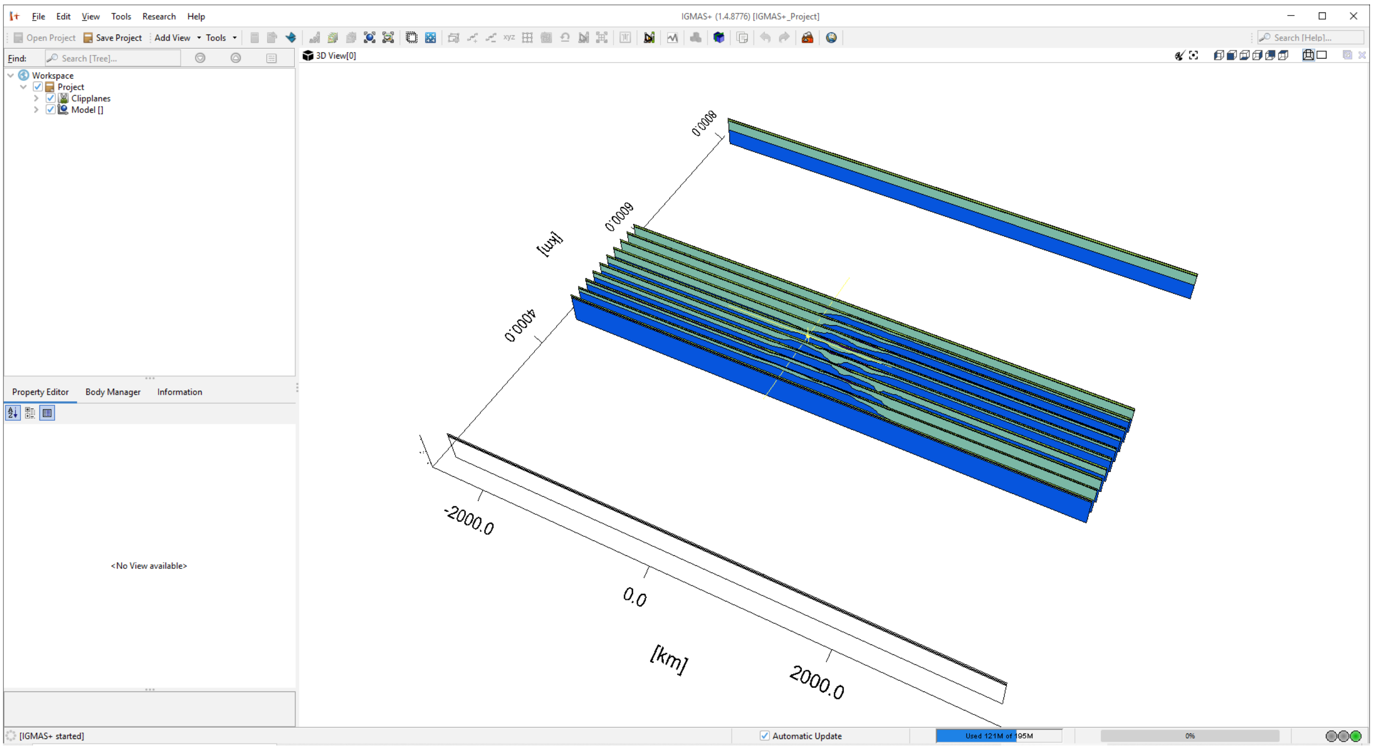
☞ In the example, the number of vertical sections has been doubled; the distance between vertical levels is reduced accordingly to 133.94 km.



Press finish

... **and VOILÁ**, our model appears in the **IGMAS+** main window, defined by the 10 vertical planes in the central part of the model and additionally a bounding section in the north and in the south - as it was entered earlier in the 2nd wizard window (above).

The model can now be moved back and forth for viewing. Click into the model with the **right mouse button** and keep it pressed. In this combination, move the model in the window. Moving the **mouse wheel** changes the zoom.



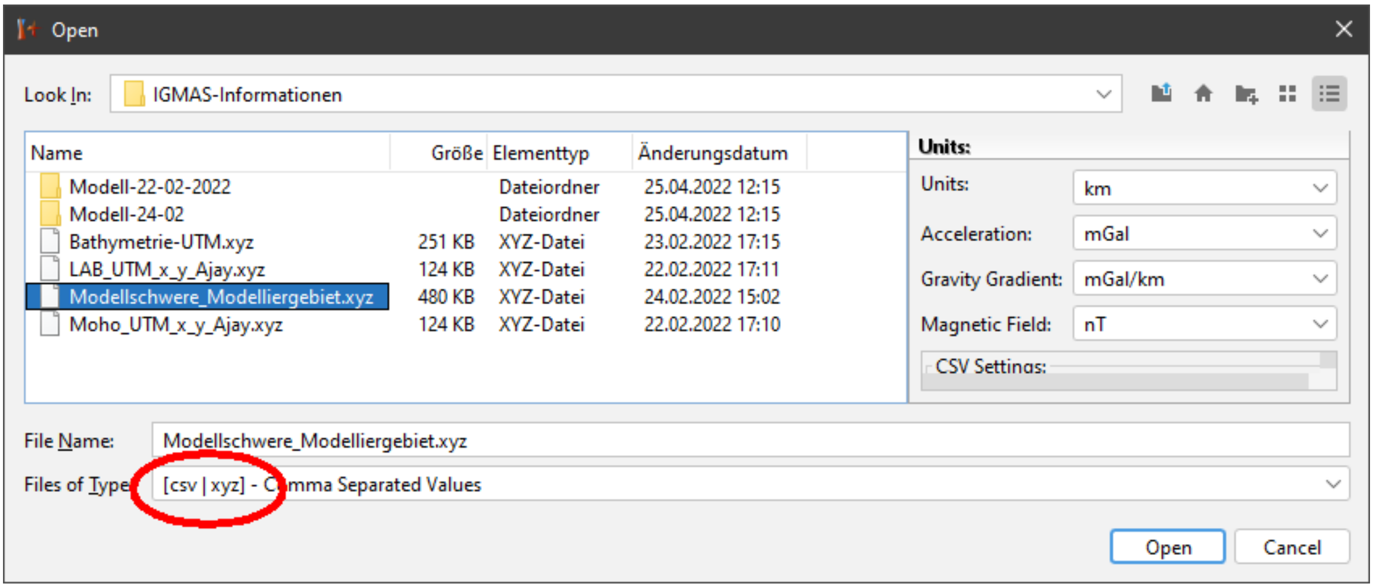
Note:

The colours of the stratigraphic layers are set automatically by the program. How to change them is shown below (refer to **Colors**). We still have no stations, no reference gravity field and the model densities loaded.

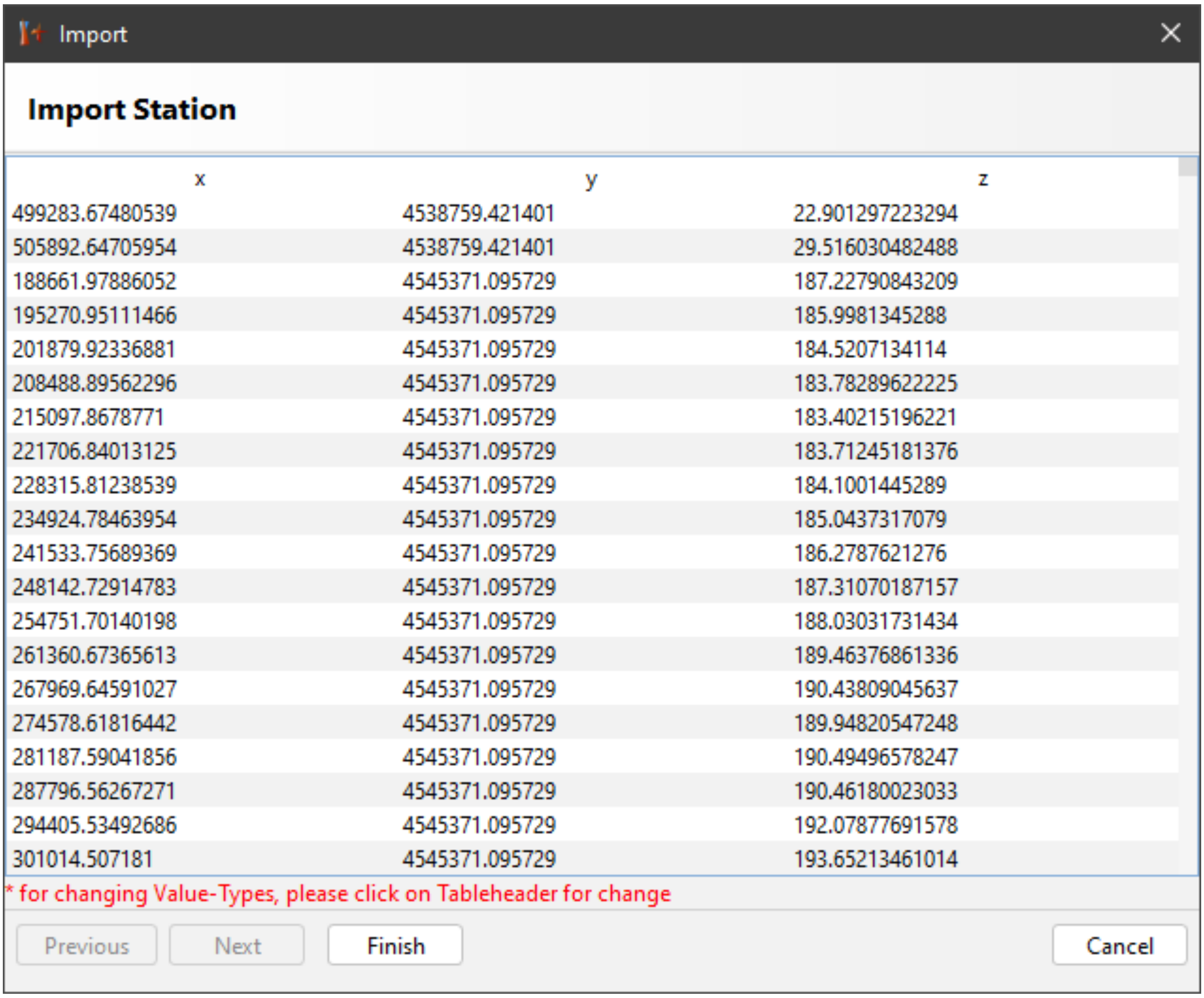
But we can already have a quick look at the vertical sections. If you are interested, go straight to the item "**show vertical cross sections**" below and return later to this position.

How to import reference gravity/gradient/magnetic field and topography/bathymetry?

Use the **File > Import > Stations**

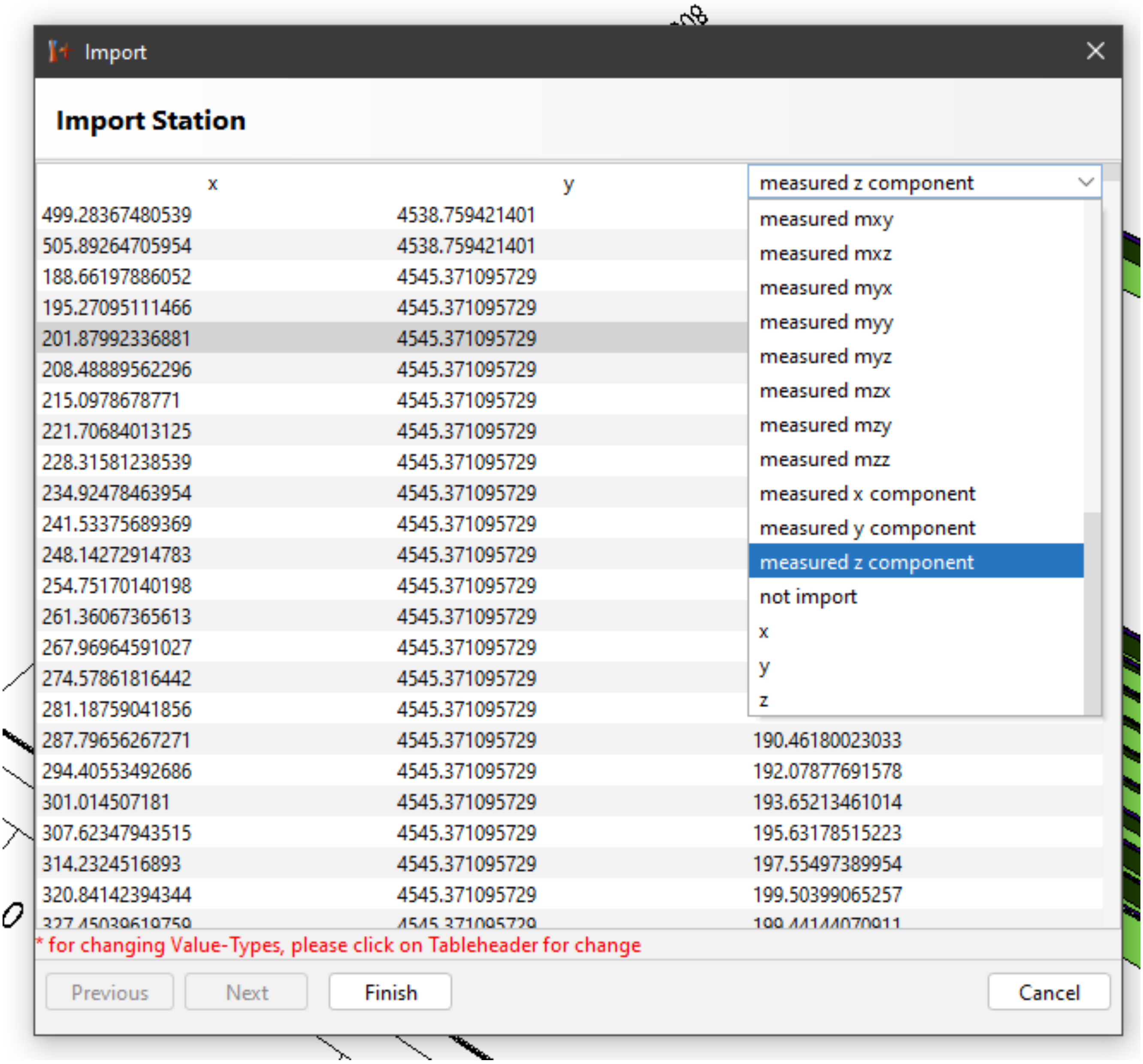


Be sure to use the correct units and file type (*.csv* or *.xyz*)

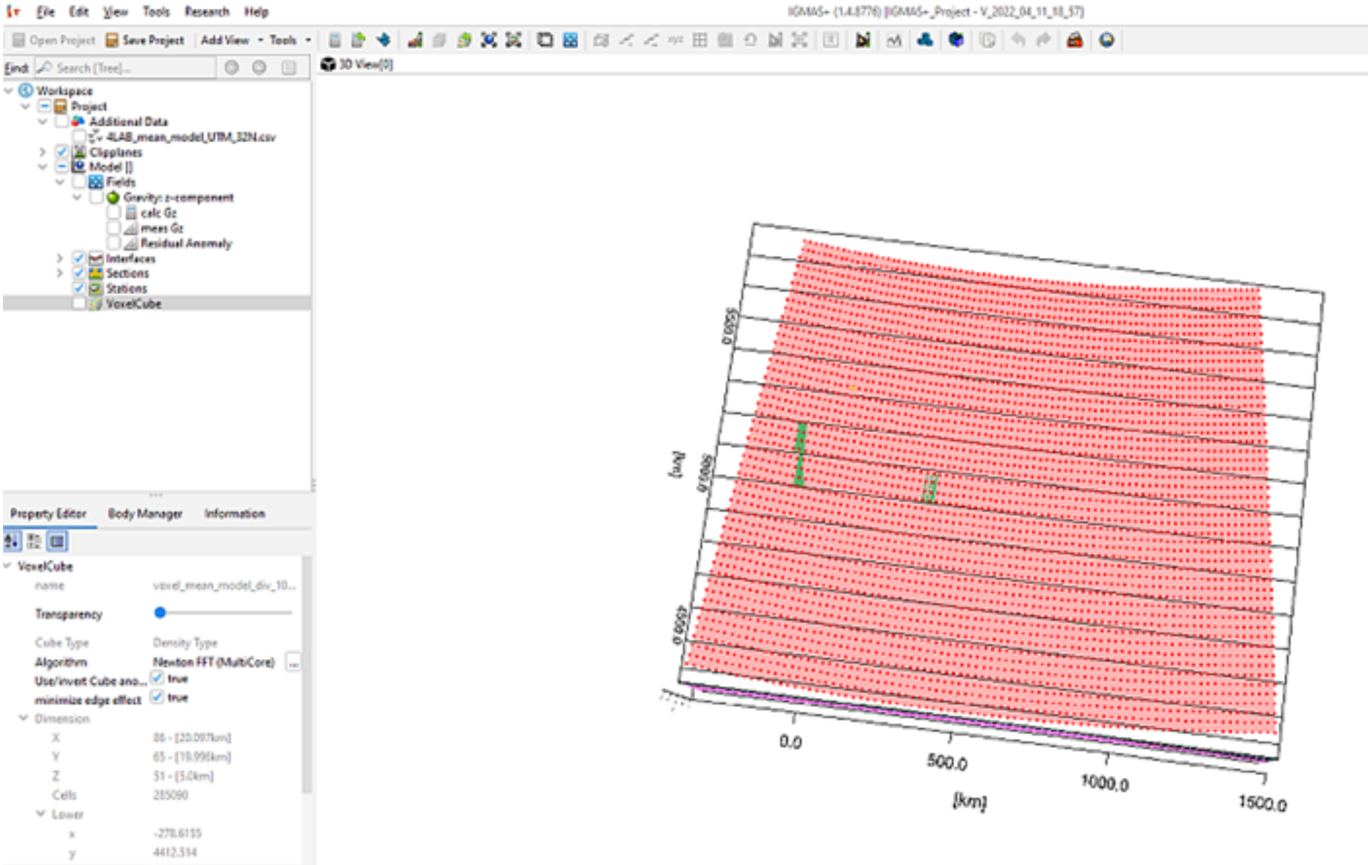


x	y	z
499283.67480539	4538759.421401	22.901297223294
505892.64705954	4538759.421401	29.516030482488
188661.97886052	4545371.095729	187.22790843209
195270.95111466	4545371.095729	185.9981345288
201879.92336881	4545371.095729	184.5207134114
208488.89562296	4545371.095729	183.78289622225
215097.8678771	4545371.095729	183.40215196221
221706.84013125	4545371.095729	183.71245181376
228315.81238539	4545371.095729	184.1001445289
234924.78463954	4545371.095729	185.0437317079
241533.75689369	4545371.095729	186.2787621276
248142.72914783	4545371.095729	187.31070187157
254751.70140198	4545371.095729	188.03031731434
261360.67365613	4545371.095729	189.46376861336
267969.64591027	4545371.095729	190.43809045637
274578.61816442	4545371.095729	189.94820547248
281187.59041856	4545371.095729	190.49496578247
287796.56267271	4545371.095729	190.46180023033
294405.53492686	4545371.095729	192.07877691578
301014.507181	4545371.095729	193.65213461014

In this input window you have the chance to assign different input parameters to the individual columns X - Y - Z. Column Z could also contain gradients or a magnetic field size. "Measured z component" is selected correctly.



Press Finish

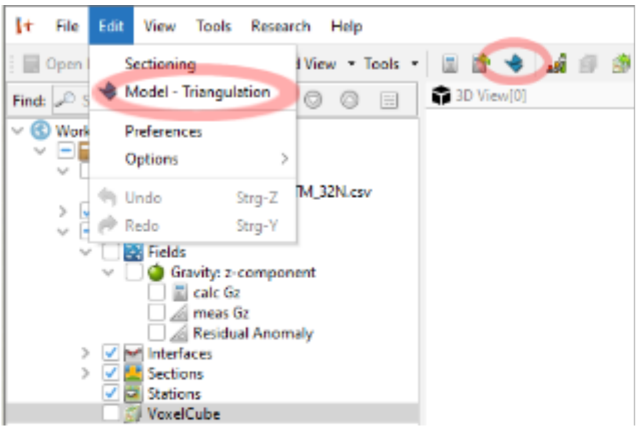


The stations are placed in red on top of the vertical cross sections.

However, we do not yet have a basis for calculating the model gravity field. For this, two steps are necessary for preparation.

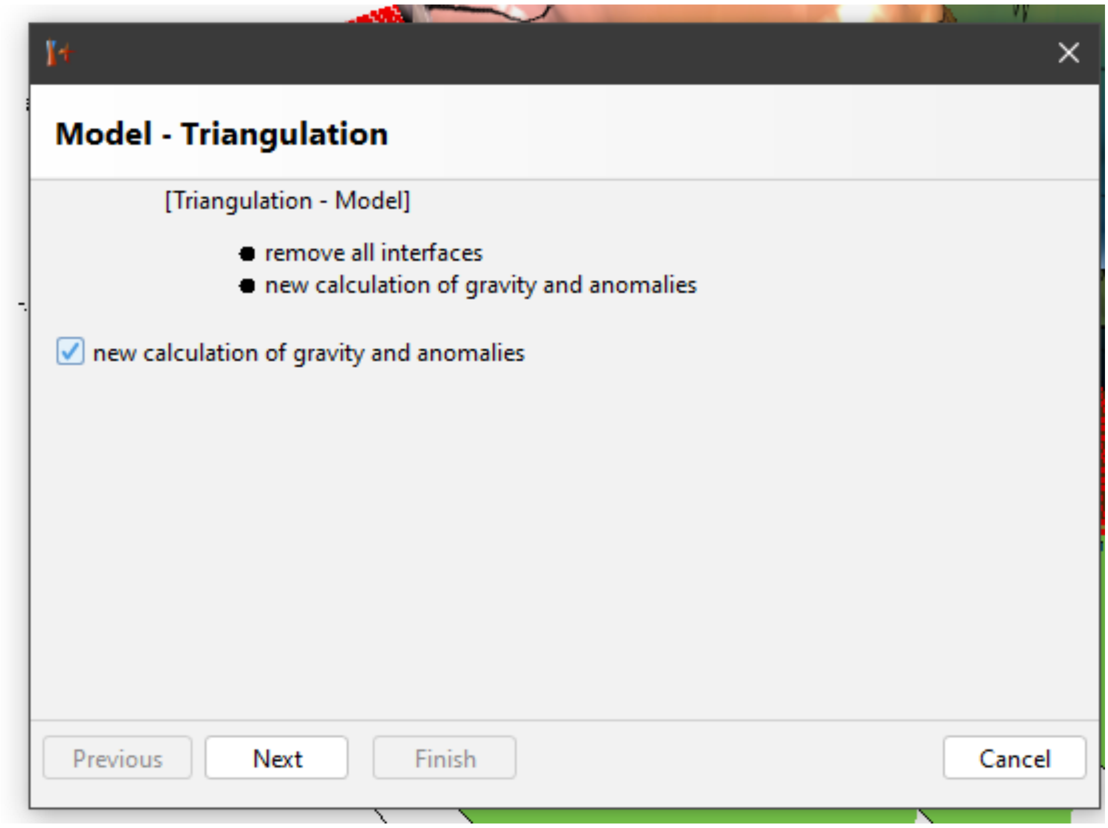
(1) Triangulate the vertical cross section, which results in a true 3D structure.

IGMAS+ offers the user two options:
Press either in the TITLE BAR > Edit > Model - Triangulation



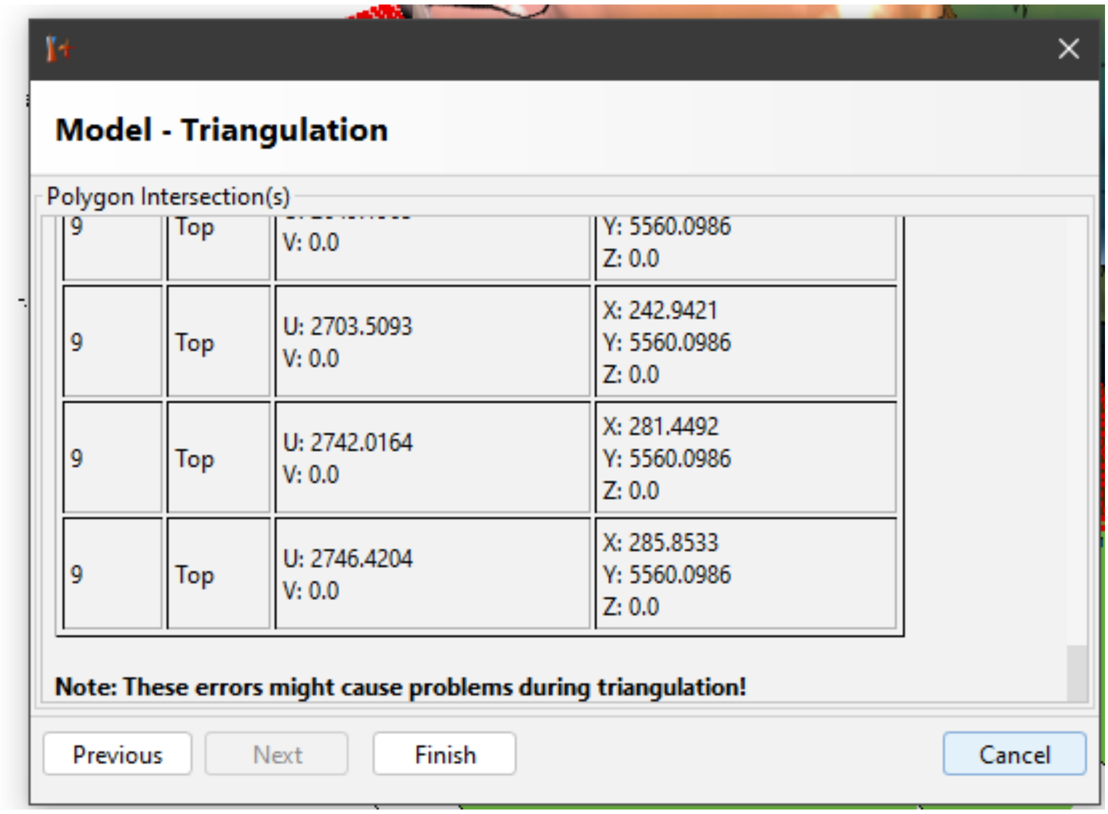
or Press in the TOOL BAR 

Next you will see this wizard:



Press Next 

... and get from the program the following information:



Check the messages in the table. *Here possible errors during triangulation are indicated, but at the same time it is pointed out that they will not be serious.* This is a numerical instability in the visualization, which has no influence on the gravity calculation.

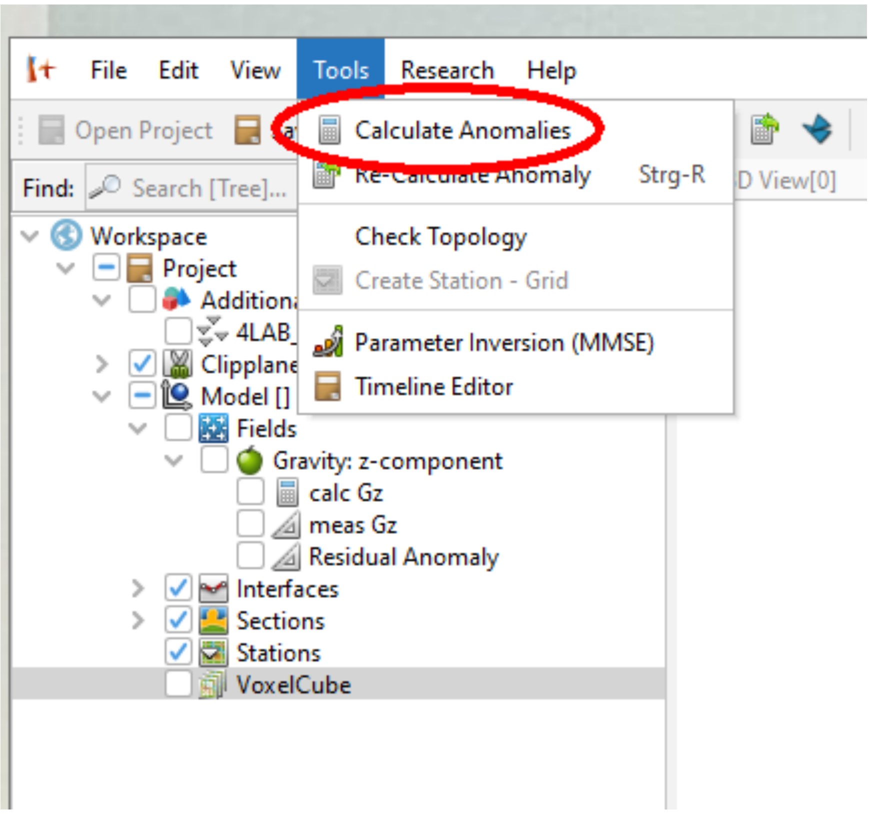
PRESS Finish

In the status information (below) the message will be shown that your model has no errors (green light), and we can proceed to calculate the modelled gravity field.

To calculate the modelled fields, **IGMAS+** offers two possibilities:

Click in the **TITLE BAR >Tools > Calculate Anomalies**

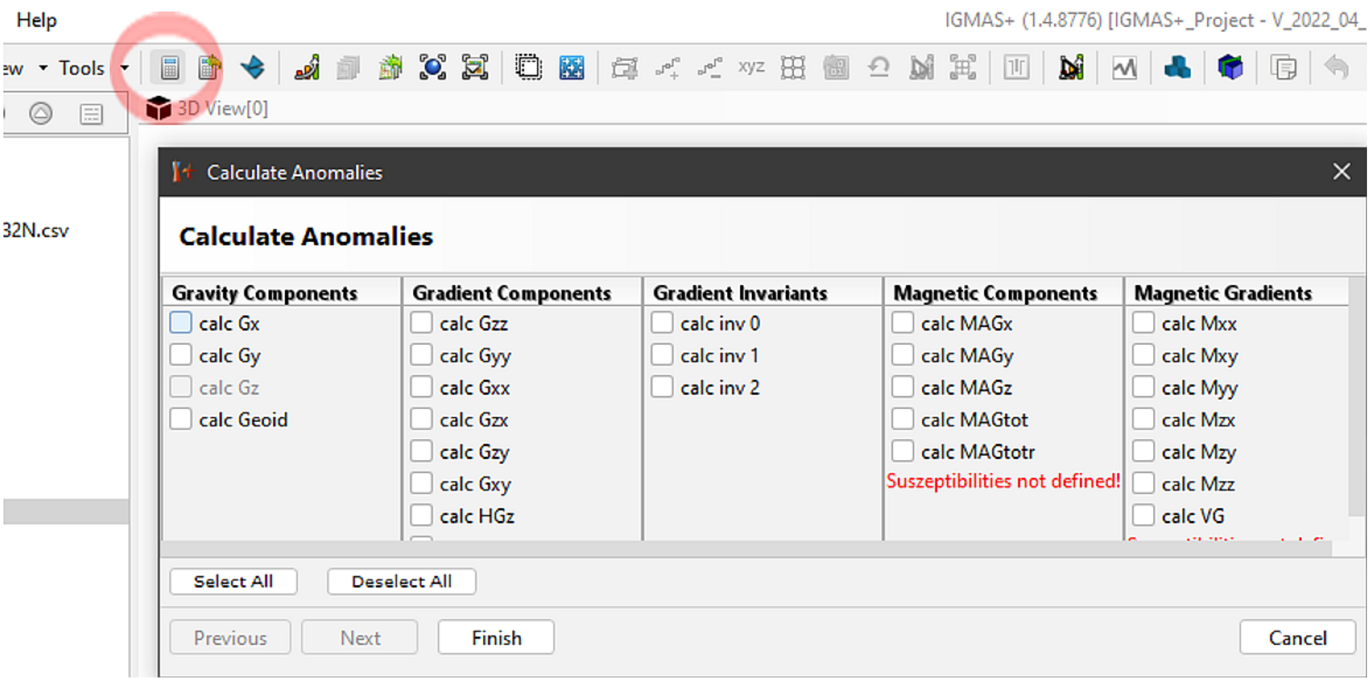
and select Calculate Anomalies.



or

press in the **TOOL BAR** 

and see the window:



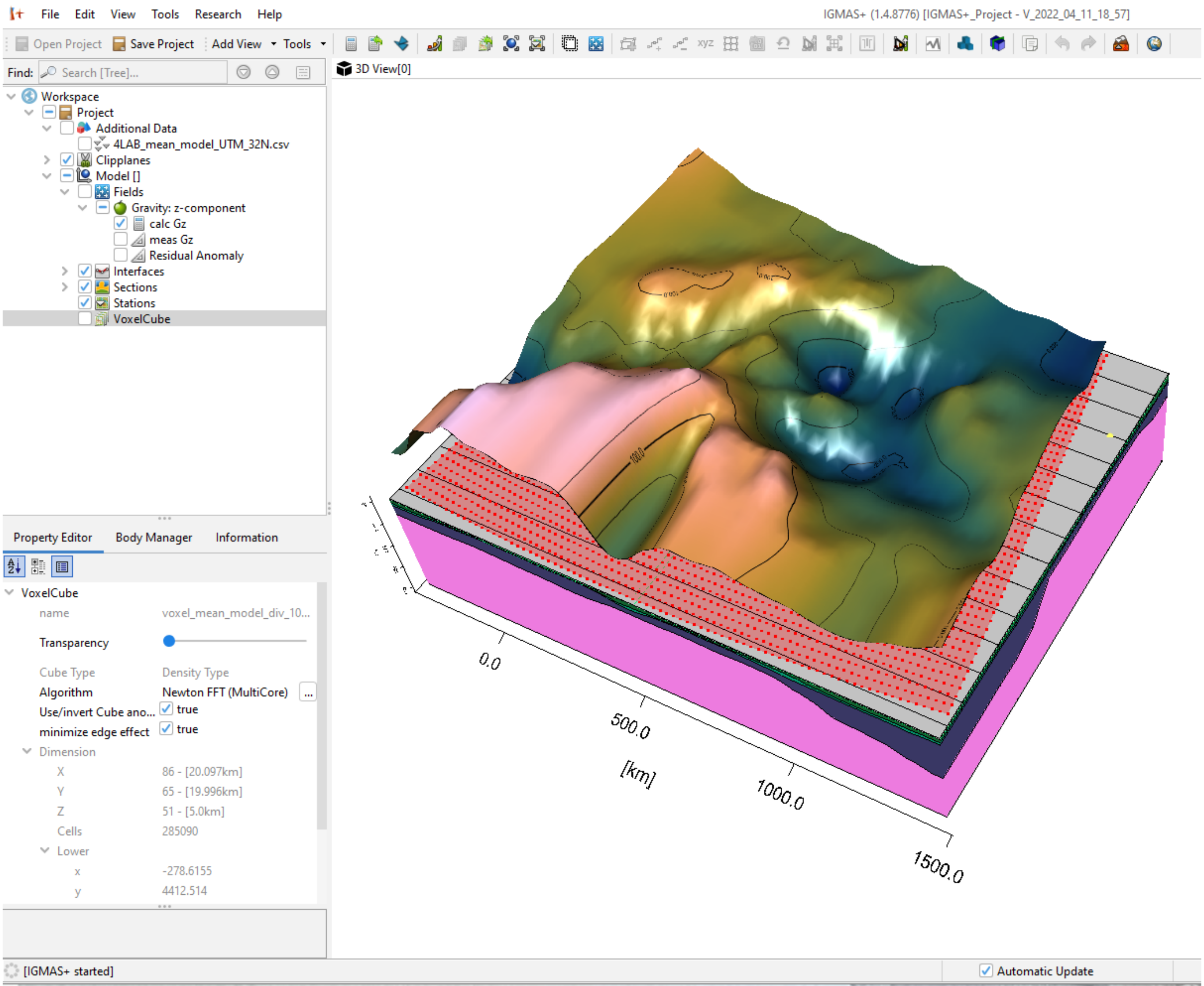
Select the field component you will calculate and then

PRESS Finish 

Of course, the length of calculation time depends on the size of the model and the number of stations. **Be patient with large models!**

The green "traffic light" of the "**progress bar**" in the "**lower status line**" gives you the certainty that everything has been calculated correctly.

... then the time has come to see the modelled field and the model in perspective on the screen.



Very well done and that's done for now... 

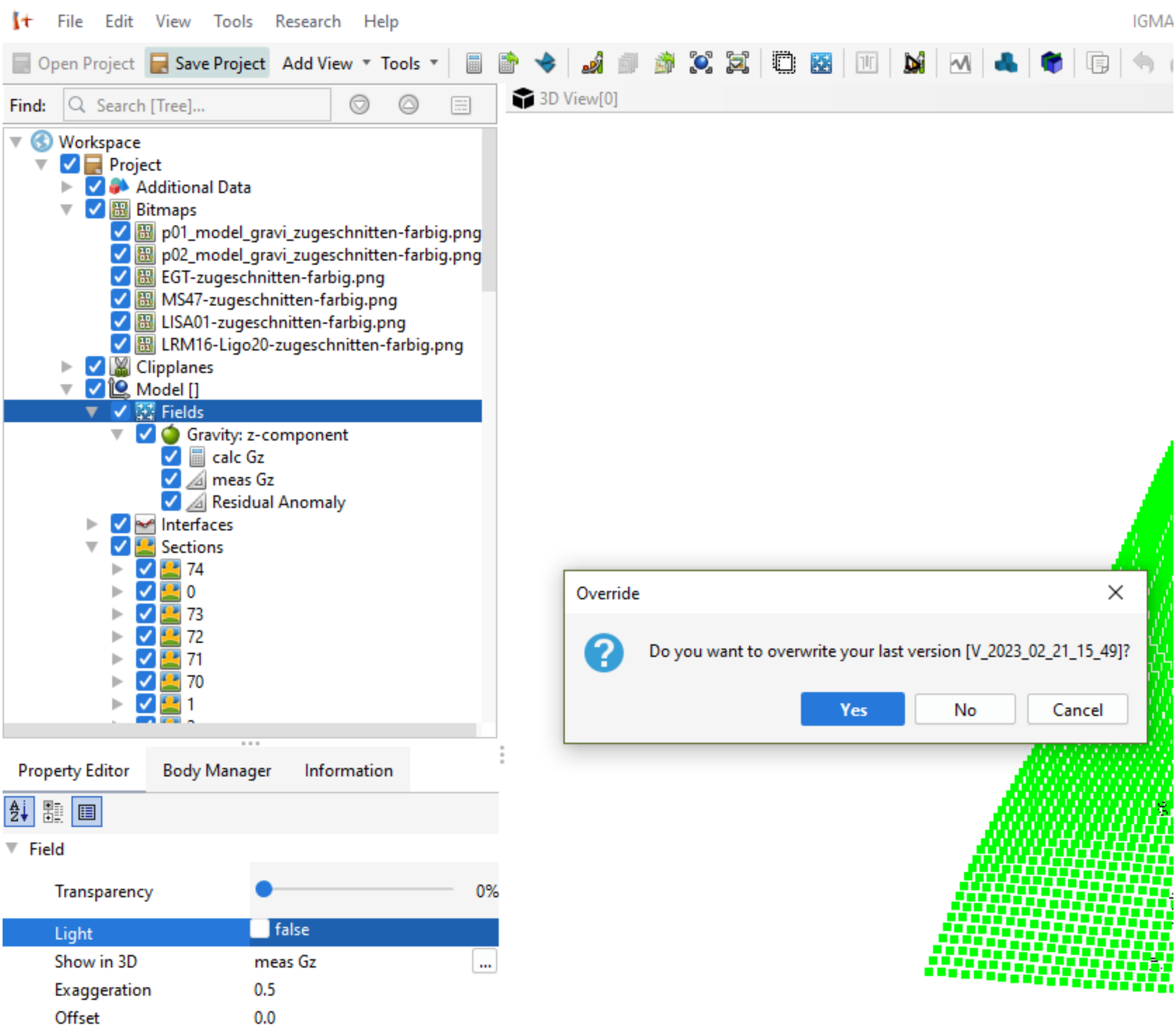
2.4 Saving a project

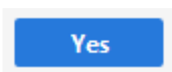
Before we start to explore the model, the fields and their possibilities for representation, we should learn how a model and its fields are stored.
This should be done from time to time by the user himself.

IGMAS+ offers two types of storage (see below):

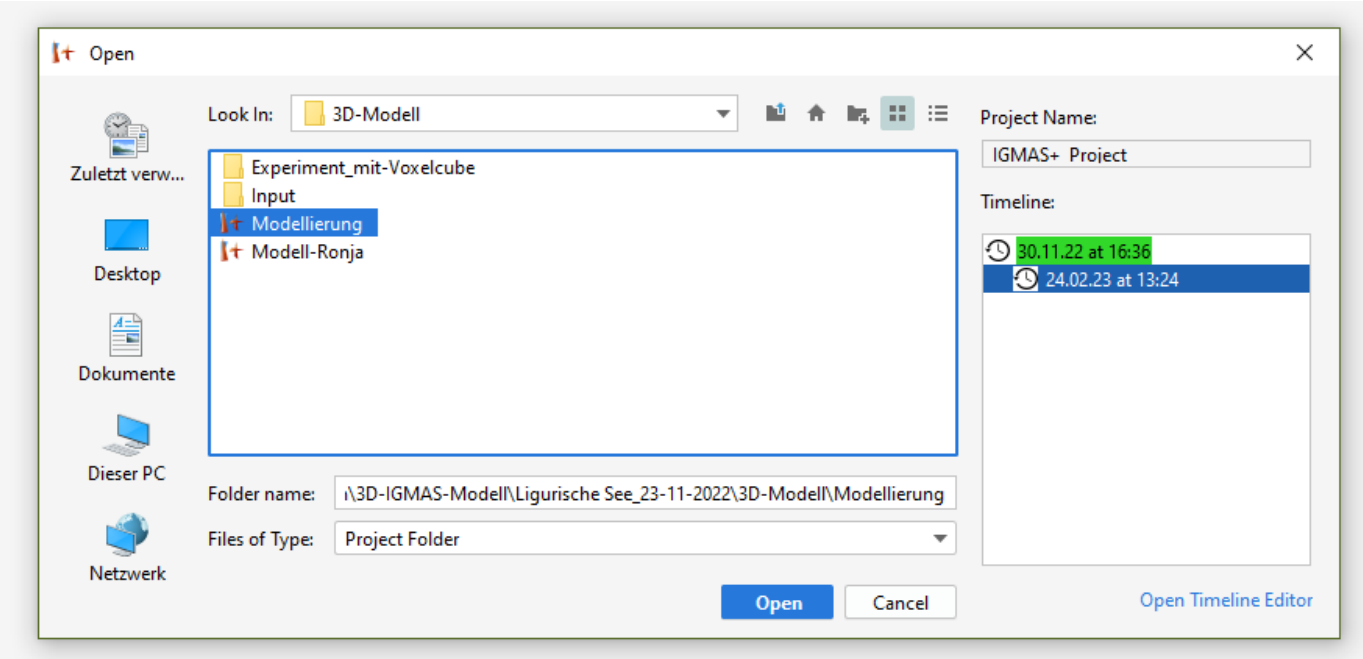
- SAVE PROJECT and
- SAVE AS ...

(1) The SAVE project action is initiated by a click in the **TOOL BAR > "SAVE PROJECT"**.

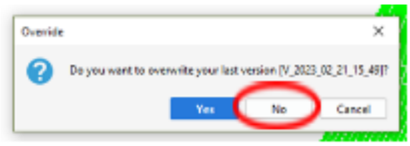


A window will appear warning you not to overwrite the current model version. If this is desired, click 

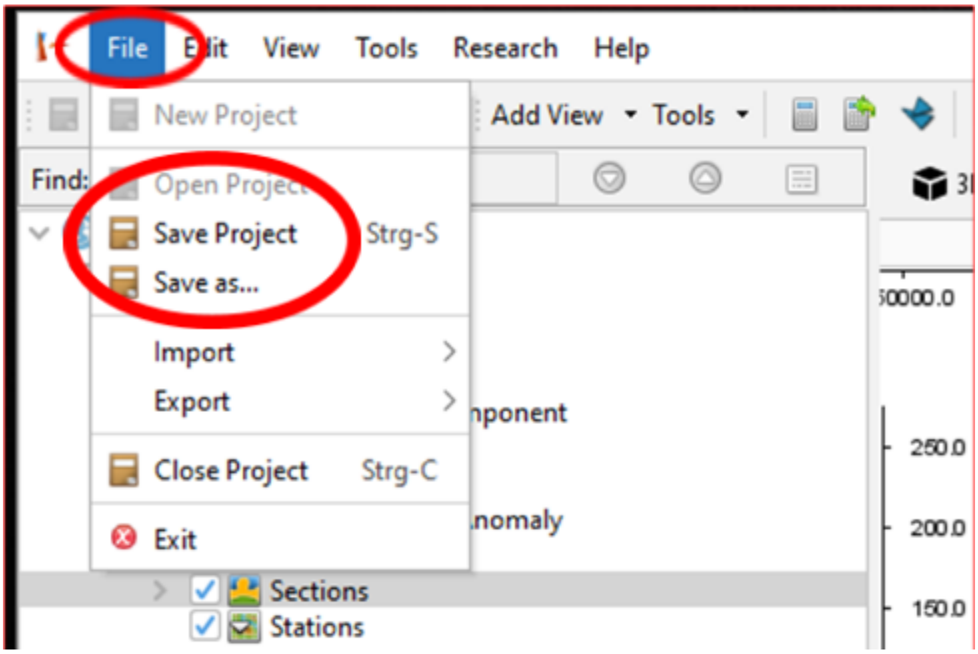
IGMAS+ will create a new Model INPUT. Loading a model file in the next working phase you see that in the Timeline appears the former model (in green colour) and the new model blue shaded:



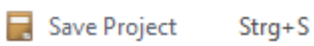
If you click ***No***, nothing will happen and the model will remain. ***CANCEL*** will terminate the action without any decision.



(2) There is a second possibility to save model changes.



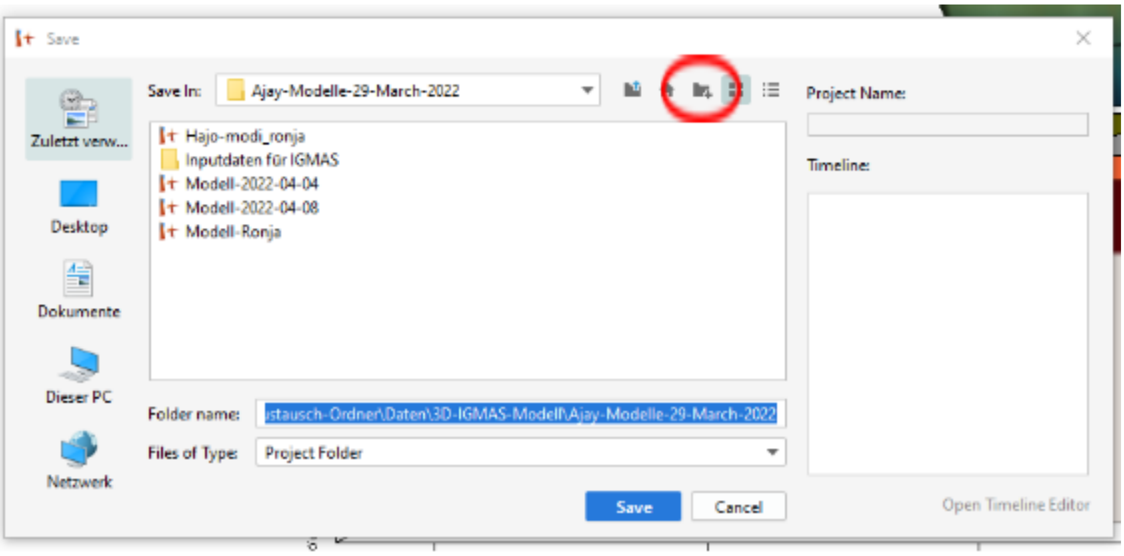
Click on "**File** *in the TITLE BAR**



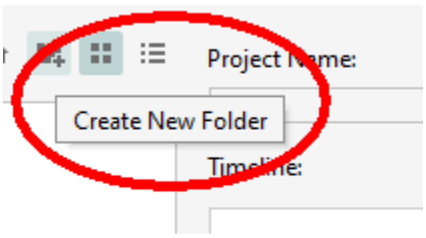
In the pull down menu appears (short key is “Strg+S” bottom).

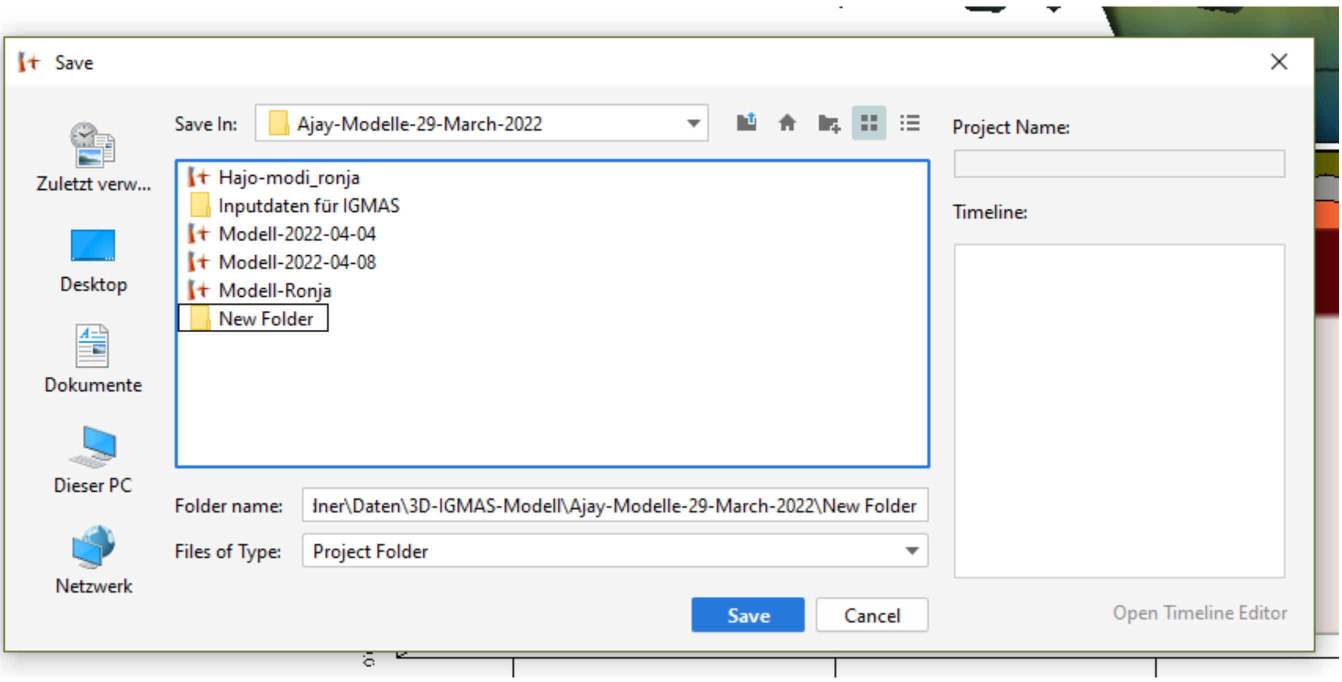
“Save project” will save the entire model as already described above in (1).

enables the user to give a new name to the model output.

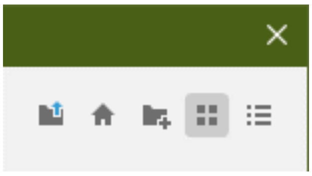


Click on the “create a new folder symbol”  , rename the new folder and press **“Save”**.





The small symbols indicate from left to right:



From left to right:

Go one level up in the folder hierarchy - Go to home directory - Add a new folder - Show folders - Show folders listed.

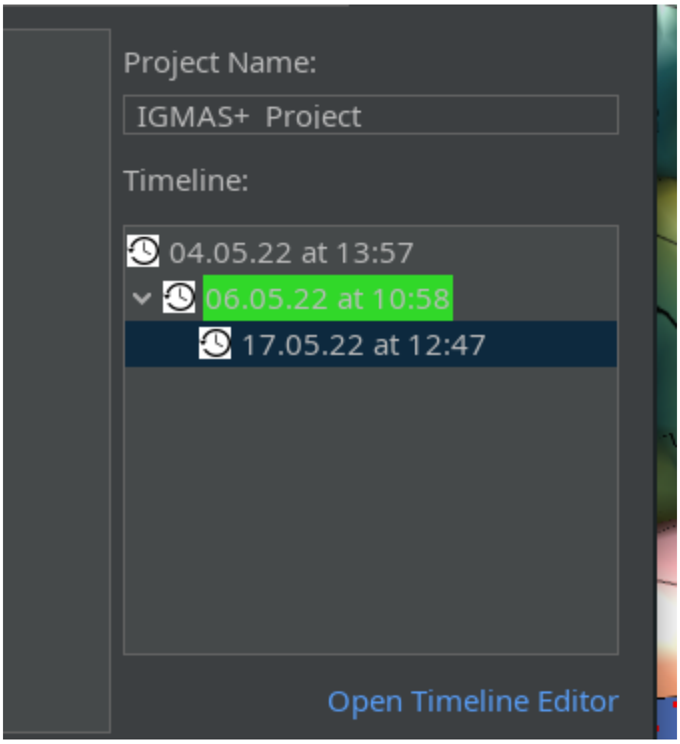
2.5 Loading models

In the reverse case of loading a model that has already been saved, first select
"Open Project".

Open a version

When opening a project, several versions are displayed. These are all versions that have been saved earlier.

Select the following:



> **Note**
>
> Dark or light interface appearance can be set by the user.

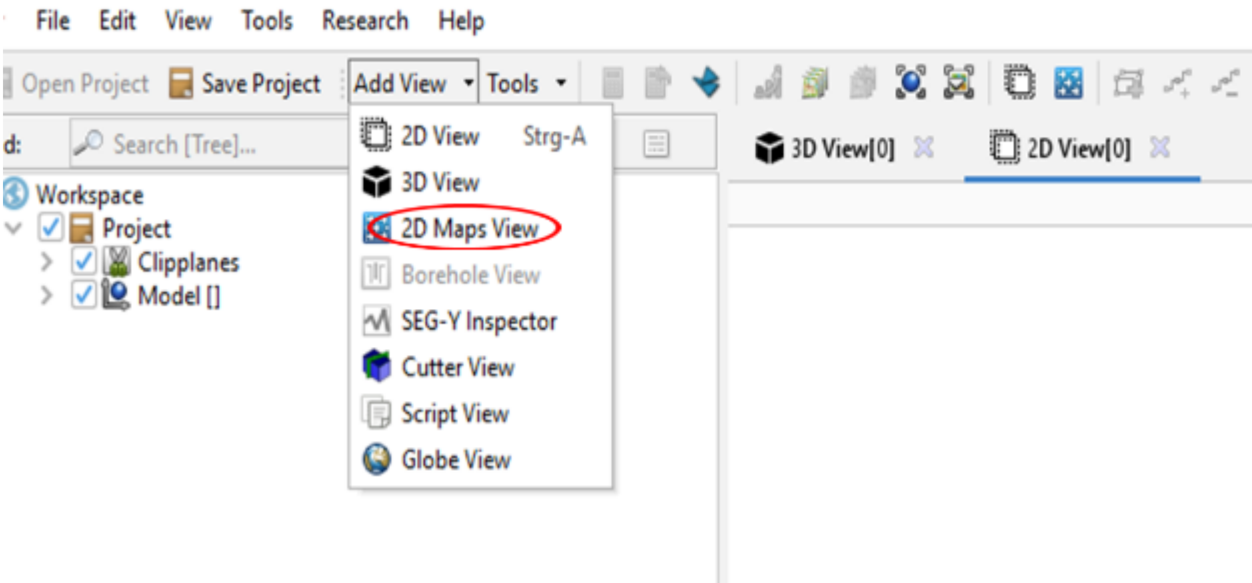
... and this also brings us to the next point in familiarizing ourselves with **IGMAS+**:

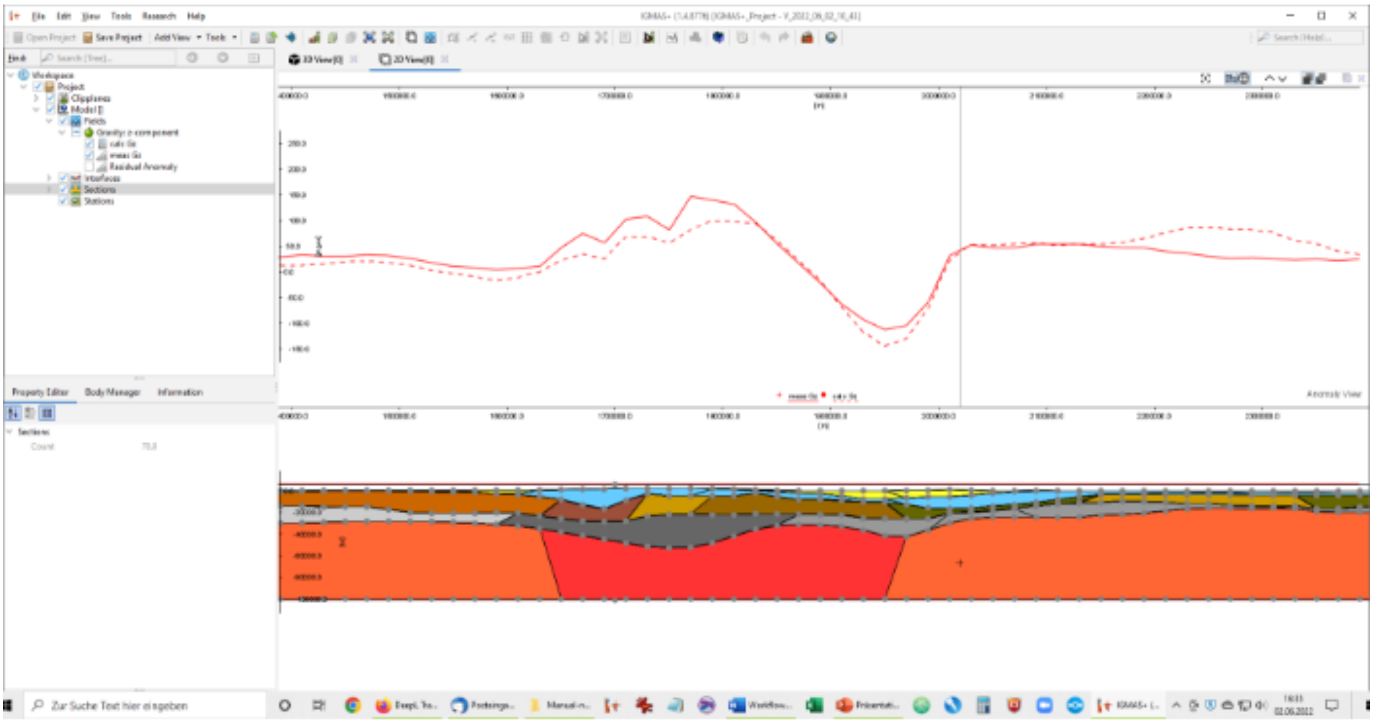
2.6 Displays & visualization

Above, we have already introduced the **3D view**. If you want to go through the model step by step (vertical cross section for vertical cross section) then select on the **IGMAS+** TOOL BAR under "Add Views", the item **2D View**.

Add view > 2D View > click 

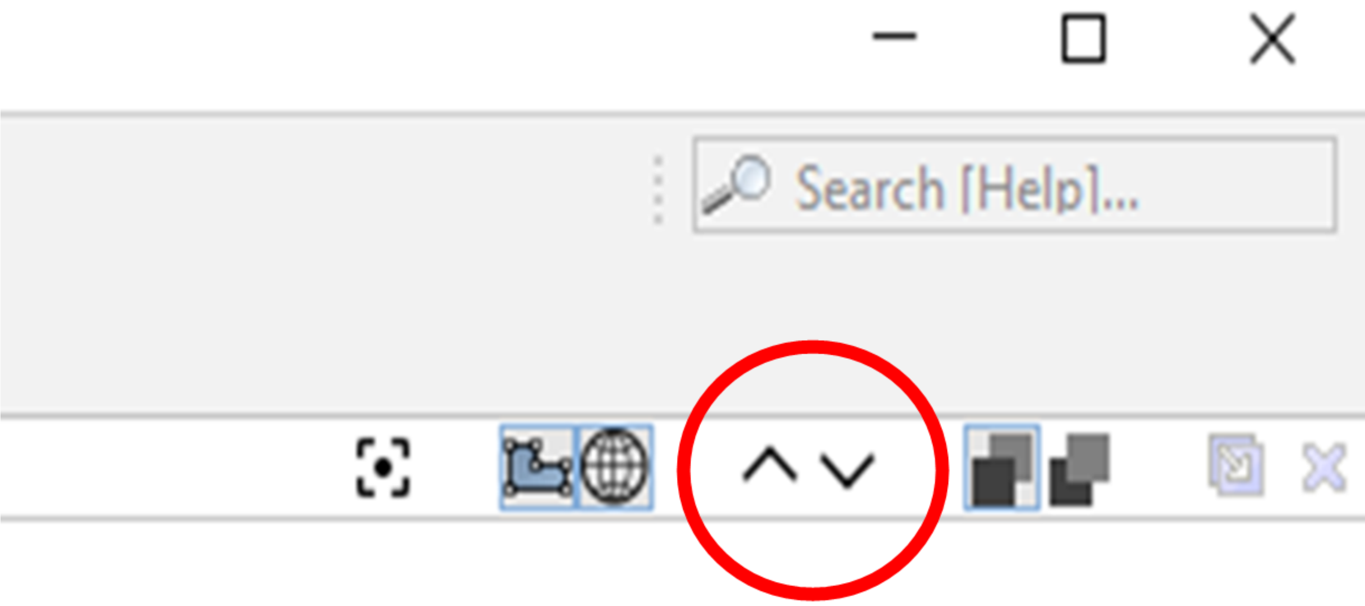
... and immediately the vertical section appears in the **IGMAS+** Workspace window. Use pull-down menu “Add View”, select “2D View” and the 2D view appears in the headline below the icons and the **first vertical cross section** of the model is displayed.





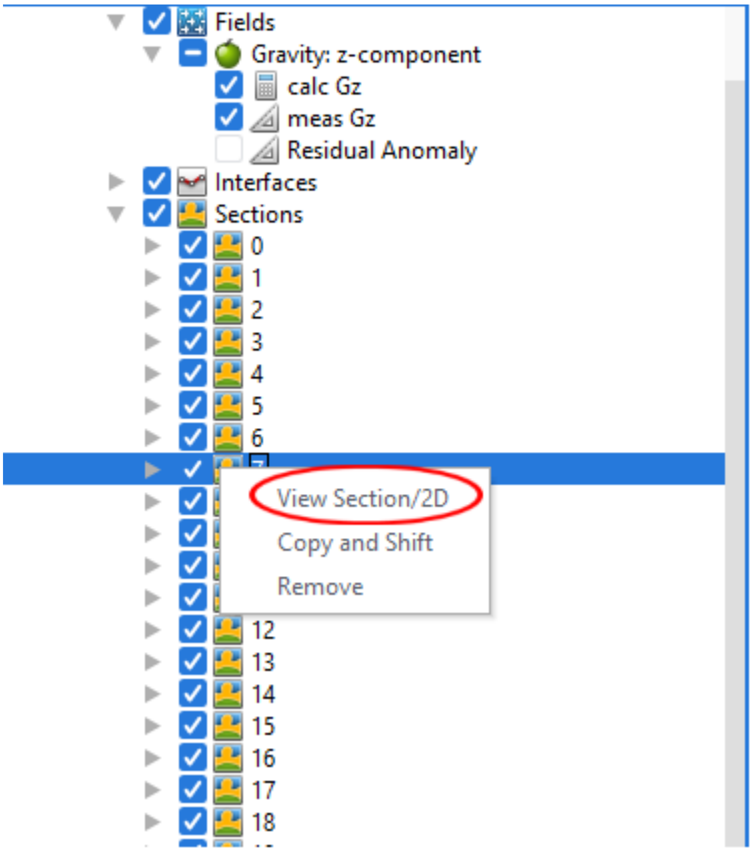
There are several ways to step through the vertical sections of the model.

(1) Use the ˄ (up) and ˅ (down) in the right upper part of the main window to step through the model.



Now let's learn about two other options:

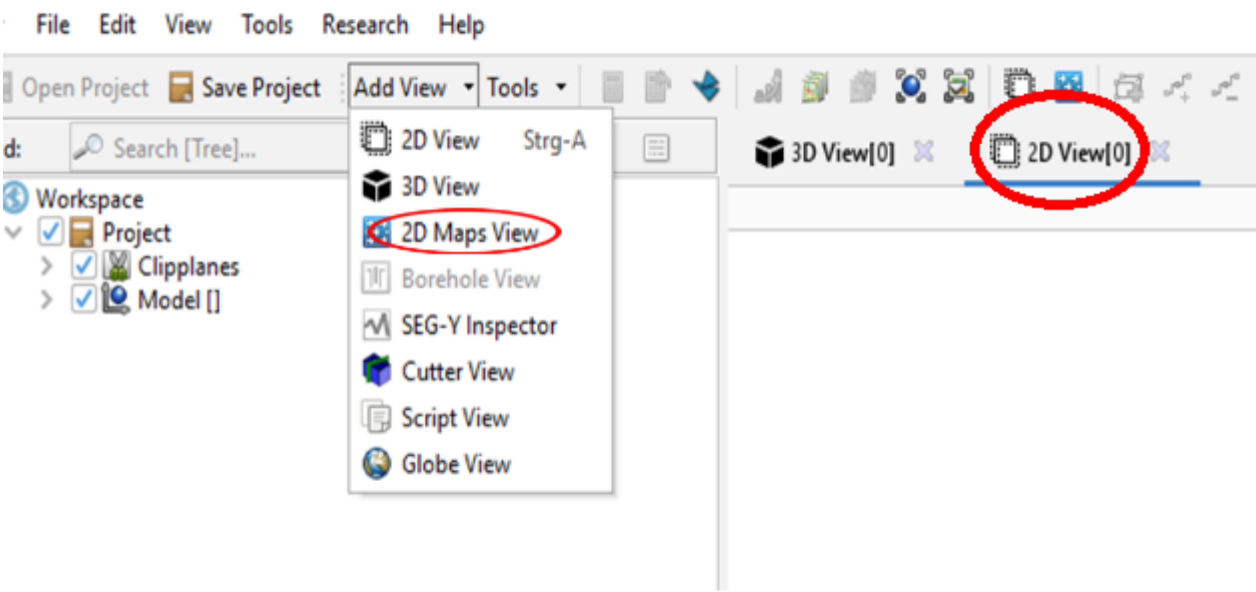
(2) Open the sections in the "**OBJECT-TREE**" window of **IGMAS+** and select the section to be visualized (for example section 7). Click with the right mouse button on the section symbol and select "View Section/2D" in the window. The selected section will appear. Because each section must be clicked individually, it will take longer to view large models than with the method described above.



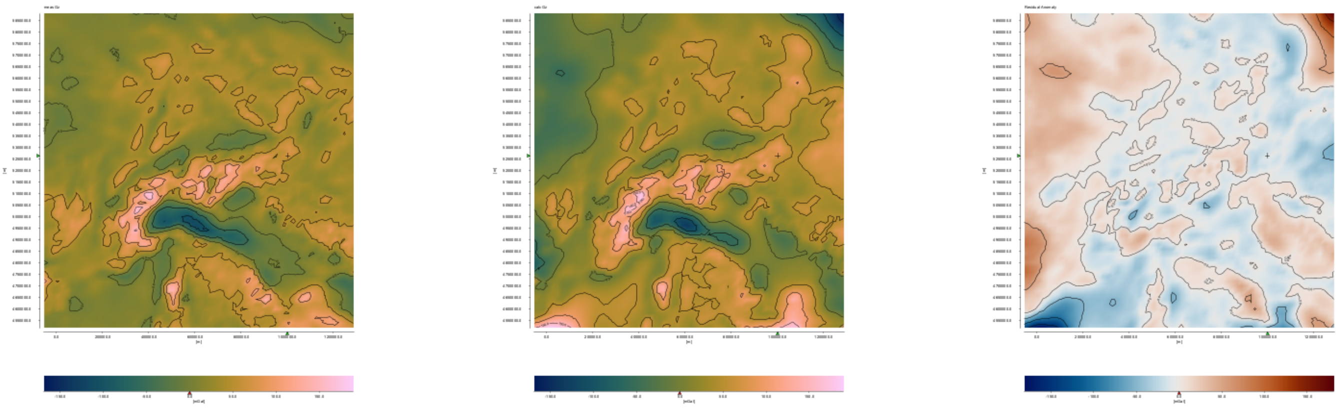
The third possibility to visualize sections is realized via the "Map display".

Add view > 2D Maps View (click)

Then the three maps appear that are active in the Object tree under **"Fields"**.



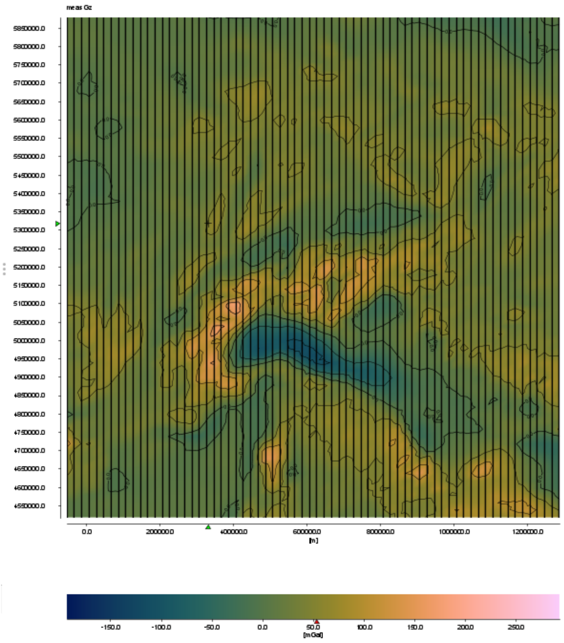
Then the three maps appear (measured - calculated residial field), which are active in the object tree under "Fields". From left to right you can see the map of the measured field, the modeled field, and the differences between the measured and the modeled field.

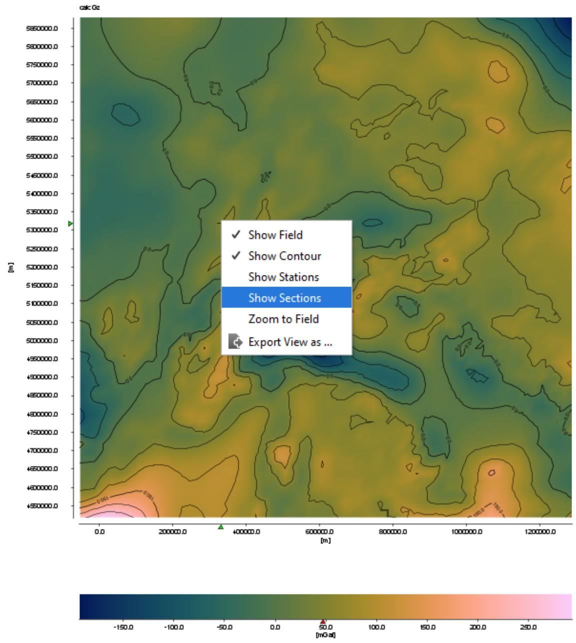


A map enlargement can be seen in the next figure. Click with the right mouse button on the map layer and the window that opens offers the possibility to draw the section (click "Show sections").

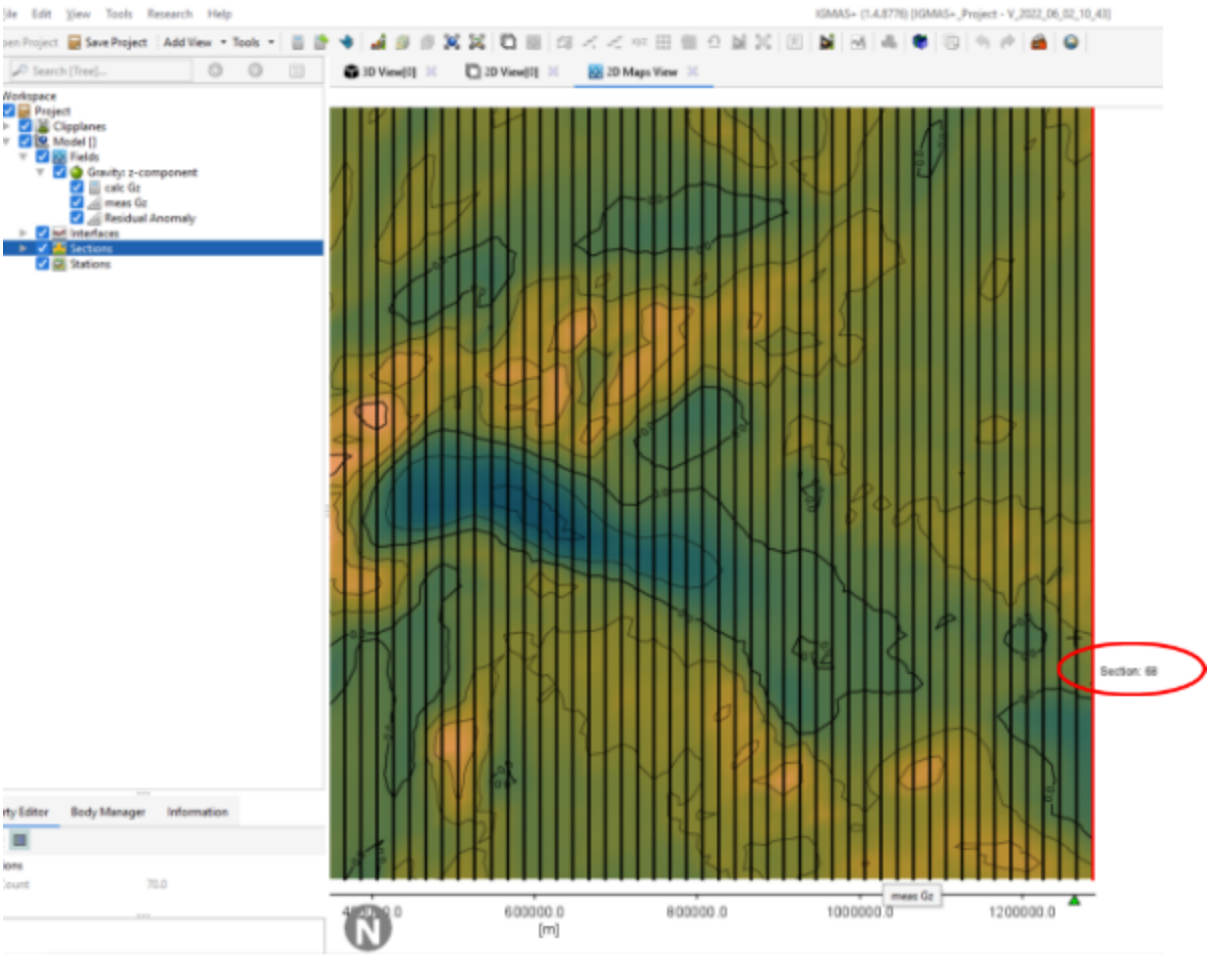
NOTE: In the same way, other information can be selected in the same window.

For example, "**Show Stations**", "**Show Contours**", etc.





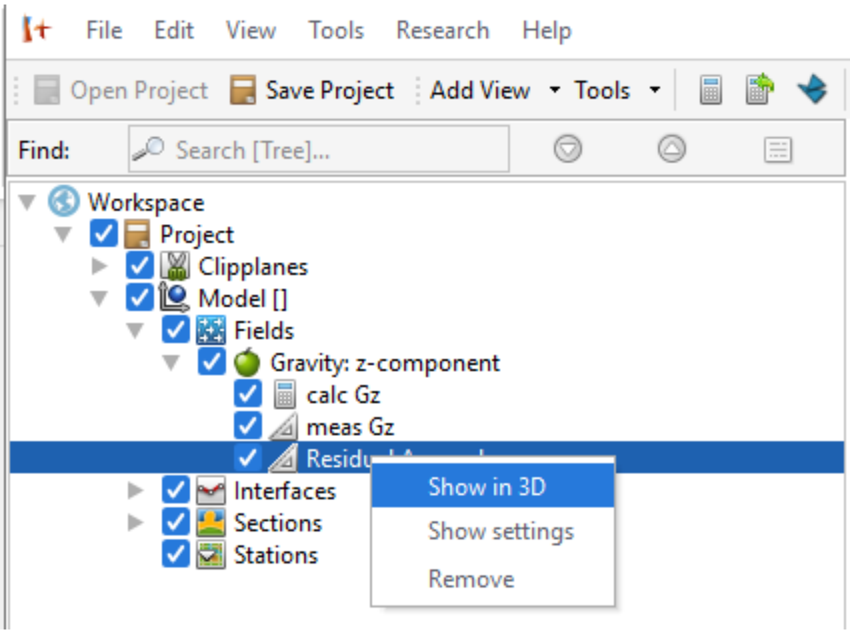
Click on one of the lines/vertical sections. It will be highlighted in red and the section name will be displayed.



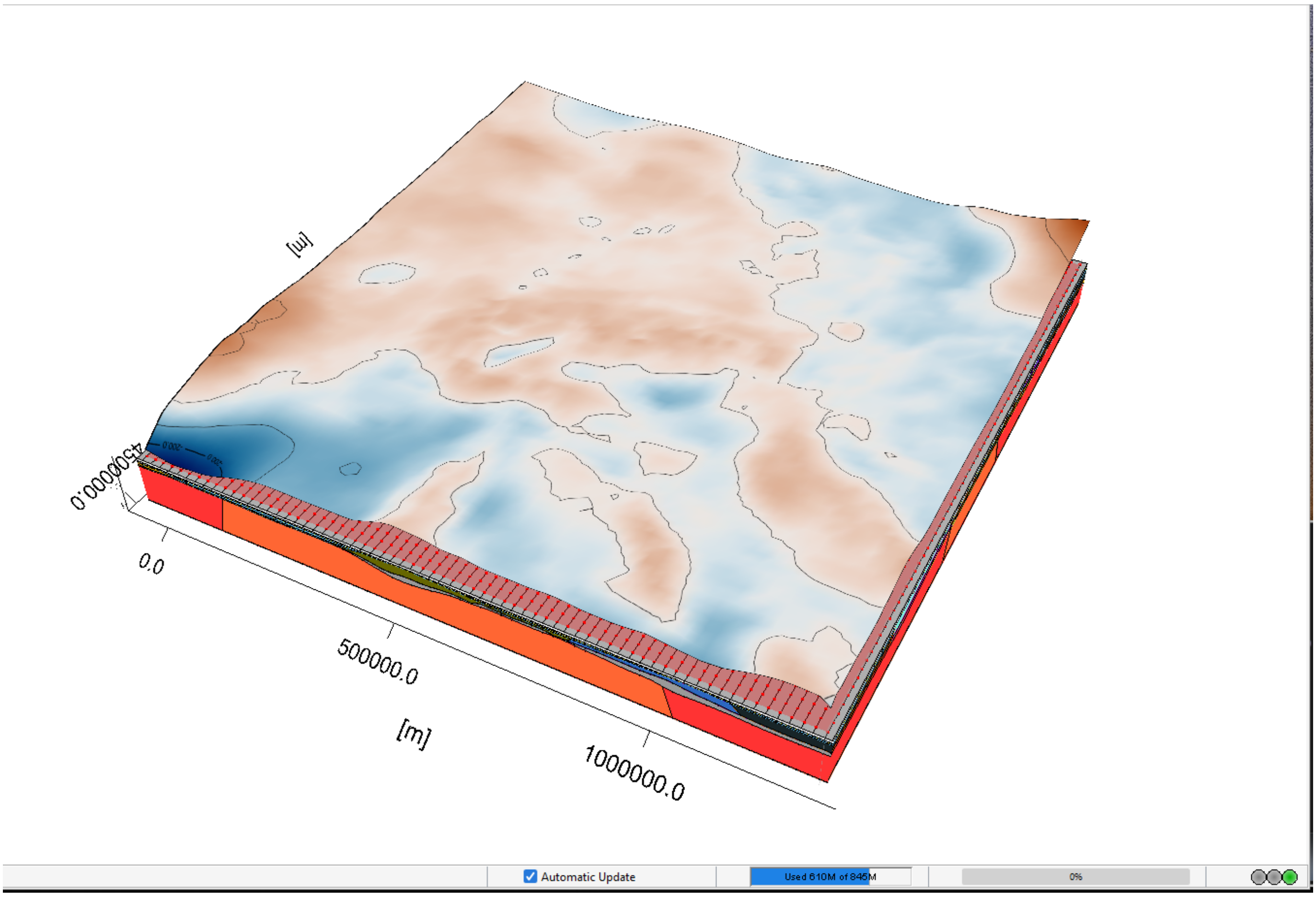
Clicking with the right mouse button on the selected line opens the 2D view of this section.

The default setting is always the perspective display of the reference field (measured field). The default setting is always the perspective display of the reference field (measured field). This can be adjusted by clicking the following button in the **TOOL-BAR** line:

Add view > 3D Model > click 

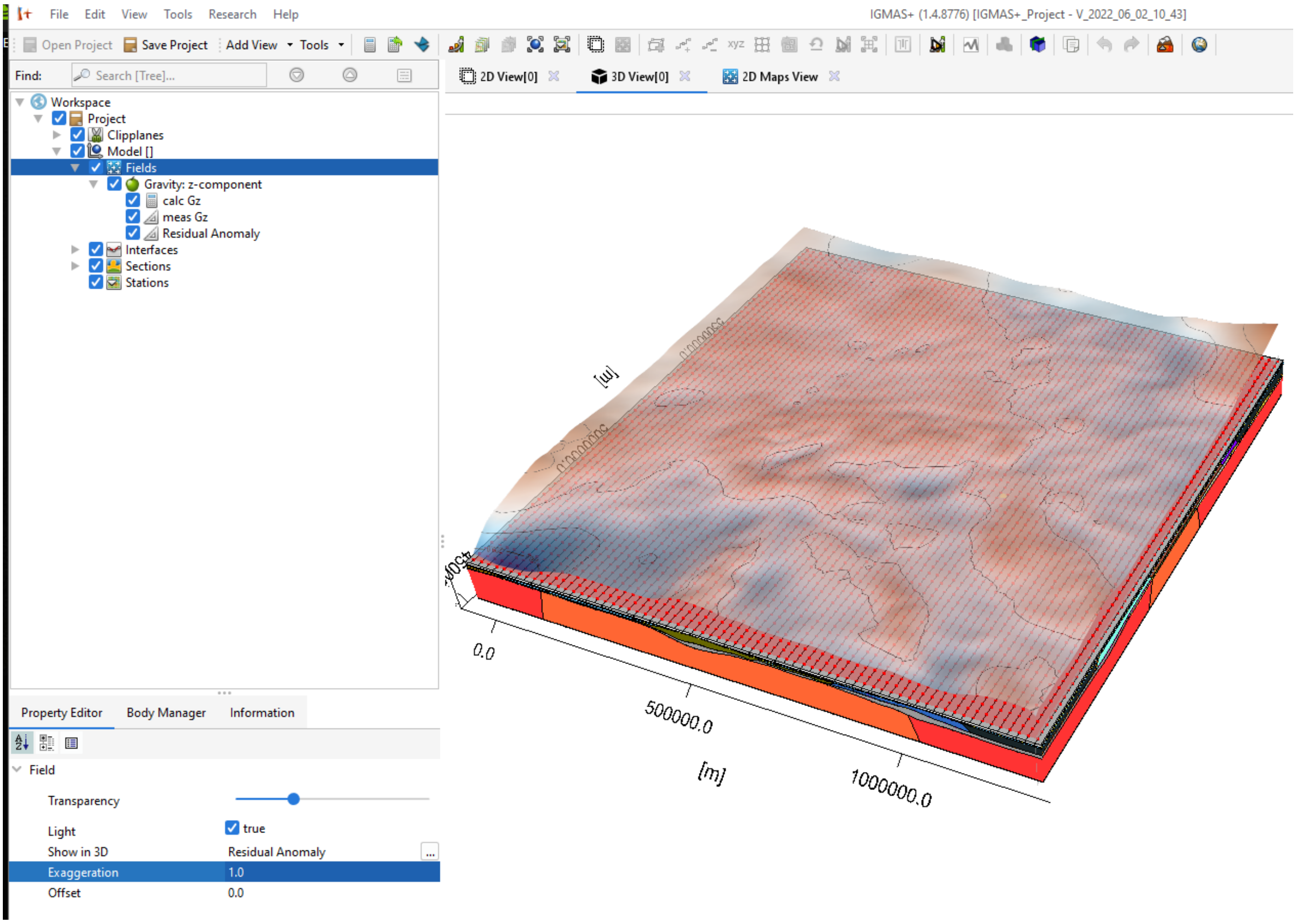


If the display of the comparison field is not desired, the user has the option to change this in the 3D display. In the following the difference field is to be represented. A right mouse button click on "**Residual Field**" opens the window and one selects "**Show in 3D**":



If you want to visualize the underlying information (e.g. positions of sections), you can change the transparency of the field display. Go to "Fields" in the **OBJECT TREE** and activate "**Property Editor**" in the **BODY MANAGER** below.

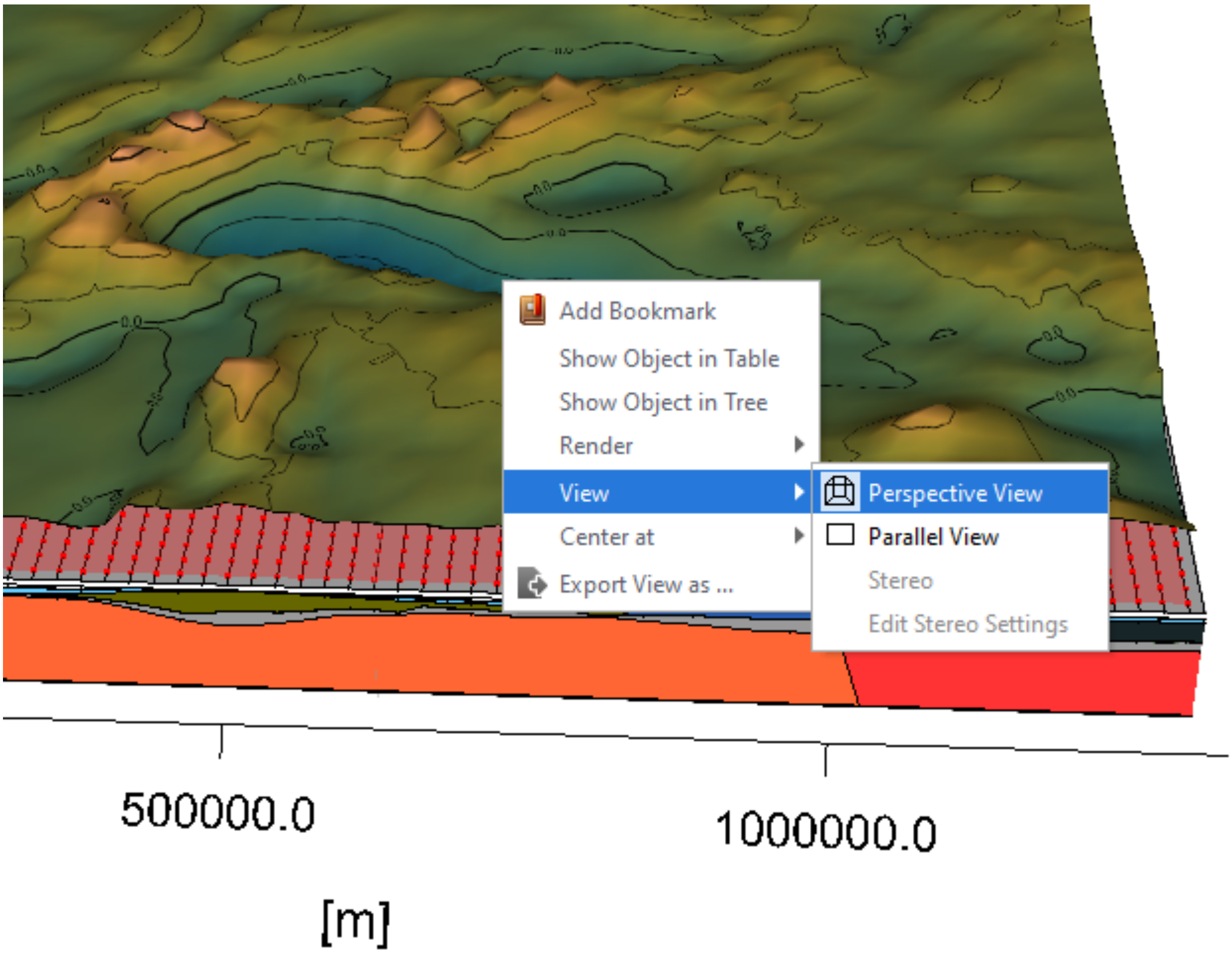
Here you can change the transparency (using the slider). In addition, a "shading" of the surface can be created and an exaggeration of the field.



The value for exaggeration is always smaller than 1: ***ValExagg \< 1***

2.7 Perspective of 3D Model

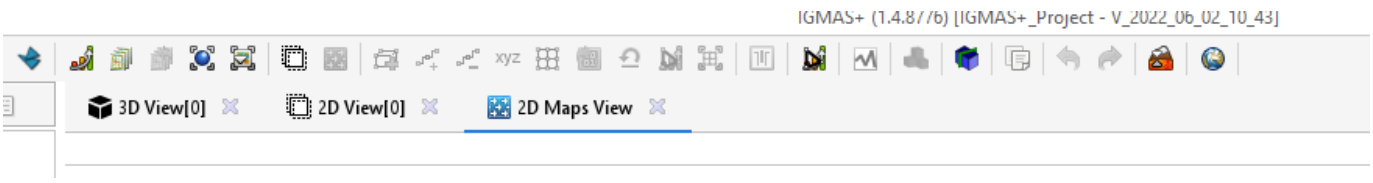
The 3D model can be displayed in two perspectives. The default is the perspective view. Modification: click with the **right mouse button** in the model and select "**View**" in the window and select the perspective with the **left mouse button**:



A *second, alternate procedure* is:

Go to the line below the “**TOOL BAR**” and click the shown options for model perspective:

If all three types of display are selected, you will see below the **TOOL BAR**:



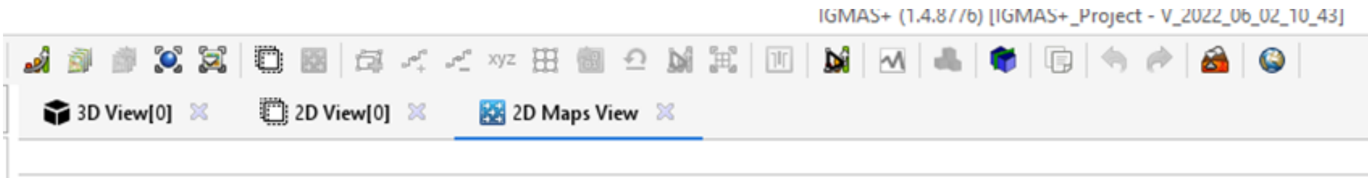
The three windows can be removed again by clicking on the **X**.

2.8 Zoom in, zoom out, move and place IGMAS+ elements

Click in the workspace window on the object to be enlarged/down sized.

- **ZOOM in** with a movement of the **mouse wheel** *t o w a r d s the user*,
- **ZOOM out** with a movement of the **mouse wheel** *a w a y* from the user.

This is generally true for all three "views:



But click for **2D View** in the model.

Click with the **right mouse** button on the object and moved it pressed:

Moving objects of: 

Click with the **right mouse button** on the model and moved it pressed up and down, to the left and right. The window with the field curves will be placed correctly above the model.

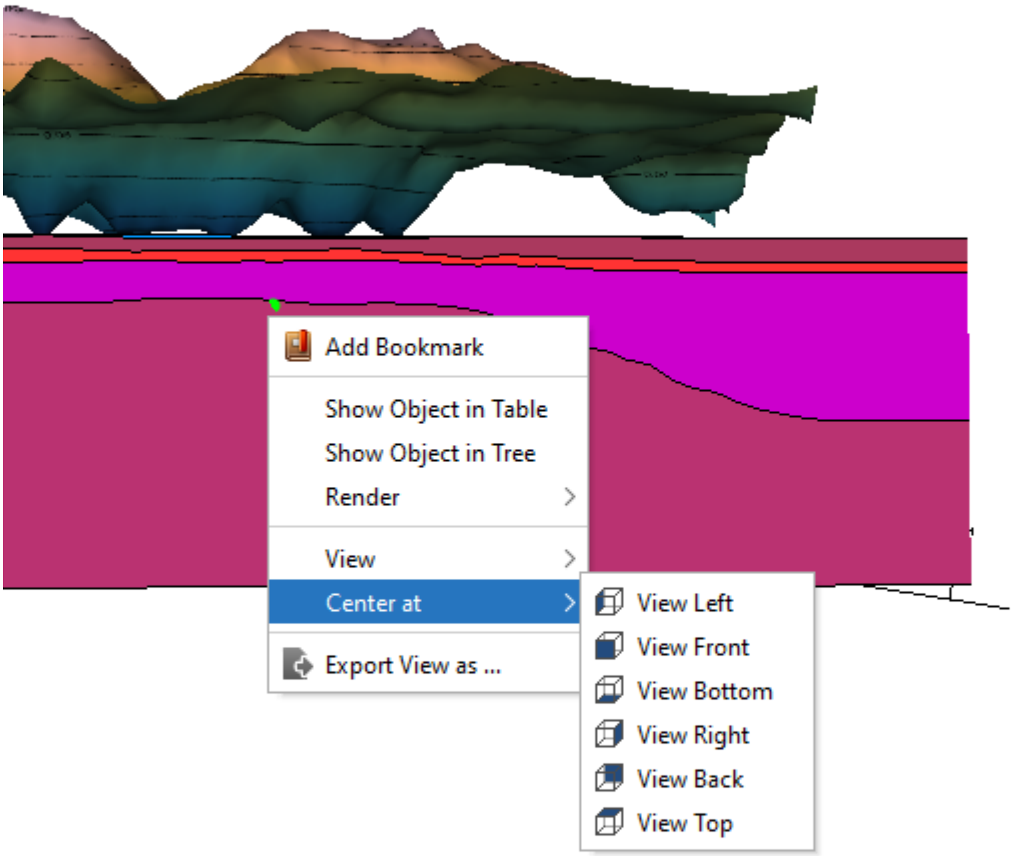
Tilting a 3D View in its actual position: 

Click with the **left mouse button** in the workspace window and moved it pressed:

Center objects

Center model and 2D map views: 

Click with the **right mouse button** in the model, select "**Center at**" in the window and select the perspective with the **left mouse button**:



A *second, alternate procedure* is:

Go to the line below the "**Tool bar**" and click the shown options for centering the model:

Center 2D View:

Go to the line below the "Tool bar" and click the shown options for centering the 2D cross section:

The cross section (lower panel)) together with the field values above it (upper panel) is centered in the area where stations are located.

2D View Section front/back side

In vertical cross sections that show the geometry of different bodies on their front and back sides (also called: *double occupancy*), the two icons of the following figure determine whether the front side (left icon) or the back side (right icon) should be shown.

2.9 Change model geometry

If changes to the geometry of the model become necessary, the user can make model adjustments based on changes to model vertices.

The actions **Insert - Delete - Move vertices** are described here.

Insert a vertex:

Press key I-key  and navigate with **left mouse button** on the position of an interface/horizon > **click**  .

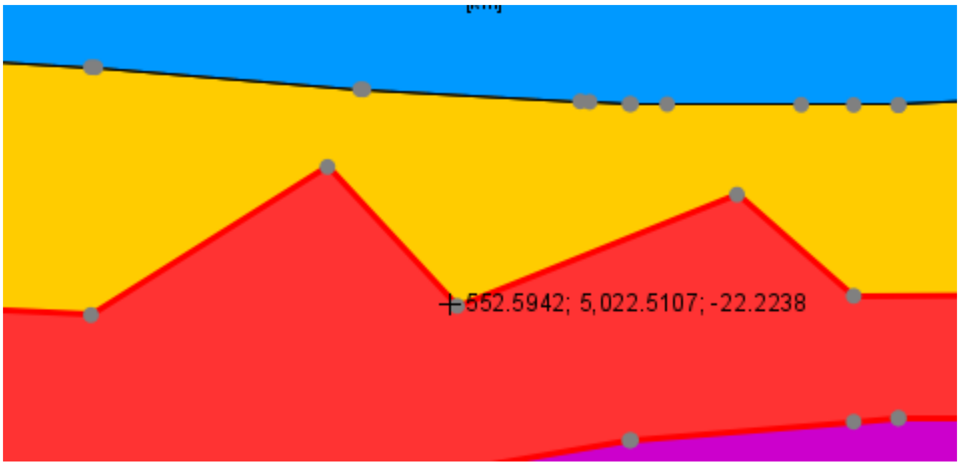
Delete a vertex

Press shift key  and navigate with **left mouse button** on the vertex > **click**  .

Be sure to see the coordinates of the vertex to delete on the screen:

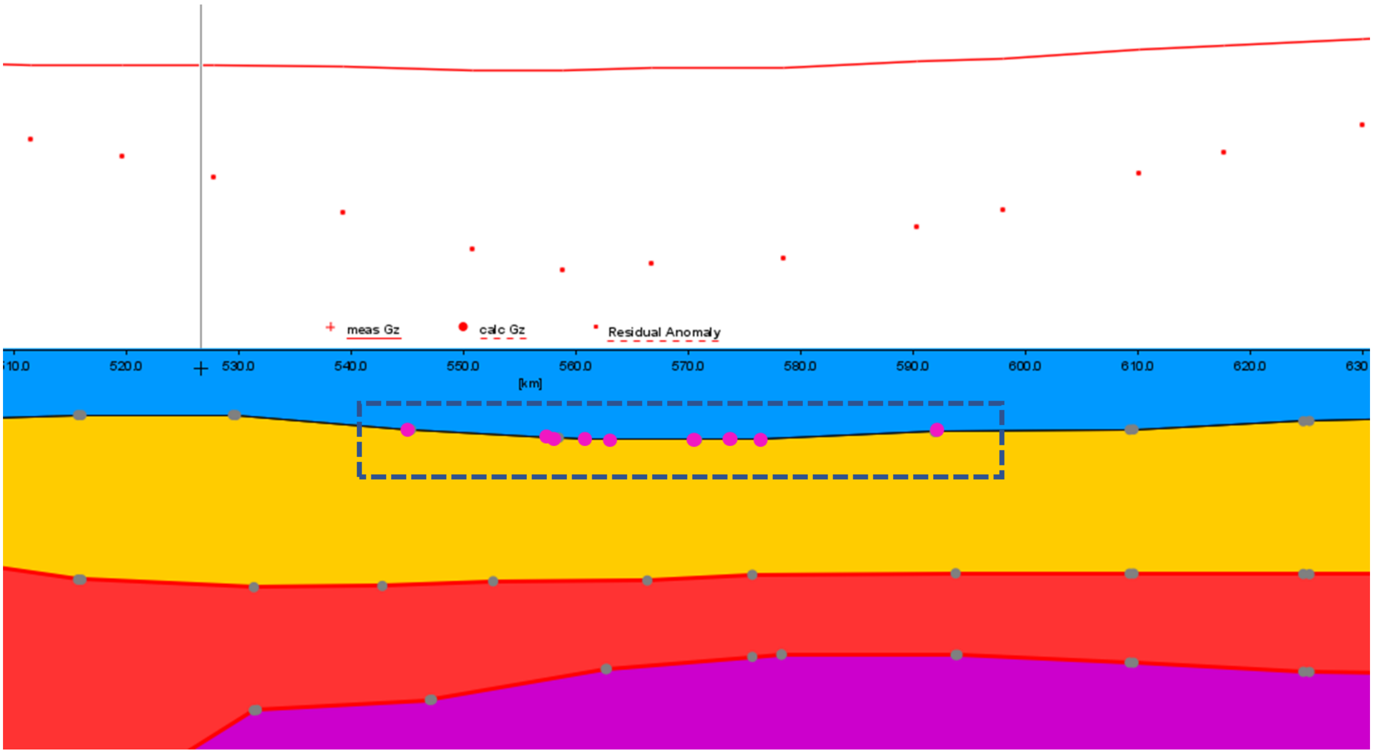
Shift a vertex:

Press shift-key  and navigate with **left mouse button** on the vertex to be shifted > **click**  .

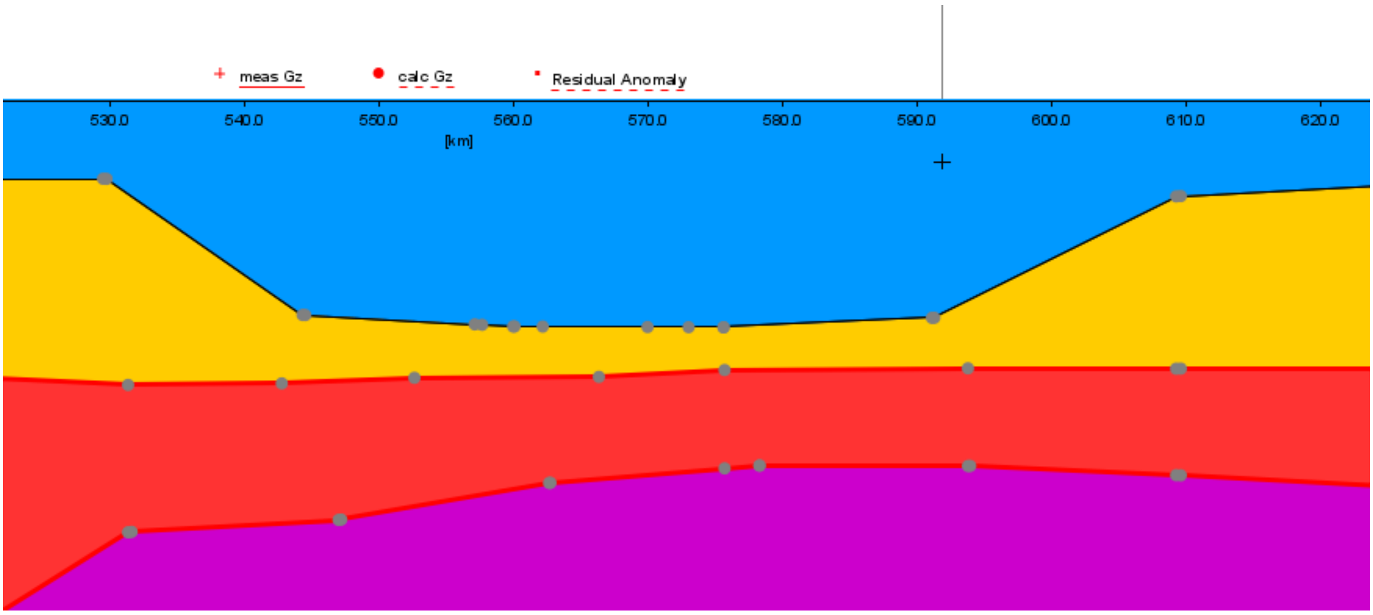


Shift grouped vertices:

Press shift-key  together with the key . Then define region of vertices to be shifted by open a window with **left mouse button** and move pressed **left mouse button** into the new position

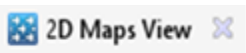


Release the **left mouse button**. This is the result:



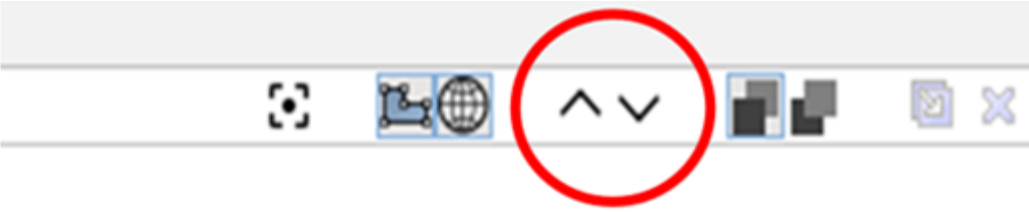
The model gravity field is automatically recalculated.

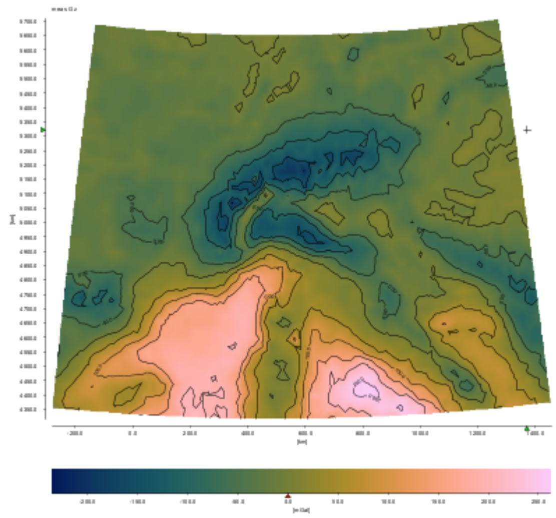
2.10 Split a body/polyhedron on a specific vertical cross section

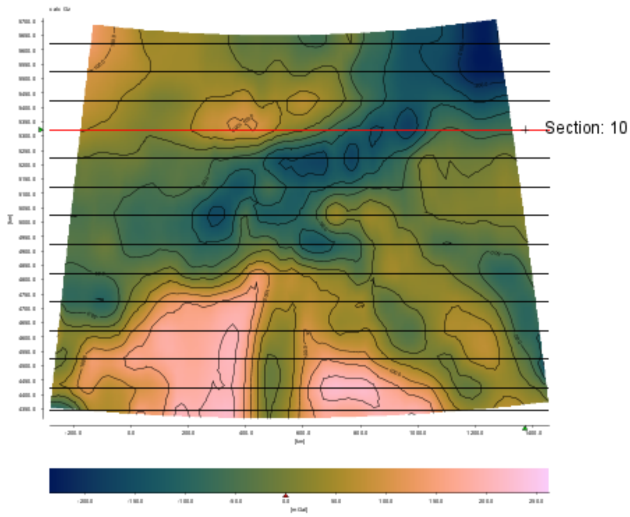
Select "**2D maps view**" 

and mark in the map the cross section on which the density of the body should change (in ascending section number order). Here section 10 was selected; it is marked in red.

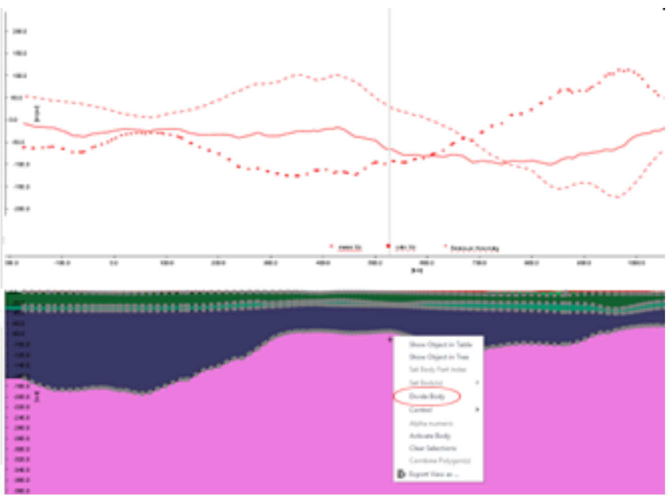
Alternatively, the vertical section can also be selected (1) in the **OBJECT TREE** or (2) by the "section up & down":





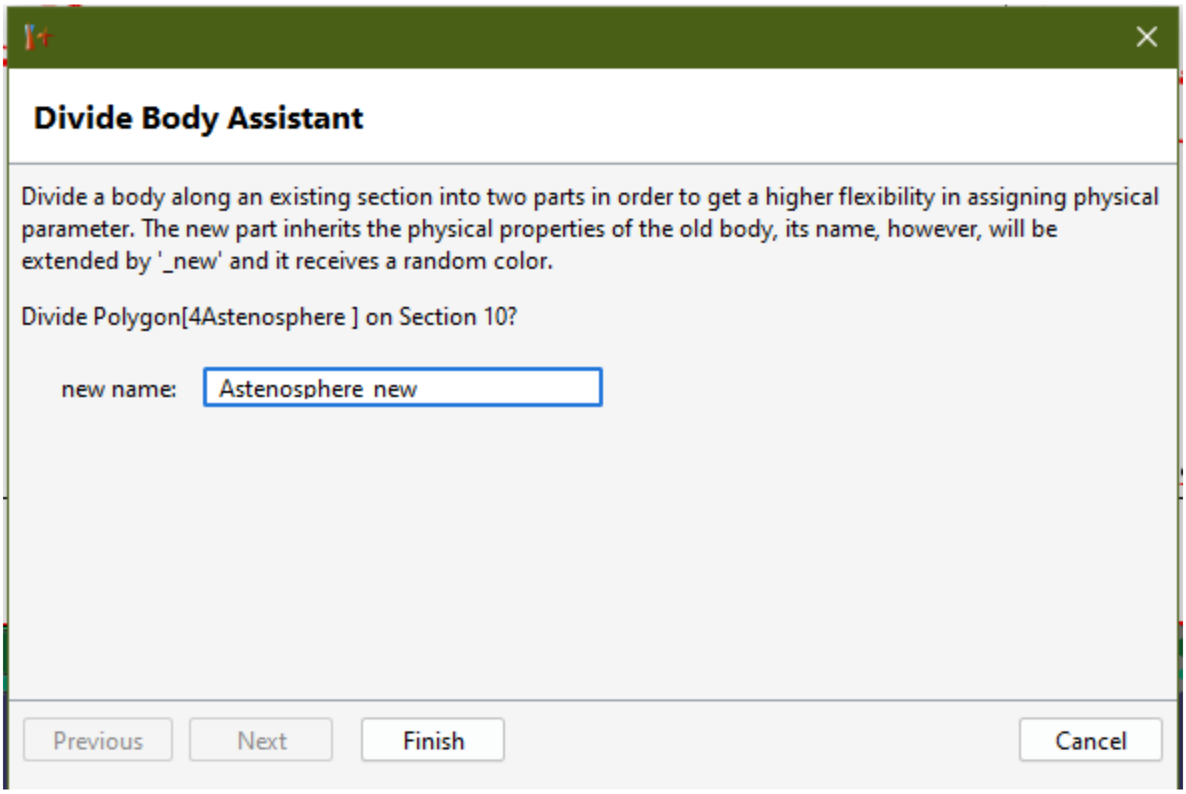


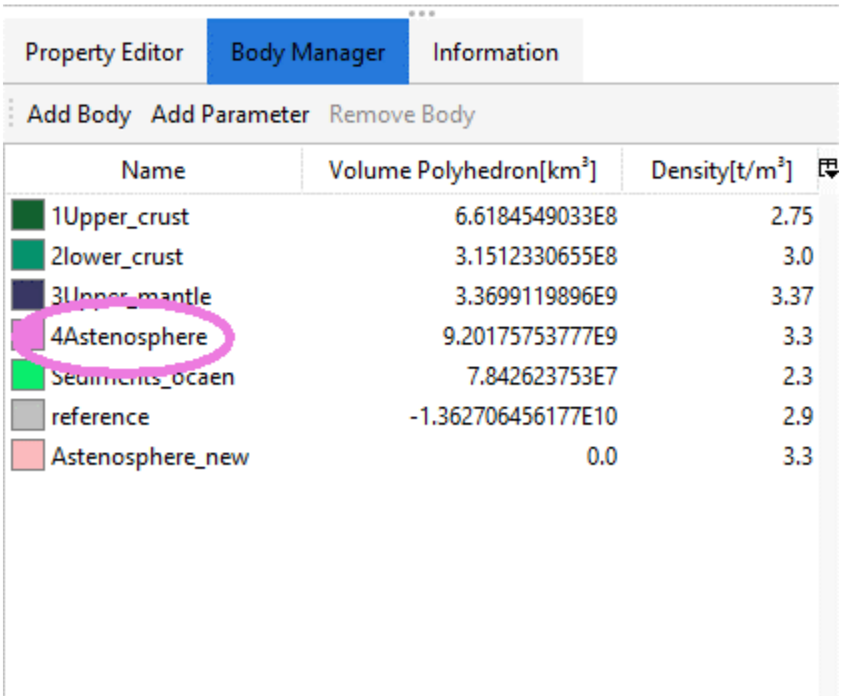
Click on the body to be divided (e.g. astenosphere) with the **right mouse button** and select "**divide body**".



The "**divide body assistant**" appears with the new name “Astenosphere new”.

Click "finish"

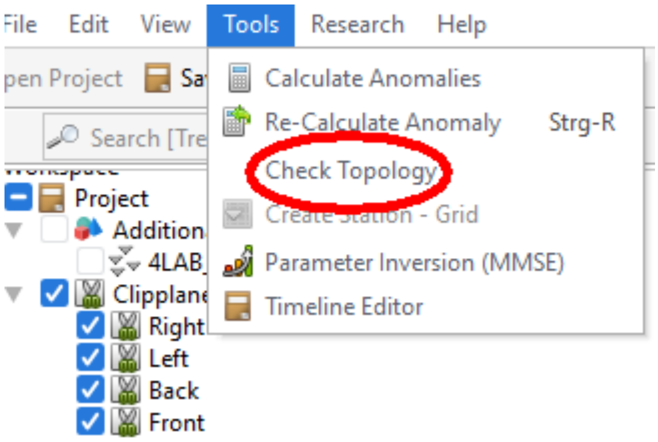




In the **PROPERTY EDITOR** (lower left window) the list of updated bodies with their properties appears (here “volume” and “density” are selected).

Note these important points:

(1) The newly inserted body (Astenosphere new) **still has the same density as the old one**. The color has been selected by the program and can be changed by the user (see section "Colors").
(2) Check the topology of the “new model”. Select Tools in the **TITLE BAR** and select “**Check Topology**”:

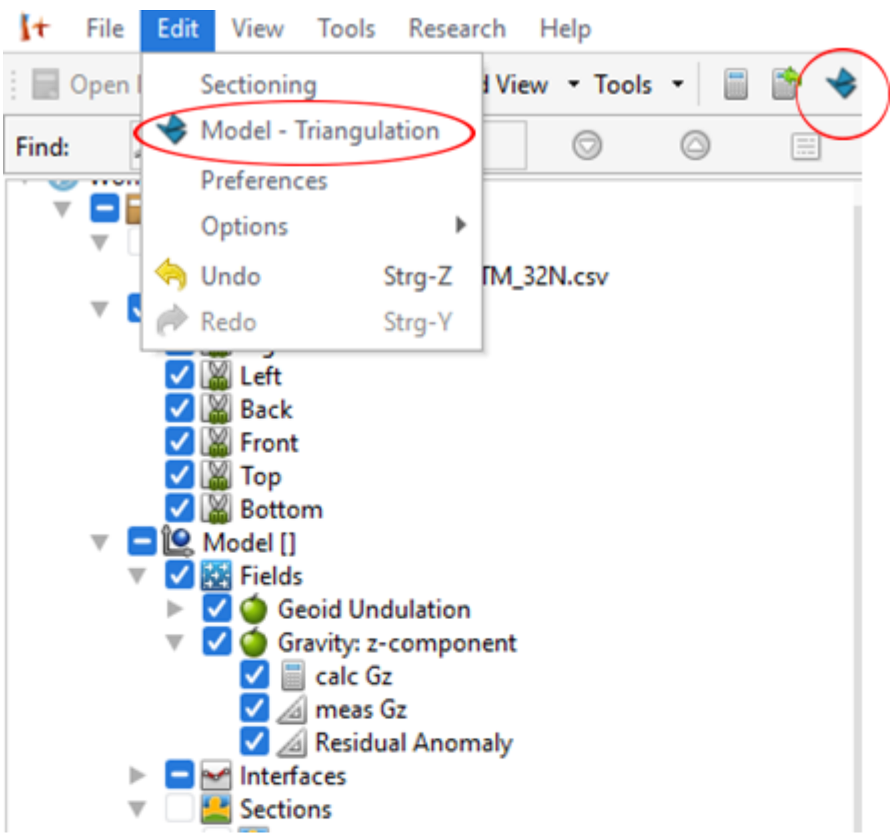


If now “error” is detected (normal case) continue with the next step. You may notice that the **PROGRESS BAR** (traffic light) indicates **red light**:

Explanation:

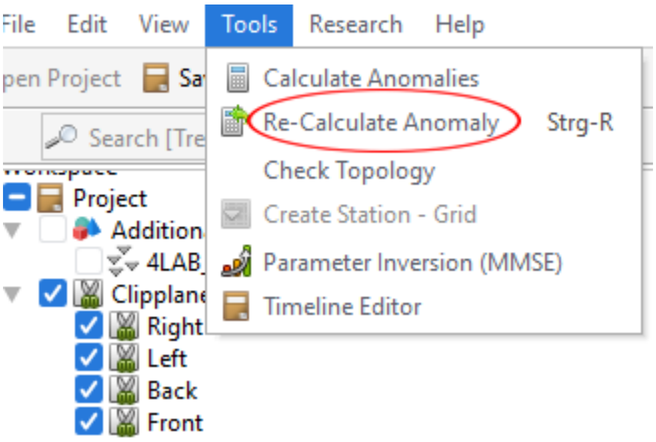
The model has been changed and both triangulation and modeled gravity are no longer correct. Start with:

(3) “Model – Triangulation” to the new model. Select **Edit** in the **TITLE BAR** and select “**Model-triangulation**”:



Alternatively, the  icon can be used for model triangulation. Go to the **TOOL BAR** line and select .

(4) Re-calculate the gravity of the "new model". Select **Tools** in the **TITLE BAR** and select "Re-calculate Anomaly":



… and the **PROGRESS BAR** (traffic light) indicates **green light.**

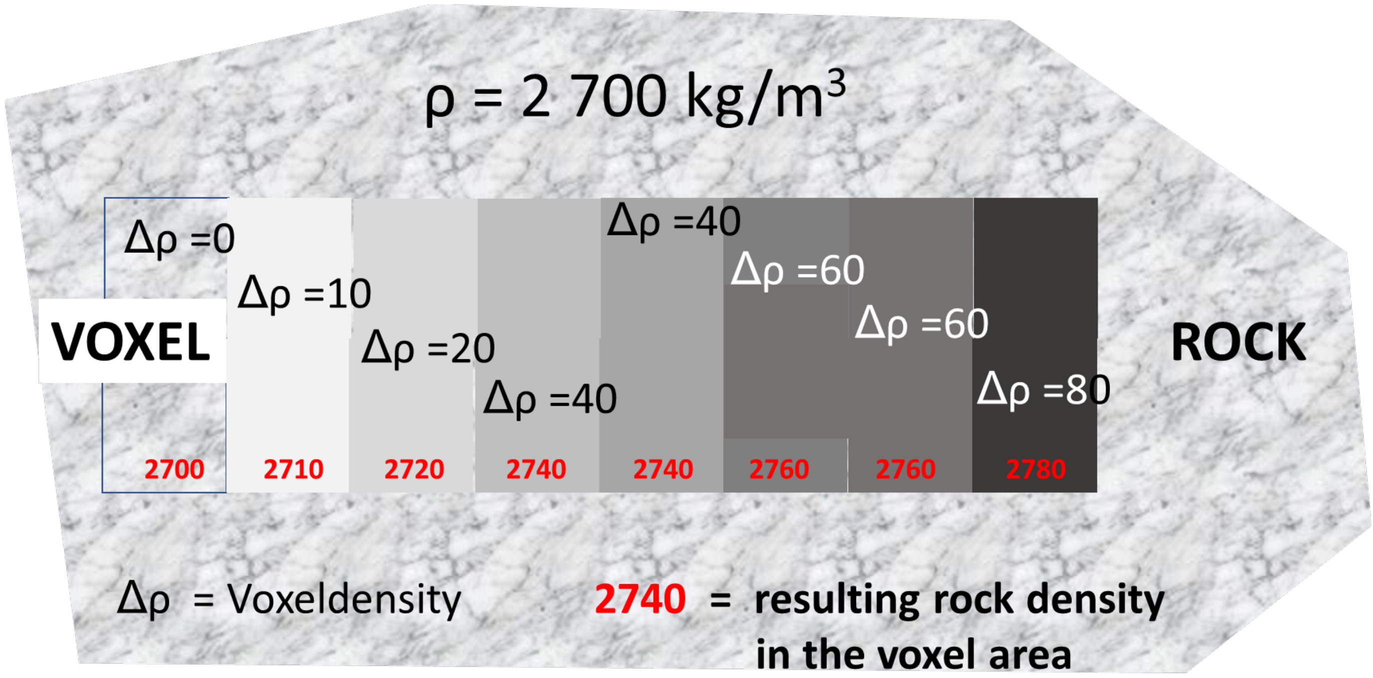
If necessary, change density of the new body by "**double click**" on the density value and insert a new value: PROPERTY EDITOR**

> Body manager > double click" on the density of the new body

**

2.11 Voxel Cube

The use of a voxel cube (density cube) also fits into the thematic environment of density changes. In **IGMAS+**, a voxel cube is a cube consisting of many sub cubes. The size of the cube as well as the size of the sub cubes can be specified by the user. For example, think of a velocity cube in 3D seismic. Quite analogously, the 3D density cube is used in **IGMAS+**. The densities of the cube overlay the densities of the polyhedra/rock bodies in the three-dimensional modeling space. A typical application would be to define a depth-depending or laterally changing density function to a sedimentary body, as shown in the figure **below**: the grey colors indicate varying densities for the underlying rock density.

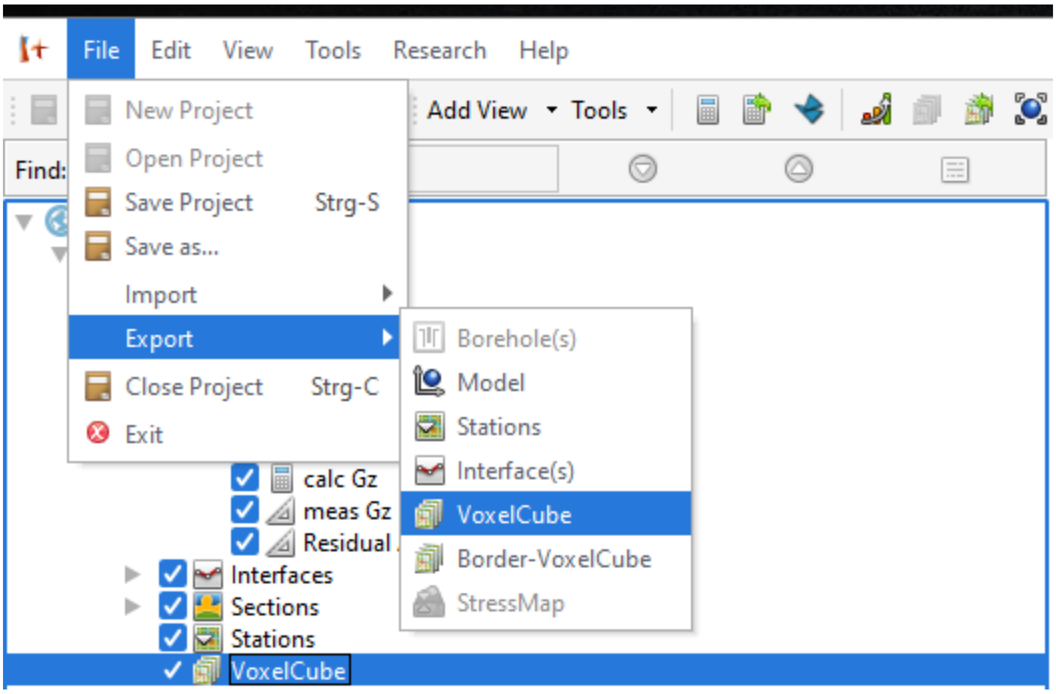


The voxel function may also be used to calculate the anomalies of an imported seismic velocity cube, applying a function for the conversion of velocities (normally Vp) into densities. If only the effect of an imported voxel cube has to be calculated, the simplest **IGMAS++** model, a cube, might be defined with constant density ρ = 0. Refer to the following figure for basic information and to the **IGMAS+ User Manual page 104**.

2.11.1 Import/export and delete a voxel cube

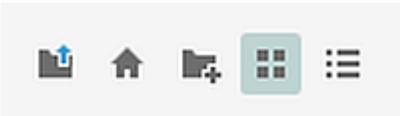
Note: only one voxel cube can be loaded in a current modeling. Any existing voxel cube must be deleted beforehand (see below: **Delete a voxel cube**).

Select **File** in the “**TITLE BAR**” > **click Import** > select **VoxelCube** > click with **left mouse button** on it  .



Navigate in the new “**Open**” window to the directory where the file with the voxel cube is stored.

IGMAS+ provides several possibilities for navigation by the small icons at the right side of the directory pull down menu:



These icons allow the user to do the following – goto/show:

- **Up on level -**
- **Home**
- **Create new folder**
- **List**

Details:

Of course, you can also navigate to the desired directory with the ▼ next to the folder name; see next figure.

The **“Open”** window provides important information and enable the user to check the input data:

Most important:
Does your voxel file have the extension “xxx.**vxo**”? If not, rename file before you continue!

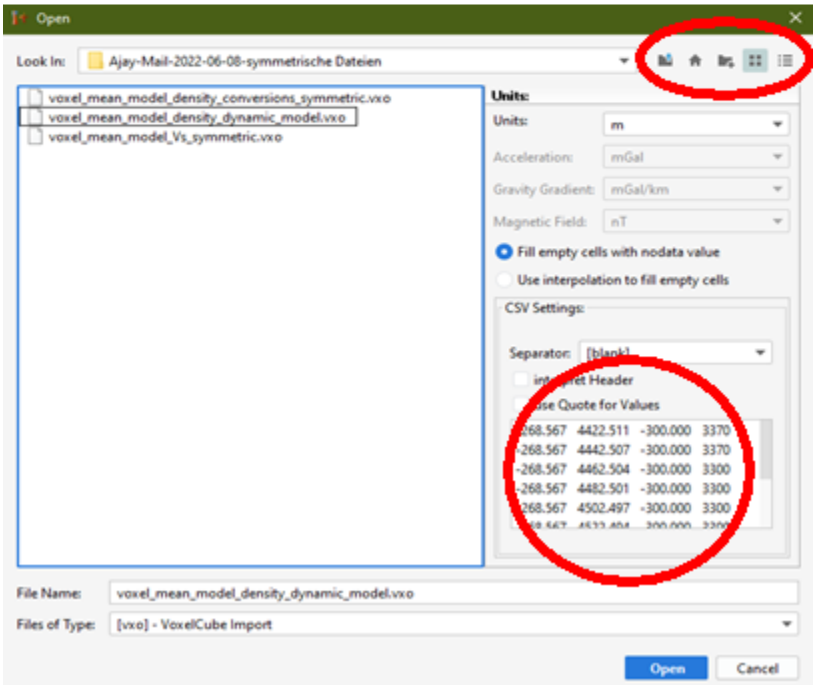
Units: Also important and often neglected
Ensure that units of voxel positions (x,y,z = depth) correspond to units of polyhedrons (either in meter or kilometers > or feet). Select units in the pull-down menu “units” on the upper right of the “Open” window.

Leave all other settings as they are: for “*Acceleration*” (gravity field), “*Gravity Gradient*” and/or *Magnetic Field*.

In the next menu item of the **OPEN** window, the user decides how to proceed with any unoccupied voxel cube elements. The default action is "*Fill empty cells with nodata value*". This means that **IGMAS+** inserts numbers with unrealistically high values (e.g. 1039) at the corresponding positions in the cube. If the alternative "*Use interpolation to fill empty cells*" is selected, corresponding values in the cube are interpolated.

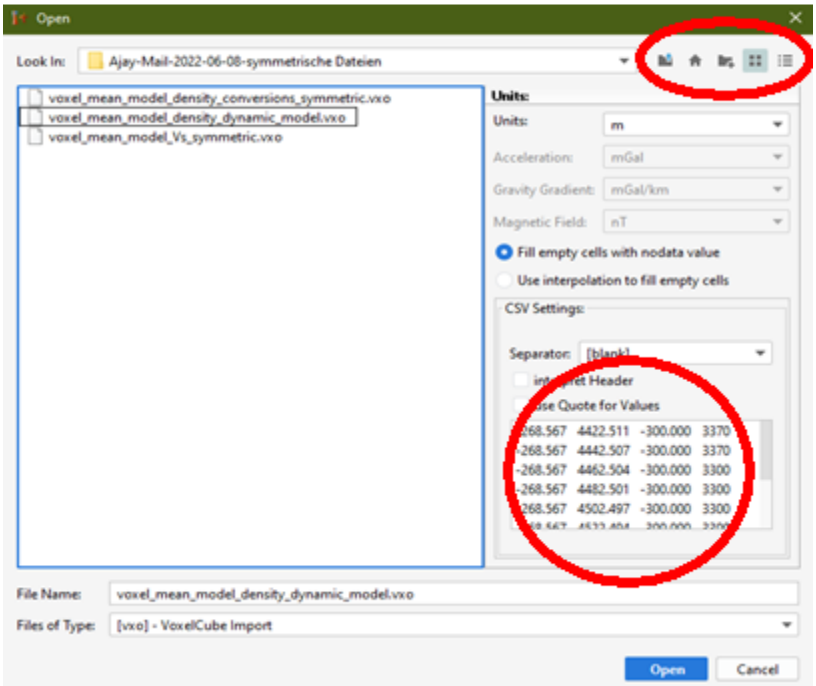
The use of a CSV setting is strongly suggested. The separation of the values is indicated with "*blank*" in the example. In the following it is still determined whether a header is placed ahead of the data of the voxel file ("*Interprete Header*") and/or whether the cube values are separated with quotes ("*use Quote for Values*").

A few lines of the voxel cube input is given as an example for visual inspection.



The columns contain from left to right: x-, y- and z-values (depths) of the voxel elements; **note the direction of Z: it is negative downwards** . The last column shows densities of voxel cube elements.

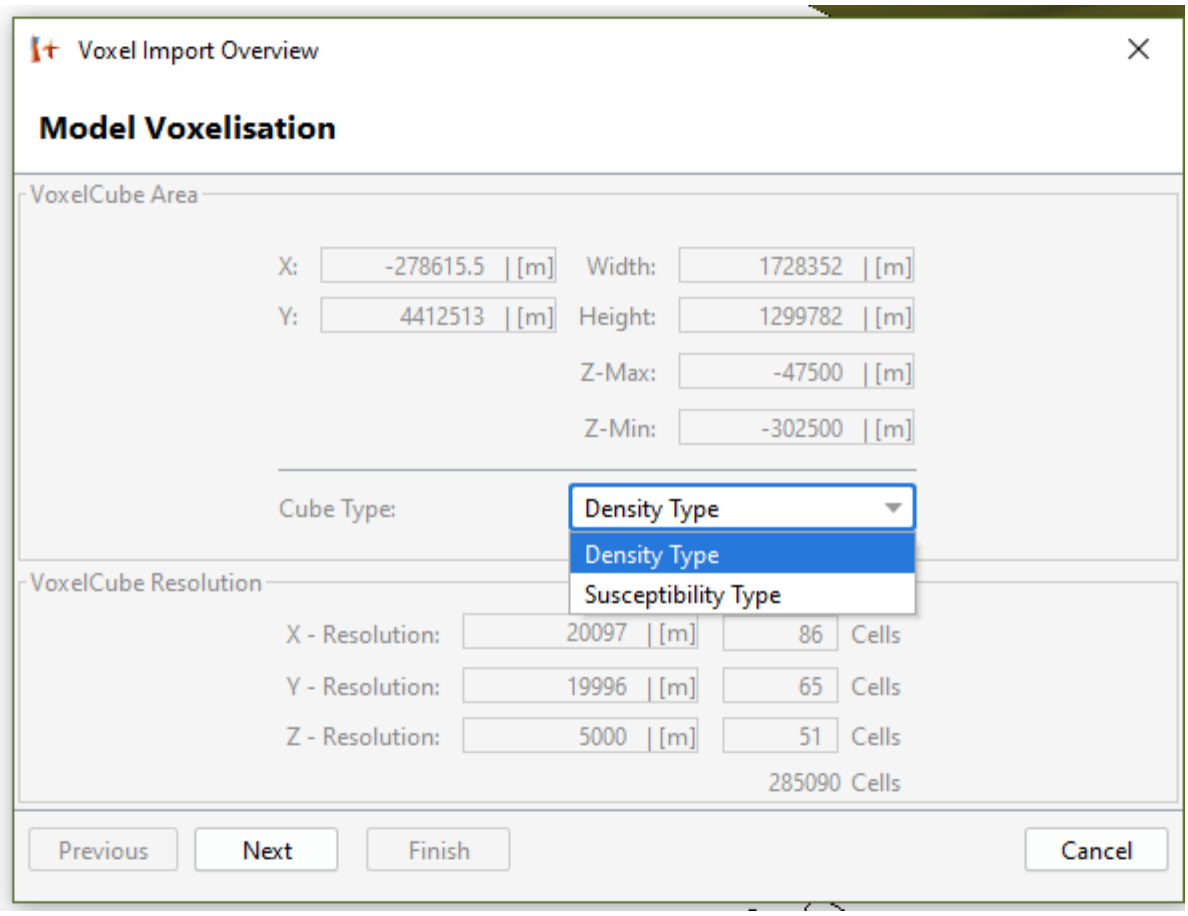
Here all lengths are given in km!!! **Click on "km"** to select the correct unit.



Otherwise, the data in the voxelcube file will be read in meters, with the consequence that the size of the voxelcube does not match the size of the density model: the voxelcube becomes too small by a factor of 1000 per unit length.

If all input boxes are filled in, click on **Open** with the **left mouse button**.

You get the window and sect “D**ensity type**” for gravity modelling and “**Susceptibility type**” for magnetic modelling; **click “Next”** :

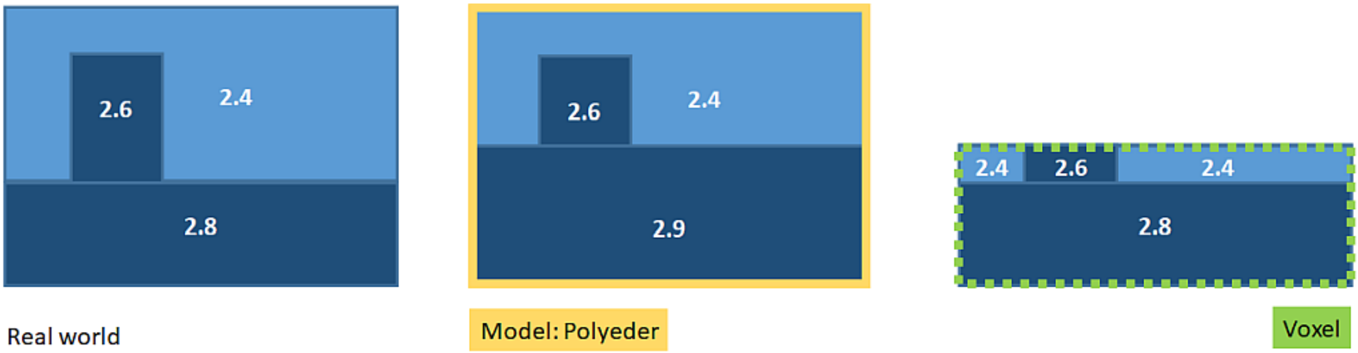


You get the window “**Model Voxellisation**” which contains further specifications regarding the use of the voxelcube in the context of combined Polyeder/Voxelcube - modeling. In the following INSET we explain the resulting possibilities for a correct 3D modeling.

INSET VOXELISATION

The **Voxelisation** is an important part of modeling with **IGMAS+** and is quite different from other software packages > for modeling potential fields. For example, it is possible to realize very elegantly 3D density changes with depth (for example by compaction). The V**oxelization** function allows the user to take over a seismic velocity cube 1:1, whose velocities (Vp) in densities are performed by means of self-created or predefined functions in the software.

We start with a **textbook example** which was elaborated by Sabine Schmidt (February 15, 2023):

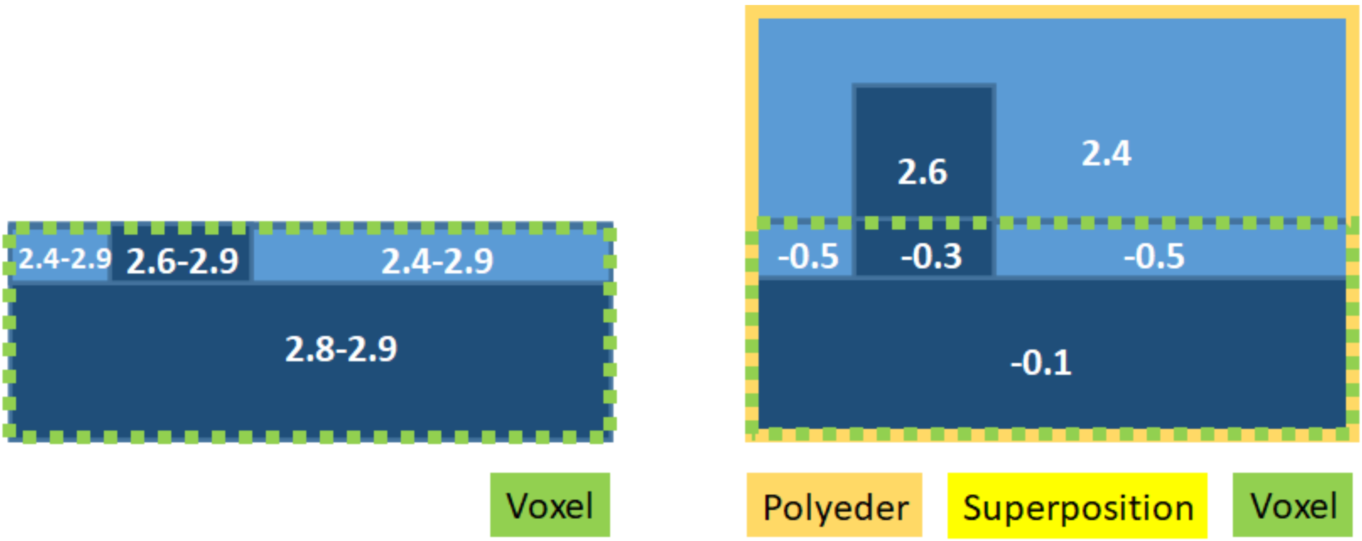


On the right side of the above figure, a density distribution is given in t/m3 (2.6 - 2.4 - 2.8). This corresponds to reality (blue, Real world). The middle figure shows the modeling conducted for this purpose (yellow, Model: Polyeder). We recognize that the density distribution with 2.9 was modeled at a lower depth - thus outlining a deviation from reality. This deviation can be corrected by blending a voxelcube model with the polyhedron model. This could have been determined from independent measurements and contains the densities 2.4 - 2.6 - 2.4 -2.8).

IGMAS+ allows the user to blend the voxelcube and polyhedron model with a special input function. The voxel function is called:

*** "cellvalue - density" ***

and corresponds to the import of a voxelcube with density differences, which, however, are determined by the software > independently of the user.

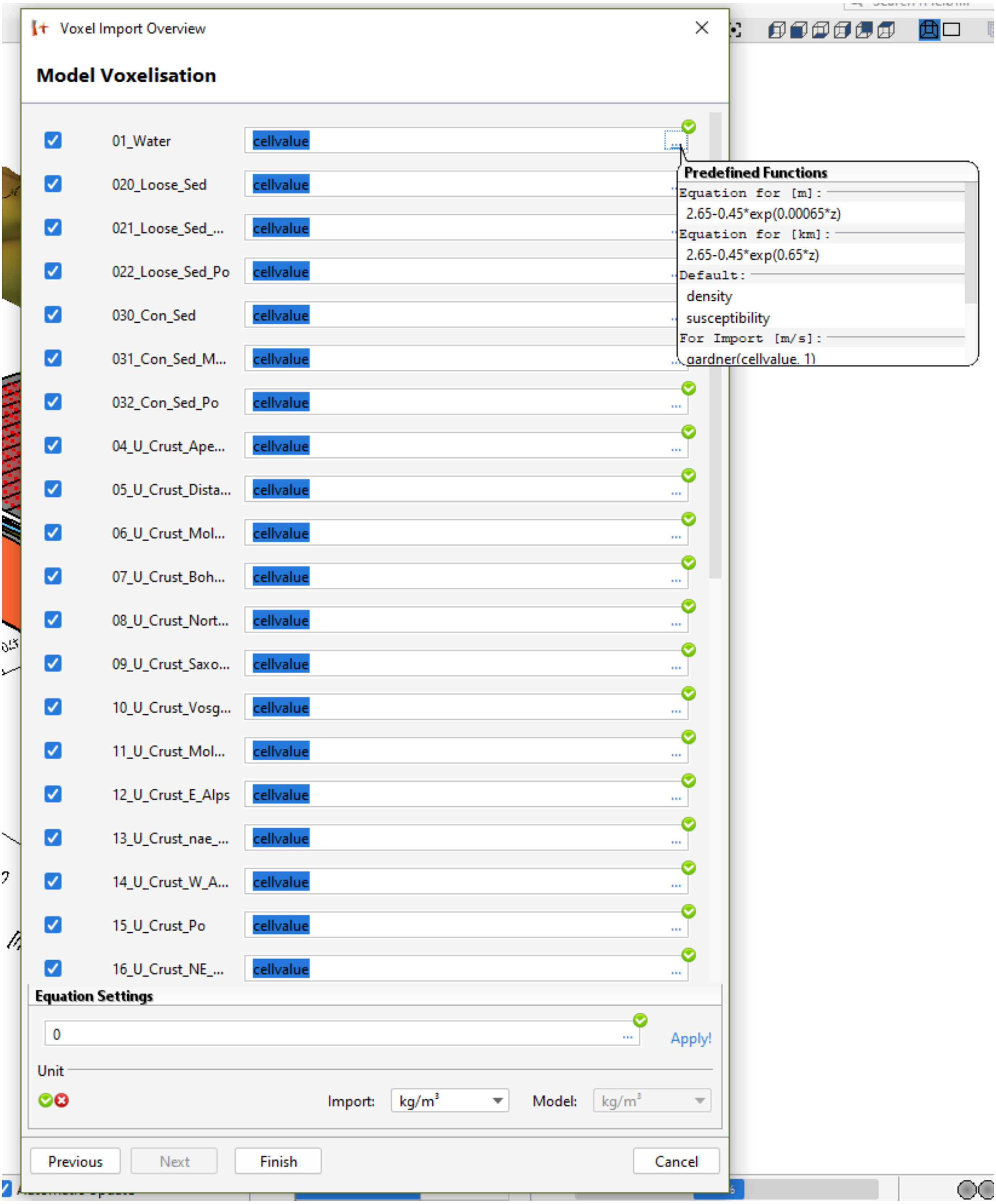


In the voxelcube domain, the "effective" densities are then obtained from the superposition of the polyhedron and voxelcube models: the left side shows the difference formation, the right side the superposition of both for the two models.

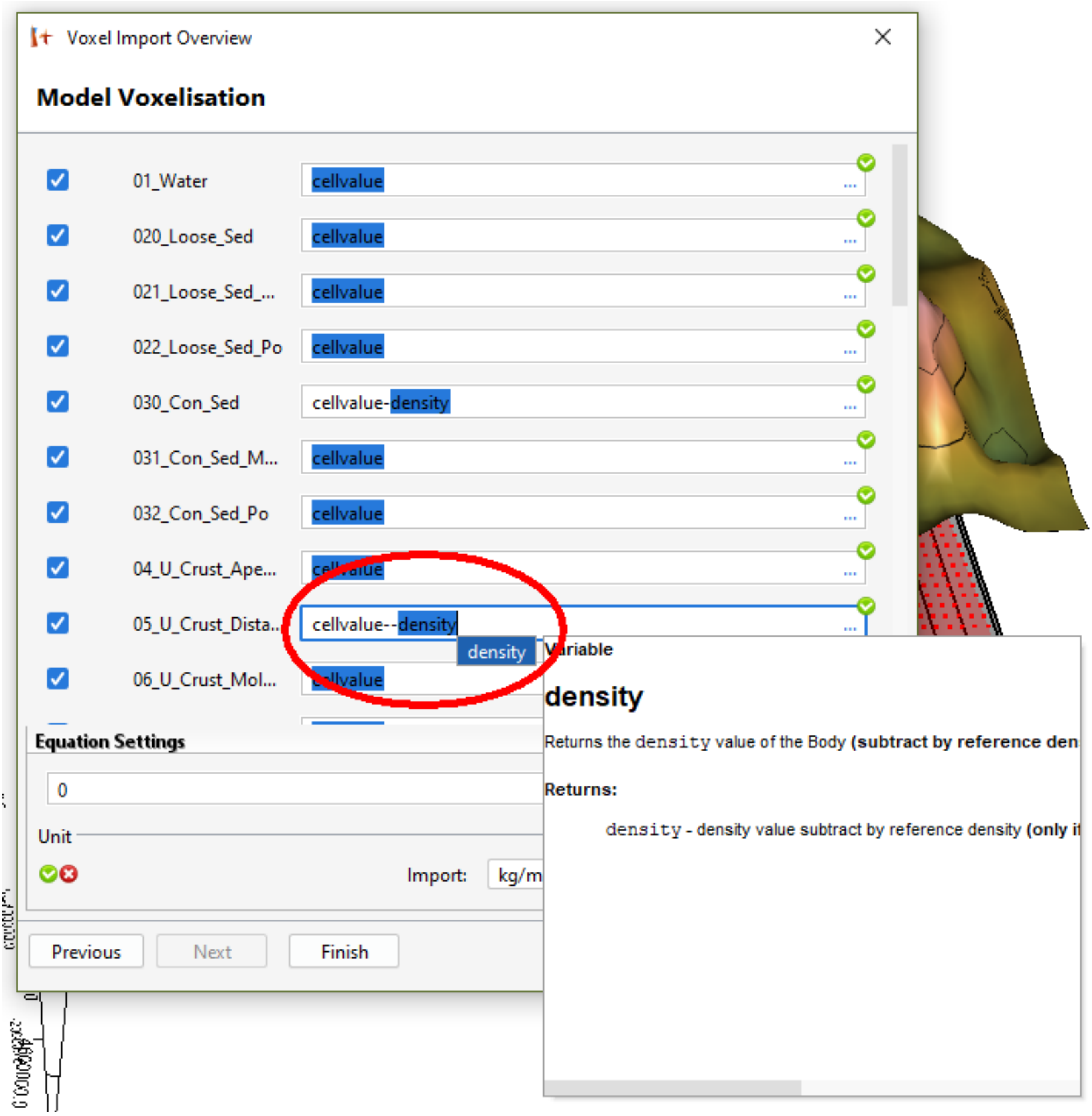
The superimposed density model has the same effect as the "real world" density model. We call this "hybrid modeling" and take advantage of the fact that the total density of all masses corresponds to the superposition principle. By dimensioning the voxel size, extremely fine tuning can be achieved within the 3D density model. The computation of millions of voxels is possible without lasting disturbance of the interactive processing or very long computation time.

Let's move back to the description of the voxelcube input (voxelization window).

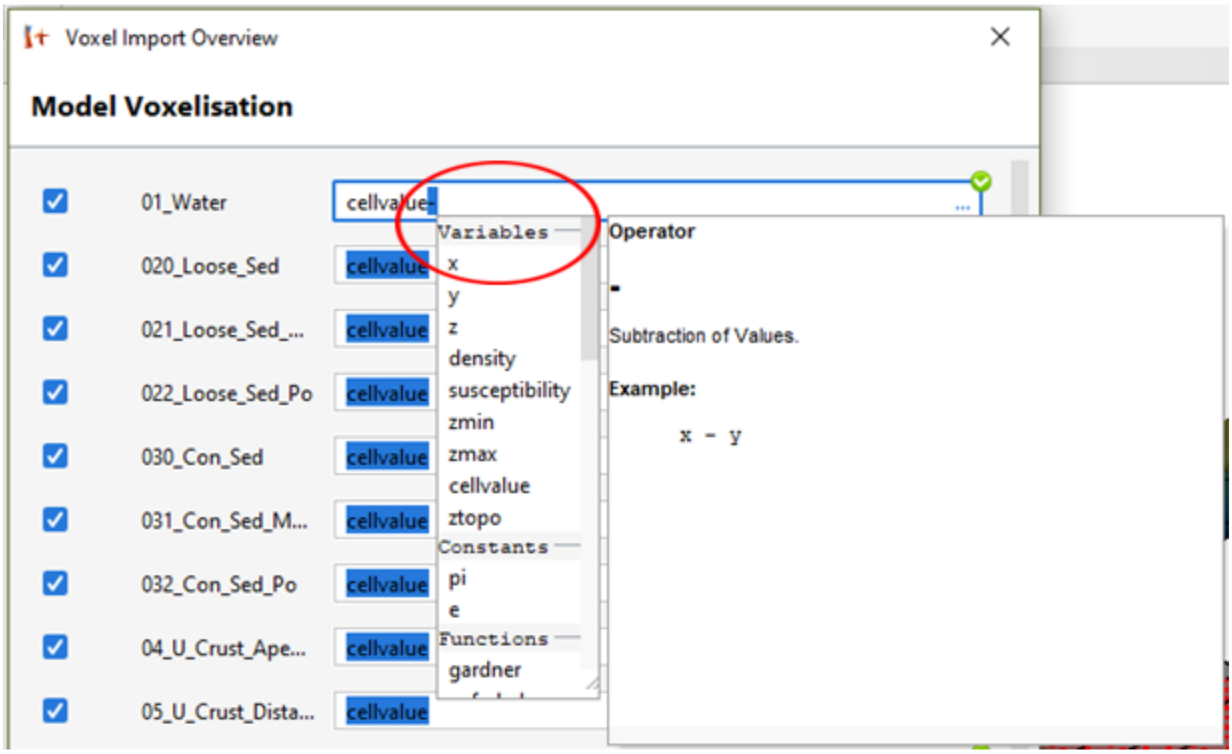
The window for Model Voxelisation



For all geological bodies, special procedures for the use of the voxel cube can be defined here. Of course, this is only the case where the voxelcube covers the polyhedra. If this is the case, minus density can be entered directly after "**cellvalue**"; cellvalue contains the density element of the voxelcube element:



When entering a function, the user is supported by operators, mathematical functions, and the definition of constants.

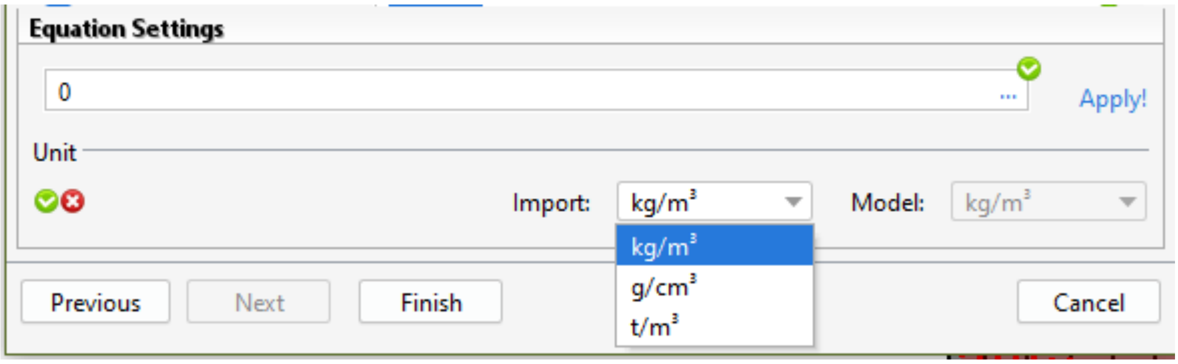


It is also possible to use pre-defined functions (to convert velocities into densities such as the **Gardener and/or Nafe & Drake - relations** . These are provided for dimensioning the model in "meters/second" or "kilometers/seconds" and are used for the conversion of seismic velocity models into density models. Click the three small dots.

It is also possible to formulate your own conversions and calculations using the instructions provided.

In the lower part of the voxelization window there are still three input possibilities to be explained:

(1) **Equation Settings**, (2) **Unit** and (3) 



(1) **Equation Settings** allows the definition of a voxel function for

A L L geological bodies in the model. This is only useful if the voxelcube really covers all bodies.

(2) **Unit**: Here the units for the voxelcube densities are defined. Attention: the definition must not be forgotten, otherwise the model gravity field will not be calculated correctly.

(3)  Here all those bodies can be hidden altogether (or switched on again), which are not covered by the voxelcube.

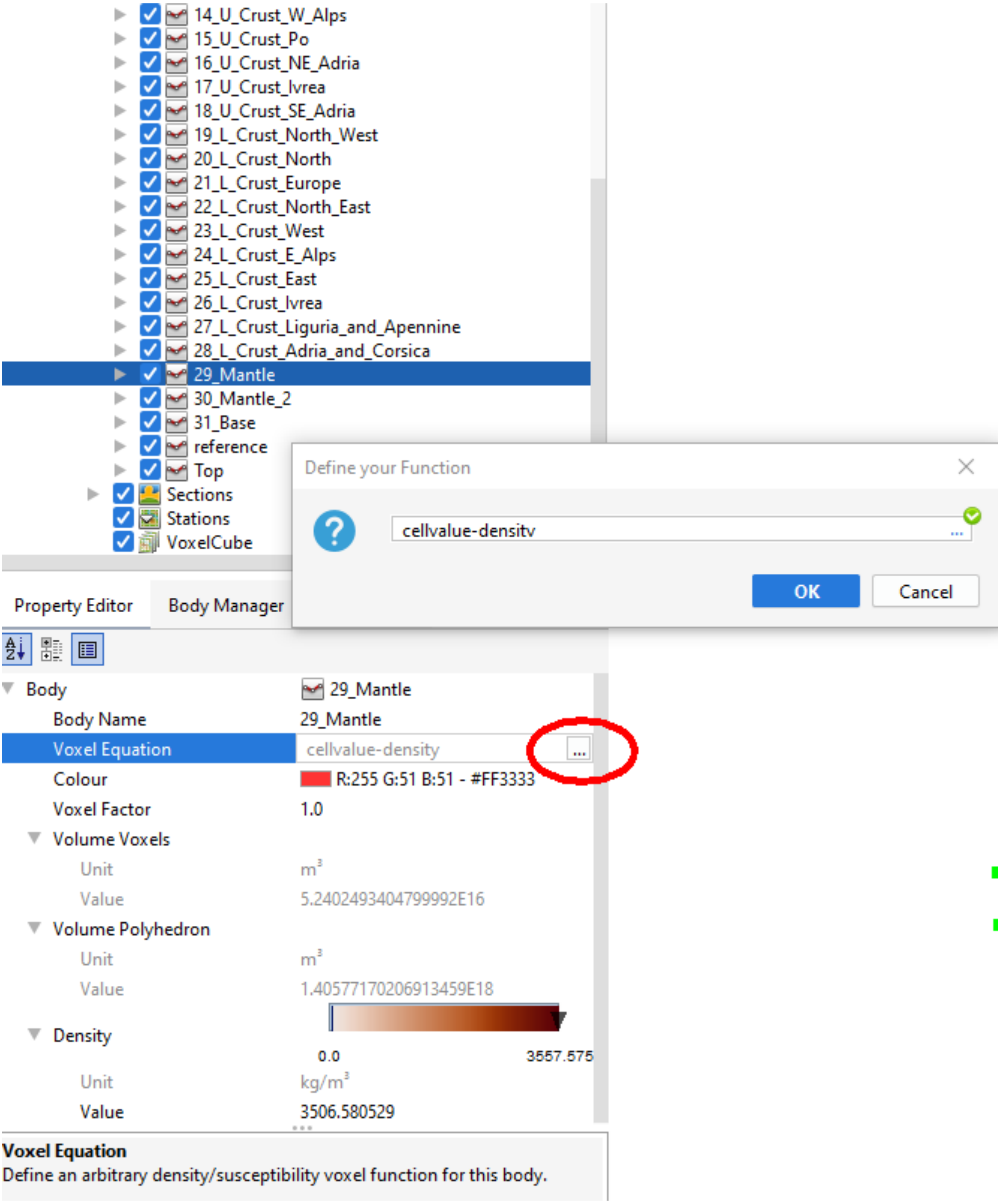
When all is defined**,** click **FINISH** 

2.11.2 Later changes of voxelcube functions

Regardless of the equation specified when importing the voxel (refer to the explanations before), the original cellvalue is always saved and can be changed manually for each body independently later.

Select in **Interfaces** of the **OBJECT TREE** the body whose the cellvalue function should be changed (29_Mantle in the example)

and click: 



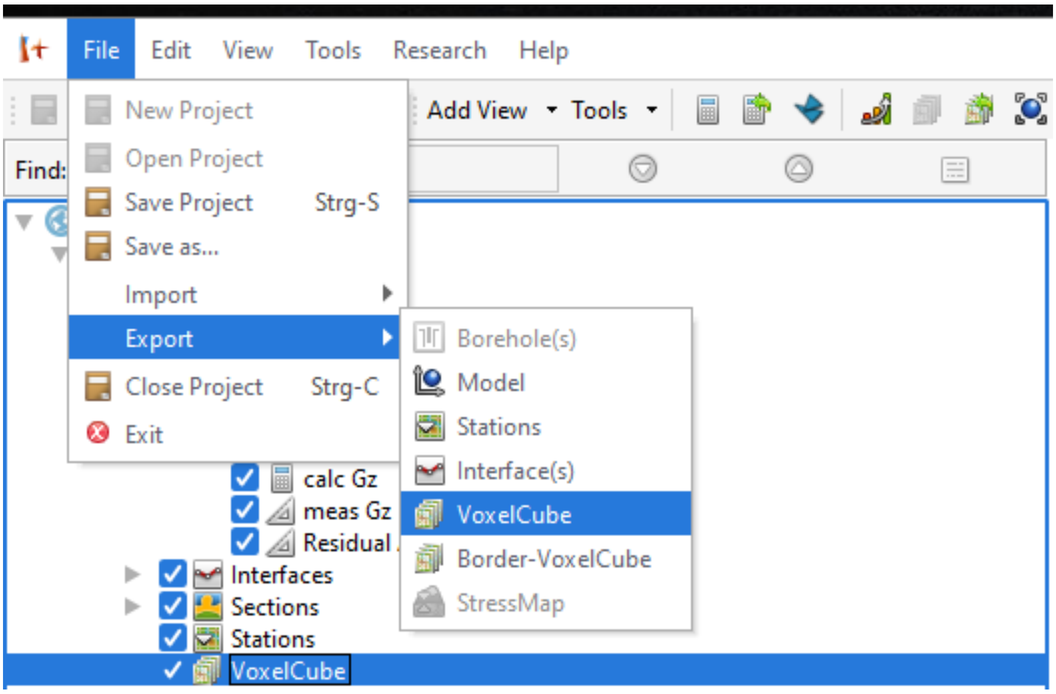
In the **PROPERTY EDITOR** body 29 is displayed with the

Body name

Voxel equation: cellvalue-density.
If the user will change this function, click on the three small dots and an other window for the new input will be opened. If you like, change cellvalue by the definition as before.

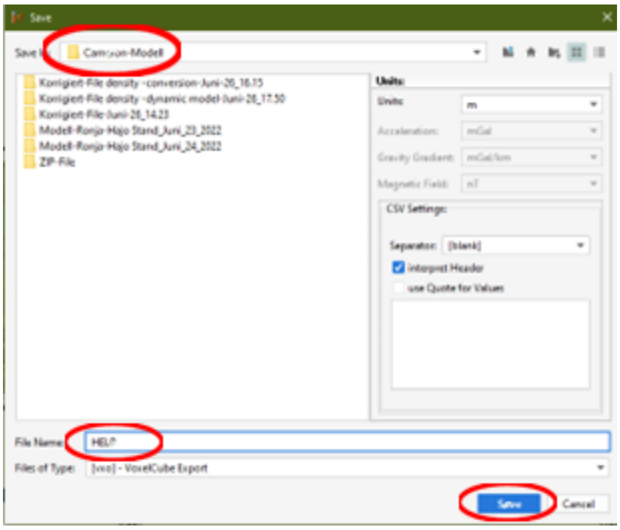
2.11.3 Export a voxel cube

Select **File** in the "**TITLE BAR**" > **click Export** > select **VoxelCube** > click with **left mouse button** on it  .



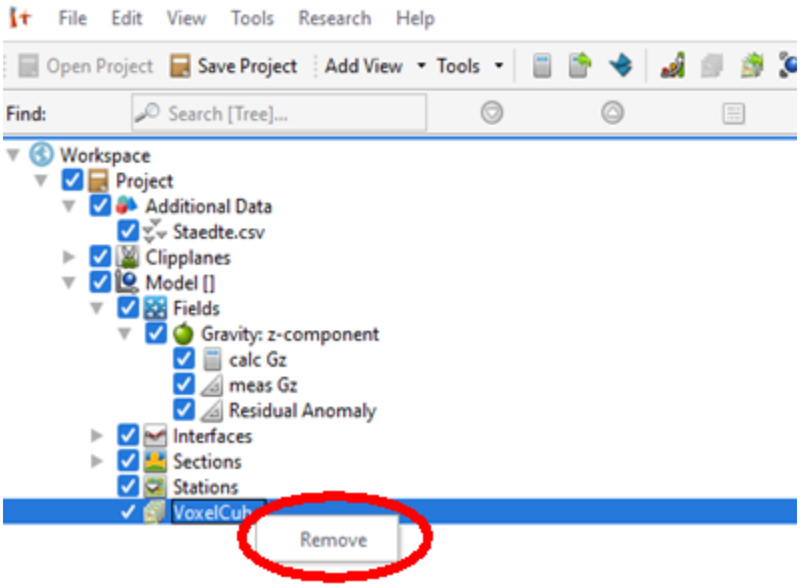
In the **Save** window select the folder where the voxel cube will be stored under the user specified file name. **Press** "save"


.



2.11.4 Delete a voxel cube

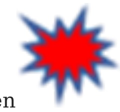
If you want to delete a voxel cube or replace it with a new (updated) one, **click** with the **right mouse button** on the letters of "VoxelCube" in the "**OBJECT TREE**": the "Remove" window opens. **Click** with the **left mouse button** in the window and the voxel cube will be deleted from the model visualization (Screen).

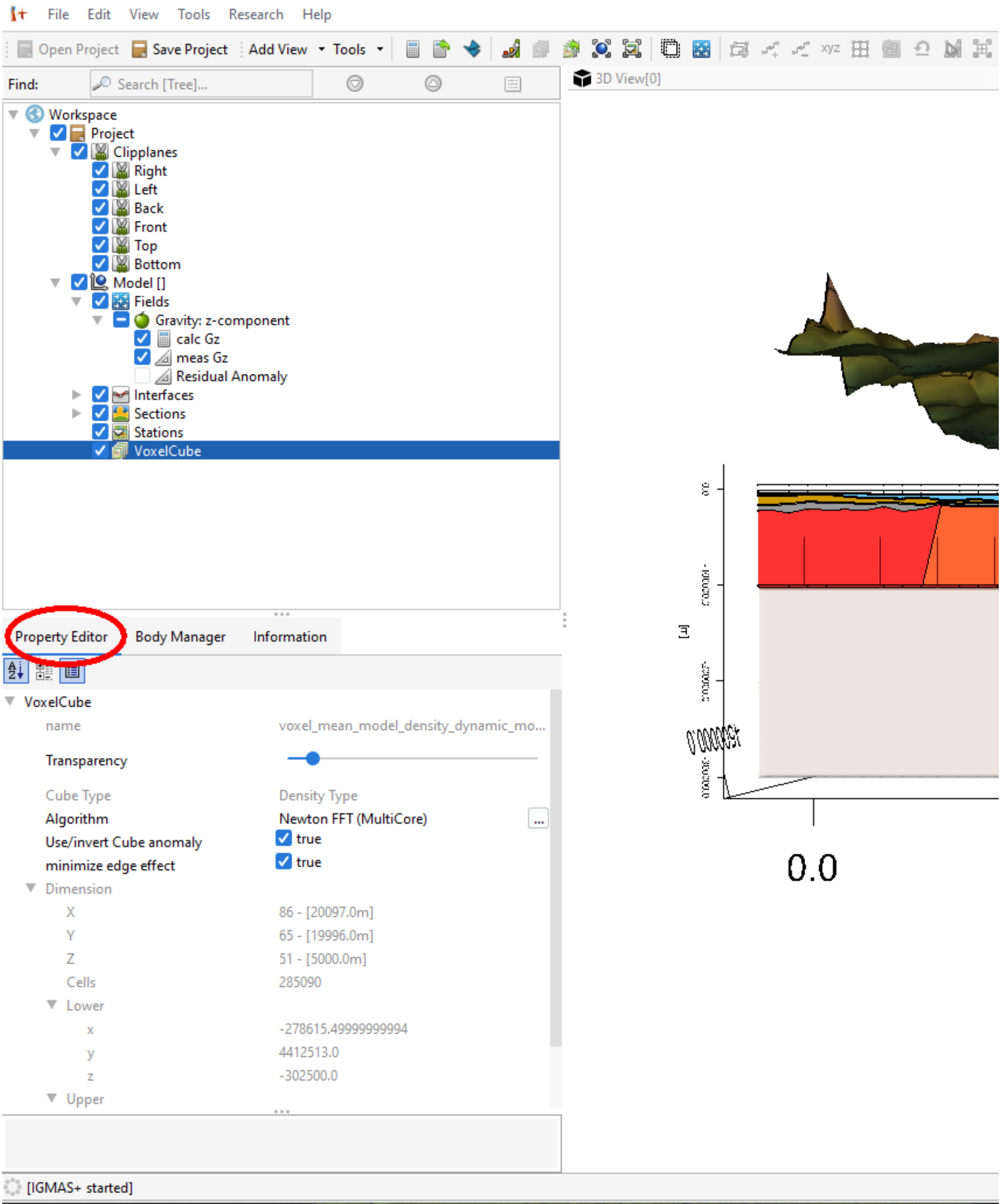


Important:

However, the gravity effect of the voxel cube is not yet eliminated from the overall gravity field of the model. The next section explains how to delete the gravity effect of the voxel cube from the modeled gravity field. See the section "**Use/invert Cube anomaly**" at the end.

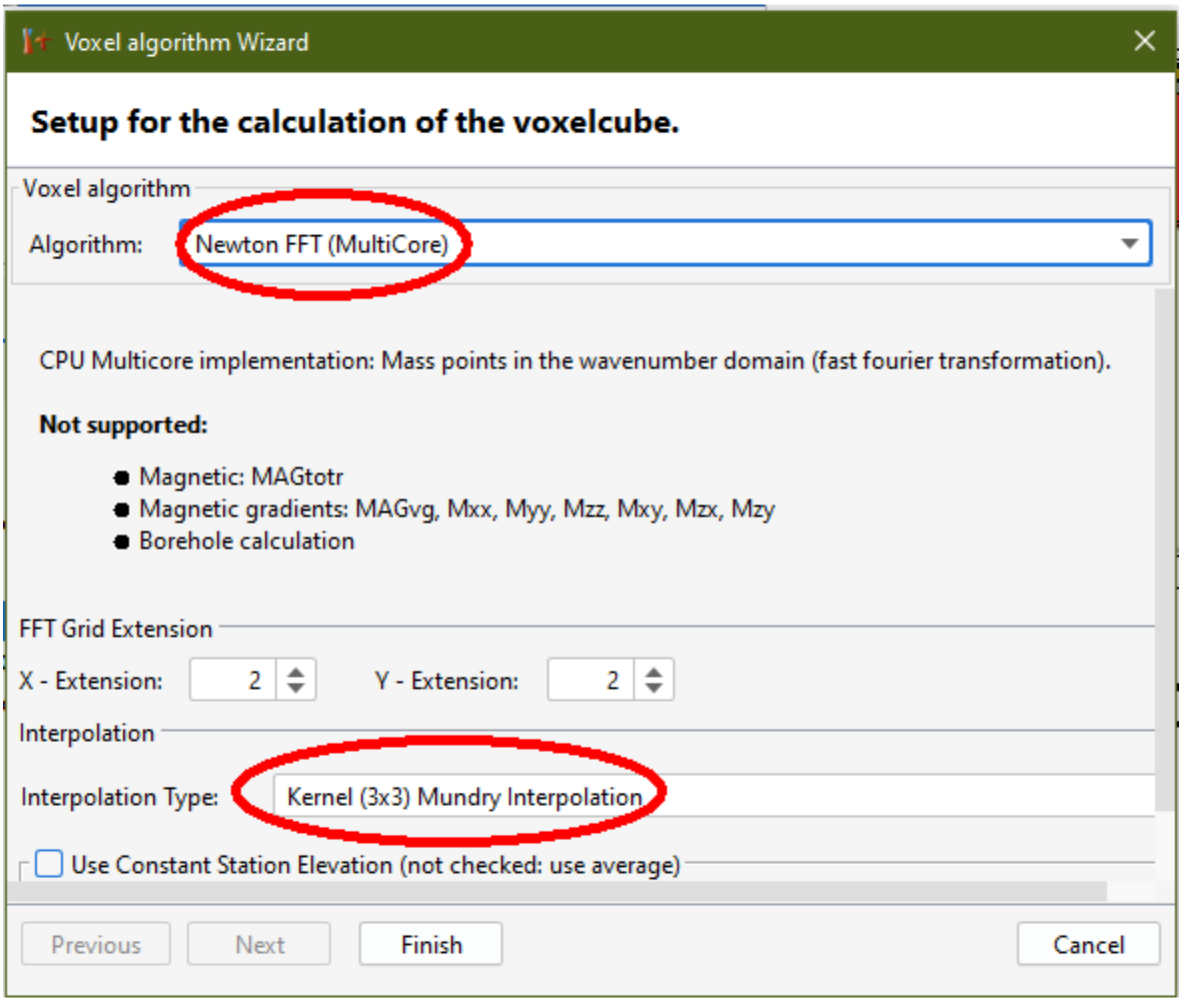
2.11.5 Voxel cube effects and their visualization

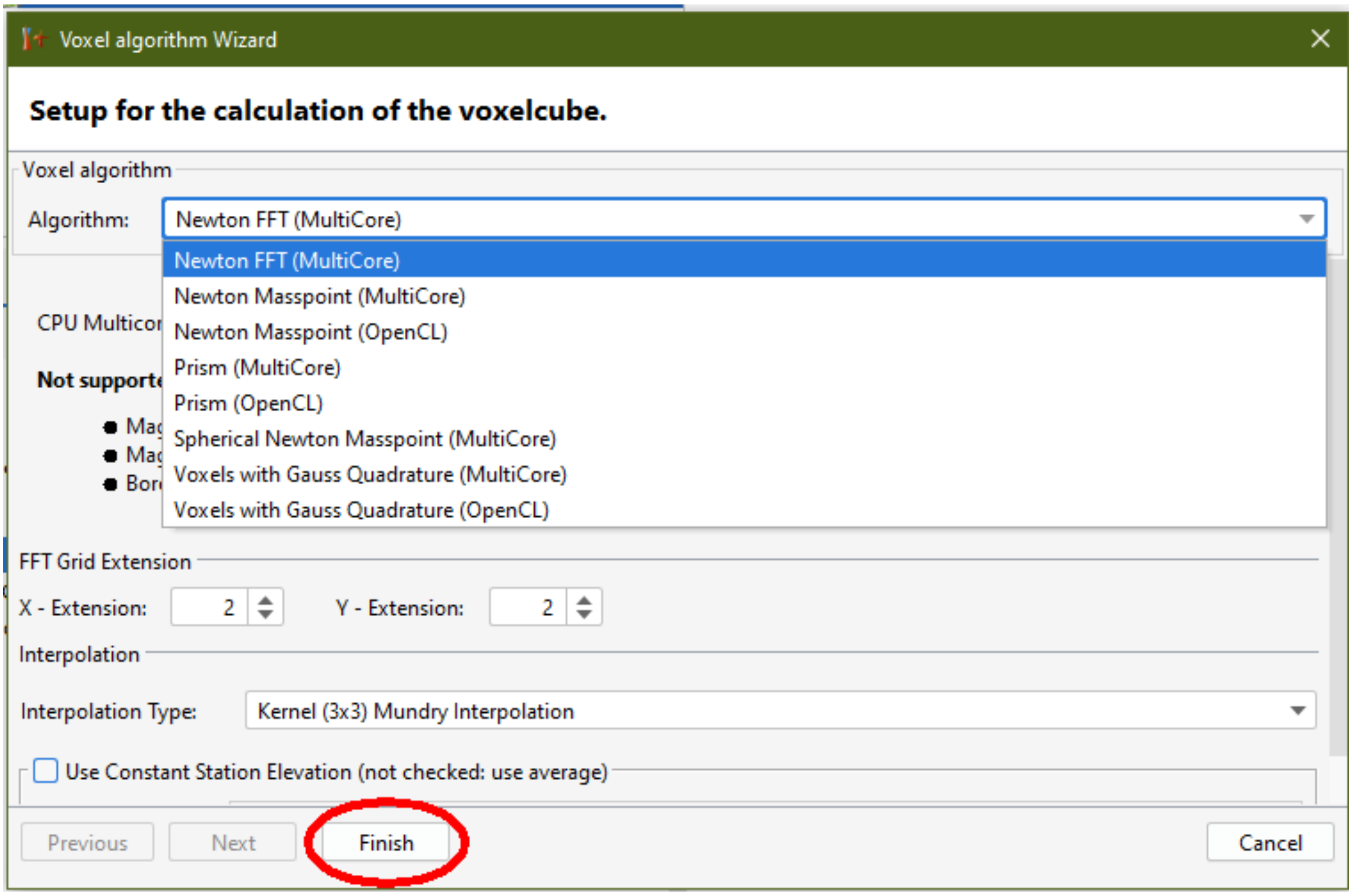
Information about the voxel cube can be obtained by clicking on "*VoxelCube*" in the **"OBJECT TREE"** and then activating the **PROPERTY EDITOR** (window at the bottom left). Click on VoxelCube then you see this screen  :


File Edit View Tools Research Help
Open Project Save Project Add View Tools
Find: Search [Tree]...
3D View[0]
Workspace
Project
Clipplanes
Right
Left
Back
Front
Top
Bottom
Model []
Fields
Gravity: z-component
calc Gz
meas Gz
Residual Anomaly
Interfaces
Sections
Stations
VoxelCube
Property Editor
Body Manager
Information
VoxelCube
name
voxel_mean_model_density_dynamic_mo...
Transparency
Cube Type
Density Type
Algorithm
Newton FFT (MultiCore)
Use/invert Cube anomaly
true
minimize edge effect
true
Dimension
X
86 - [20097.0m]
Y
65 - [19996.0m]
Z
51 - [5000.0m]
Cells
285090
Lower
x
-278615.49999999994
y
4412513.0
z
-302500.0
Upper
0.0
[IGMAS+ started]

The window shows the name of the used voxel field (in light grey). The "*Transparency*" slider controls the transparency of the voxel cube in the "**WORKSPACE WINDOW**".

- "*Cube Type*" indicates either a density or susceptibility voxel cube.
- "*Algorithm*" provides information on the calculation of voxel cube effects. In the example above a Newton Fast Fourier (Newton FFT) method is set calculating on multi cores. This is a fast and normal procedure. More information/other methos are available if you press the three small dots right of "*Algorithm*". The "*Voxel algorithm Wizard*" opens:





We read that a CPU multicore implementation is active and the (gravity) effects of mass points are calculated in the wave number domain (FFT).

Again, this is a fast method to calculate the gravity effects. Other methos are also available after clicking the pull-down menu “*Algorithm*”:

- Newton mass points calculation by OpenCL or
- Prism calculation (both multicore and OpenCL) or
- Gauss Quadrature (both multicore and OpenCL) even
- Spherical Newton mass point calculations are available if calculations are spherically done.

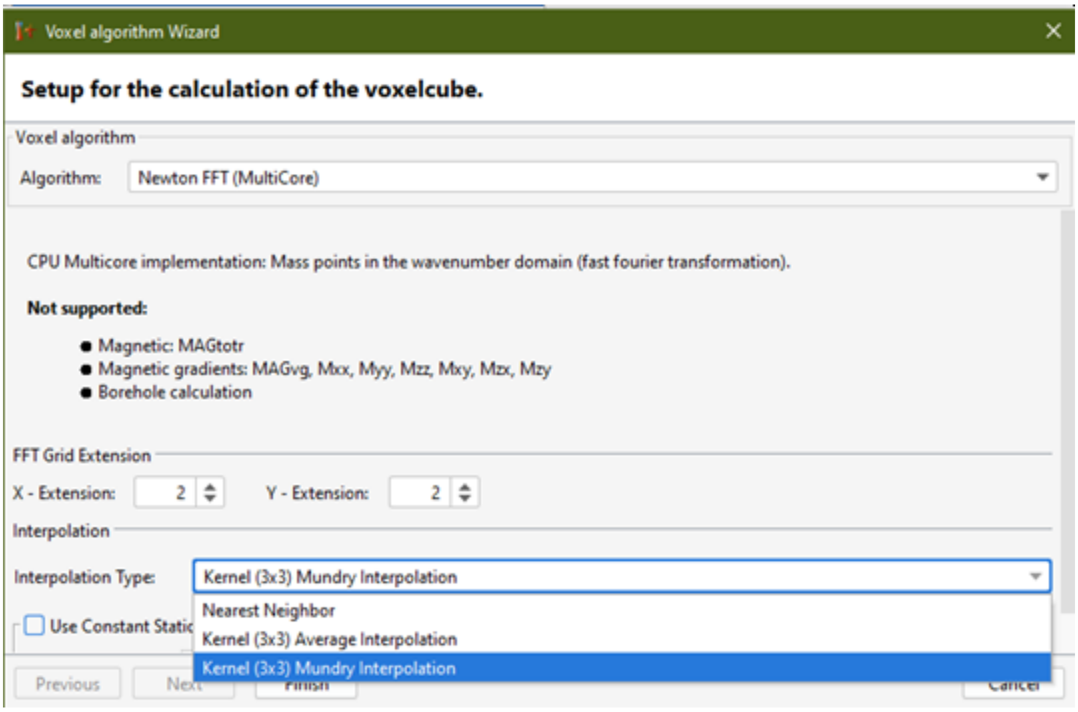
One can also **extend the FFT grid**.

If you click in the “Voxel algorithm Wizard” on the item “*Interpolation Type*” (Refer to the last image, left side) the types of interpolation are listed. An interpolation is necessary to transfer the calculated values at the FFT nodes to the measuring stations.

There are three methods to choose from:

- Kernel (3x3) Mundry interpolation,
- Nearest neighbor and
- Kernel (3x3) average interpolation.

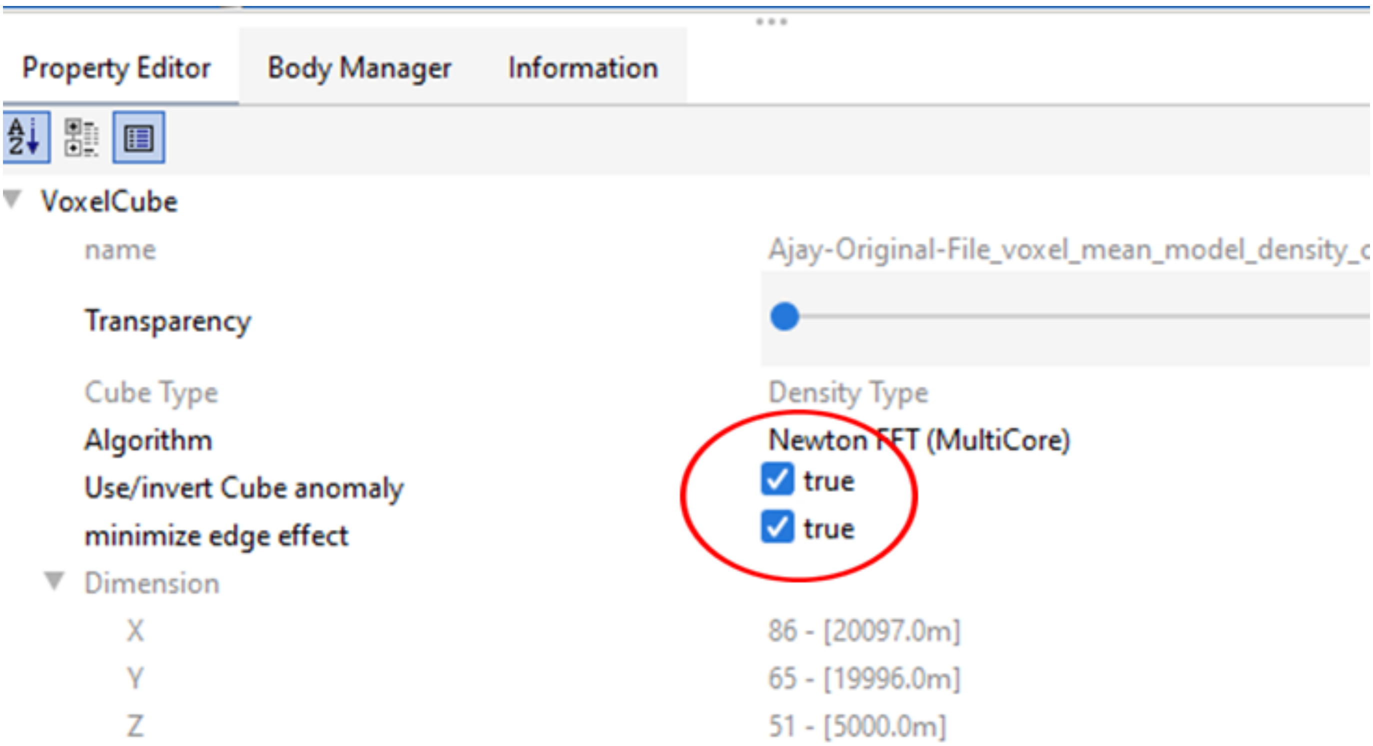
Kernel (3x3) Mundry interpolation is robust and reliable.



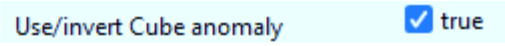
If stations are located in a constant height, click on “Use Constant Station Elevation”.

Click “Finish”

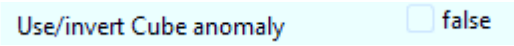
Activate “**VoxelCube**” and go to the “**PROPERTY EDITOR**”



The item “**Use/invert Cube anomaly**” in the **PROPERTY EDITOR** plays an important role. If it is “true”:



the gravity effects of the voxel cube **and** the polyhedrons are calculated at all stations; if it is “false”:



And the gravity of the polyhedrons will be calculated **without** the effect of the voxel file.

2.12 Modify model parameters (densities/susceptibilities)

We already knew this action when it came to changing the density/susceptibility of a new body (see also " Split a body/ polyhedron on a specific vertical cross section ").

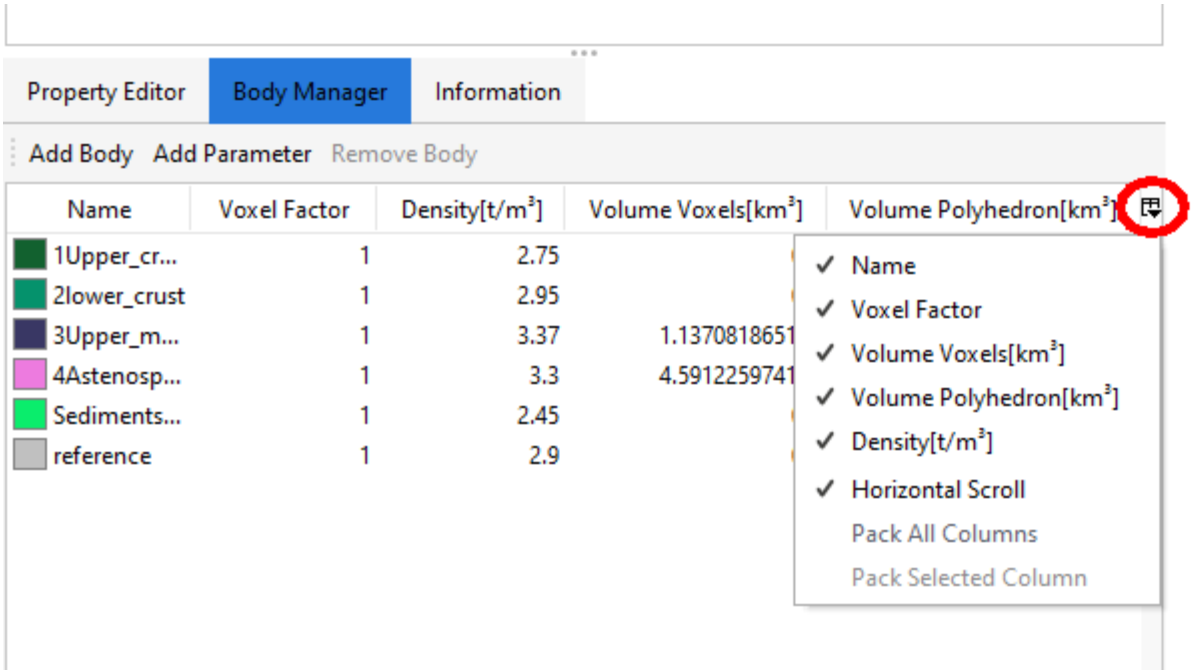
2.12.1 Change densities/susceptibilities

Select in the window of **BODY MANAGER / PROPERTY Editor** (bottom left) and select **Body manager.**

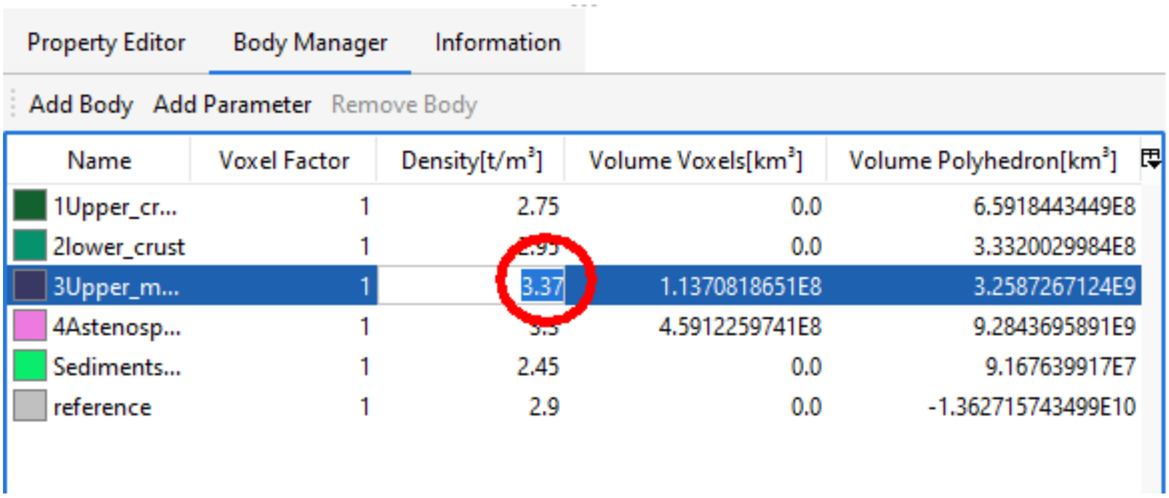
The names of the existing model bodies are displayed with their selected colors. Then follow from left to right "voxel factor", "density [t/m^3]", "volume voxels [km^3]" and "volume polyhedron [km]". What of this information is displayed, the user can specify

by clicking the small  in the right corner.

The various parameters can be changed in their horizontal position: Click with the **left mouse button** on the parameter to be moved and **drag it** to the desired position with the **mouse button** lowered.



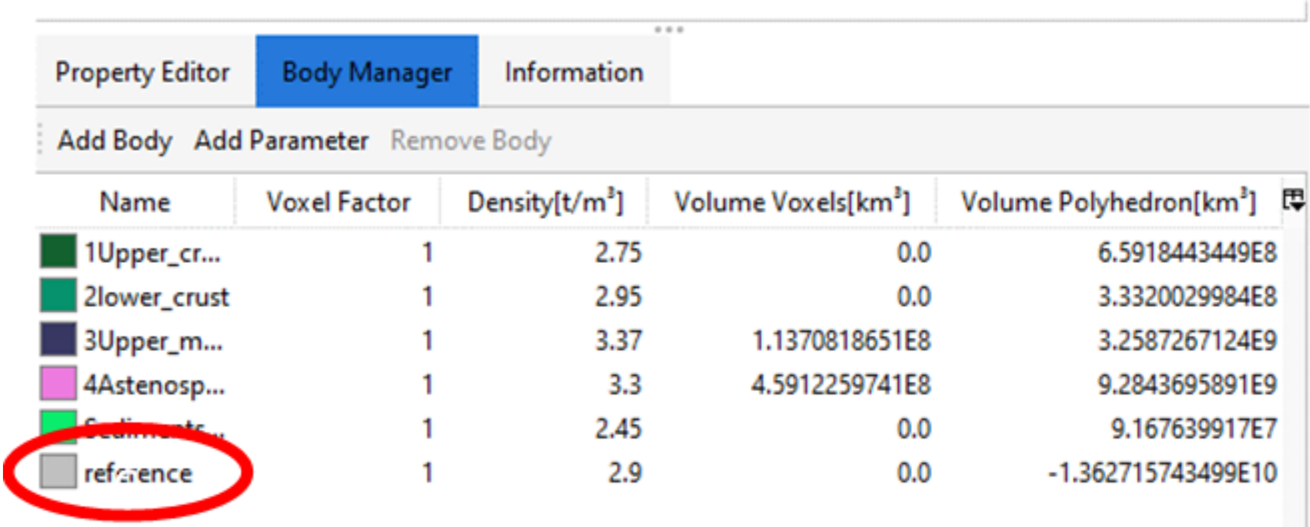
Double left mouse click  on the body (here upper mantle) where the density/susceptibility is to be changed and type in the new density alpha-numerically.



Name	Voxel Factor	Density[t/m³]	Volume Voxels[km³]	Volume Polyhedron[km³]
1Upper_cr...	1	2.75	0.0	6.5918443449E8
2lower_crust	1	2.95	0.0	3.3320029984E8
3Upper_m...	1	3.37	1.1370818651E8	3.2587267124E9
4Astenosp...	1	3.3	4.5912259741E8	9.2843695891E9
Sediments...	1	2.45	0.0	9.167639917E7
reference	1	2.9	0.0	-1.362715743499E10

Note: The resulting change in model gravity is displayed immediately, that is, the density change is performed automatically by the program.

The definition of „**reference density**" is import because it minimizes the edge effect" of the model. Always set the reference density so that the edge effect is a minimum! **Try this out on your model.**



Name	Voxel Factor	Density[t/m³]	Volume Voxels[km³]	Volume Polyhedron[km³]
1Upper_cr...	1	2.75	0.0	6.5918443449E8
2lower_crust	1	2.95	0.0	3.3320029984E8
3Upper_m...	1	3.37	1.1370818651E8	3.2587267124E9
4Astenosp...	1	3.3	4.5912259741E8	9.2843695891E9
Sediments...	1	2.45	0.0	9.167639917E7
reference	1	2.9	0.0	-1.362715743499E10

2.13 Density Inversion

Besides the possibility to change densities directly by the user, **IGMAS+** also offers the possibility of an automatic calculation (inversion).

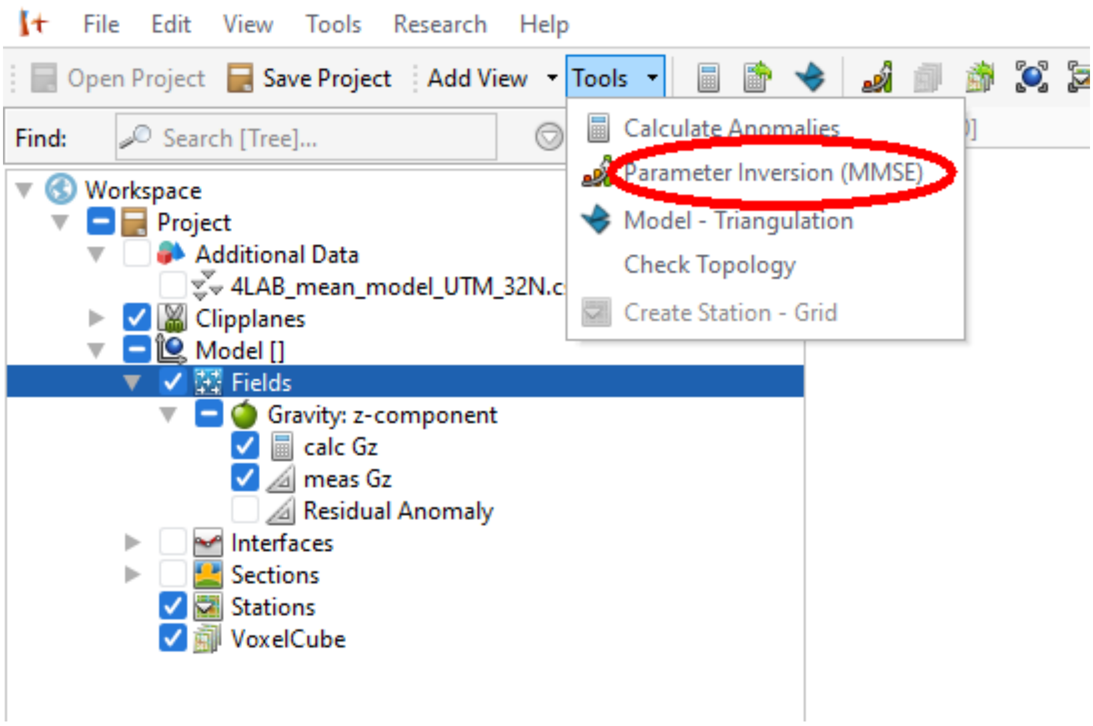
ATTENTION: the inversion does not make sense if all or very many densities are to be changed in a model. The system of equations would then have too many parameters, is overdetermined and the result is meaningless. You have to try it out! One or two densities should be allowed for an inversion (out of about 10 model densities).

The **MMSE method** is used in **IGMAS+**. MMSE stands for "Minimum Mean Square Error" and utilizes the mean square approach and Gaussian random variables within a statistical framework.

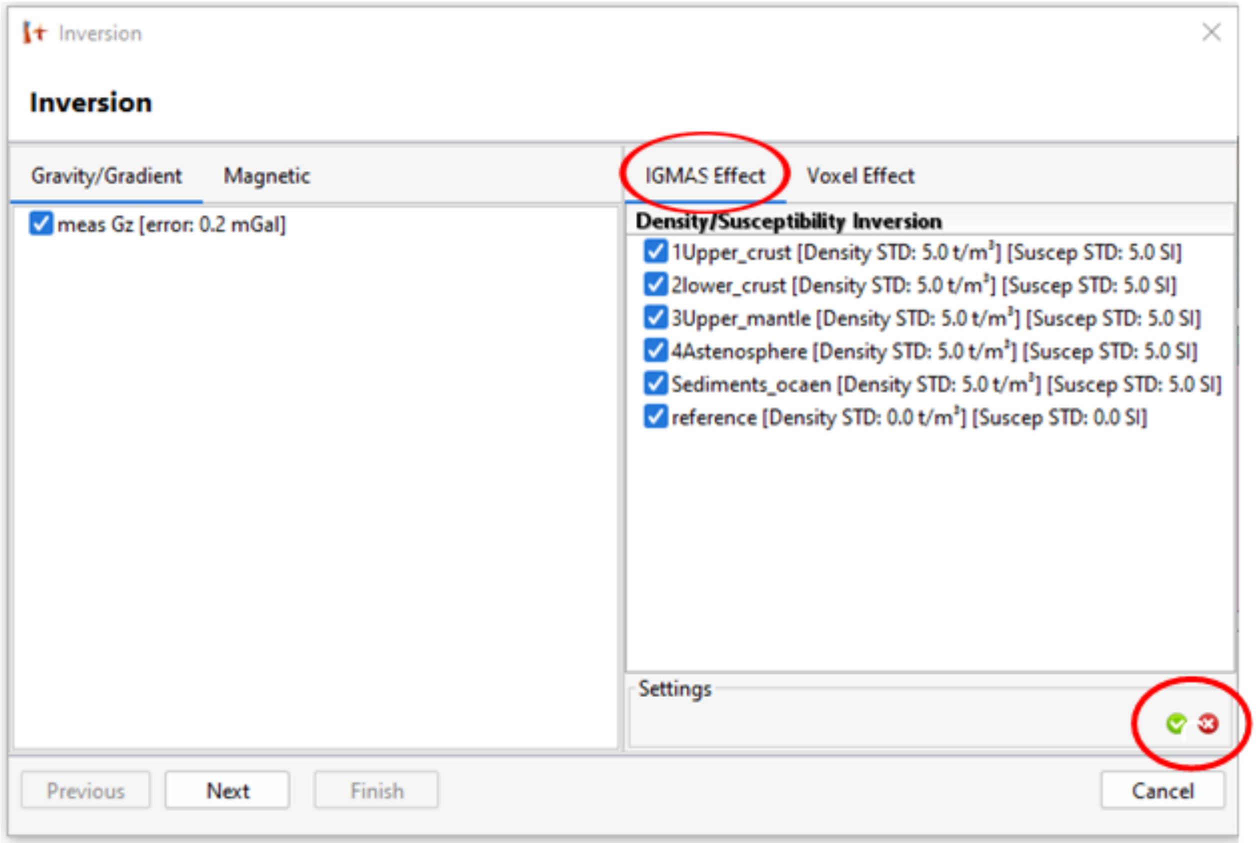
(Refer e.g. to: *C. Haase, Dissertation, Uni Kiel, 2014:*

https://macau.uni-kiel.de/servlets/MCRFileNodeServlet/dissertation_derivate_00005626/diss_haase_2014.pdf)

Select in the **TITLE BAR "Tools"** among other important program activities – we already know **–** klick on **"Parameter inversion (MMSE)**. Here is what you see:



The next window opens:



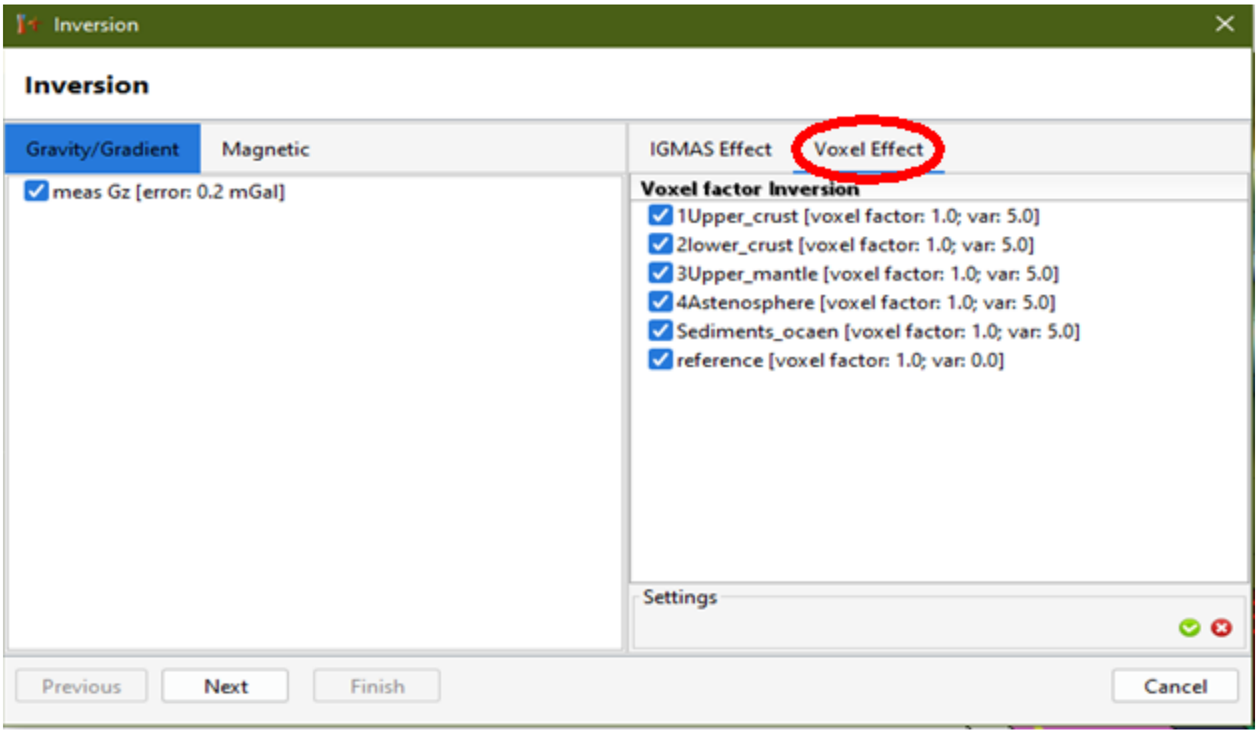
First, one has the possibility to select the density-inversion by means of **Gravity and/or Gradients”;** with “M**agnetic**” one would make an inversion of susceptibilities (no susceptibilities exist in this example); refer to figure above.

To *modify* the error given for the field(s) (here 0.2 mGal) refer to scenario “**Change error of measured fields**” in last wizard.

At the right side of the above window, under the tab "**IGMAS effect**", the inversion of densities of polyhedra is to be selected (figure above). To set and/or to modify the standard deviations for the different densities in the menu above (STD: 5.0 t/m3) refer to scenario “**Change standard deviation of densities/susceptibilities**” below. For the inversion it will be sufficient in most cases to leave the values (STD) unchanged.

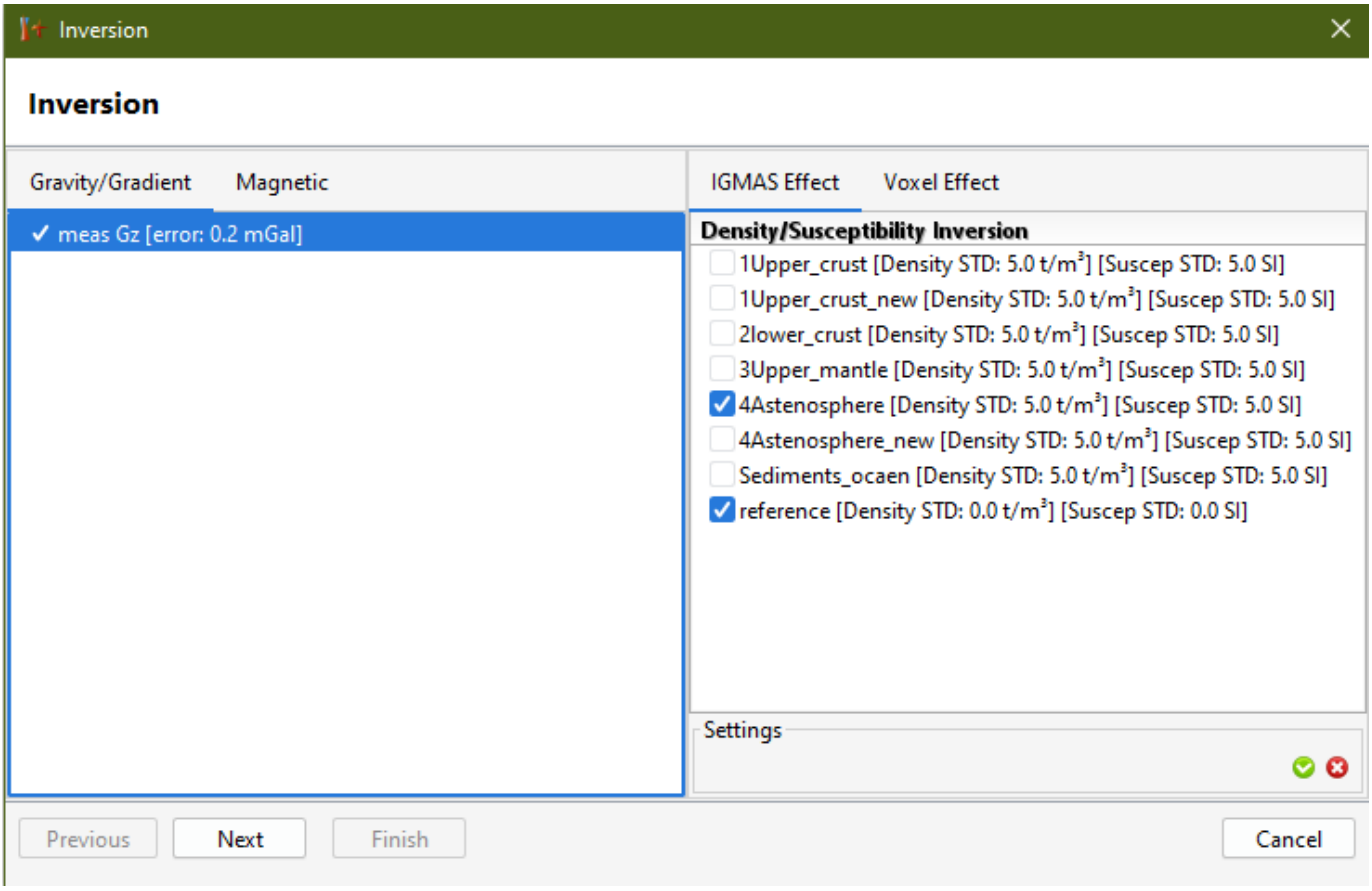
Otherwise, the densities of the voxel cube “**Voxel Effect**” can also be inverted (next figure).

To set and/or to modify the *voxel factor* (here 1.0) and the variance/STD 5.0) for the different bodies in the menu above refer to scenario “**Change standard deviation of densities/susceptibilities**” below. For the inversion it will be sufficient in most cases to leave the values (“voxel factor” and STD) unchanged. The “voxel factor” is explained in detail in the scenario “Voxelcube).

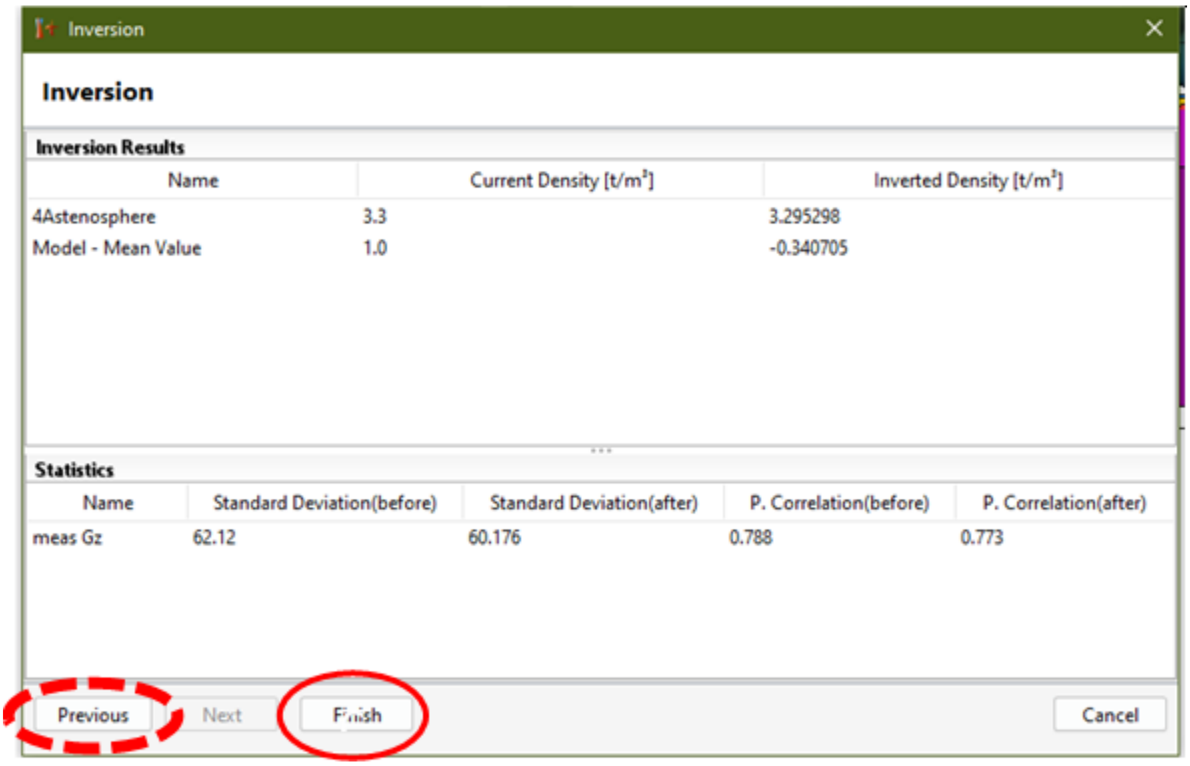


Below under “**settings**” you can switch off or switch on  the of geological bodies listed above.

Invert the densities of polyhedra “4Astenosphere” and “reference” (under IGMAS Effect). **All bodies under “Voxel Effect” are disabled now**:



Click Next and the result will be presented in the next window  :



Click Finish to accept the new densities

.

The upper panel lists the densities before and after the inversion and the lower statistics panel shows the standard deviations (before/after) and the *Pearson correlation coefficients*. Since the correlation after the inversion is better than before, the result of the inversion was accepted.

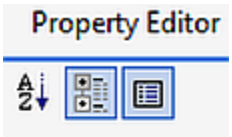
In the other case, by clicking on "**Previous**", the user would have the possibility to select other bodies, respectively to change the standard deviations and errors.

Attention:

To change standard deviations and errors, the inversion must be canceled. It is not possible to change the above parameters in the inversion window.

2.13.1 Change error of measured fields

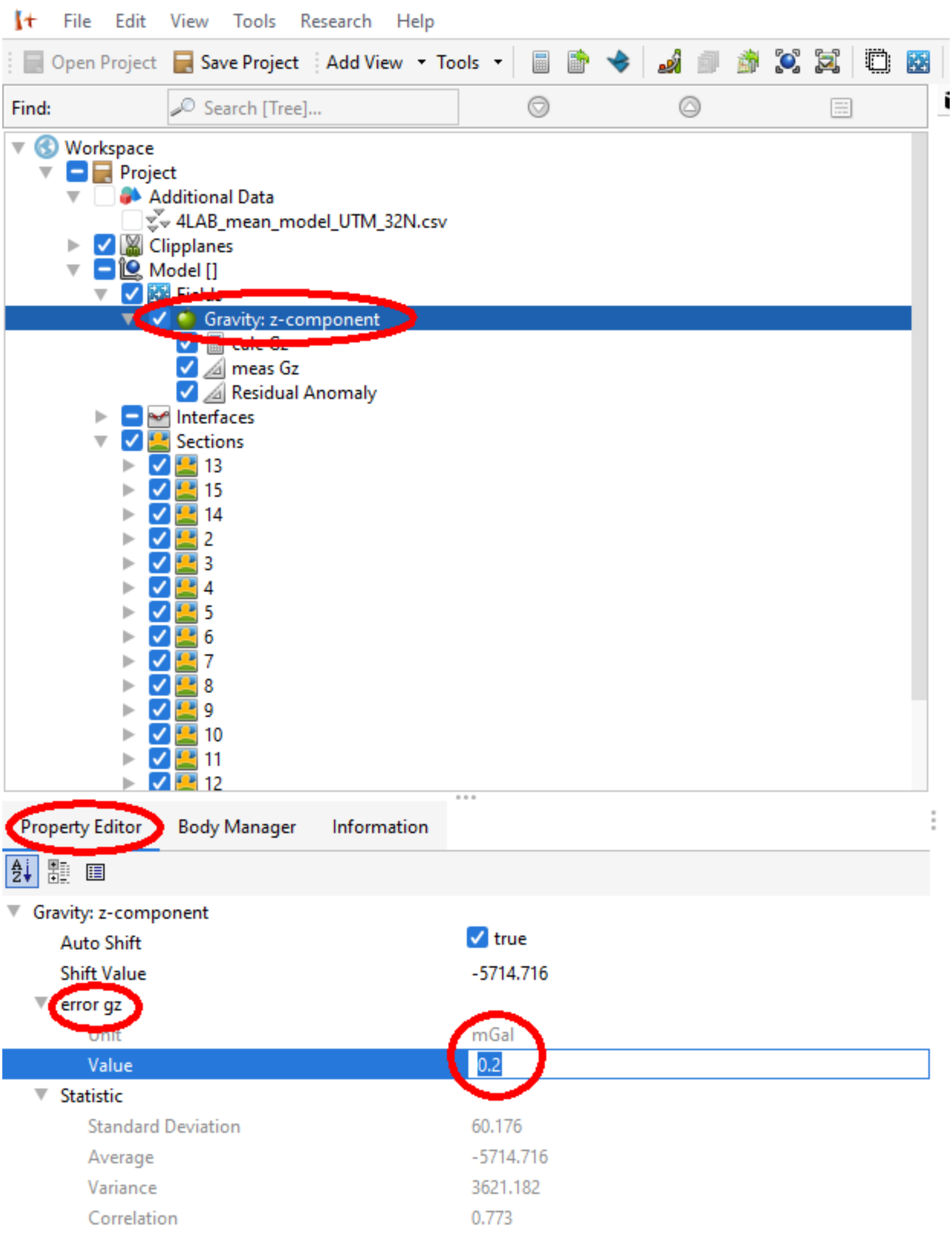
Click in the **OBJECT TREE** on "**Gravity z-component**". Then select **Property editor**

And select one of the icons 

:

Click on "error gz" and then on **"Value". Double click** with **left mouse button**

Enables the user to input a new value for the error of measured gravity field.



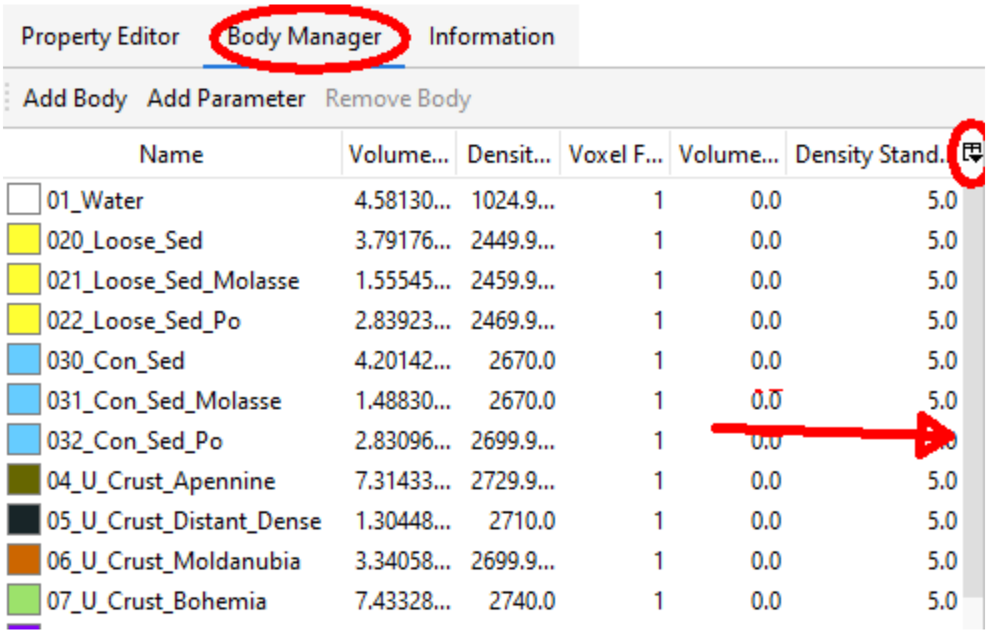
2.13.2 Change standard deviation of densities/suceptibilities

Click in the **OBJECT TREE** on “**Gravity z-component**”. Then select **Body Manager**.

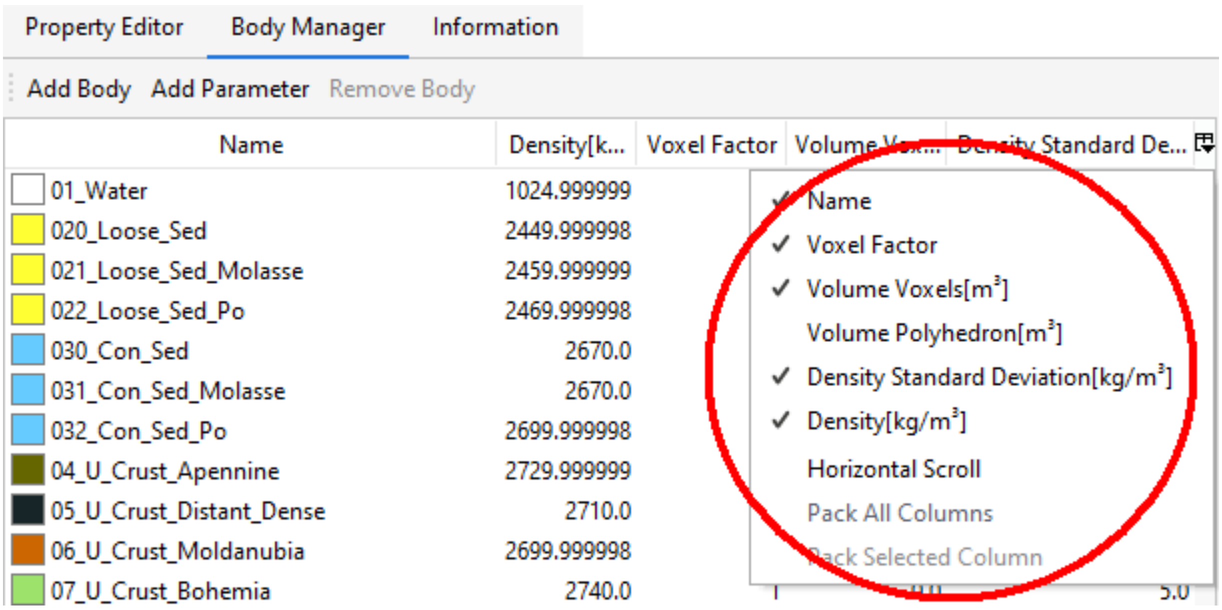
You will see a window like this; (be aware: this here is only a snippet):

In the next step it is important to move the displayed parameters so that the items to be changed are visible. To do this, the window can be enlarged (keep the **left mouse button pressed** on the right edge of the **BODY MANAGERS** and drag it larger...).

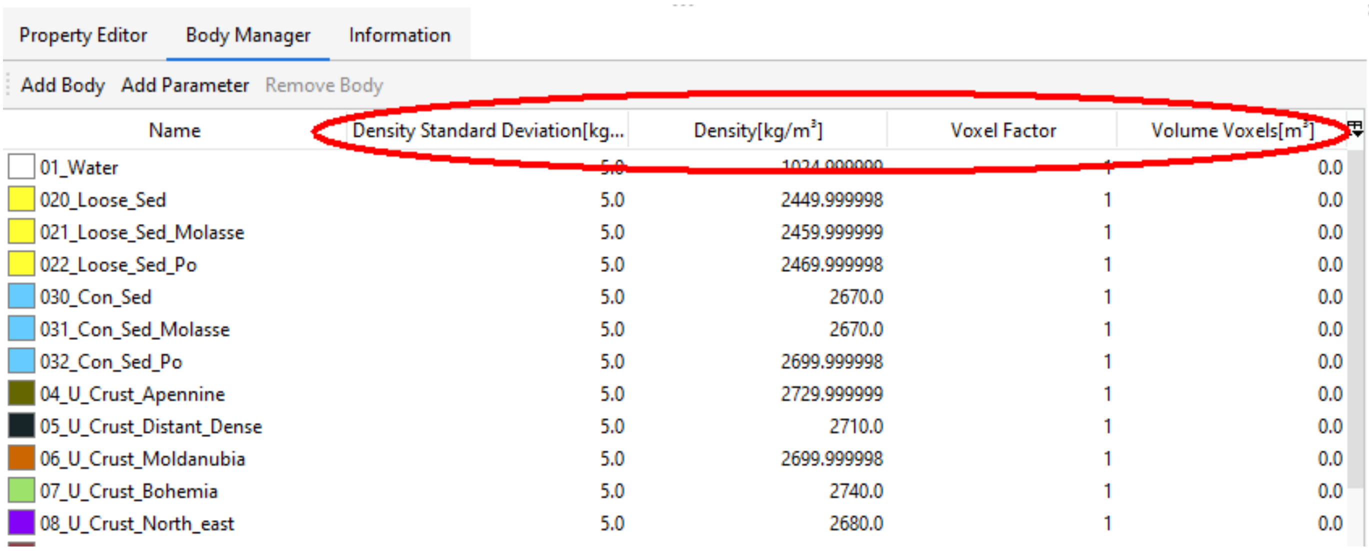
Then, by clicking the ICON above right corner, a selection of the parameters can be made. Now it is important that **Standard deviation** is selected - for the density or for the susceptibility.



This results in the next screen:



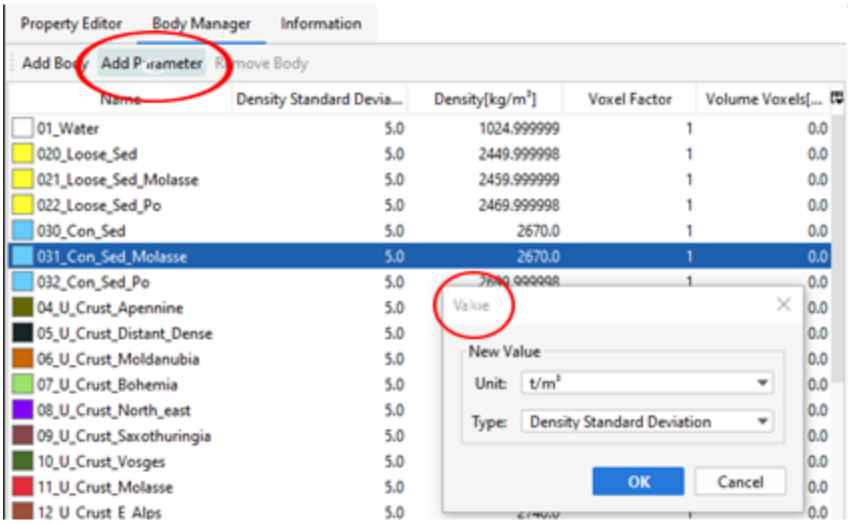
... and after moving/sorting the parameters by *pressing* **left mouse button** and *moving* them into another position in the **BODY MANGER**, we see:



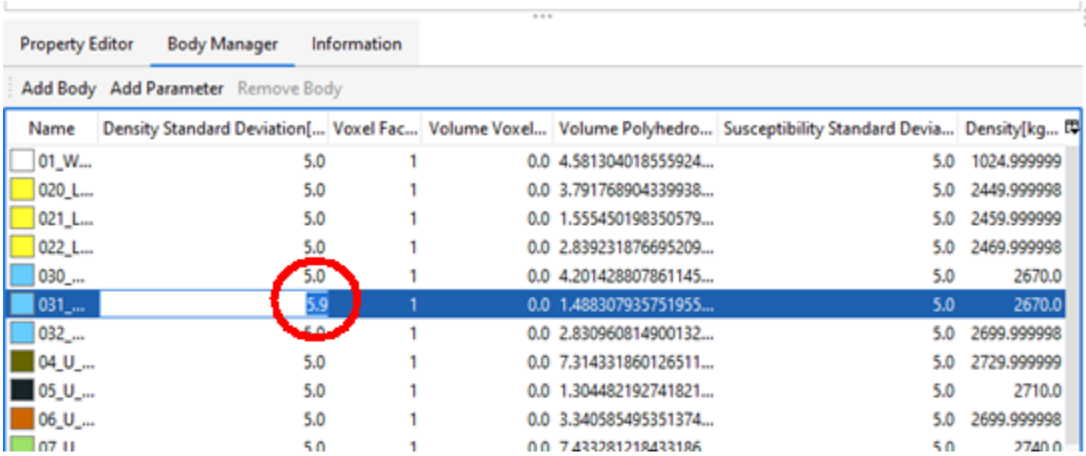
To select a new Standard deviation for the density/susceptibility of one of the geological bodies

> **click** on the body > and then on "Add Parameter"

In the small window that is displayed you may **select** the correct units (here t/m^3) and the **type** you will change: "**Density Standard Deviation**":



... finally **double click** with the **left mouse button** on body and include the new value:



In the same way, the other parameters can be changed - for example, the "**Voxel Factor**", which can also be inverted. In this case, the "**Voxel Effect" tab** must be activated in the "Inversion" window (see "**DENSITY INVERSION**" above).

2.14 Colours

Colors are used in **IGMAS+** in two very different areas:

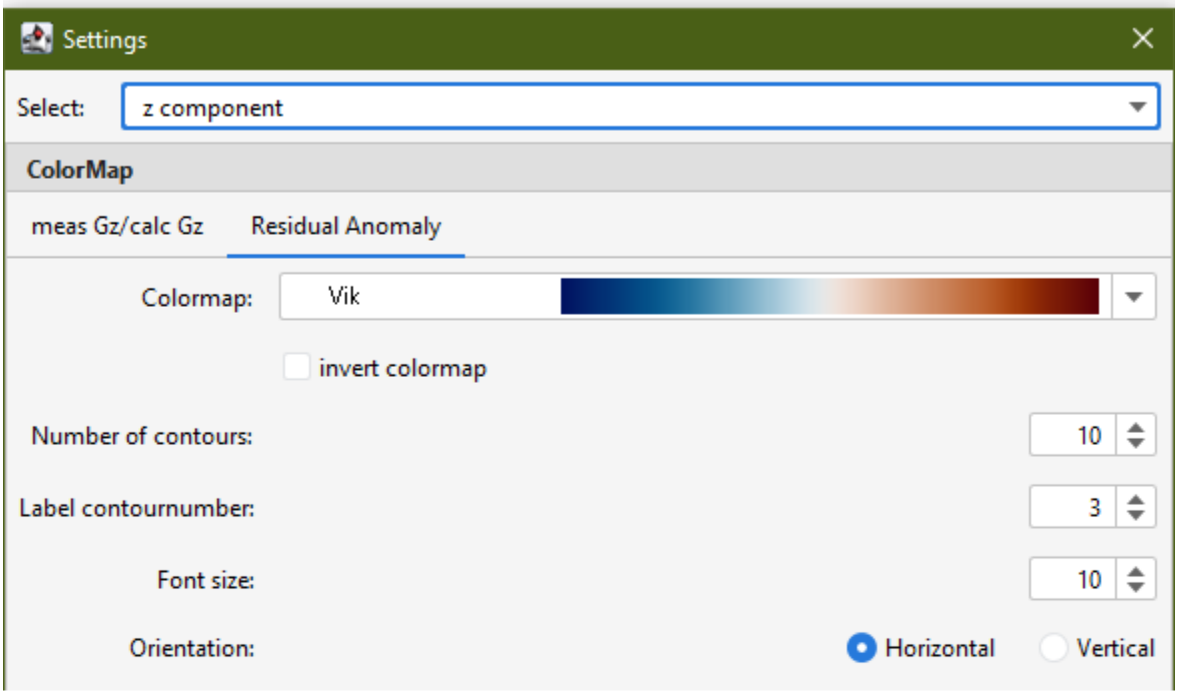
- (1) For the differentiation of **bodies** (geological structures) or

- (2) in the **map representation** of the used fields.

For the differentiation of bodies (1) the program distinguishes between two color schemes:

- either the (geological) bodies are filled according to the colors known in geology (e.g. **blue for Jurassic, green for Cretaceous** and **yellow for Tertiary** rocks) or
- the colors are determined according to the **density of the body**. **Blue colors** correspond to **high** densities of rocks, **brownish colors** to **low** densities.

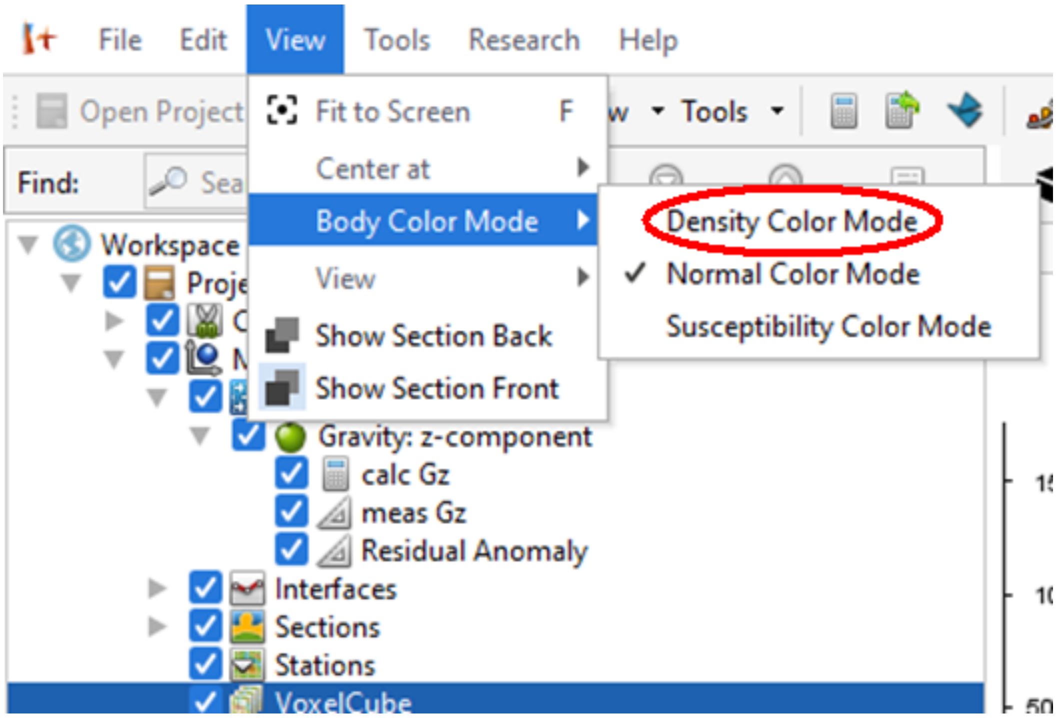
  This color spectrum is automatically set by the program and is based on the color scale used to create the residual gravity maps. In the current **IGMAS+** version, the user does not have the possibility to change the scaling or the colors of the color scale. You can see the color palette (Vik) here; the way to get there is described in this chapter below.



Note: At the beginning of a modeling project **IGMAS+** automatically sets the colors for geological bodies. They must then be changed by the user according to the two color schemes.

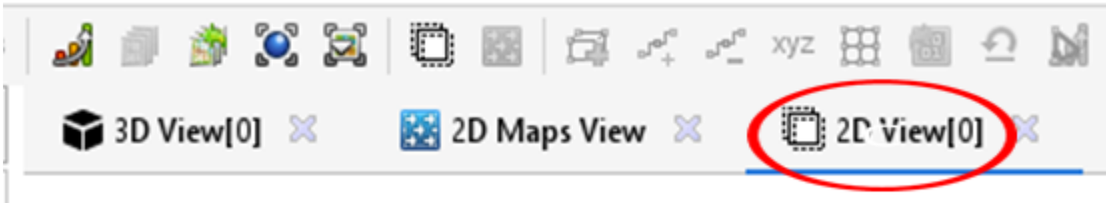
2.14.1 Change colors for geological bodies/polyhedrons

Be sure to have selected the "**Normal Color Mode**" after clicking View in the **TITLE BAR** > "**Body Color Mode**" in the popped-up window > and set "**Normal Color Mode**".

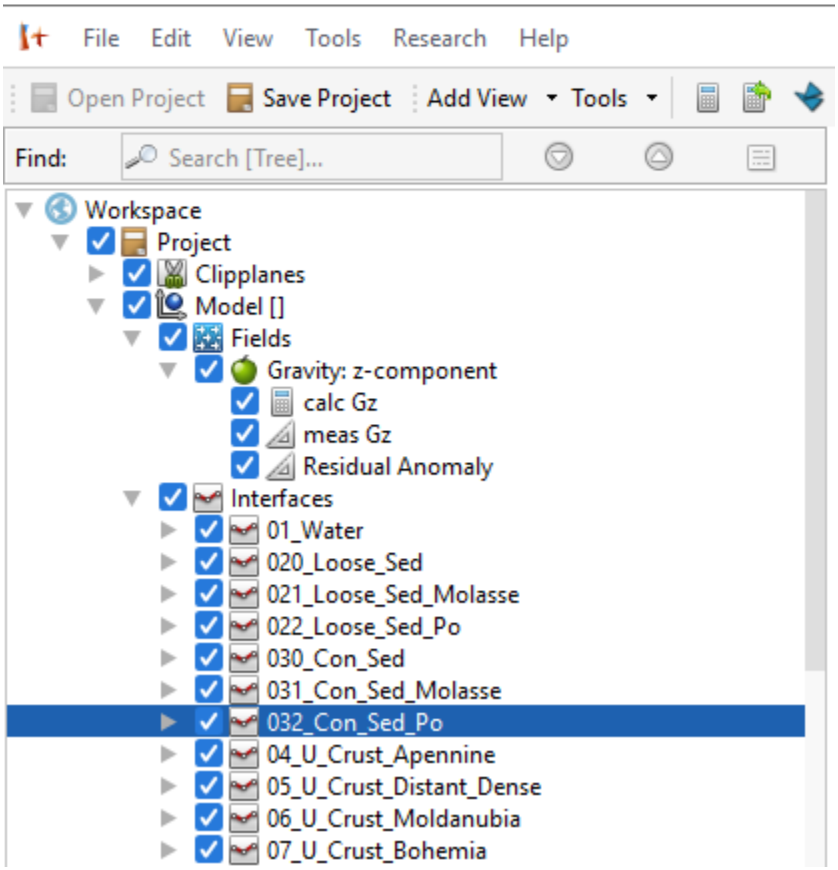


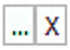
If the colors for the susceptibility of the bodies are to be set, then of course "**Susceptibility Color Mode**" must be selected in the window shown above. The process is analogous to the selection of the "**Normal Color Mode**".

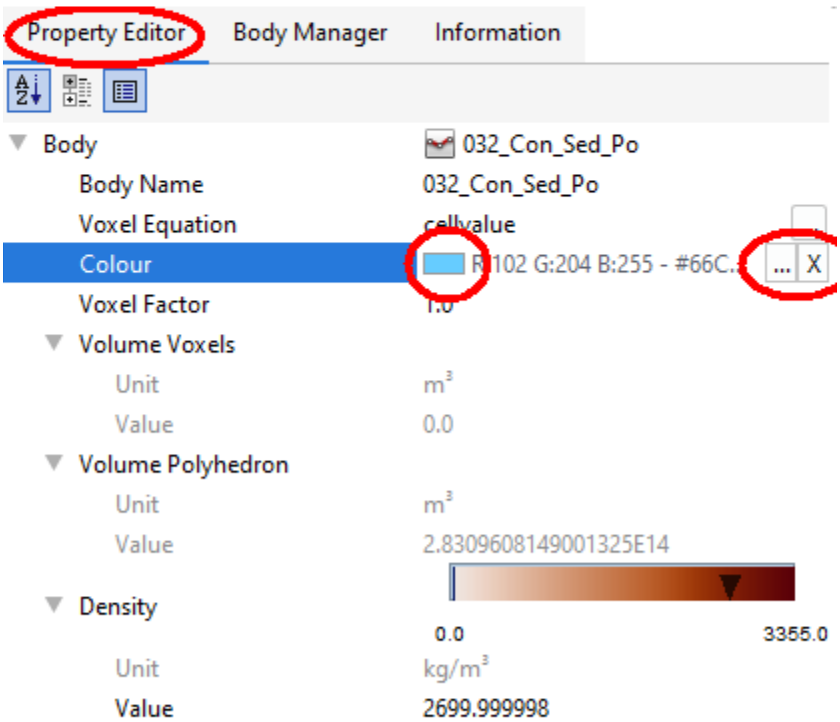
Select “**Add View”** in the **TITLE BAR** and klick on “**2D View**”. Below the **TOOL BAR** the icon for “2D View” is set:



Then go to the “**Object tree”** (top left), click on  to open the "**Interfaces**" tree and select the body whose color is to be changed (here: 032_con_Sed_Po; blue bar):

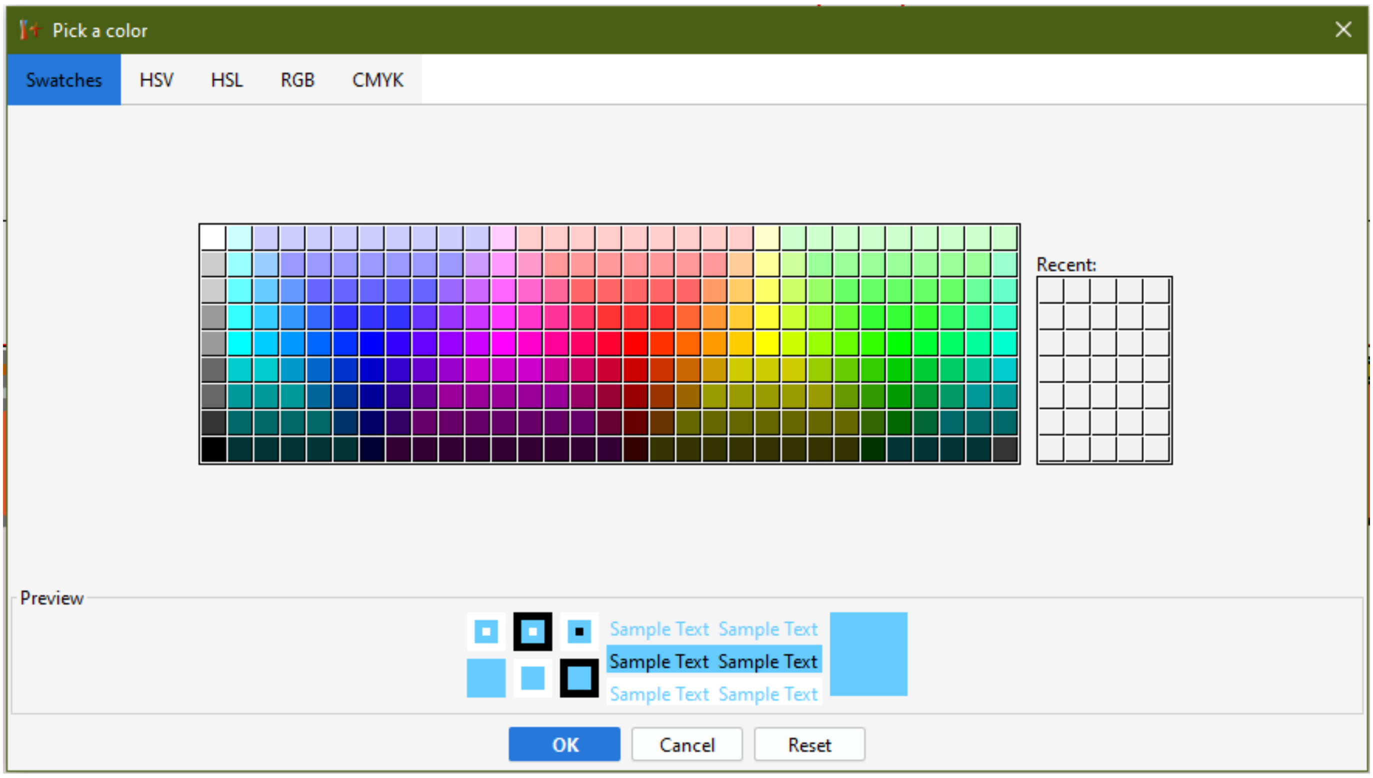


... go to the „**Property Editor**“ > click in the opened menu in „**Body**“ and „**Color**“ > click on the small color window and click on the three **grey points**  :

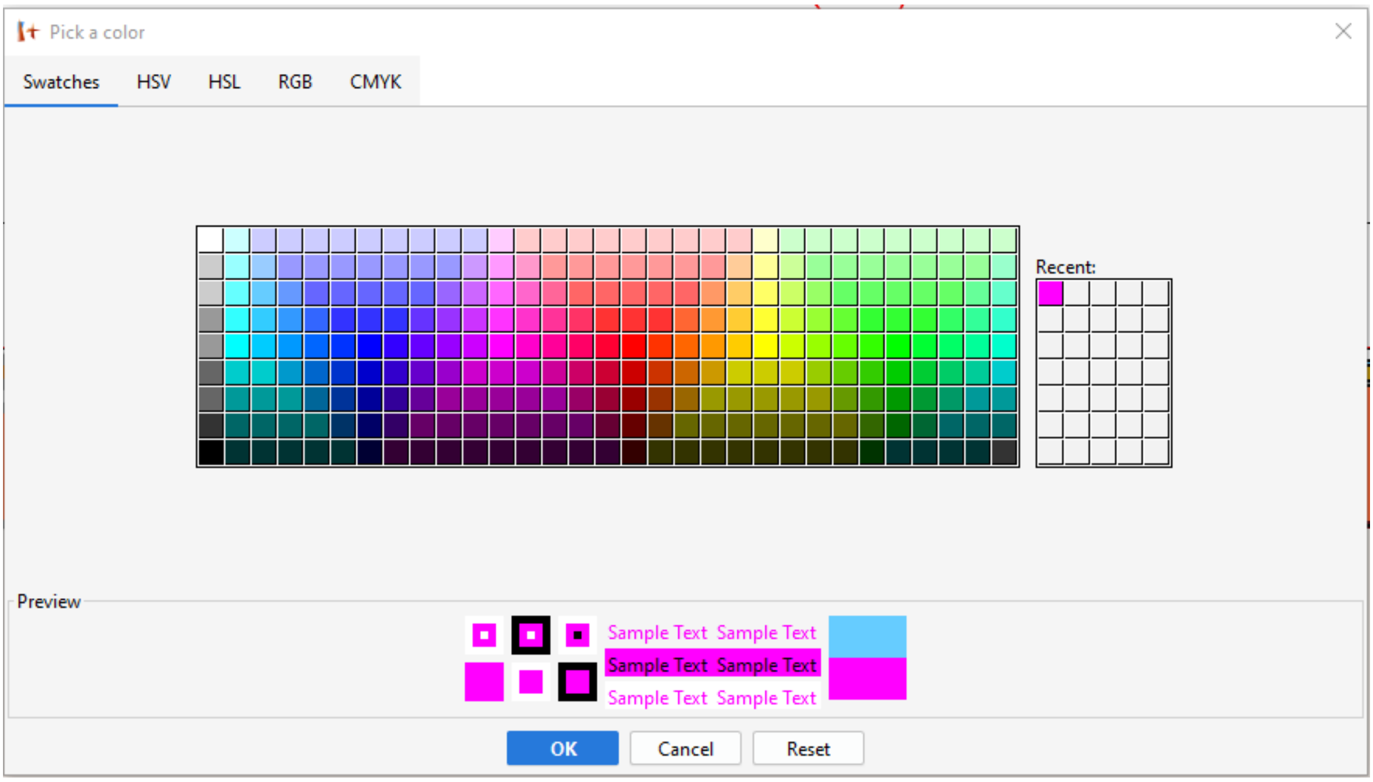


The color is also identified in the RGB color scheme (R:102 - G:204 – B:255).

Clicking the three grey points (figure above) this window popped up:



Select by clicking a new color :



Alternatively, the colors can be changed in this window using the HSV - HSL - RGB - CMYK color scales. The effect is the same everywhere.

2.14.2 Change colors for IGMAS+ maps

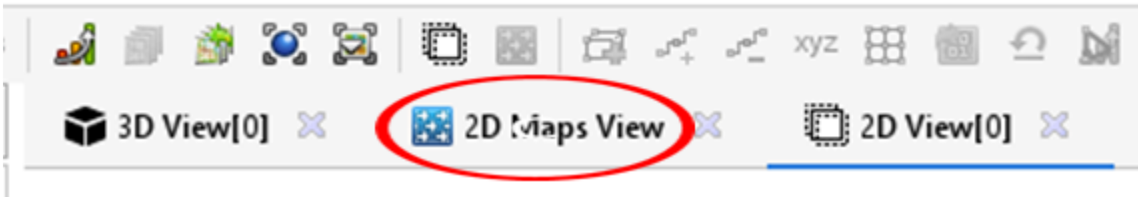
The color palettes used in **IGMAS+** for map display follow new findings regarding the **physiology of perception** of healthy and visually impaired people (see for example:

https://theconversation.com/how-rainbow-colour-maps-can-distort-data-and-be-misleading-167159.

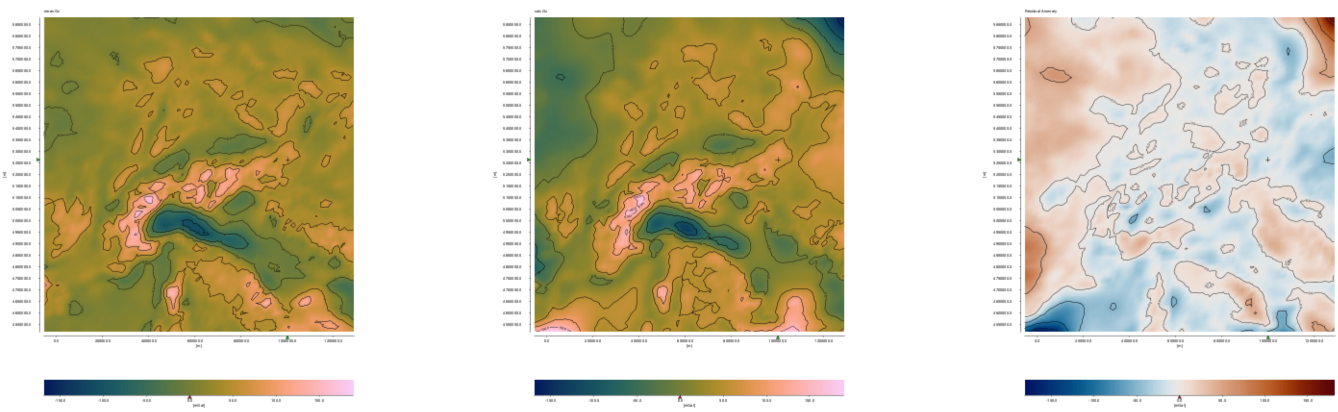
IGMAS+ uses two options for selecting different color palettes for displaying the comparison field (measured gravity/magnetic field) and the modeled field (calculated) on one side and for displaying the residual field on the other.

Selection of the color palette for measured and modeled field

Select “**Add View”** in the **TITLE BAR** and klick on “2**D Maps View**”. Below the **TOOL BAR** the icon for “2D View” is set:



Three maps are shown:

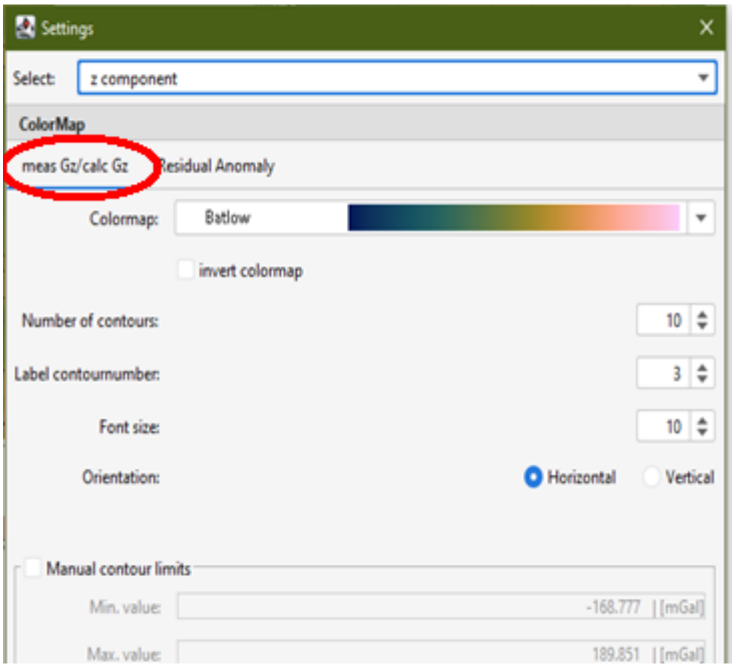


Measured field (left) --- Calculated field (middel) --------------------------- Residual field (right)

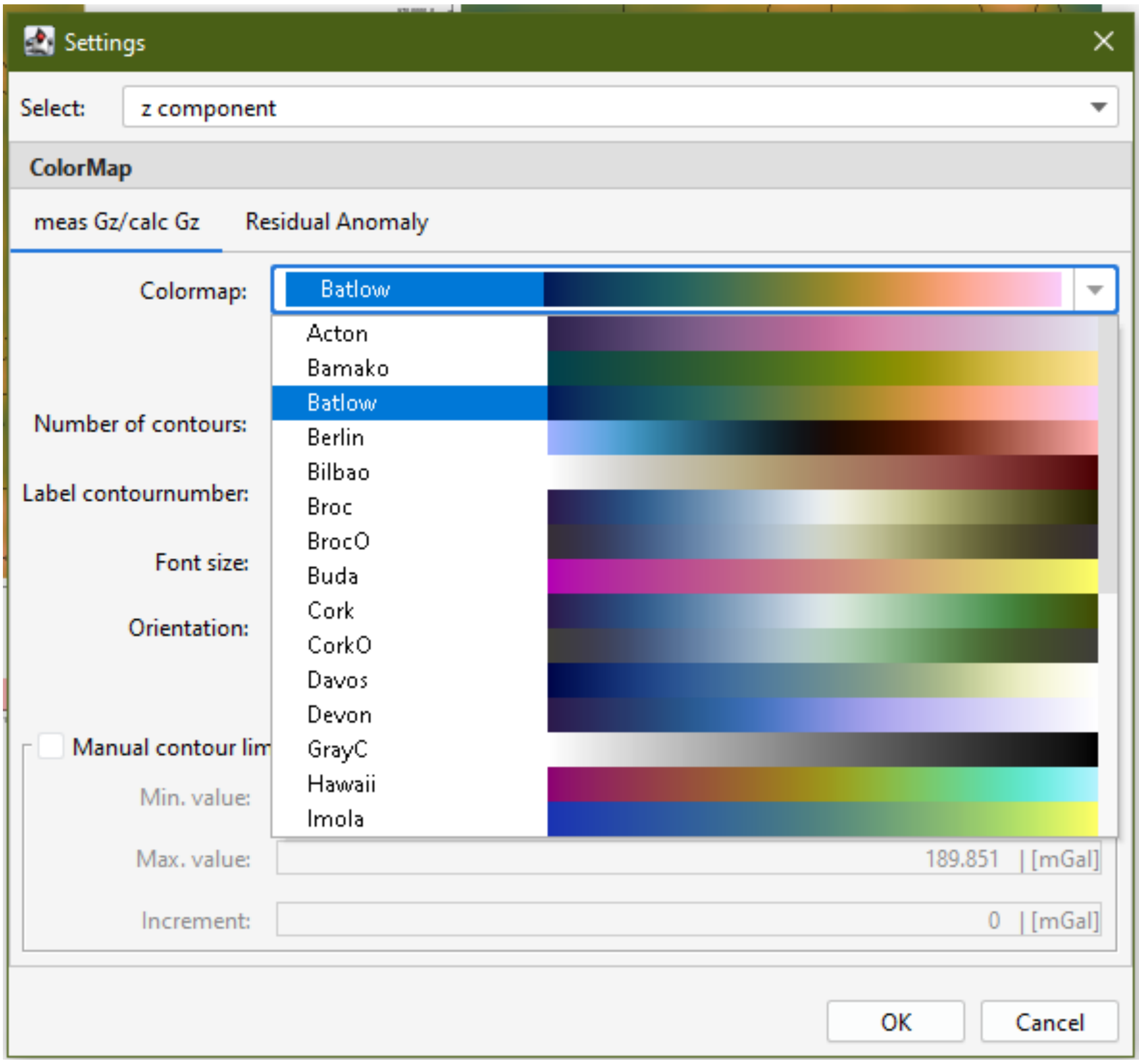
Select below the **TOOL BAR** on the right upper corner the icon 

and select the tab “**meas Gz/calc Gz**”.

Get a window which visualize the **Batlow palette.**

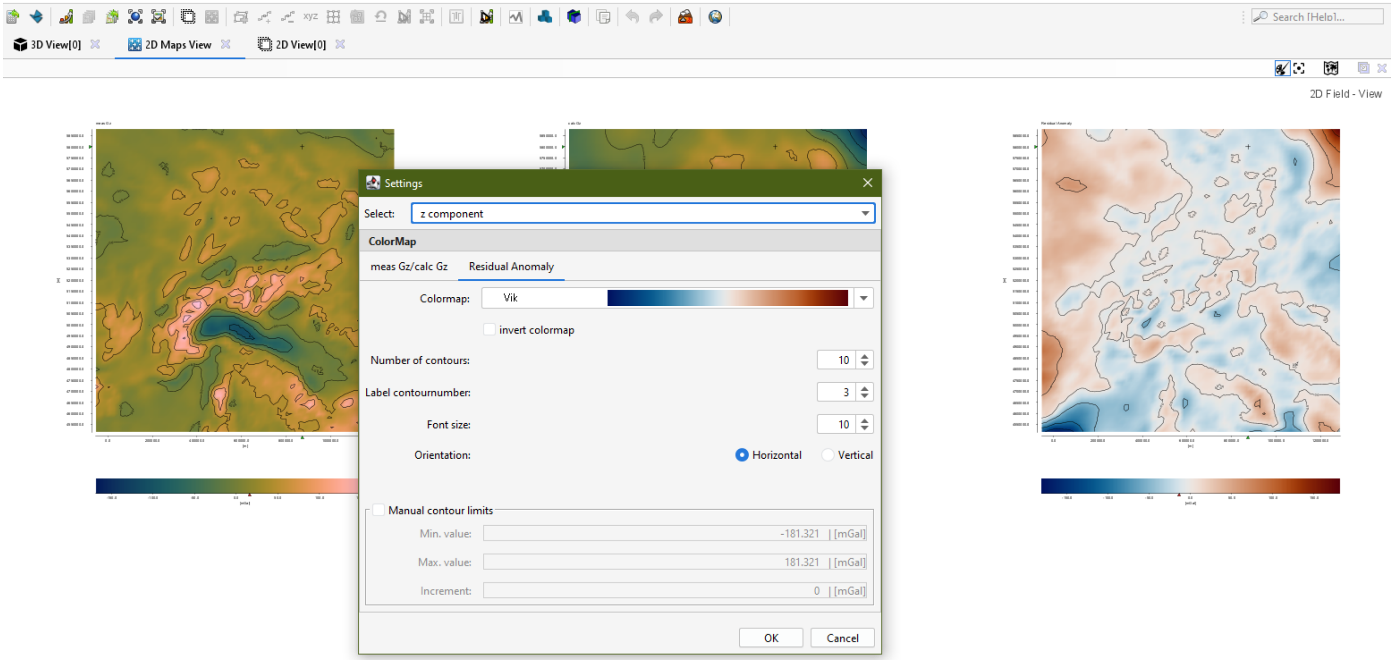


By click on  of the **Colormaps**, other palettes may be selected:



Note: The selection of the Batlow palette represents a good compromise, in terms of the previously often traditional "rainbow colors" palette and the currently recommended.

To select the color palette for the **residual field/"Residual Anomaly"** select the tab "**Residual Anomaly**":



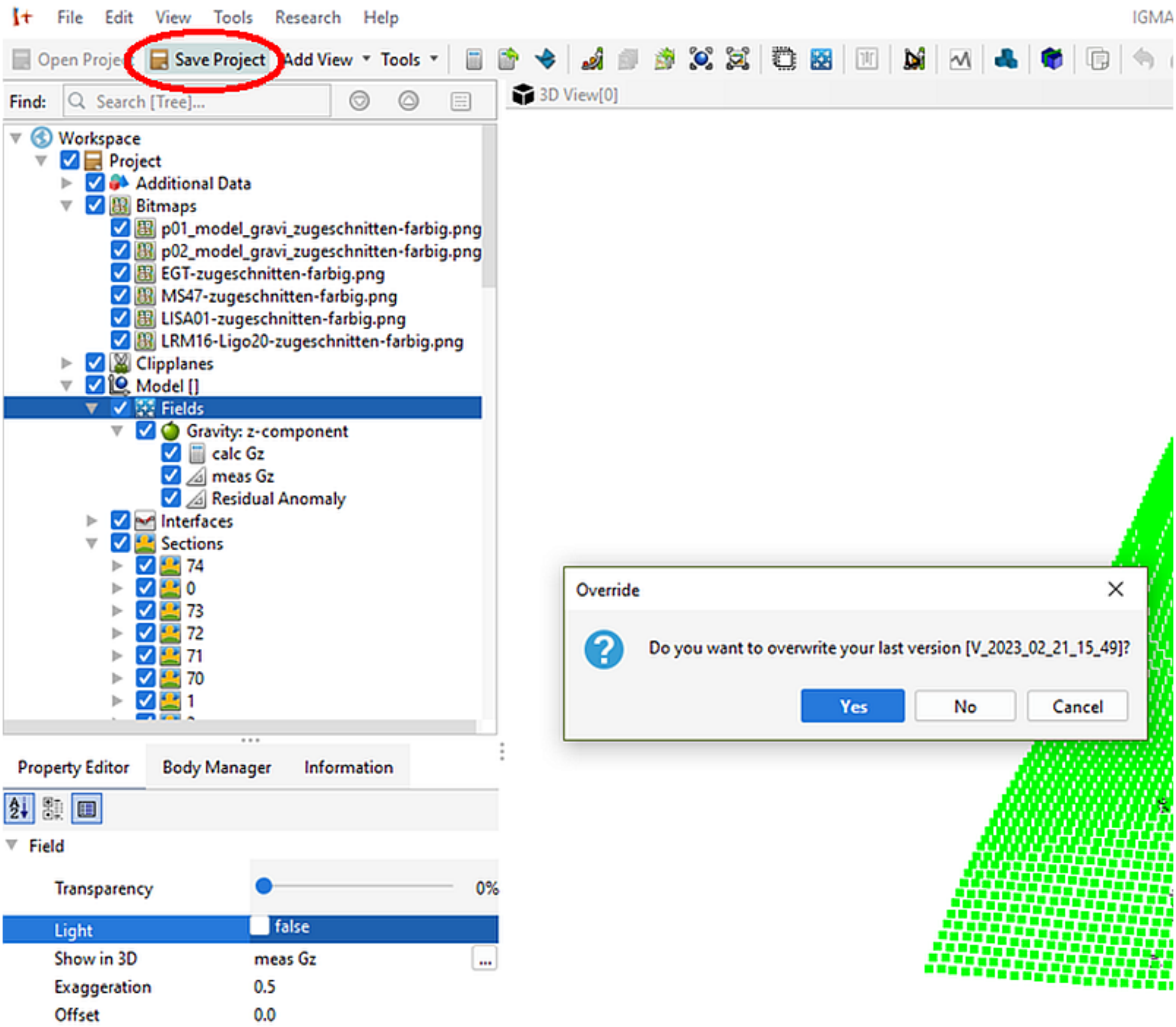
The **Vik** palette is grouped around a central value (here: the Null value of the residual anomaly).

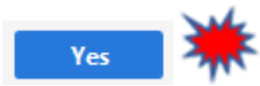
By click on of the **Colormaps**, other palettes can be selected. 

2.15 Save project

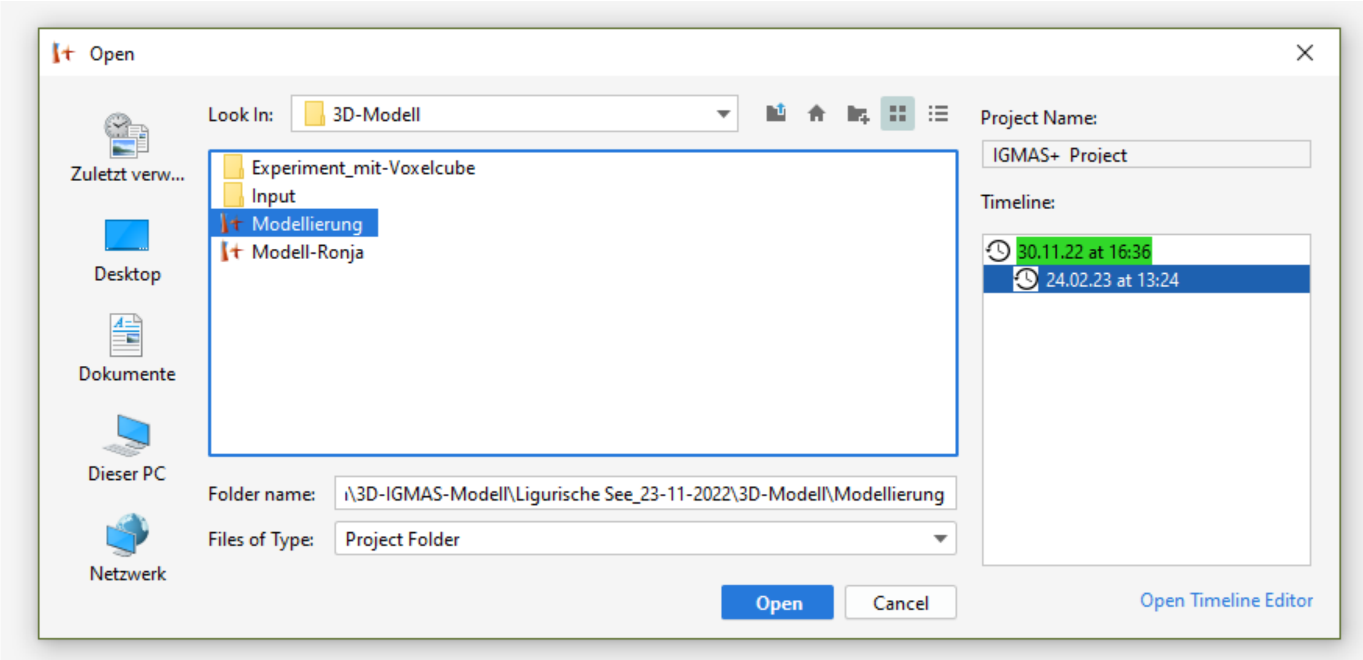
At the end of each working phase, but also frequently during this process, it is advisable to save the model.

(1) This action is initiated by a click in the toolbar "**SAVE PROJECT**".

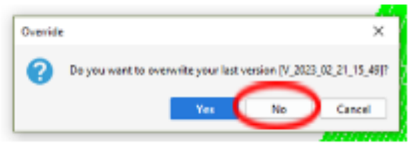


A window will appear warning you not to overwrite the current model version. If this is desired, click 

IGMAS+ will create a new Model INPUT. Loading a model file in the next working phase you see that in the Timeline appears the former model (in green colour) and the new model blue shaded:

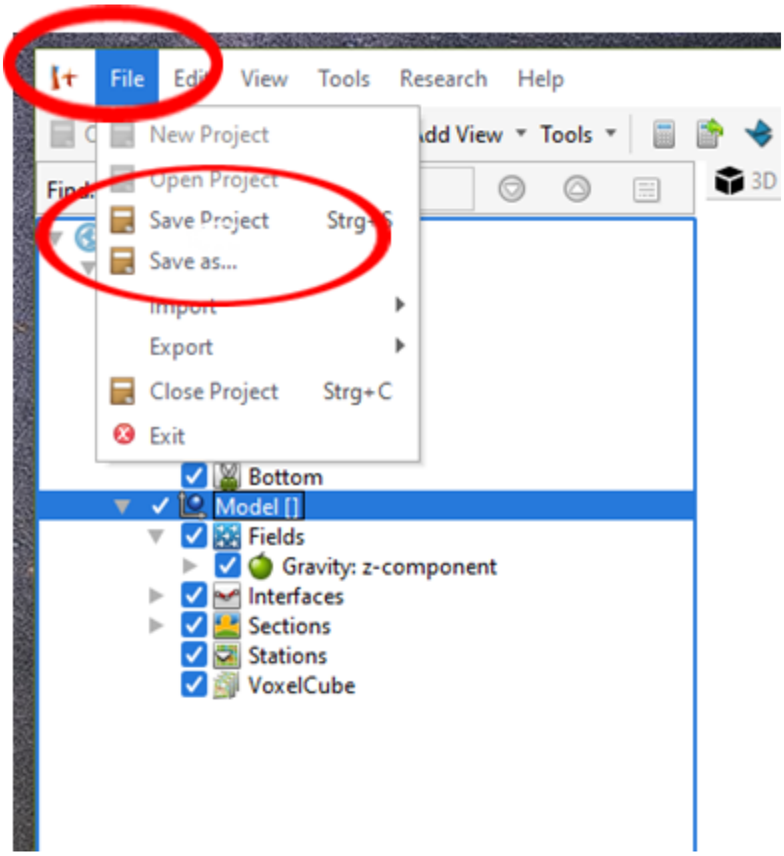


If you click ***NO***, nothing will happen and the model will remain. CANCEL will terminate the action without decision.



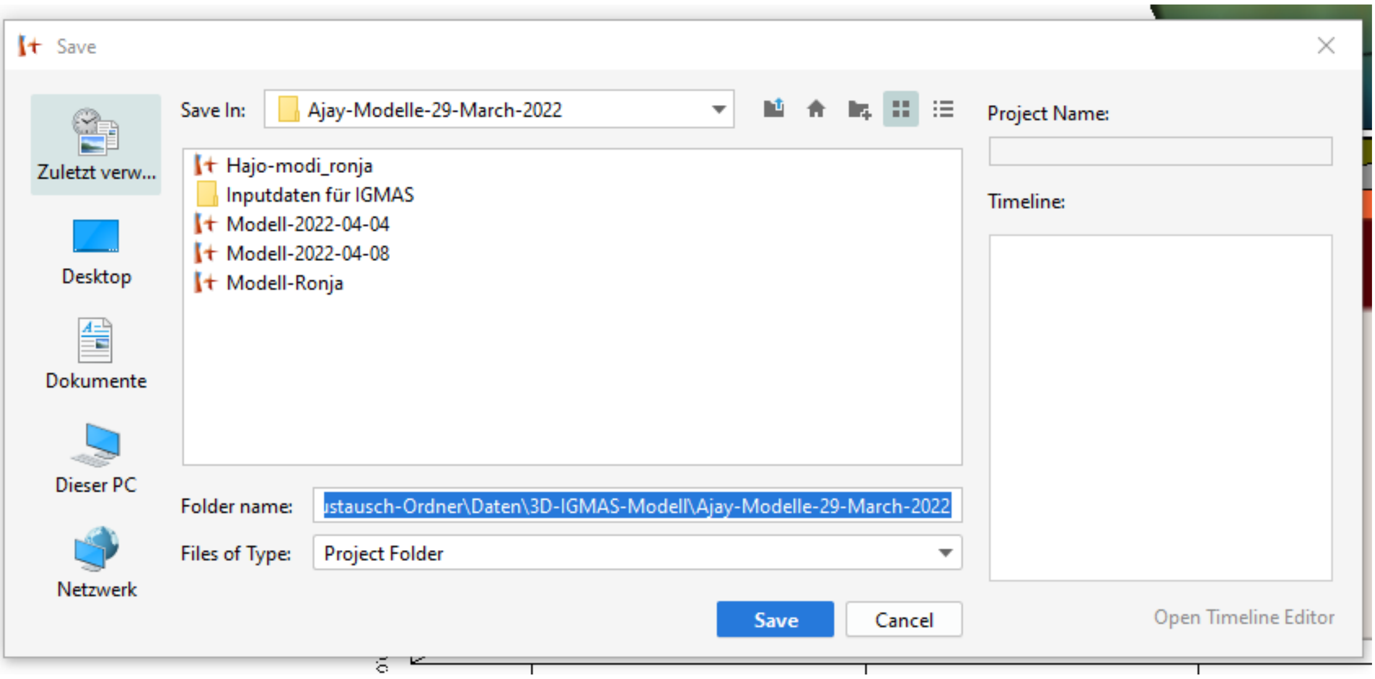
(2) There is a second possibility to save model changes.

Click on “File” in the **TITLE BAR**

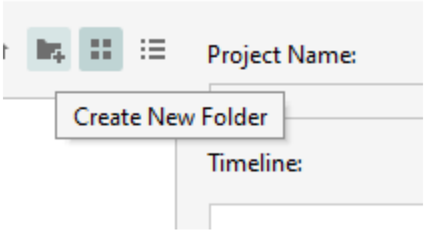


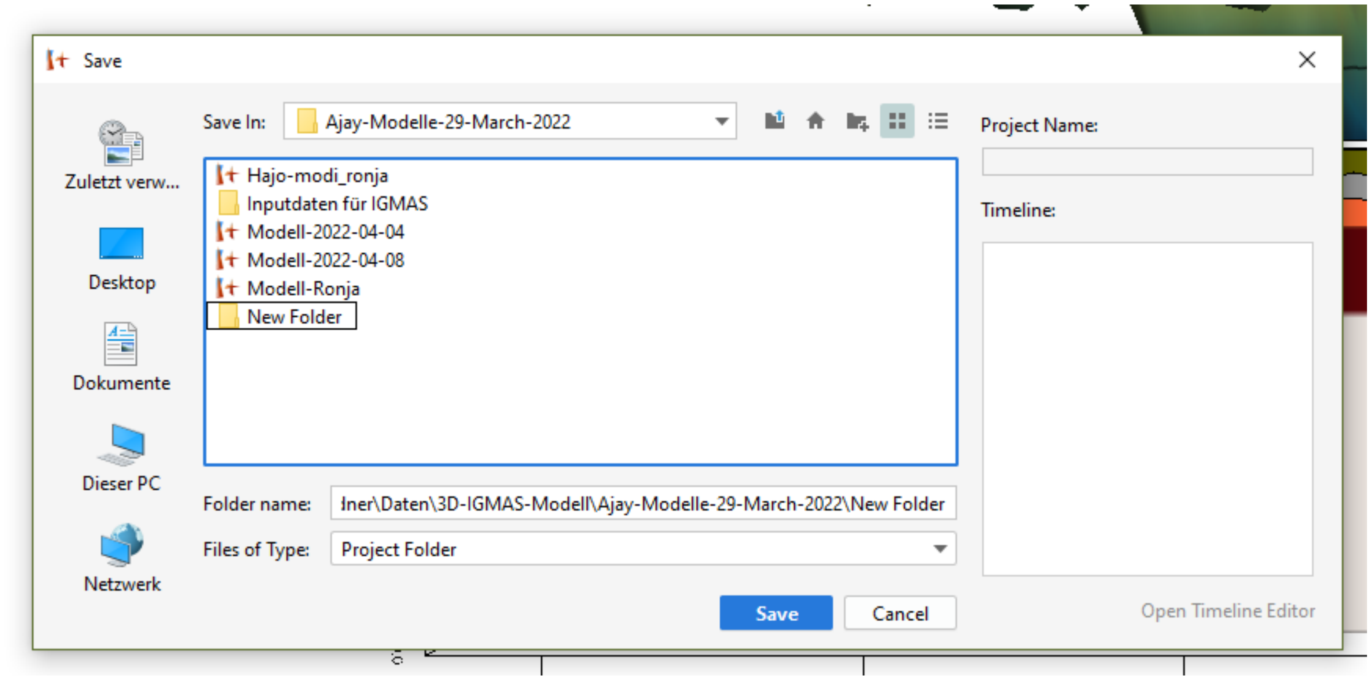
In the pull down menu appears Save Project Strg+S (short key is “Strg+S” bottom) and Save as... .

- **“Save project”** will save the entire model as already described above in (1).
- **“Save as”** enables the user to give a new name to the model output.



Click on the “create a new folder symbol” , and ...



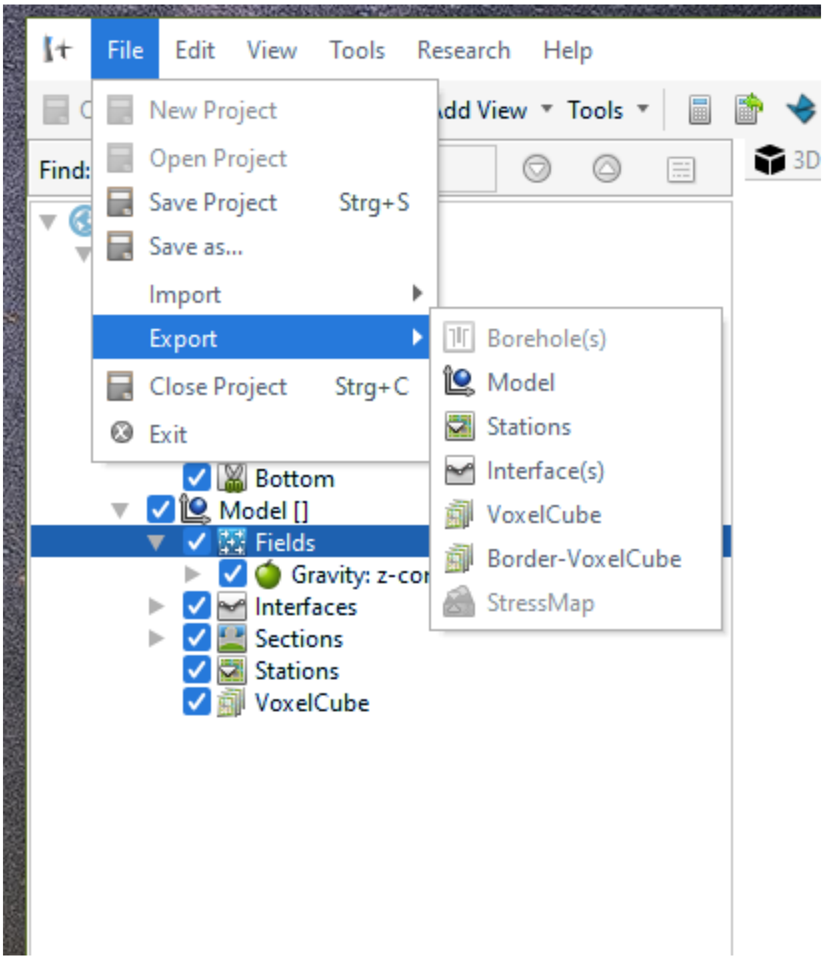


rename the new folder and press **“save”**.

2.16 Export Results and Model components

IGMAS+ does not provide the user with direct tools for printing model components and fields (calculated, measured and residual fields). It is not necessarily the task of an interactive modeling software to offer all possibilities of a modern graphics processing. However, in order to take advantage of this, there are a number of possibilities for the user to further process **IGMAS+** results with this other software.

Clicking FILE in the TITLE BAR select “Export” and get information on the components to export:



IGMAS+ offers seven Export actions:

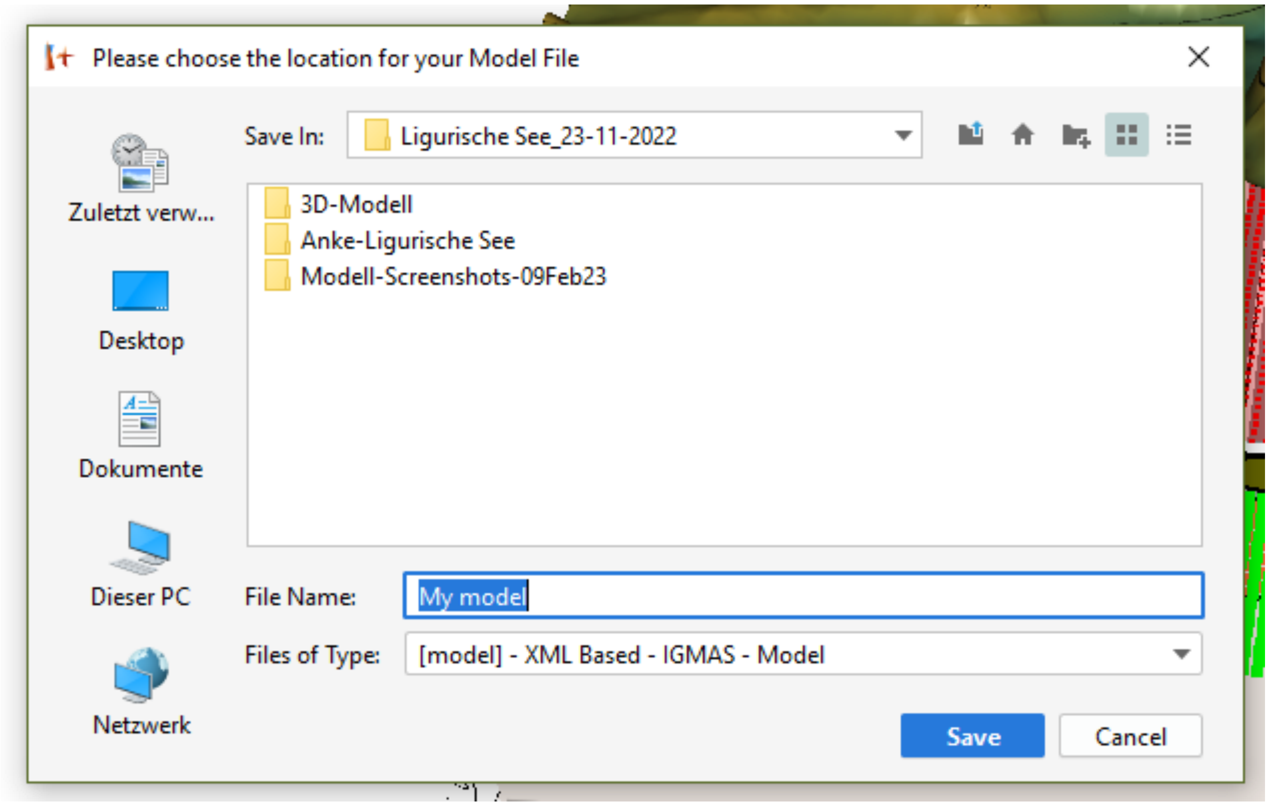
- (1) Borehole(s),
- (2) Model,
- (3) Stations,
- (4) Interface(s),
- (5) Voxelcube,
- (6) Border-VoxelCube and
- (7) StressMap.

The exports are alpha-numeric and are used for further processing of the model results in external software.

2.16.1 (1) Borehole(s) (To be done)

2.16.2 (2) Model

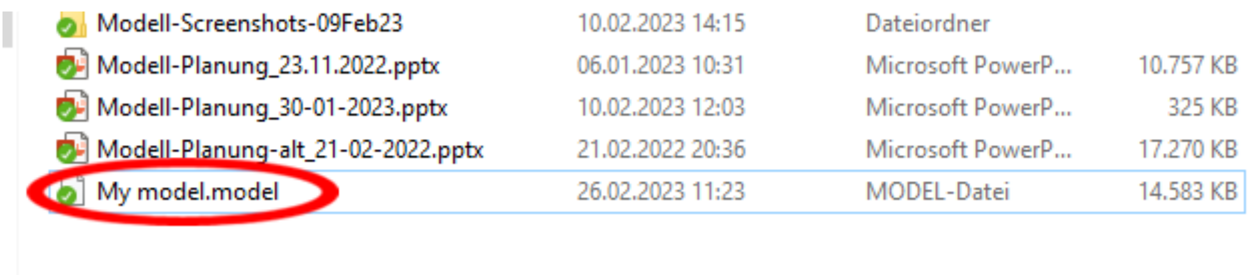
After clicking this wizard appears on the screen.



Note: There is currently only one file type available: XML (Extensible Markup Language).

Click: Save

In the selected folder in your PC folder structure you will find the new file My model.model:



The file is opened with an editor and the entire model structure with the **IGMAS+** geometry, the fields and other components can be seen in plain text:

Here we show snippets from the relatively large XML file:

```
<?xml version="1.0" encoding="UTF-8"?>
<!-- <!DOCTYPE geodata SYSTEM "geodata.dtd"> -->
<geodata name="">
    <projection name="unknown" units="m"></projection>
    <magnetic_field units="nT" total_field="49441.0" inclination="69.0" declina-
tion="1.0"></magnetic_field>
    <property name="body" value="01_Water">
        <property name="voxel equation" units="SI" value="1.0">cellvalue</property>
        <property name="density" units="kg/m³" value="1024.999999"></property>
        <color red="1.0" green="1.0" blue="1.0"></color>
    </property>
```

or:

```
 <vertex id="161531" x="1870365.0" z="-211.79015"></vertex>
       <vertex id="161530" x="1890365.0" z="-205.92818"></vertex>
       <vertex id="161529" x="1910365.0" z="-220.2628"></vertex>
       <vertex id="161528" x="1930365.0" z="-232.17464"></vertex>
       <vertex id="161527" x="1950365.0" z="-211.60571"></vertex>
       <vertex id="161526" x="1970365.0" z="-173.67699"></vertex>
       <vertex id="161525" x="1990365.0" z="-177.02841"></vertex>
       <vertex id="161524" x="2010365.0" z="-271.95752"></vertex>
       <vertex id="161523" x="2030365.0" z="-324.32602"></vertex>
```

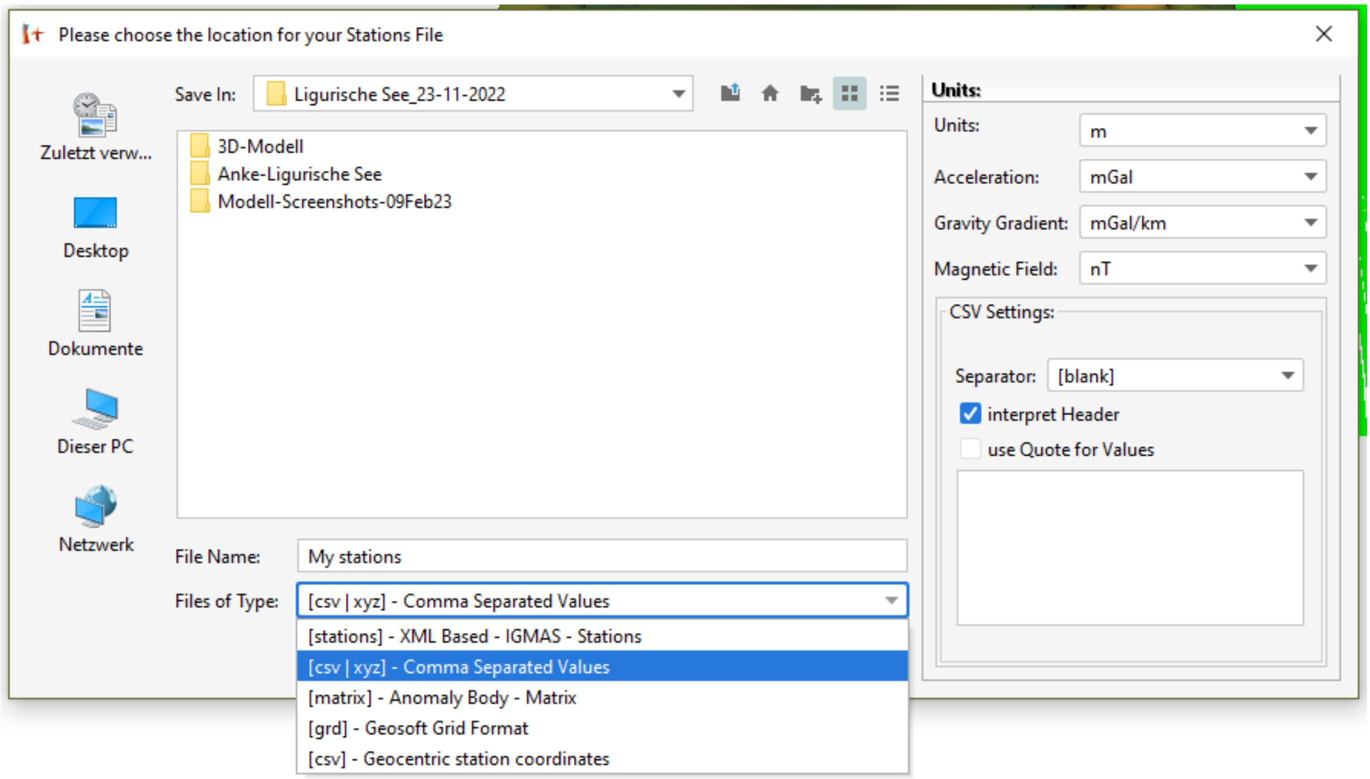
or:

```
<entry type="polygon" id_list="17794 125418 125419 125420 125421 125422 125423
125424 125425 125426 125427 125428 125429 125430
           125431 125432 125433 125434 125435 125436 125437 125438 125439 125440
125441 125442 125443 125444 125445
           125446 125447 125448 125449 125450 125451 125452 125453 125454 125455
125456 125457 125458 125459 125460
           125461 125462 125463 125464 125465 125466 125467 125468 125469 125470
125471 125472 125473 125474 125475
           125476 125477 125478 125479 125480 125481 125482 125483 125484 125485
125486 17796 62735 135560 135559
           135558 135557 135556 135555 135554 135553 135552 135551 135550 135549
135548 135547 135546 135545 135544
           135543 135542 135541 135540 135539 135538 135537 135536 135535 135534
135533 135532 135531 135530 135529
           135528 135527 135526 135525 135524 135523 135522 135521 135520 135519
135518 135517 135516 135515 135514
           135513 135512 135511 135510 135509 135508 135507 135506 135505 135504
135503 135502 135501 135500 135499
           135498 135497 135496 135495 135494 135493 135492 62734 ">


....
```

2.16.3 **(3) Stations**

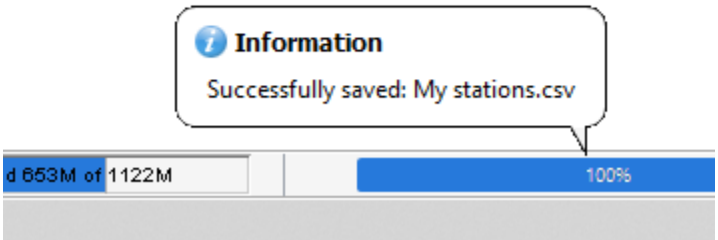
In contrast to the model export, we select ***[csv] [xyz] - Comma Separated Values***, which can be used in many external computer programs for further processing.



Make sure that the ***units*** of the station data (here: meters), the ***acceleration/gravity*** (here: mGal), the ***gravity Gradient(s)*** and or the ***magnetic Field*** are specified correctly according to the modelling. In the separator field, **"blank"** (used in the example above) or a tabulator can be used.

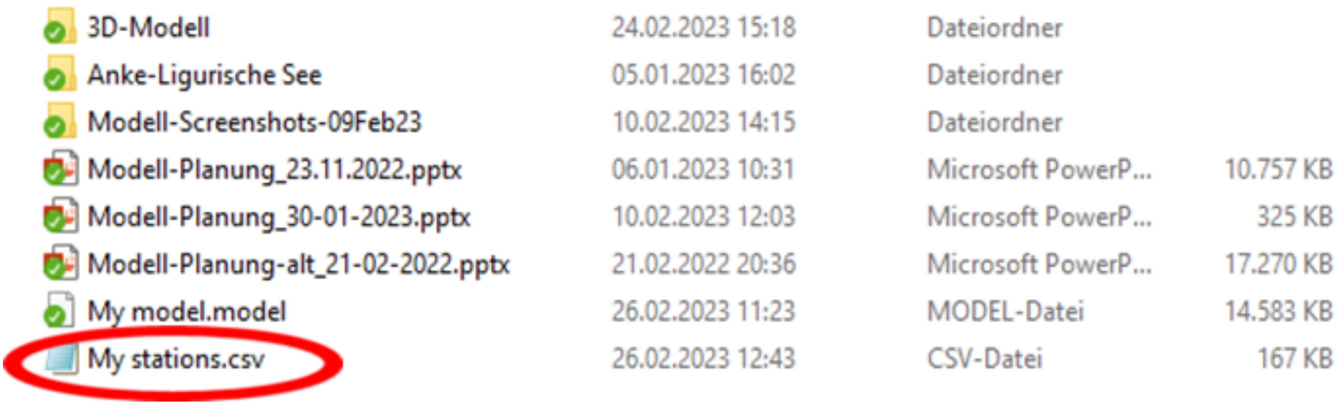
Click: Save 

... and above the progress bar (bottom right of the screen) you will read the information that the stations were successfully saved:



In the selected folder in your PC folder structure you will find the new file

My stations.model:

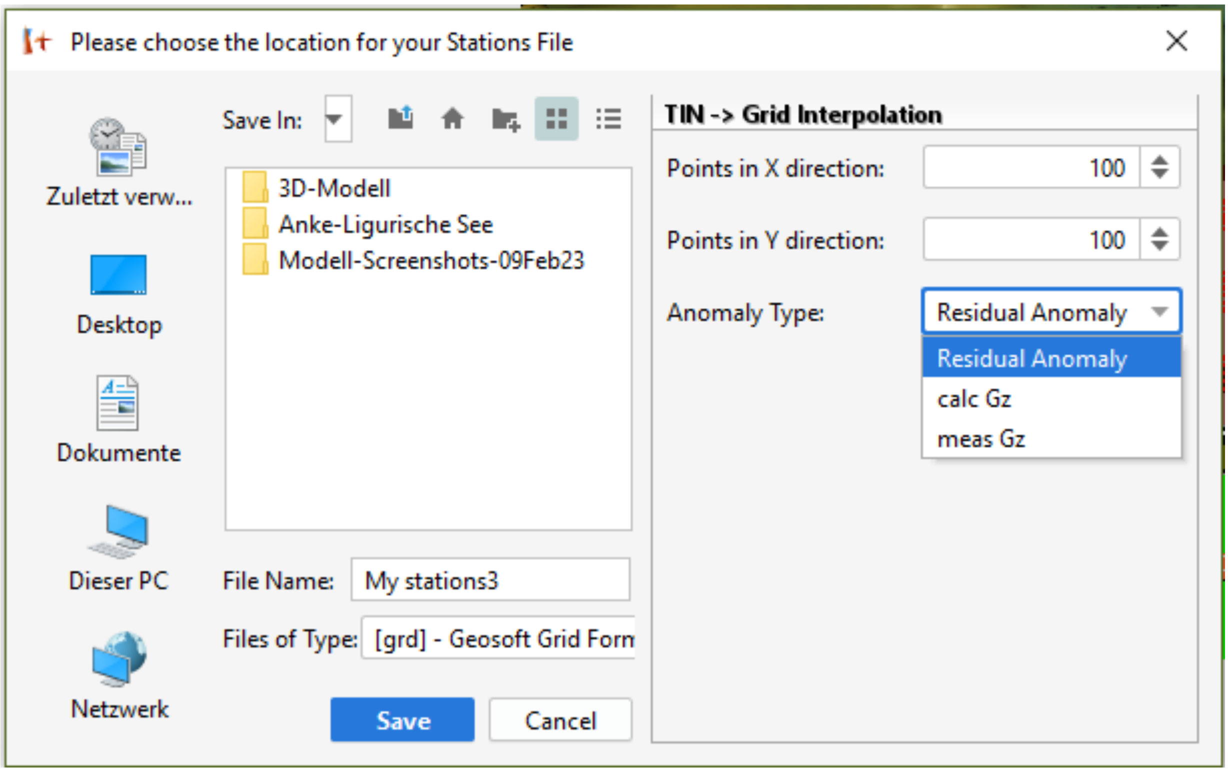


This file is much smaller than the saved “Model file” and looks like this:

"x" "y" "z" "measured z component" "calculated z component" "residual z component"

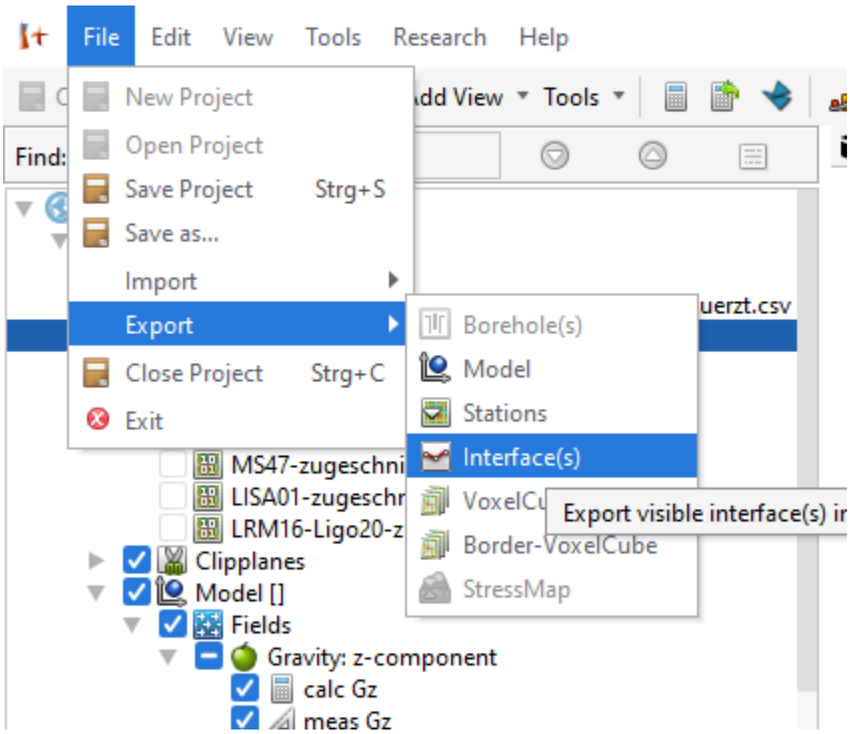
```
"x" "y" "z" "measured z component" "calculated z component" "residual z component"
27108.205 5000491.0 6040.0 66.76312 55.43412 11.329002
34989.69 4999910.0 6040.0 61.73326 53.930534 7.802725
42871.18 4999339.0 6040.0 64.05209 56.973095 7.078998
50752.676 4998778.0 6040.0 75.33136 60.72146 14.609901
58634.176 4998226.5 6040.0 77.31881 63.2091 14.10971
66515.68 4997685.0 6040.0 68.36469 64.44984 3.9148555
74397.19 4997153.5 6040.0 65.703705 65.785255 -0.08155286
82278.7 4996631.5 6040.0 68.181786 67.08897 1.0928235
90160.21 4996119.5 6040.0 64.13962 68.077194 -3.9375777
...
```

When continuing to process the station file externally, you should make sure that the software can process the header in the station file.

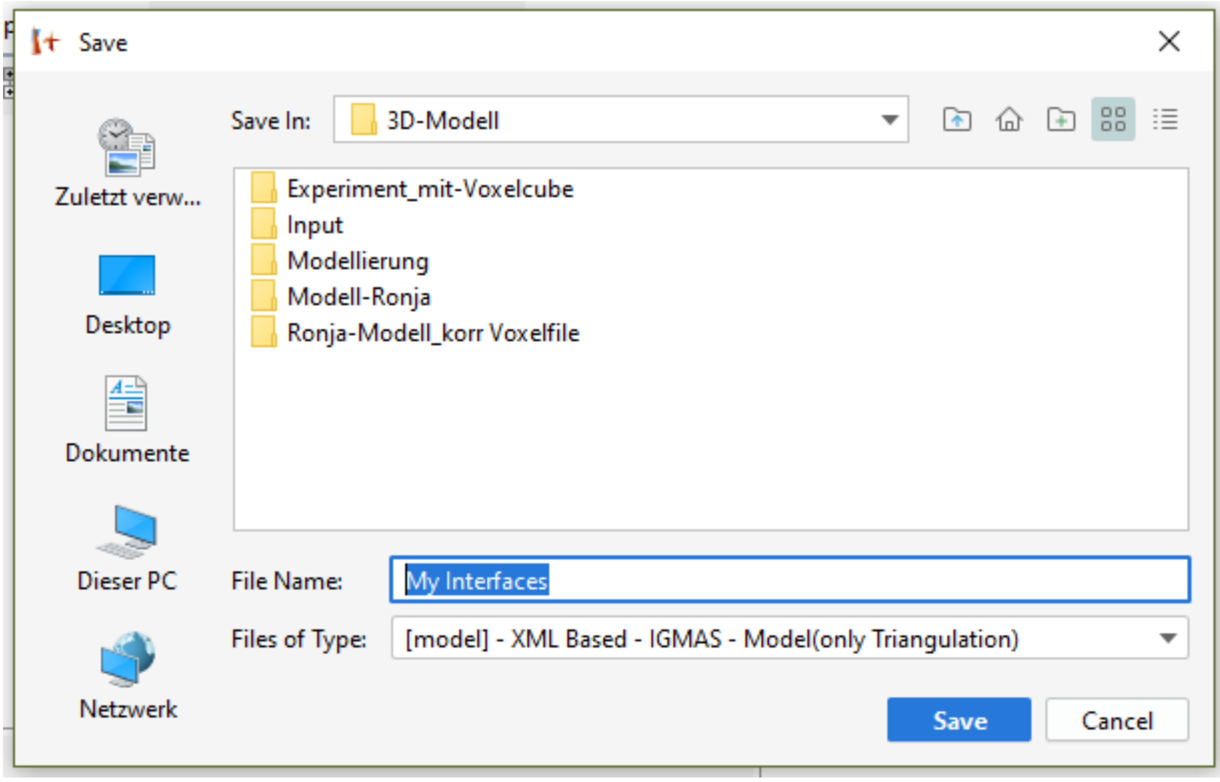


2.16.4 (4) Interface(s)

Select in the **TITLE BAR** Export > Exort > Interface(s)



and get the screen:



Check "the file "My Interfaces:

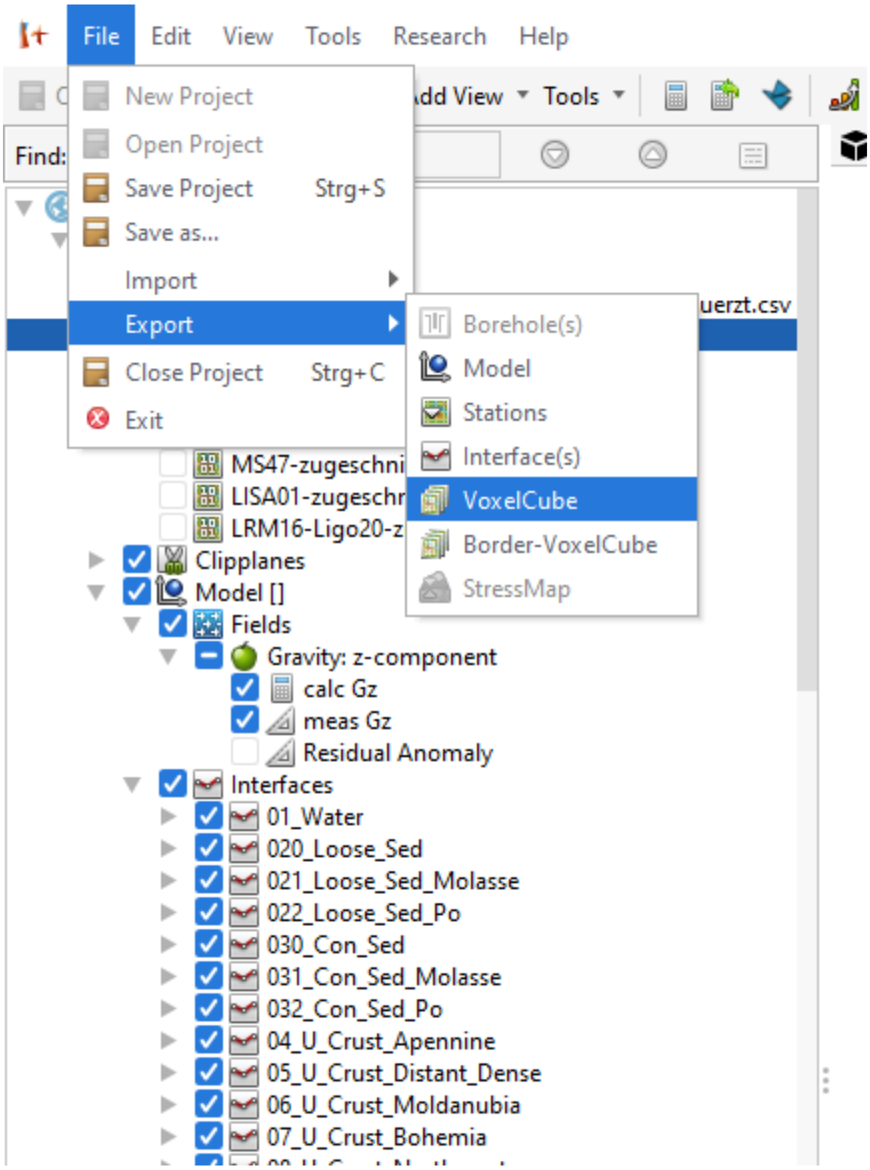
My Interfaces.model - Editor

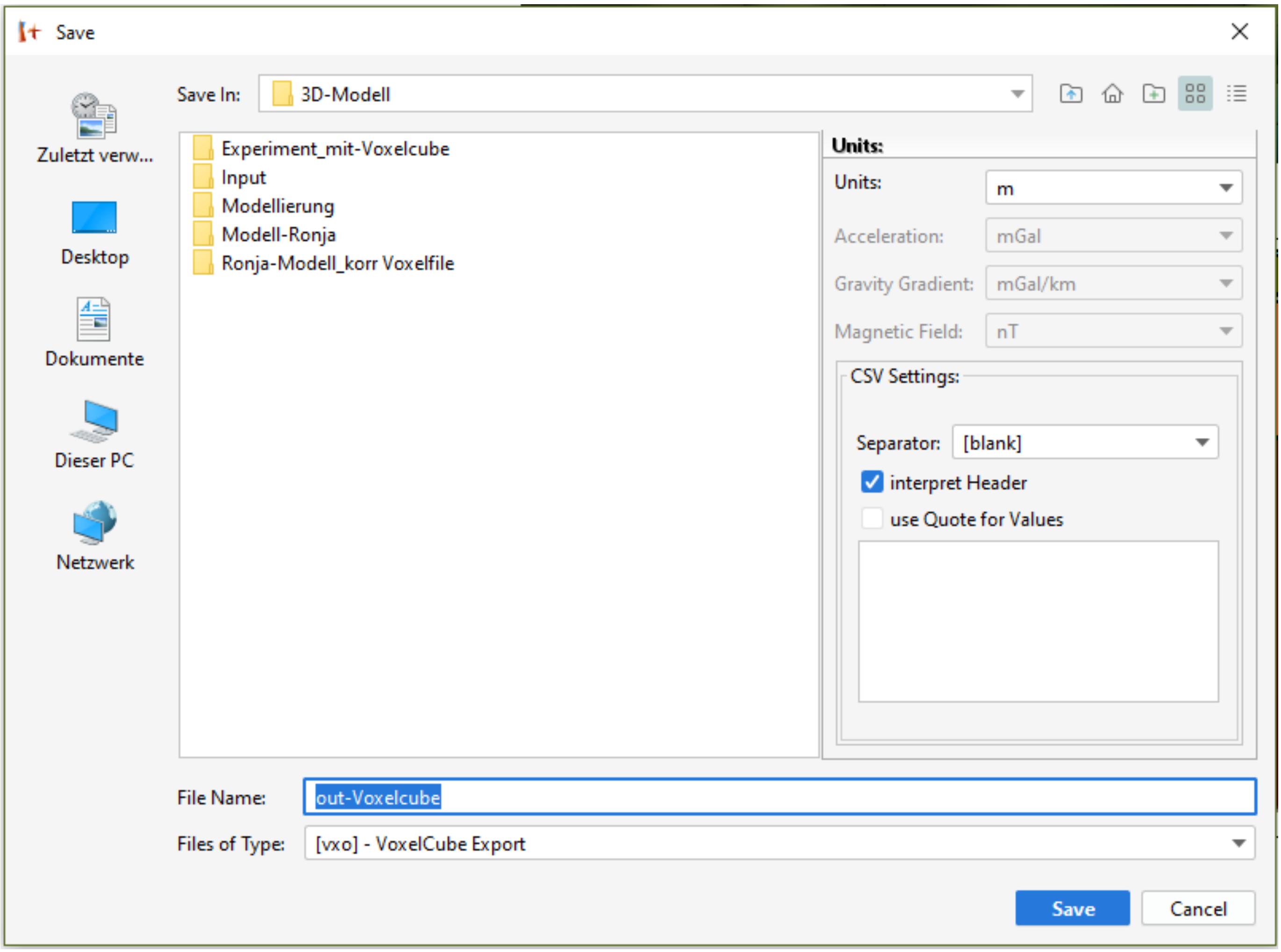
Datei Bearbeiten Format Ansicht Hilfe


```
<?xml version="1.0" encoding="UTF-8"?>
<!-- <!DOCTYPE geodata SYSTEM "geodata.dtd"> -->
<geodata name="">
  <projection name="utm" hemisphere="north" ref_mer="9" delta_x="0.0" delta_y="0.0" units="m"></projection>
  <magnetic_field units="nT" total_field="49441.0" inclination="69.0" declination="1.0"></magnetic_field>
  <property name="body" value="01_Water">
    <property name="voxel equation" units="SI" value="1.0">cellvalue</property>
    <property name="density" units="kg/m³" value="1024.999998"></property>
    <color red="1.0" green="1.0" blue="1.0"></color>
  </property>
  <property name="body" value="020_Loose_Sed">
    <property name="voxel equation" units="SI" value="1.0">cellvalue</property>
    <property name="density" units="kg/m³" value="2467.324788"></property>
    <color red="1.0" green="1.0" blue="0.2"></color>
  </property>
  <property name="body" value="021_Loose_Sed_Molasse">
    <property name="voxel equation" units="SI" value="1.0">cellvalue</property>
    <property name="density" units="kg/m³" value="2459.999996"></property>
    <color red="1.0" green="1.0" blue="0.2"></color>
  </property>
  <property name="body" value="022_Loose_Sed_Po">
    <property name="voxel equation" units="SI" value="1.0">cellvalue</property>
    <property name="density" units="kg/m³" value="2469.999997"></property>
    <color red="1.0" green="1.0" blue="0.2"></color>
  </property>
  <property name="body" value="030_Con_Sed">
    <property name="voxel equation" units="SI" value="1.0">cellvalue</property>
    <property name="density" units="kg/m³" value="2670.0"></property>
    <color red="0.4" green="0.8" blue="1.0"></color>
  </property>
  <property name="body" value="031_Con_Sed_Molasse">
    <property name="voxel equation" units="SI" value="1.0">cellvalue</property>
    <property name="density" units="kg/m³" value="2670.0"></property>
    <color red="0.4" green="0.8" blue="1.0"></color>
  </property>
  <property name="body" value="032_Con_Sed_Po">
    <property name="voxel equation" units="SI" value="1.0">cellvalue</property>
    <property name="density" units="kg/m³" value="2698.198993"></property>
    <color red="0.4" green="0.8" blue="1.0"></color>
  </property>
  <property name="body" value="04_U_Crust_Apennine">
    <property name="voxel equation" units="SI" value="1.0">cellvalue</property>
    <property name="density" units="kg/m³" value="2700.0"></property>
```

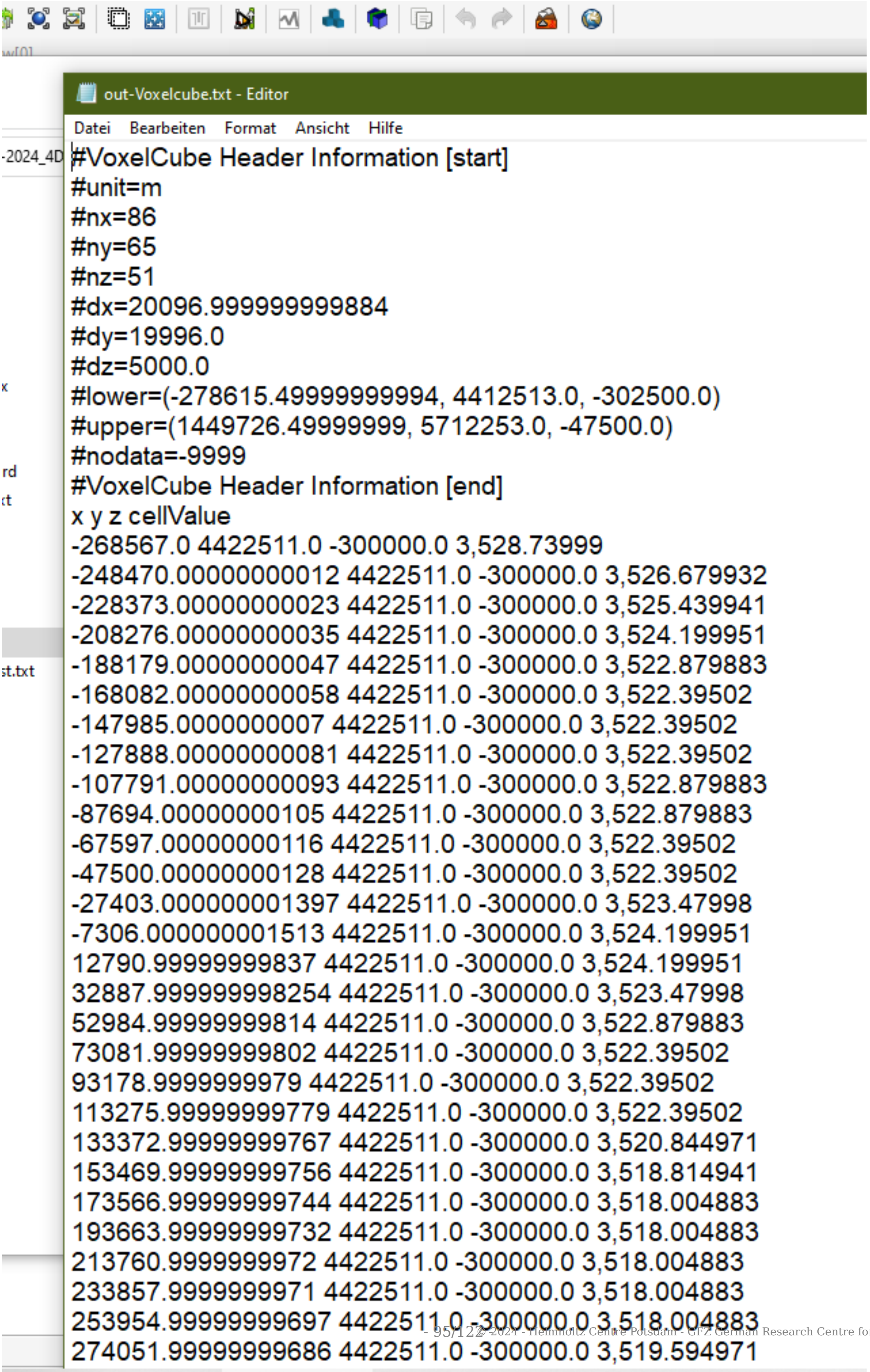

This ia large file (22 MB); here we prsent a short parge only to get information on its structure.

2.16.5 (5) Voxelcube





The saved Voxelcube always has the extension **".vxo"**. The file can be renamed without problems and get the extension ".***txt"*** - then it can be read with any editor.. The file-header and the first lines of the file look like this:




```
#VoxelCube Header Information [start]
#unit=m
#nx=86
#ny=65
#nz=51
#dx=20096.999999999884
#dy=19996.0
#dz=5000.0
#lower=(-278615.49999999994, 4412513.0, -302500.0)
#upper=(1449726.49999999, 5712253.0, -47500.0)
#nodata=-9999
#VoxelCube Header Information [end]
x y z cellValue
-268567.0 4422511.0 -300000.0 3,528.73999
-248470.00000000012 4422511.0 -300000.0 3,526.679932
-228373.00000000023 4422511.0 -300000.0 3,525.439941
-208276.00000000035 4422511.0 -300000.0 3,524.199951
-188179.00000000047 4422511.0 -300000.0 3,522.879883
-168082.00000000058 4422511.0 -300000.0 3,522.39502
-147985.0000000007 4422511.0 -300000.0 3,522.39502
-127888.00000000081 4422511.0 -300000.0 3,522.39502
-107791.00000000093 4422511.0 -300000.0 3,522.879883
-87694.00000000105 4422511.0 -300000.0 3,522.879883
-67597.00000000116 4422511.0 -300000.0 3,522.39502
-47500.00000000128 4422511.0 -300000.0 3,522.39502
-27403.00000001397 4422511.0 -300000.0 3,523.47998
-7306.00000001513 4422511.0 -300000.0 3,524.199951
12790.9999999837 4422511.0 -300000.0 3,524.199951
32887.999999998254 4422511.0 -300000.0 3,523.47998
52984.9999999814 4422511.0 -300000.0 3,522.879883
73081.9999999802 4422511.0 -300000.0 3,522.39502
93178.999999979 4422511.0 -300000.0 3,522.39502
113275.99999999779 4422511.0 -300000.0 3,522.39502
133372.99999999767 4422511.0 -300000.0 3,520.844971
153469.99999999756 4422511.0 -300000.0 3,518.814941
173566.99999999744 4422511.0 -300000.0 3,518.004883
193663.99999999732 4422511.0 -300000.0 3,518.004883
213760.9999999972 4422511.0 -300000.0 3,518.004883
233857.9999999971 4422511.0 -300000.0 3,518.004883
253954.99999999697 4422511.0 -300000.0 3,518.004883
274051.9999999686 4422511.0 -300000.0 3,519.594971
```

2.16.6 (6) Border-Voxelcube

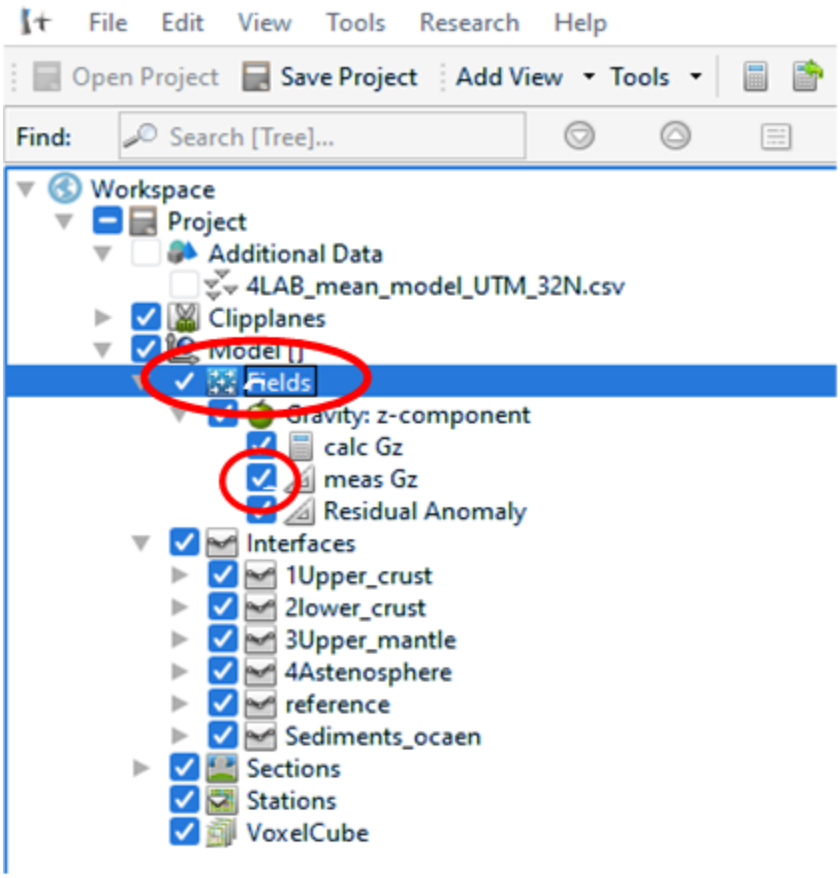
to be added

2.16.7 (7) Stress map (to be done)

2.17 Miscellaneous

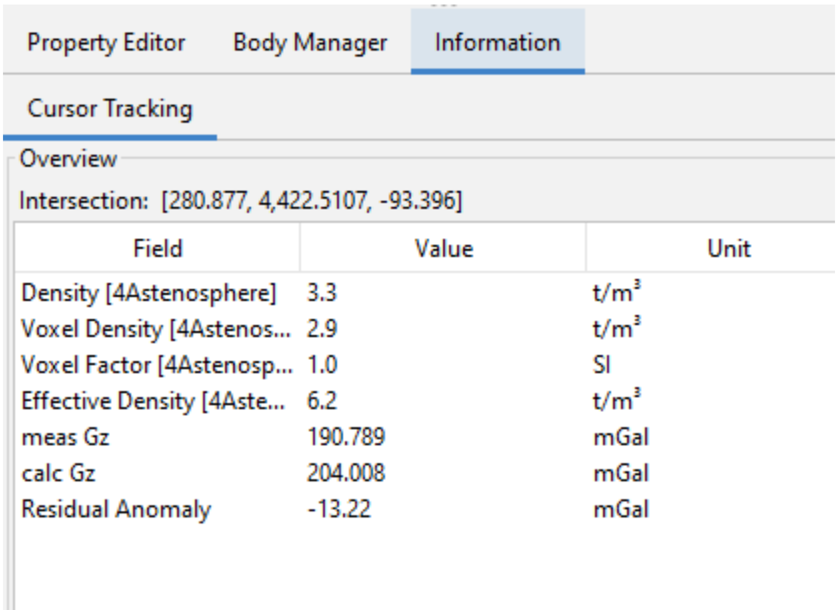
2.17.1 Switch on and off fields

Refer to **OBJECT TREE** an select **Fields.** If you don't want any fields to be displayed at all, uncheck the box with the blue checkmark in front of **Fields**. If fields are to be displayed, then expand the tree under Fields, by clicking on . By unchecking the blue tick boxes in front of the corresponding fields (*calc Gz* or *meas Gz* or *Residual Anomaly*), the corresponding field can then be switched off/off respectively.



2.17.2 Point information of model parts

In addition to the Property Editor and Body Manager, there is also the Information Tab. Click on Information > move the mouse over the screen. The window now shows the information about the respective item.


Property Editor
Body Manager
Information
Cursor Tracking
Overview
Intersection: [280.877, 4,422.5107, -93.396]
Field
Value
Unit
Density [4Astenosphere]
3.3
t/m³
Voxel Density [4Astenos...
2.9
t/m³
Voxel Factor [4Astenosp...
1.0
SI
Effective Density [4Aste...
6.2
t/m³
meas Gz
190.789
mGal
calc Gz
204.008
mGal
Residual Anomaly
-13.22
mGal

2.18 IGMAS+ Shortcut table

IGMAS+

Interactive Geophysical Modelling ASsistant

The Manual

List of Shortcuts

General Shortcut	Function
Ctrl + A	Add 2D View
Ctrl + C	Close Model
Ctrl + O	Open Model
Ctrl + S	Save Model
Ctrl + [F4]	close view tab
Ctrl + [F5]	detach/attach view tab
Ctrl + [PgUp]	toggle view tab (left)
Ctrl + [PgDn]	toggle view tab (right)
[Ecs]	Cancel
[f]	Fit to Screen

2D Shortcut	Function
[s] + [define region with left mouse button] + [move mouse]	Parallel-shift multiple vertices from within region with one move
[i] + [left click]	Insert / delete vertex
PgDown	Previous Section
PgUp	Next Section
[right click] + [move mouse]	Shift Section
[mouse wheel] or [alt] + [hold left mouse button click] + [move mouse up/down]	zoom in and out
[z] + [left click] + [move mouse]	zoom into region
[shift] + [left mouse button click] + [move mouse]	Shift Vertex
[d] + [left click] + [move mouse]	divide polygon between vertices (! with de-selected 'interactive modelling' !)
[x] + [left click]	select polygon (! with de-selected 'interactive modelling' !)
[v]	toggle vertex display

3D Shortcut	Function
Alt + [left click] + [move mouse]	zoom in and out

2024-02-02

3. Tutorial

3.1 Tutorial

Quote

You can't blame gravity for falling in love
— *Albert Einstein*

3.1.1 Preface

This tutorial provides a basic working concept of **IGMAS+** when used to investigate gravity and magnetic fields, including all aspects that need to be considered when starting an **IGMAS+** project. It is intended to bridge general textbook knowledge on gravity modelling with the specific "how-to" information given in other chapters. Hence, it provides both key words from the gravity research field (without repeating textbook contents) and definitions for **IGMAS+** specific terms which can be further looked up in the documentation.

3.1.2 Potential fields

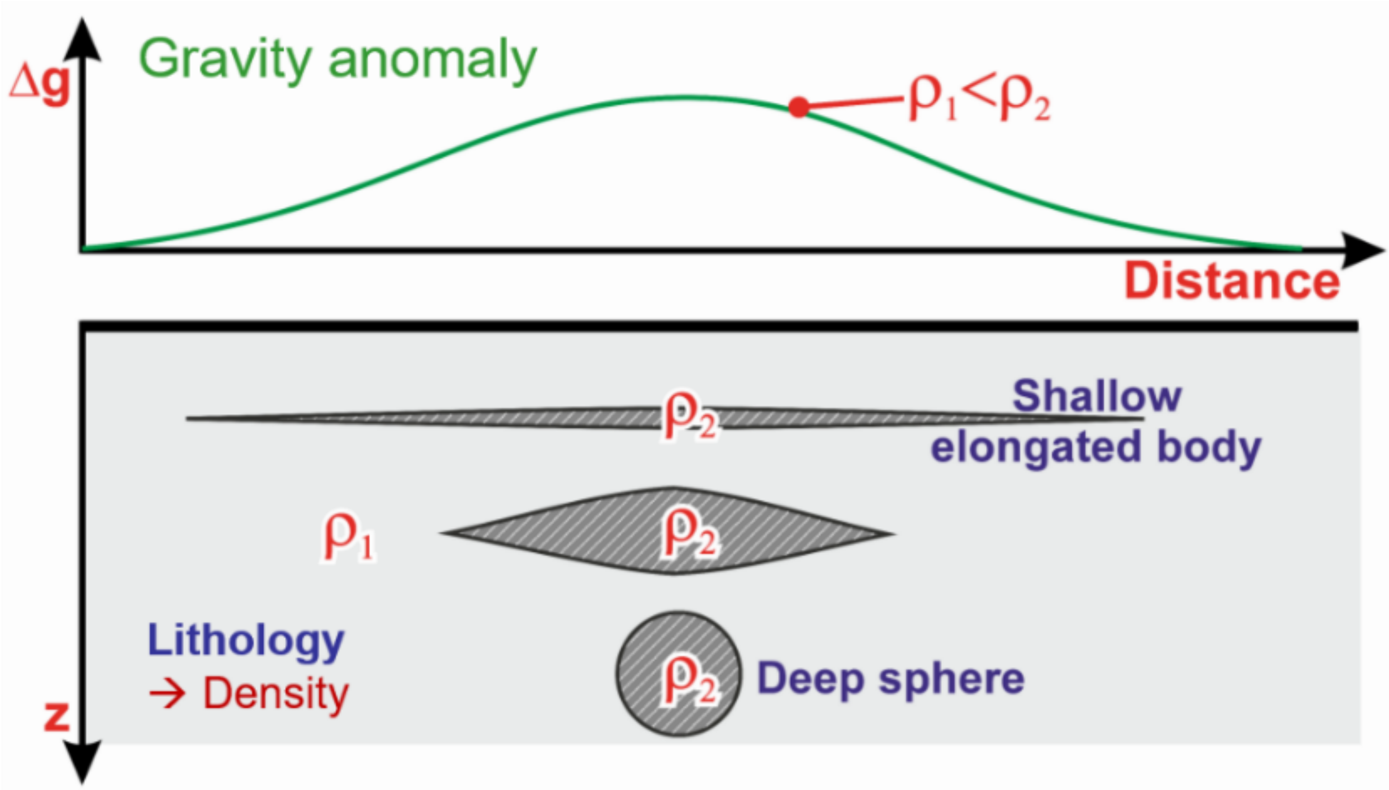
IGMAS+ calculates both fields of the potential methods: the gravity field and the magnetic field. It is user friendly and allows very fast calculations. In this tutorial we focus on the explanations with gravity field modelling. The calculation of the magnetic field of geological bodies is equivalent: one replaces the rock parameter "density" by the rock parameter "magnetic susceptibility" or, where it is necessary, by the "remanent magnetization" of rocks. All explanations are valid for modelling with both fields.

3.1.3 Gravity anomalies

Gravity anomalies - i.e. deviations from the normal field or theoretical gravity field of the Earth,

$$\Delta g = g_{measured} - \gamma_{normal}$$

provide us with insights into the geological structure and related density distribution of a region.
For a specific gravity anomaly, or, more realistically expressed, for an ensemble of anomalies to be explained, however, an infinite number of density distributions can theoretically cause these anomalies (see Figure).



Non-uniqueness of gravity interpretations. Three differently shaped bodies with density ρ2 are embedded in a material of lower density ρ1. The gravity anomaly above the section corresponds to only one of these bodies and shows a central high due to the density difference given. Without any other independent information (constraints) it cannot be concluded, which of the ρ2-bodies is responsible for the observed gravity anomaly.

Note the ambiguity of all potential field observations!

It is essential to the modelling philosophy of **IGMAS+** to overcome this ambiguity by means of gravity-independent observations (constraints). With this software package, *Free Air, Bouguer*- and *geoid anomalies* can be modelled (among others: Götze and Lahmeyer, 1988, Schmidt et al., 2011, Schmidt et al., 2020).

At the beginning of each modelling, the user should decide whether to work with **Bouguer** or **Free Air anomalies**:

- work with **Free Air anomalies** if no terrain and Bouguer slab corrections were calculated before and
- work with **Bouguer anomalies** if both corrections had been applied to measurements.

This is an important decision, because the model must be built accordingly. **IGMAS+** does not calculate one or the other anomaly, but the static part (attraction) of the gravity field of an Earth model, a sedimentary basin, a cavity or a mountain range which are represented as an ensemble of three-dimensional closed density bodies. For the following it will be agreed that the geophysical term "Free Air anomaly" is equivalent to the geodetic term "Disturbance".

Free Air anomaly (disturbance in geodesy):

$$FA = g_P - \gamma + \delta g_F$$

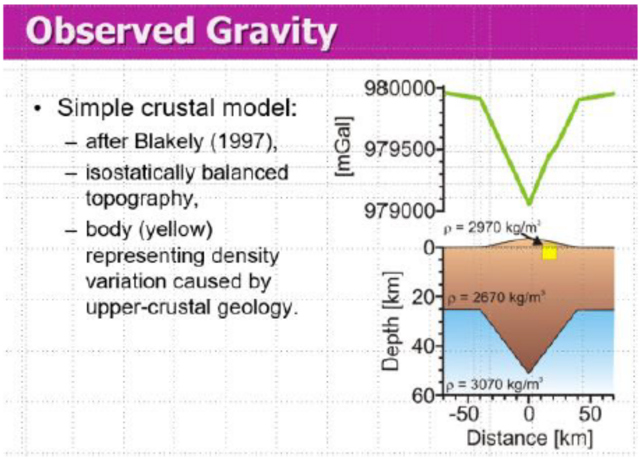
Bouguer anomaly:

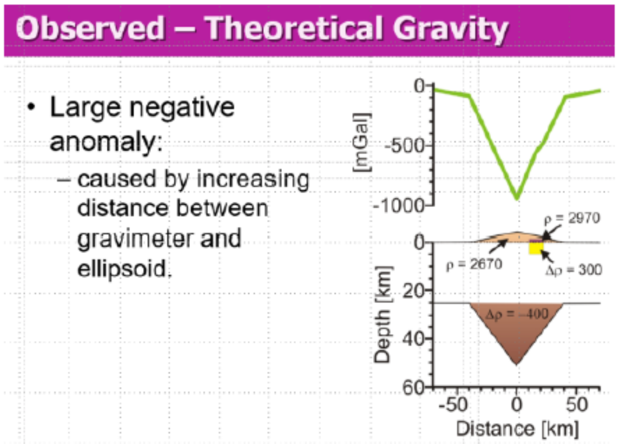
$$BA = FA - \delta g_B$$

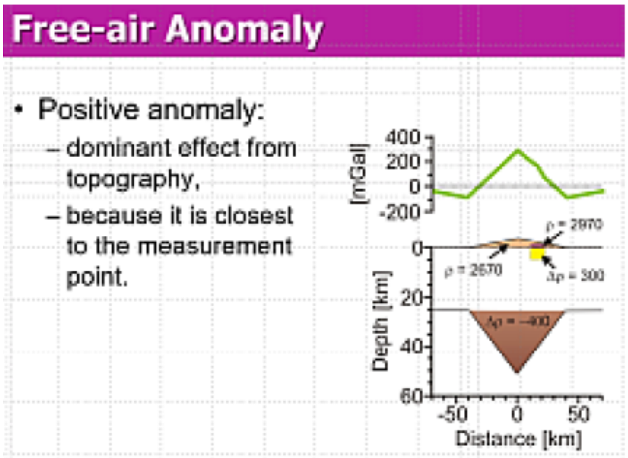
with:

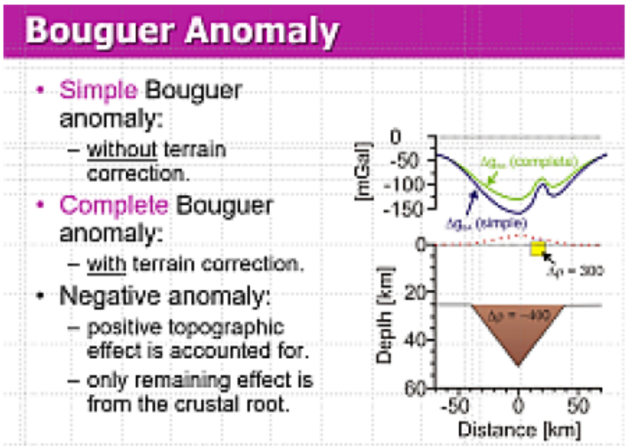
- g_P -- observed/measured gravity value at station P
- γ -- normal gravity at the ellipsoid
- δg_F -- Free Air correction (normal gravity at station P)
- δg_B -- Bouguer mass correction (gravity effect of masses between the station P and the ellipsoid)

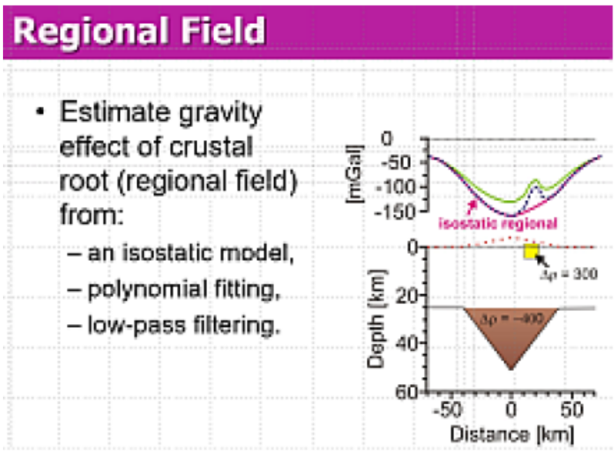
The cartoon illustrates the diverse processing steps which are necessary to calculate gravity anomalies.

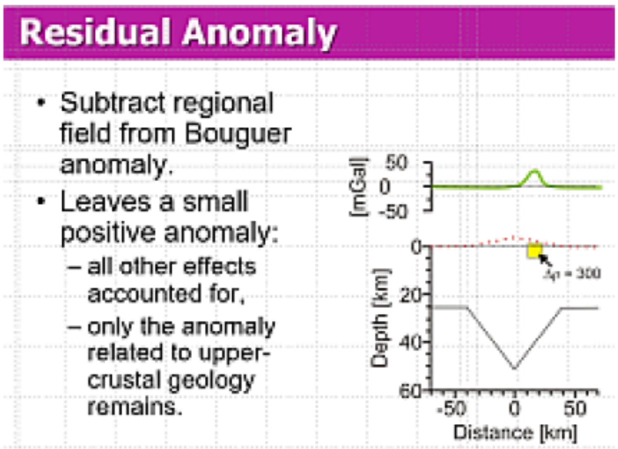












This cartoon visualises the various steps required to compute a geophysical anomaly and the resulting changes in the processed gravity field. The individual images are to be read from top left to bottom right. They are taken from a presentation by Ron Hackney & Hajo Götze (pers. comm.)

Calculation of γ, δg_F and δg_B is not a part of **IGMAS+** modelling and must be performed in advance. δg_F and δg_B are called correction terms, sometimes also ''reduction'' terms. The user should look more closely into these correction terms while using downloaded gravity fields from the ICGEM website.

IGMAS+ allows users to fit measured gravity observations to 3D and 2D density models and interactively compare the calculated fields to the observed anomalies. We mention ''observed anomalies'' and by this mean that comparative values of the gravity fields can originate from two different sources:

- Specific processed field measurements, or
- Global models like those available on the ICGEM website.

Please refer also to the remarks on the use of the ICGEM gravity datasets.

To obtain an interactively optimized fit between calculated and observed anomalies, users can:

1. manually adjust a density configuration by changing the density values and the geometries of density bodies
2. automatically invert a gravity field for a density configuration.

In this workflow, gravity independent observations (such as geological maps, borehole information, seismic velocities and discontinuities, cross sections derived from other geological and geophysical interpretations, etc.) are integrated at two stages:

1. when defining the density configuration of an initial 3D model and
2. when interactively modifying the model while simultaneously visualizing the independent constraints.

Common to all inverse approaches, the number of the "free" parameters (degrees of freedom) in the modelling process should be significantly reduced before the final forward field matching, respectively inverse density calculation. For example, the final modelling step may be limited to the adjustment of the thickness and the lateral extent of a model unit with the pre-defined density (variation). Fixing as many other parameters of the initial 3D density model as possible requires the input data of appropriate spatial coverage and (in the best case) "old familiar" uncertainties. On the other hand, the model should be kept simple, in other words, one should choose complexity just to be able to answer a properly defined scientific question.

Remember:

> **Quote**
>
> A model which images any detail of the reality is as useful as a map of scale one to one.
> — *Joan V. Robinson*

Note also the different scales for the individual results of the gravity calculations. This procedure must be done by the user before modelling.

2024-01-31

3.2 Setting up a density model

Quote

Lorraine, my density has popped me to you.
— George McFly, Back to the Future, 1985

For the modeller, each compilation of a density/susceptibility model always consists of two activities that result from a theoretical approach: a **body** must be defined which contains a mass/magnetic material (here density and/or susceptibility), and the distances from stations where the gravity and/or magnetic fields were measured. Therefore, model stations must be defined (see below).

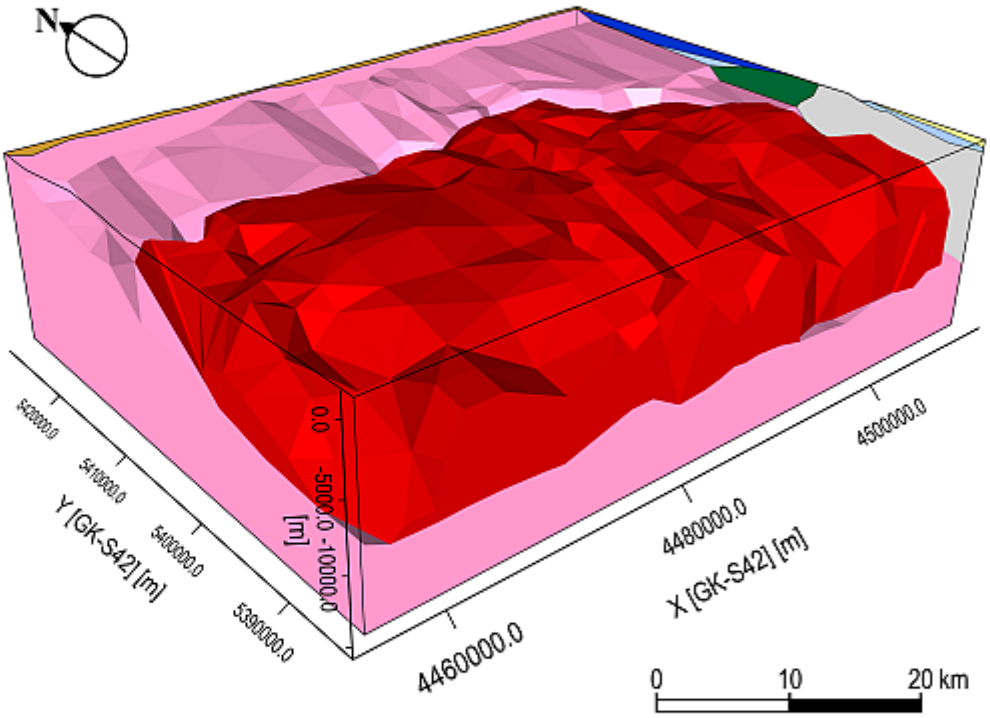
At first, the origin point of the model (its zero point) has to be fixed, which is not only the origin of model geometry, but also of model stations, of the corresponding gravity/magnetic fields which should be matched, of the voxel cube and of any available additional map information, for example from a geographical and/or a digitized geological map.

We start with the explanation on how to handle the bodies and densities and continue with the explanation for stations.

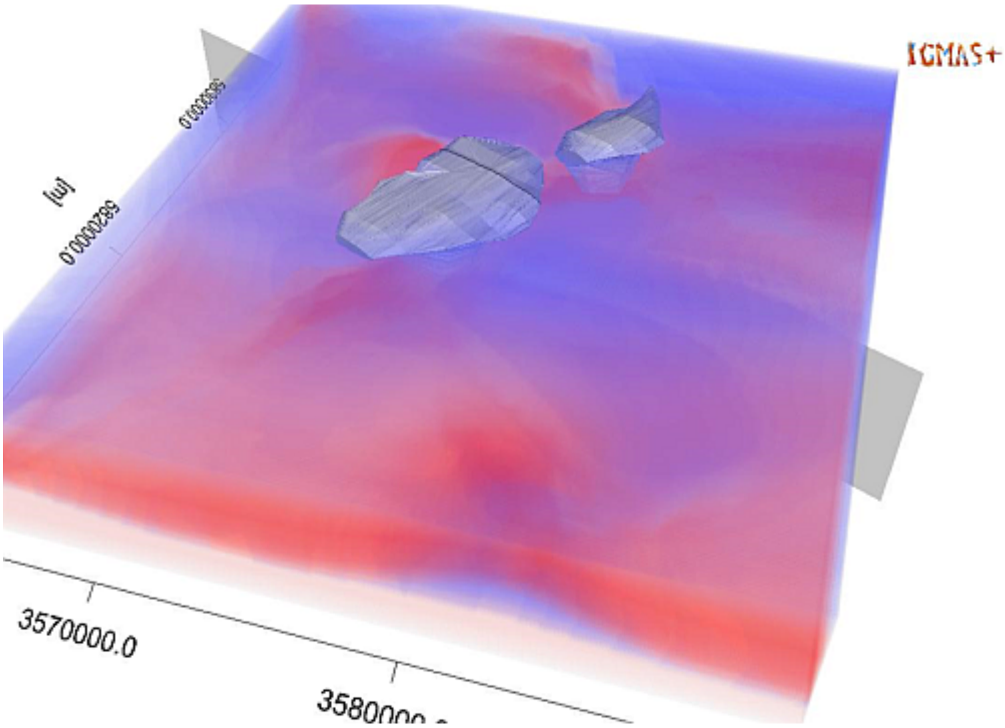
3.2.1 Model bodies

In **IGMAS+**, density in space can be defined either in terms of

1. triangulated polyhedra surrounding a certain volume of constant density, or
2. a 3D **voxel cube** containing numerous voxels, each carrying its own density value.



A model with two polyhedra of constant densities (pink and red).



A voxel model defining sedimentary density structures.

All polyhedra with the same density definition make up a model **body** (Body Manager), while a single model body may be divided into several geometrically separated polyhedra (called "**indexed body parts**"). The hull of a polyhedron is composed of interfaces and the geometry of each interface is defined by vertices.

The user-defined positioning of these **vertices** is crucial for the triangulation process by which **IGMAS+** geometrically approximates the 3D density structure.
The obtained model topology is defined based on the position of such vertices on pre-defined, parallel oriented, vertical planes (vertical **working sections**).

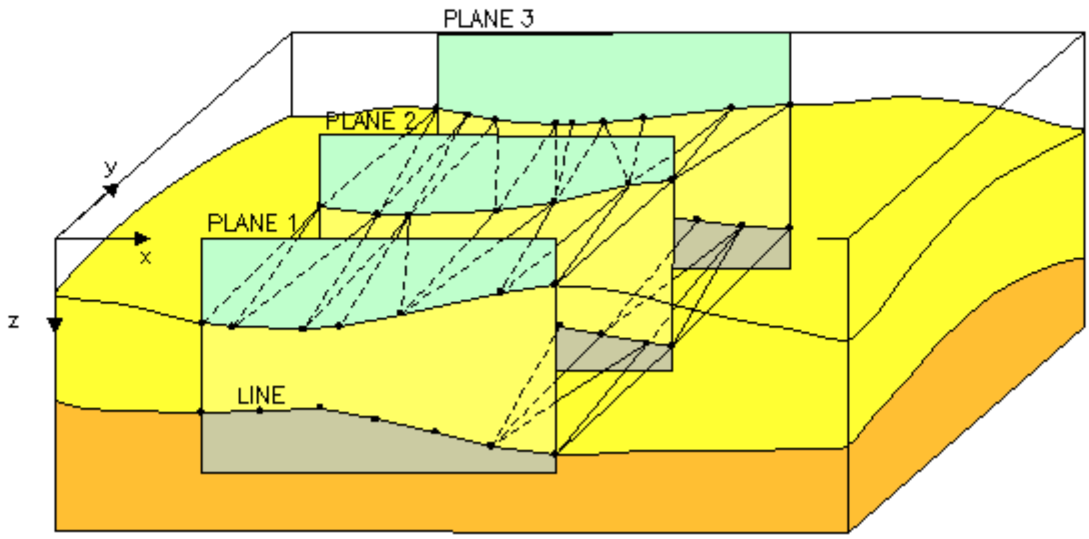


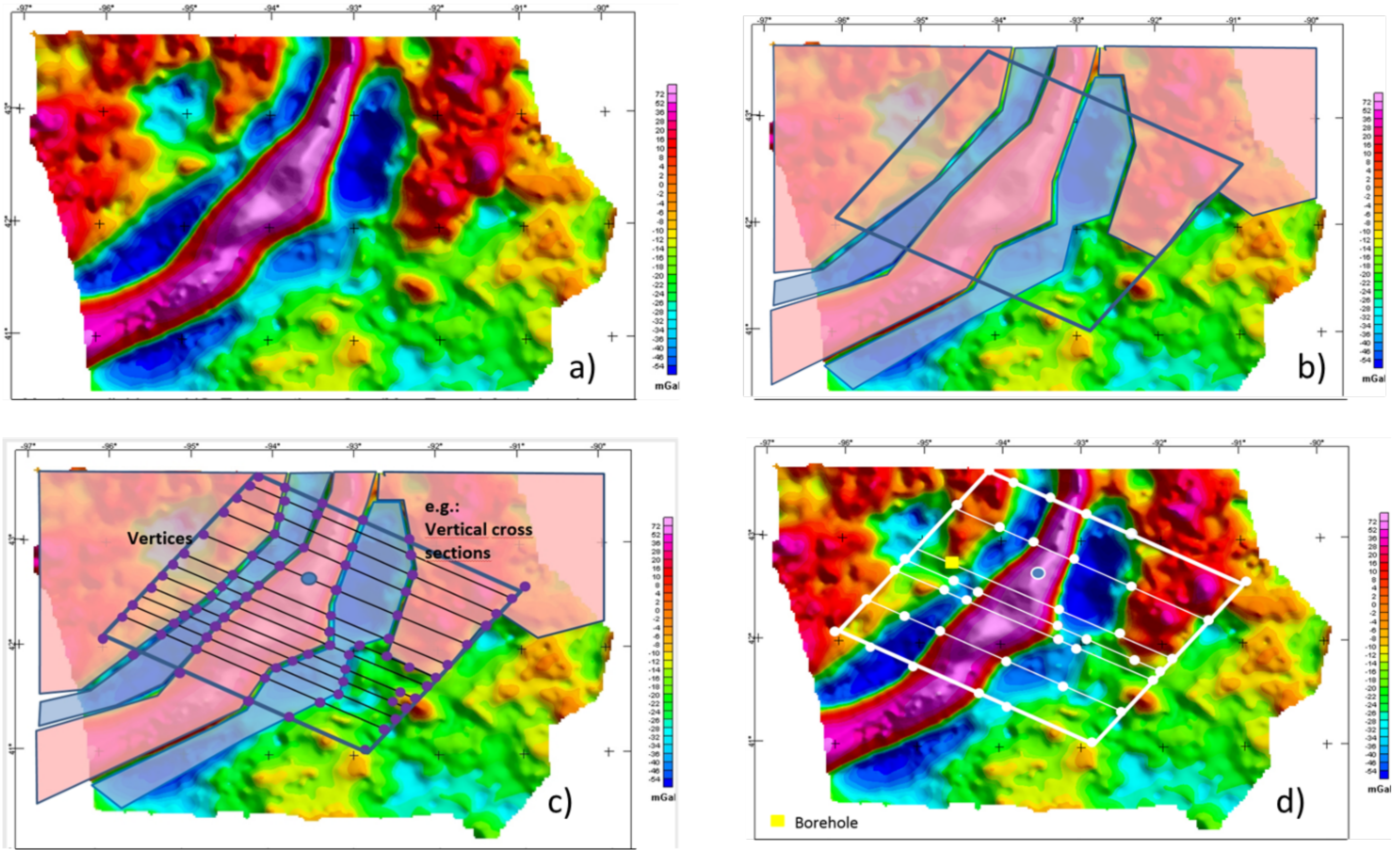
Illustration of basic terms for IGMAS+ model construction: vertices (black points), triangles (black lines), and working sections (vertical planes).

These working sections are the virtual scenes for implementing any interactive modifications of model geometries, for example, by **adding**, **deleting**, or **moving vertices**.

In case the model is built on **working sections**, there are no vertices located between the working sections. The user therefore should define the number, spacing and horizontal orientation (strike direction) of these working sections:

1. to keep sufficient control of model geometries throughout the interactive modelling process, and
2. to allow for a proper analysis of elongated gravity anomalies (i.e., orient working sections perpendicular to the strike of major anomalies).

Working sections are always parallel:



Four steps that are important when defining the geometry of the model bodies by “sections”. (a) Decide which anomalies should be modelled. (b) Select the area to be modelled. (c) Mark the sections on the area to be modelled and define the intersections of the sections with the anomaly. (d) Consider which of the sections and the intersections are really important to model the anomaly correctly.

> **Tip**
>
> Remember: the simpler the model - the better it is.

IGMAS+ calculates gravity effect either for a flat or a spherically curved model. The latter is required for very extensive model domains. To get an impression of the Earth surface "depression" of a spherical model compared to a flat one, note the following numbers:

Distance [km]	Depression [m]
10	7.85
50	196
100	784
200	~3000
250	~5000

In addition, it should be considered that in a spherical model the calculation of the direction of the vertical component changes continuously according to the curvature of the Earth because it always points to the centre of the Earth. Thereby, a spherical model assumes that the Earth is approximated by a sphere; an elliptical shape cannot yet be realized (but this is negligible for many lithosphere modelling applications). Test calculations have shown that for a model extending by, e.g., 2000×2000 km^2 and reaching a depth of 200 km, there is a difference in calculated gravity between a spherical and flat modelling approach of about $20 - 25 \times 10^{-5}$ m/s^2 ($20 - 25$ mGal).

Depending on the user’s objectives and the characteristics of gravity/magnetics independent information at hand, there are basically three different ways of building up an initial 3D density model ready to be analyzed in terms of its gravity/magnetics effects:

- a) “Defining sections” approach: define working sections before loading or creating model vertices.
- b) “Loading layers/interfaces/horizons” approach: load point sets forming body interfaces before defining working sections.
- c) “Loading a voxel cube” after defining the model space according to (a) or (b)

When selecting the **“sections” approach (a)**, the user builds the model from scratch by first defining the 3D model extent and the vertical (working) sections and then loading or creating vertices to construct interfaces that separate bodies of different density. Any gravity-independent data which are loaded into the obtained model space to help constructing the density bodies (e.g., bitmaps, point sets) can be projected and visualized on the vertical sections.

In this case, the sections should be appropriately positioned to keep the projection-related distortions of observed structures small. Since all vertical sections need to be parallel, it might not be possible to represent all available structural information ideally in the model domain. Hence, option (a) suits well to solve generic problems independent of correctly geo-referenced structures. Additionally, the approach may be selected if the spatial coverage of gravity-independent structural input data (e.g. seismic profiles, boreholes) is very limited with respect to a larger number of observed gravity anomalies. For example, the interpreted structure of a single 2D seismic section could thus be continued laterally by inferring a variety of consistent 3D models from the observed gravity field. Thereby, one would strategically start with a simple density configuration and increase the model extent and complexity stepwise.

If the spatial coverage of structural input data is dense enough and the depth/thickness configuration of several density bodies can be derived directly and modelled outside of **IGMAS+**, then the **“layer” approach (b)** offers the proper functionality. In this case, the user can load continuous **interfaces** or **horizons** -- sets of regularly or irregularly spaced points with XYZ coordinates. Each horizon defines the top of a spatial domain that -- according to gravity-/magnetics-independent observations -- has been identified as a potential contrast in density with respect to adjacent domains. The loaded interfaces/horizons are stacked by IGMAS+ and collectively define the default 3D model extent (to be changed optionally), while the working sections are defined only after this stage. As part of the model building process, **IGMAS+** interpolates between the loaded XYZ points of a horizon, derives the intersections of the horizon with the working sections and accordingly creates a number of vertices positioned on the latter. Hence, the initially loaded point sets are not identical with the final vertices representing a horizon! Care should be taken that the **horizons/layers/interfaces** do not intersect each other (corresponding to a negative thickness of the respective layer in between).

Generally speaking, there are no specific suggestions for the use of case (a) or (b). Recently, there has been some preference for the use of case (b), since many modelers prefer to work with predefined layers from open databases (for example CRUST1.0, LITHO1.0, ETOPO1 and many others). Layers cannot be eliminated from the model afterwards. But you can assign the same density to the horizon as to its neighbouring horizons, to the side of it, above it or below it. Then it has no more gravity effect on the model stations.

After setting up a model either following approach a) or b), one or several model bodies may be selected for **"voxelization" approach (c)**, i.e., for being differentiated into numerous voxels, each carrying its own density value. In this way, smaller-scale density variations derived from independent observations (e.g., seismic, mineralogical-petrological) can be superimposed on the geological structure and considered for the gravity calculation. Each voxel is associated with an effective density representing the sum of:

1. a constant body density, and
2. a voxel density.

One way of defining the voxel density is to first create a voxel grid and then apply a certain function to implement physical laws or empirical concepts such as seismic-velocity-to-density conversions or depth-controlled porosity-density functions. Alternatively, the voxel cube may be defined completely by data import including both the coordinates and density values of the voxels. Additional **IGMAS+** functionality related to voxel cubes is provided in terms of:

1. multiplication of the voxel density with a voxel factor for fast model modifications,
2. automatic edge effect minimization and
3. transformation of voxel-related density variations into triangulated isosurfaces.

> **Note**
>
> Currently only one voxel cube can be applied to an **IGMAS+** model.

3.2.2 Model densities

Concerning the **density value** assigned to each model body, it does not matter if absolute or relative density values are chosen, since the resulting gravity effect only depends on the density differences at modelled interfaces and the distances from stations. This implies that gravity modelling alone cannot determine absolute values of densities.
For a deeper understanding of these statements, a more detailed description of the basic mathematical-physical formulas for the calculation of the gravity effect in **IGMAS+** would be beneficial. However, this would go beyond the scope of this tutorial. Therefore, the original publications by Götze and Lahmeyer (1988) or by Götze (2014) are recommended.

3.2.3 Model stations

The observed and calculated gravity fields are defined at the stations, each being defined by its XYZ coordinates. The station height (Z) refers to its elevation with respect to the geoid, in case of elliptical coordinates -- also to the ellipsoid. It either represents the vertical position of the original gravimeter measurement (daylight surface for terrestrial data, height above the sea level for ship data, flight height for airborne and satellite data, etc.) or a reference level to which the acquired remote data have been continued (see chapter "Fitting gravity anomalies" and Figures for CBA (simple), FA (simple) and FA (difficult)). The only condition that must be met for the height of all stations is that they must be located above all model masses. It has its meaning for modelling exclusively when using Free Air anomalies.

Practical experience and examples for heights of the user-defined reference level can be found here:

Mountain range	**Top mountain**	**Minimum height of the reference level (m)**
European Mittelgebirge (low mountain ranges)	Brocken (Germany)	1500
Eastern Alps	Großglockner (Austria)	5000
Western Alps	Mont Blanc (Italy/France)	6000
Andes	Aconcagua (Argentina)	7000
Himalayas	Everest (Nepal/China)	8000

Note that to avoid numerical/theoretical problems (namely, local outliers in the calculated gravity), the stations should neither be located inside a model body nor precisely on its edges or surfaces (hence, check the Z values with respect to the top of the uppermost model body).
In case of doubt, add 13 cm to the height of the body surface -- the height of the gravimeter measuring system (see Figure).

The spatial coverage and spacing of the stations (i.e. their XY coordinates), together with the wavelengths of the associated observed anomalies, provide limits to the scales and resolution of subsurface density heterogeneities that can be derived -- an important aspect when planning a gravity modelling project.
In the context of resolution, **IGMAS+** allows gravity calculations for a large number of stations -- but user should keep in mind the memory size limit.

In general, there are two different types of station data that **IGMAS+** users may use: irregularly or regularly spaced data. When working with original irregularly spaced measurements (i.e. scattered and clustered XY station coordinates), the observed and the modelled gravity have the same relative position with respect to the causative density bodies. If one chooses to interpret anomalies that have been transferred to a regular grid (e.g., by use of ICGEM data sets, or other grids), however, one accepts that the model bodies have a smaller effect with respect to the stations than the real bodies due to interpolation procedures. Hence, it is generally recommended to use irregularly distributed stations instead of gridded gravity data.

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3.3 Modelling field components and gradients

IGMAS+ allows modelling of the three components of gravity (G_x, G_y, G_z) of which G_z, the gravity field, is typically used for density modelling. In addition, the six independent tensor components of the gravity gradient (G_{xx}, G_{xy}, G_{xz}, G_{yx}, G_{yz}, G_{zz}) can be calculated.
Gradients provide a higher resolution than the vertical component of the gravity field. The calculation of gravity mass effects require:

1. a successfully triangulated model geometry,
2. bodies to be assigned with density values, and
3. stations to be located in the study area.

Note on magnetic modelling

As just described for the gravitational field, modelling of the Earth's magnetic field (H) is also possible if the modelling parameters are given (i.e. triangulated model bodies with defined magnetic susceptibility but also magnetic remanence). **IGMAS+** thus yields the three components of the magnetic field (H_x, H_y and H_z) and the six independent gradients for the magnetic field components (H_{xx}, H_{yy}, H_{zz}, H_{xy}, H_{xz} and H_{yz}).

IGMAS+ uses the algorithm of Götze and Lahmeyer (1988) to calculate the effect of a homogeneous polyhedron on gravity by transforming the volume integral into a sum of line integrals by the application of theorems of potential theory. The fields are first calculated for each station and each interface (i.e. the set of triangles separating two bodies) separately and then the effects of all interfaces are summed up to obtain the total amount at a station.
Likewise, the anomaly effect of a voxel model is calculated independently and then added to the effects of the remaining **IGMAS+** model for each station. Thereby, each voxel is approximated by a sphere with its volume being identical to the volume of the voxel. The default of the gravitational constant used for any gravitational calculation is $G = 6.67384 \cdot 10^{-11}\,\mathrm{m}^3\,\mathrm{kg}^{-1}\,\mathrm{s}^{-2}$.
The value of G used in **IGMAS+** may be changed by the user following the recommendations of the Committee on Data for Science and Technology (CODATA).

3.3.1 Handling modelling shift

There is a general gap in magnitude of the measured gravity and the calculated gravity of an **IGMAS+** density model. Gravity *measured* in the field is always caused by masses of the entire Earth. The *modelled* value in **IGMAS+** is much smaller in spatial extent and therefore consists of less mass. To handle this problem, **IGMAS+** operates with a **shift value**, thereby assuming that all far-field effects not considered by the **IGMAS+** density model cause a constant offset in the calculated with respect to the observed gravity. By default, this shift value is derived from the gravity field values at all stations as follows:

$$\mathrm{IGMAS}_{shift} = \mathrm{mean(observed\ field)} - \mathrm{mean(modelled\ field)}$$

The derived shift value (alternatively, a user-defined one) is then added to the preliminarily calculated ones:

$$\mathrm{calculated\ value} = \mathrm{modelled\ value} + \mathrm{shift}$$

This correction is updated after each modification of the calculated anomaly. By introducing the shift value, the absolute differences between the observed and calculated anomalies are suppressed in support of the relative differences, which helps identifying and localising domains of mass deficit or mass excess, in the density model. Figuratively speaking, this means that the two fields are numerically merged so that their mean values are identical. This is necessary to make the phase (maxima and minima) and the magnitudes of these anomalies directly comparable in order to get information about the plausibility of the underground structures.

3.3.2 Handling edge effects

If the density of the space surrounding an **IGMAS+** model was not defined and thus actually set equal to zero, the stations close to the model borders would reveal gravity edge effects according to the large density differences at the marginal interfaces.
In **IGMAS+** there are two solutions to this problem.

The first one is to introduce a **reference density** (refer to Body Manager) which in fact has two different meanings: first of all, it is a user-defined density assumed to be present wherever there is no model body, including the entire surroundings of the 3D model. Hence, an isolated body would automatically be surrounded by the reference density. Secondly, the reference density is subtracted from all defined densities (i.e., reference and body densities) and any gravity effects at the stations are calculated from the resulting density differences. Hence, if the reference density is chosen to correspond to an average density at the model borders, the unwanted edge effects can be substantially reduced. No reference susceptibility is needed. Further minimization of the edge effects may be obtained through the integration of a layered background reference model which accounts for general density trends, such as an overall increase with depth.

> **Note**
>
> The case with a layered background reference model has not been yet described in the documentation.

The following sequence of inputs is recommended:

- Click on Model in the "Control Window"
- Click on "Property Editor"
- Select "Border Effect" and then "Border Algorithm"
- Select "Voxel Border Effect Kernel" and define a Density-Depth function
- This will define a layered background model.

The second strategy for reducing the edge effects of flat **IGMAS+** models is to **extend the model space** for anomaly calculations beyond the initially defined model. Therefore, the four vertical border planes of the model are automatically mirrored to a set of new borders and the respective density structure is laterally continued in between. Per default, the amount of lateral extension is tenfold the total vertical depth range of the initial model. For example, we assume a vertical model extension of 100 km. Then the lateral model extension to each side should be larger or equal than 1000 km.

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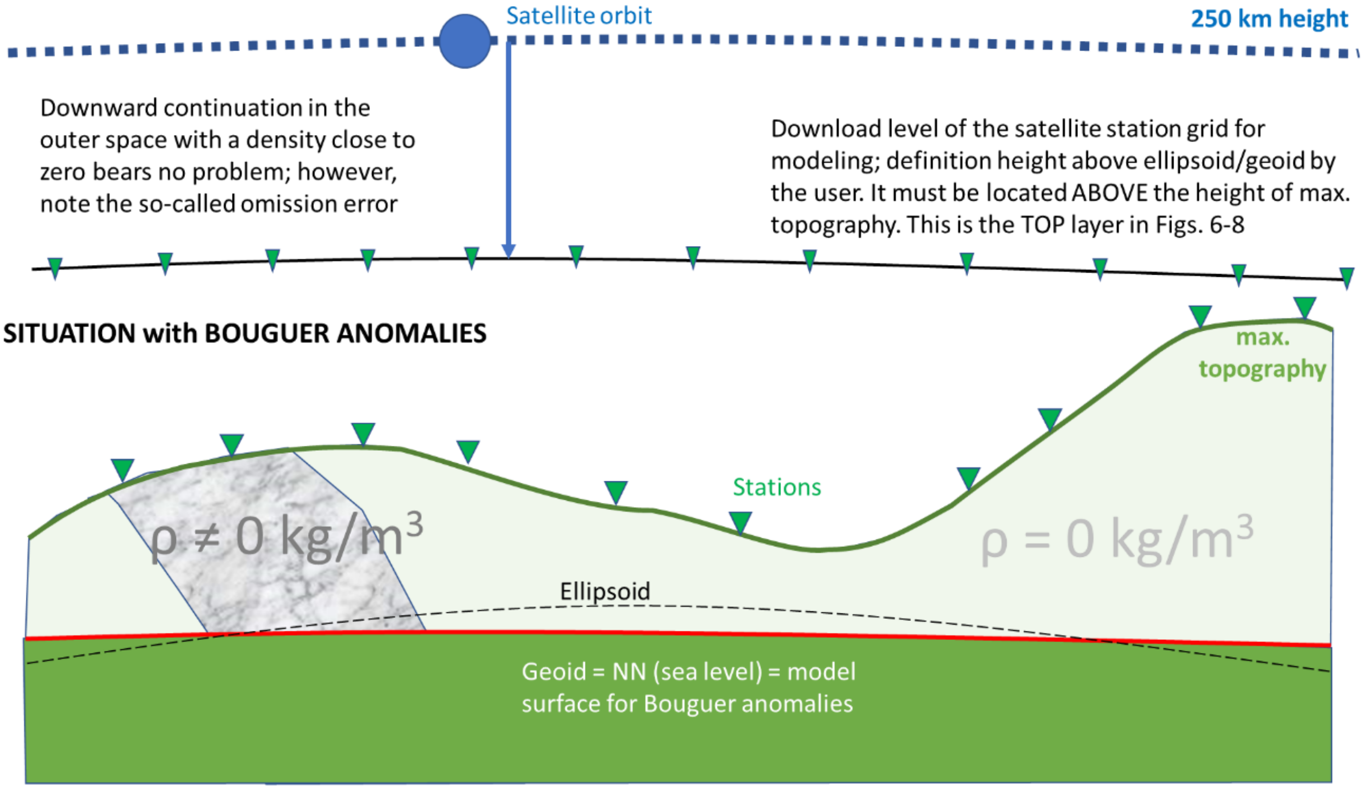
3.4 Fitting gravity anomalies

IGMAS+ is designed for analyzing the time-independent subsurface density contributions which cause the gravity field; hence, anomalies to be analyzed should already be corrected for the effects related to instrumental drifts, Earth tides, the “normal gravity” reflecting the effects of flattening and the centrifugal force as well as the free air and/or mass corrections.

Note on magnetic modelling

For magnetic field modeling it is important to eliminate the International Geomagnetic Reference Field (IGRF), which describes the Earth's main magnetic field generated in the Earth's core. In the following, some important remarks are provided that need to be considered when modelling Bouguer and Free Air gravity anomalies. Magnetic field modelling is performed like modelling of the Free Air anomalies, since normally no magnetic effects of the topographic masses are subtracted from the field measurements.

3.4.1 Complete Bouguer anomaly (CBA): the "simple" situation



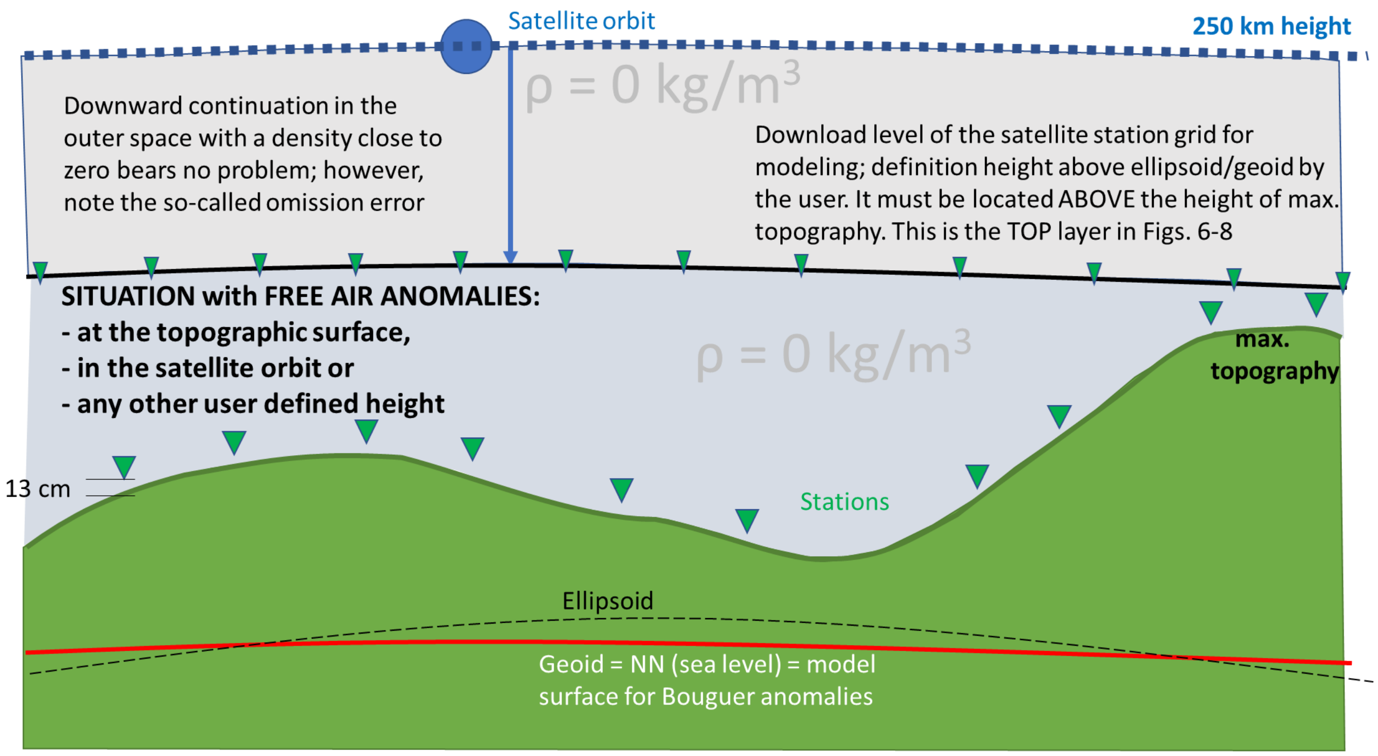
Modelling the complete Bouguer anomaly (CBA). Data are collected at the green stations (triangles) on the topographic surface or in the orbit of satellites (stippled line) or on any other height level outside the model bodies (small green triangles). After definition of Bouguer anomalies the masses between ellipsoid/geoid are removed. It is irrelevant whether the ellipsoid or the geoid is the reference surface.

1. The gravity effects of the topographical masses have been eliminated from the measured values by the mass correction. This means, the terrain correction is included, accounting for the deviation of local topographic features by a flat or a spherical slab. Therefore, the background of the topo-masses is drawn transparent and bright in Figure. Stations of the terrestrial measurements are indicated by the green triangles; satellite gravity is measured at the orbit level (blue stippled line in Figure).
2. The density model extends to the geoid/ellipsoid surface. The model stations lie on the topography, at the orbit height or at any other user defined height. It must be ensured that model stations are identical with the heights and positions of gravity stations in the field/airplane or satellite orbit.
   Note: The density model is bordered by a constant model surface (geoid) as well as by a constant model bottom surface if model is built by vertical sections (refer to chapter "Model bodies", approach (a)). In case where horizons are used for model building (chapter "Model bodies". approach (b)), we face a special situation which is described later: a body with the density “0” is added automatically by the software.
3. It is irrelevant whether the modelling of satellite gravity is done at the orbit height, or at an arbitrarily chosen level (black with green triangles in Figure) above the highest elevation. It should be noted, however, that in the case of downward continuation of the satellite gravity field (from the satellite height to the arbitrarily chosen level), the so-called **omission error** (geodetic term) increases the further the chosen level is moved downwards. Reason: the gravity at the orbit height does not contain any small gravity wavelengths anymore, so that errors/inaccuracies/etc. are increased when the field continues downwards (through the massless space) and overlay the increased measurement signal.
4. The reference density of a model can be set arbitrarily by the user if the model structure does not cause a significant boundary effect.
5. It becomes difficult if not all mass effects between the surface and the reference surface (geoid/ellipsoid) could be eliminated because the rock densities deviate from the correction density (usually 2670 km/m^3). This information cannot be derived directly from gravity field modelling but must be extracted from independent information (e.g., geological maps and/or rock density determinations). In this case these deviating volumes must be later remodelled with a differential density:

$$\Delta\rho = \rho_{\text{rock mass}} - \rho_{\text{mass correction}}$$

3.4.2 Free Air anomaly (FA): the "simple" situation

In contrast to CBA, in the "simple" case of Free Air anomaly no mass correction is performed, so all masses in the model are preserved - including the topographic masses.
The surface of the density model is now topography-dependent.



Free Air anomaly (FA): the "simple" situation. As in the case of complete Bouguer anomaly, stations are positioned in the satellite orbit, on the terrestrial surface marked by green triangles or at any user defined height level (small green triangles).

The terrestrial stations remain in the positions and at the heights as shown in Figure. If original satellite gravity is used for modelling purposes, those remain at the orbit height. If a grid with satellite gravity values (e.g. from the ICGEM data bases) is used, it can be extended down to any user-defined level (black line in Figure). Again, be careful: the omission error must be considered.

Attention:

One can "design" the surface of the density model using the heights of the stations and subtracting $13\,\mathrm{cm}$ from each station height:

$$(\text{heights of gravity stations}) - 13\,\mathrm{cm} = (\text{height of model top surface})$$

It is a **TIME CONSUMING PROCEDURE** to check for all model sections whether the surface of topographic masses is $13\,\mathrm{cm}$ below the stations. The **IGMAS+** developers are currently working on a much simpler method to use 3D topographies in the modelling. The result will appear in one of the next releases.

The value of $13\,\mathrm{cm}$ comes from the height (above the "ground") of the gravity meter measuring system of LaCoste-Gravimeter. If gravimeters of other companies are used, the measuring system height must be modified. Otherwise, one can assume an "overall" model station height of $1\,\mathrm{m}$ above the model surface; the error in larger crust/lithosphere models is to be neglected.

Hint:

If the user decides to follow the "layer" approach ((b) in chapter "Model setup") and load layers/horizons for building up an initial 3D density model, **IGMAS+** automatically closes the model body upwards with a constant surface (see **Top** in the Body Manager). This "Top" body has zero density to mimic the air masses; for more detailed information please refer to this chapter.

There are two possibilities to define the model station heights (see Figure):

- the user chooses a constant height directly representing the satellite orbit (grey and pale blue body together) or
- the user continues the satellite data to a height level which is individually chosen by the modeller with reference to the heights proposed in the table of chapter "Model stations".

The **"Top"** body can be eliminated manually in the **IGMAS+** input file. However, we suggest staying with "0"-density body; it does not cause any effect on the modelled anomaly and will disappear in one of the next **IGMAS+** releases.

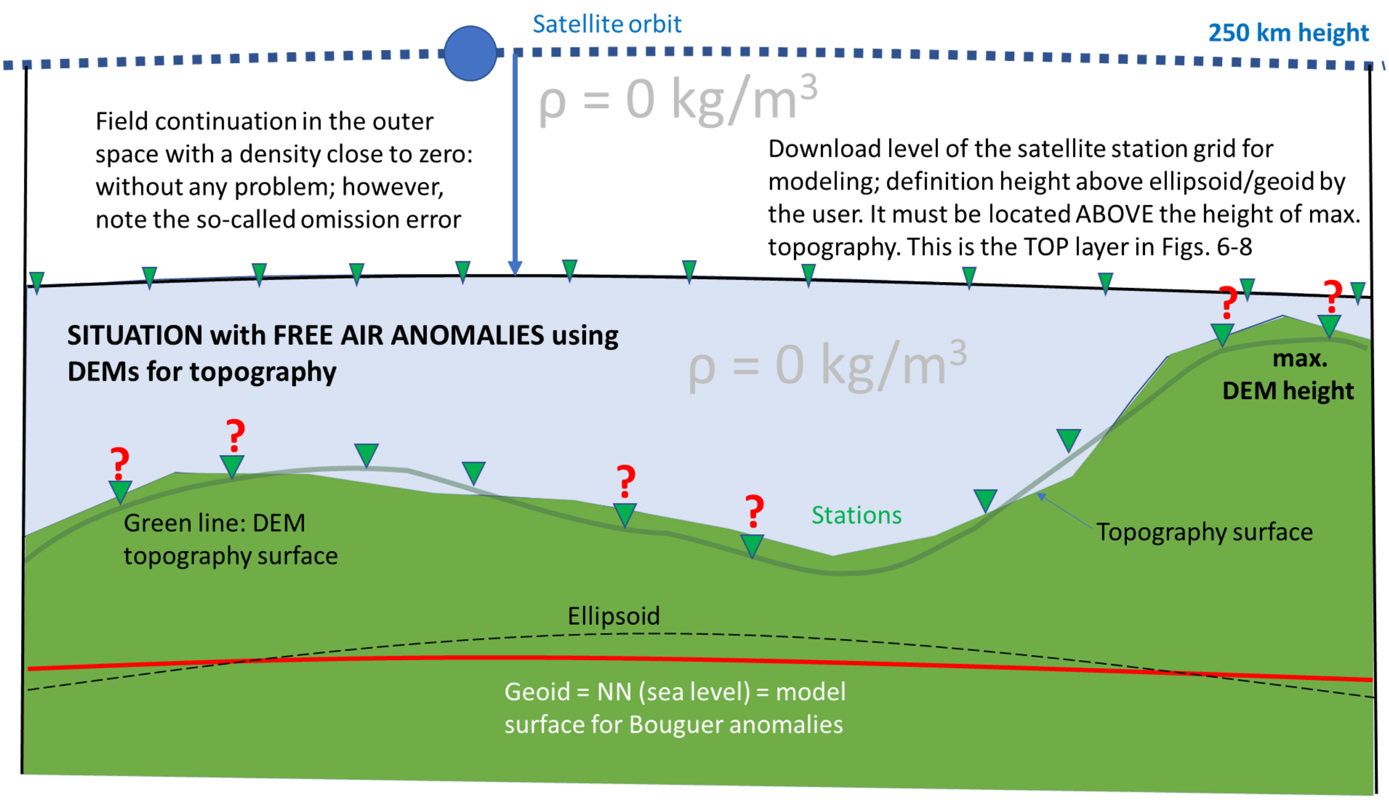
... and still, if this body disturbs someone, one can just eliminate it by hand. One can delete its polygons on every section:

- go to the first section
- right click on "Top"
- then select "Remove"
- repeat this procedure on every section.

If the "0-Body" doesn't have a single polygon anymore, you can also delete it from the Body Manager, because then "Remove Body" option is no longer greyed out.

Reference density: in the case of modelling a Free Air anomaly, the reference density must be set to zero (i.e. equal to the density of the topmost model body representing *air*)! Hence, one should check if the lateral model extensions are appropriately chosen to minimize edge effects.

3.4.3 Free Air anomaly (FA): the "difficult" situation



Free Air anomaly (FA): the "difficult" situation. The topographic surface (e.g., a digital elevation model) is downloaded from an independent database and does not match the measured station heights everywhere.

We start from the same situation as we have already studied for the Bouguer and Free Air anomalies: stations are at the orbit level or on the terrestrial surface (see Figures for CBA (simple) and FA (simple)). **BUT:** the terrain surface is now taken from a digital elevation model (DEM) or an elevation grid available on the web.

The illustration shows that the heights of the measured stations do not always correspond to the heights (often averaged) of the terrain model. Thus, it can happen that stations are located within the masses formed by the DEM. If this grid is loaded as "layer/horizon" (compare previous example), then some of the stations are located inside the mass. This leads to errors.

A similar situation must be considered if the satellite field data were continued to a level below the maximum DEM topography height. To be absolutely sure that this will not happen, choose a level that is "guaranteed" to be above the highest DEM elevation. For support refer again to chapter "Model stations".

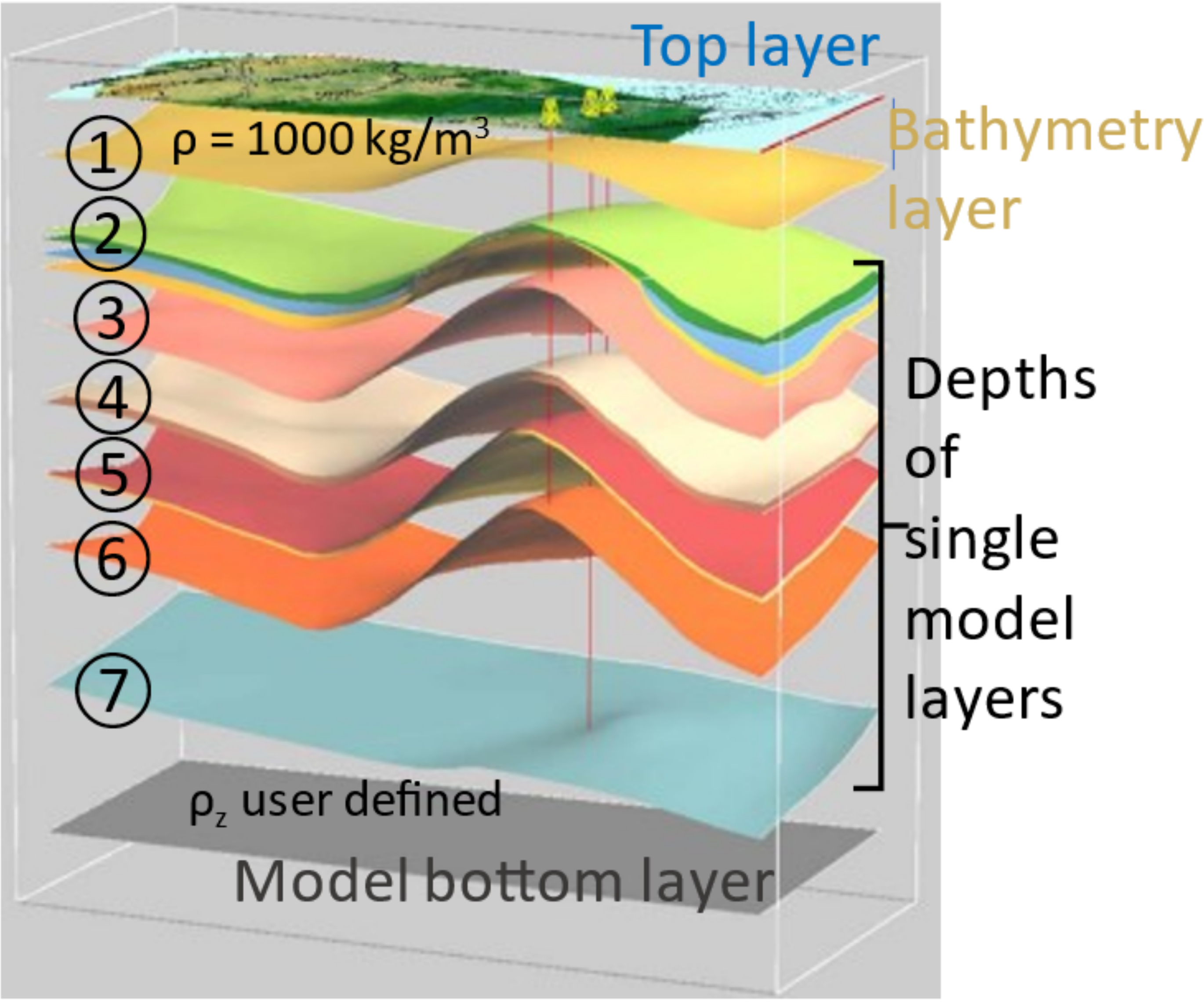
A remarkably similar problem can also occur if the model surface of water masses in an offshore modelling scenario is not exactly 0 meters and the modeling stations are not 13 cm above it.

Hint

When using grids (a) for satellite gravity (e.g. EIGEN-6C4, GOCE) for comparison with model gravity and (b) for topography (e.g. MERIT, EMODnet, etc.), always make sure that the model stations are positioned exactly on the nodes of the elevation grid. It must be ensured that both grids (gravity and heights) have the same grid structure/geometry (same grid width, same projection etc.). The grid with the satellite gravity can be downloaded for any user-defined level (see Figures for CBA (simple), FA (simple) and FA (diffucult)) above the topography.

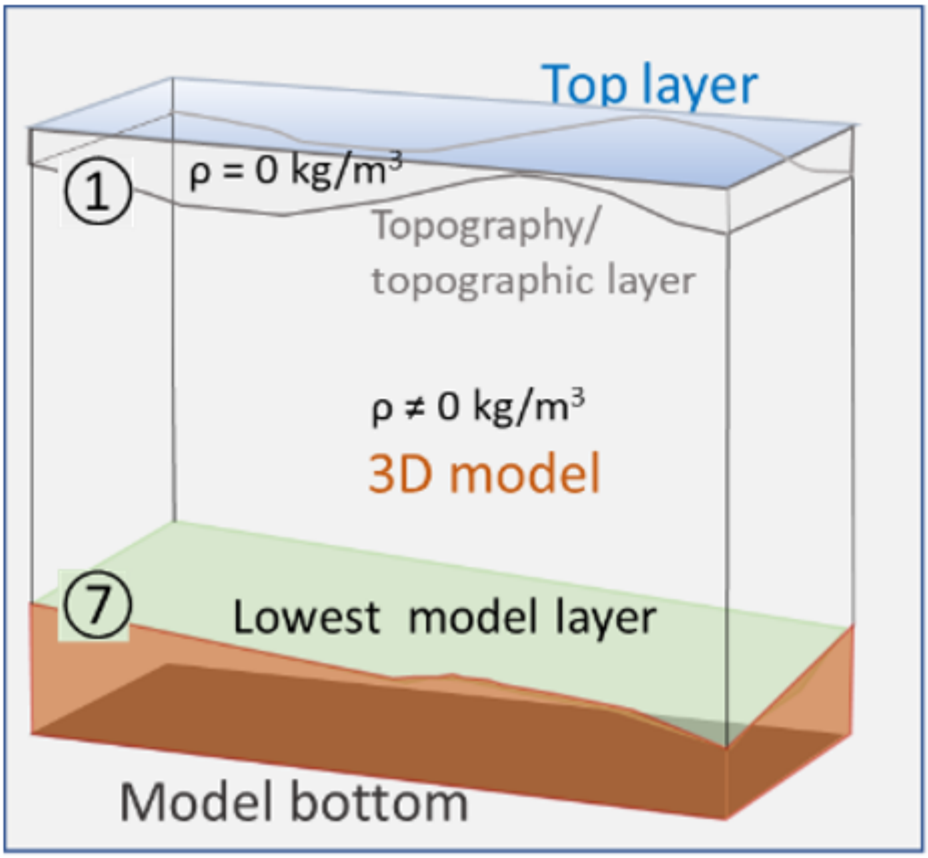
3.4.4 The "Top" body in the density model

Here we will explain the intentions of the "NULL body", which already played a role in previous chapters. This is only valid if layers/horizons were loaded. For this purpose, let us look at Figure. Originally, the **IGMAS+** function was used to read in individual horizons. Figure shows a stack of horizons that were taken as output from other survey results, e.g., from an offshore seismic campaign:



A scheme of 7 layers (horizons/interfaces) of an offshore scenario. The model consists of seven sedimentary layers, where layer ① indicates the bathymetric layer. For theoretical-methodological reasons, IGMAS+ closes the model with a "bottom layer" at the bottom and with a "top layer" at the top (here - the sea surface with height of 0 m). The user has the possibility to choose the densities for the automatically introduced bodies "Top" and "Bottom". The "Top" body is bounded by the model top layer and the bathymetry layer (with density of 1000 kg/m³). The "Bottom" body is bounded by the sediment layer ⑦ and the model bottom layer (with density ρz).

The software sorts the **stack of layers** first with ⑦ (the lowest layer) to ① (the highest layer). Because **IGMAS+** only processes closed bodies, it "closes" bodies between layers ⑦--⑥, ⑥--⑤, ⑤--④, etc. automatically with the consequence that the user has to input a layer (in this Figure the top of the "Top layer" is at the sea level) with constant user-defined height (Z-top = 0 m) above the layer ①. Likewise, a constant model bottom layer has to be defined below the layer ⑦ to close the model's bottom. Both density-values are user-defined. The "Top" body automatically generated by **IGMAS+** gets the density of the water layer: 1000 kg/m^3, the "Bottom" body -- an appropriate user-defined density ρ_z. In the case of a model that contains both onshore and offshore areas, this body, of course, must be defined accordingly.



Transfer of the offshore situation shown earlier to an onshore situation when modelling Free Air anomalies. Redefinition of layer ① into the topographic surface of a model. For more detailed information refer to the text of this chapter.

The automatic completion of an offshore model with a "Top" layer can also be used to complete an onshore model "upwards" if we model a Free-Air anomaly. In this case, the "Top" layer has a density of $0\,\mathrm{kg/m^3}$. Its upper limit is to be defined by the user and corresponds to the height at which the small green triangles lie or the blue stippled line is drawn (see Figures for CBA (simple), FA (simple) and FA (difficult)). These heights are always obligatory to be above the highest elevation of the topography. In this case of use of "interfaces/horizons" for the input of the model geometry, the "Top" layer in the model is reinterpreted as “topography layer”. **IGMAS+** will then automatically form a body whose upper boundary ("Top" layer in Figure) is defined by the user; this body is given the density $\rho = 0\,\mathrm{kg/m^3}$ and therefore has no gravity effect on the stations lying on the topography (big green triangles in Figures for CBA (simple), FA (simple) and FA (difficult)).

3.4.5 Modifications of the density model

The calculated gravity field of a density model can be analyzed based on the respective residual gravity:

When changing the density model, either by changing the density or the geometry of model bodies, **IGMAS+** automatically and instantaneously adjusts the calculated and residual gravity anomaly, which is displayed by a 3D or a 2D viewer (possibly together with additional constraining data). The 2D viewer always displays one of the working planes, which makes them the actual scenes of **interactive** geometrical modifications as implemented through:

1. **moving, deleting or adding** of vertices, or
2. **dividing** bodies through additional intersections.

Through its interactive mode, **IGMAS+** is primarily designed for analyzing and adjusting the 3D density model by visual inspection of gravity anomalies.
This clearly implies some level of subjectivity in the model evaluation but a major advantage in compression to automatic

algorithms is that it gives the user more control and especially the ability to learn how different features influences the result. For this reason, in addition to changing the density model through a complicated try-and-error procedure, **IGMAS+** also allows to **invert** for the density (of one or more bodies) by minimizing the residual of a model.

3.4.6 Remarks on the use of ICGEM gravity datasets

ICGEM stands for “International Centre for Global Earth Models” (Ince et al., 2019). For 15 years ICGEM is one of the five worldwide services coordinated by the International Gravity Field Service (IGFS) of the International Association of Geodesy (IAG). Static and temporal global gravity field models of the Earth are provided in a standardized format with a possibility to assign a DOI number and interactive calculation and visualization services of gravity field functionals are available.

For more information refer also to the instructive ICGEM poster presented at EGU-2019 and to the ICGEM documentation “Definition of functionals of the geopotential and their calculation from spherical harmonic models” (Barthelmes, 2013; see also Ince et al., 2019).

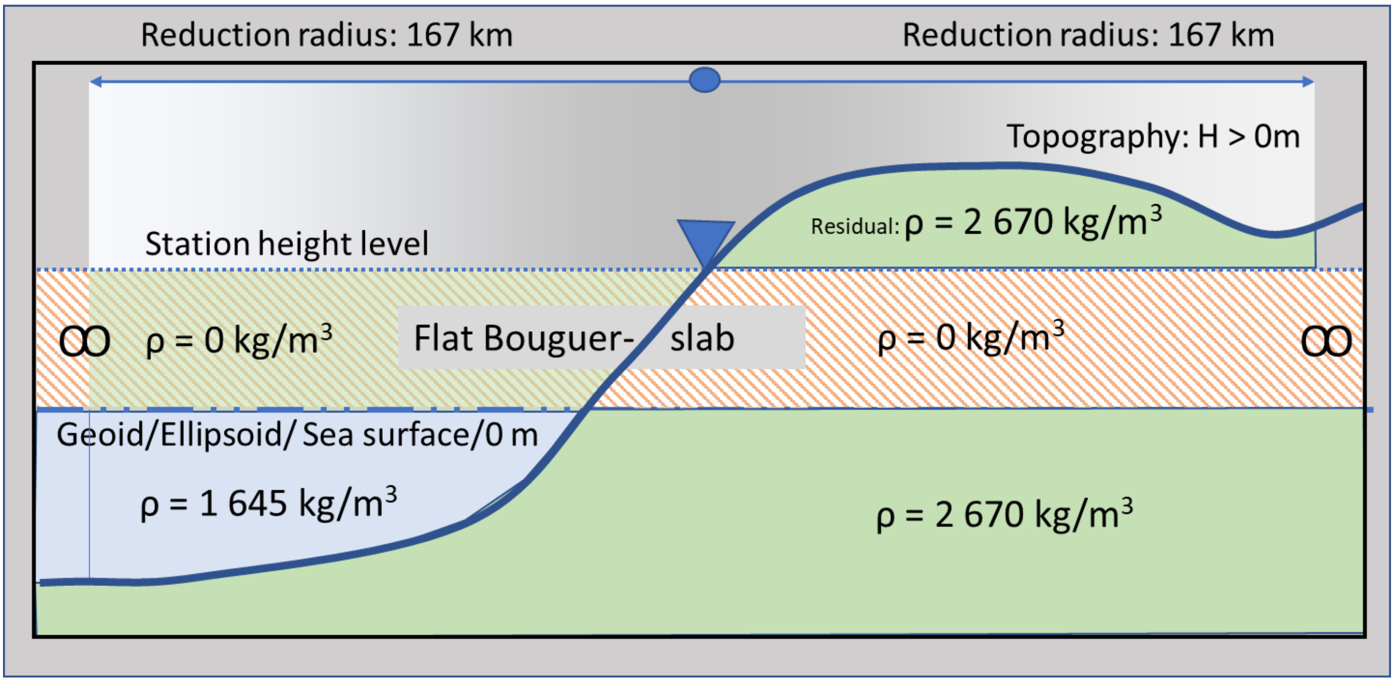
The online availability of global models opens many research possibilities worldwide. However, to use the data provided from global model grids correctly one should pay an extra attention for what dataset actually represents. In the following section we provide some hints regarding the use of ICGEM models for geophysical modelling.

The ICGEM documentation (Barthelmes, 2013) in a sophisticated mathematical-physical form shows how the different functionals and models of the gravity field are calculated. For understanding it is of great advantage to have certain geodetic knowledge. In the following we will try to give some useful hints in a very simplified manner. The first note refers to all users, who use the ICGEM anomaly `gravity_anomaly_bg`.

> **Note**
>
> The ICGEM documentation provides the following comment for the calculation of the "simple Bouguer anomaly":
>
> "The (simple) Bouguer gravity anomaly (Functional selection $\Longrightarrow$ `gravity_anomaly_bg`) is defined by the classical gravity anomaly minus the attraction of the Bouguer plate. Here it will be calculated by the spherical approximation of the classical gravity anomaly minus $2\pi G\rho H$ (eqs. 107 and 126 of STR09/02). The topographic heights $H(\lambda, \phi)$ are calculated from the spherical harmonic model of topography (ETOPO1) used up to the same maximum degree as the gravity field model:
>
> - For $H \geq 0$ (rock) $\rightarrow$ $\rho = 2670$ kg/m^3,
> - For $H < 0$ (water) $\rightarrow$ $\rho = (2670 - -1025)$ kg/m^3 is used.
>
> The density contrast between ice and rock has not been taken into account $\Longrightarrow$ the results for Greenland and Antarctica are not correct."

Please have in mind, that H is the height of topography above the geoid!

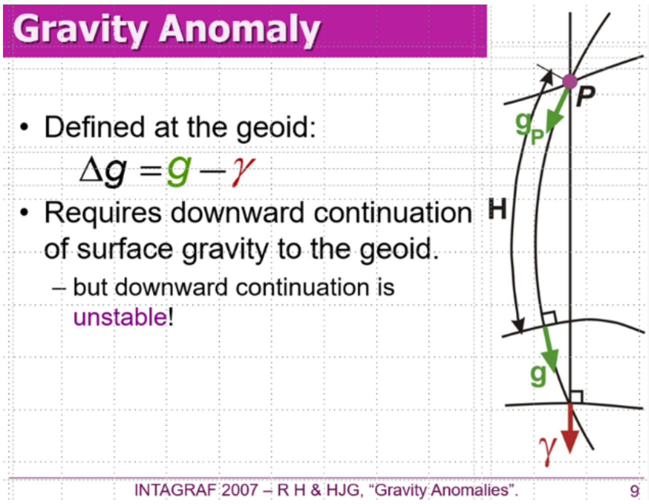
Fortunately, the differences between geoidal and ellipsoidal heights on Earth are small, however, present everywhere. From the geophysical/gravimetric viewpoint, not only the disregard of the gravity effects of ice masses is incorrect, but also the calculation itself. Firstly, a "flat bouguer plate" is considered, not a spherical Bouguer plate. Secondly, no topographic correction is conducted, which can lead to considerable errors in mountainous areas (Andes, Alps, Apennine, Himalaya). On the other hand, the transition areas between the continental margins and the oceans are also subject to errors, as Figure shows.

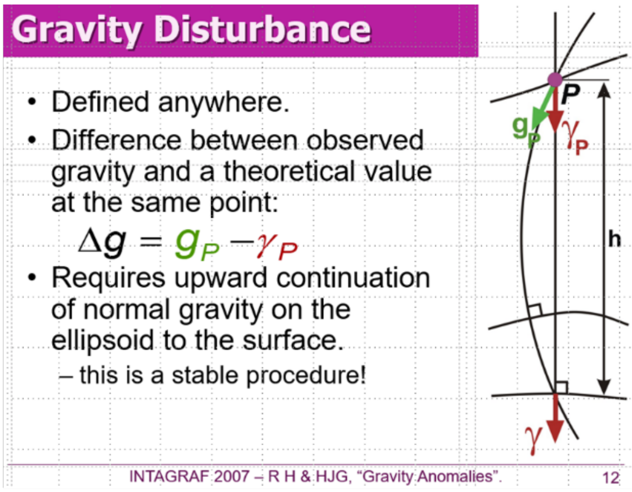


Differences of a complete mass correction of gravimetric measurements (in geophysics) in contrast to the correction performed at ICGEM, where only a flat plate is attracted.

This illustration shows that in ICGEM's `gravity_anomaly_bg` not all masses were correctly removed. Remnants remain in the topography over land (density $2670\,\mathrm{kg/m^3}$) and at the sea (density $1645\,\mathrm{kg/m^3}$). The latter residue can be minimized by modelling the sea water layer by a body with a density of $1645\,\mathrm{kg/m^3}$.

Another remark refers to the meaning of the term **anomaly** in geodesy and in geophysics (see, e.g., Li & Götze, 2001). The illustration below makes the difference graphically clear. A geodetic **anomaly** always implies, that the gravity anomaly Δg is calculated at the geoidal surface which is **NOT** the "real" topographic surface (see Figure, left). This implies a downward continuation of g_P into the topographic masses which is incorrect -- at least from a geophysical point of view.





To clarify the concept of anomaly and disturbance. In geodesy, an anomaly is always calculated on the geoid, which requires a downward field continuation (left panel) of gp by the amount of H; this is unstable and therefore forbidden. In contrast, geophysicists use an upward continuation (right panel) of the normal gravity γ from the ellipsoid by the amount of h into the position of P to compute a Free Air anomaly in P. This procedure is mathematically correct. In geodesy, a Free-Air anomaly is also called disturbance.

In contrast, geophysicists use the term **anomaly** (here, more precisely, **Free Air anomaly**) to determine the gravity difference Δg directly at the observation point P. For this purpose, it is necessary to perform an upward continuation (height h in Figure) from the ellipsoid into the measuring point level P. This is a mathematically-physically stable procedure and therefore is allowed.

Note

The geophysical Free Air anomaly is the same in meaning as a geodetic disturbance.

So, if the model gravity is to be compared with the Free Air anomaly, in the ICGEM calculation service first the gravity model is selected under the heading "Model selection" (EIGEN-6C4 is a good choice, also XGM2019), then in the heading "Functional selection" `disturbance` is selected, if no specific non-zero meter altitude is to be selected.

This is dangerous, because then, under certain circumstances, the stations of the Free Air anomaly/disturbance can lie within the model masses (see chapters on FA (simple), FA (difficult) and on the "Top" body). If the model contains topographic heights which are higher than 0 m, then select `disturbance_sa` in the column "Functional selection" and enter the height in the input mask on the right under the input of "grid step [°]". The height is freely selectable by the user and must be above the maximum of the model topography; this corresponds to the height with the small green triangles in Figures for CBA (simple), FA (simple) and FA (difficult).

To calculate complete Bouguer anomalies it is recommended to download the free-air/disturbance at station level and then perform Bouguer corrections using a DEM model for both on- and offshore masses.

2023-05-16

https://igmas.git-pages.gfz-potsdam.de/igmas-docs/