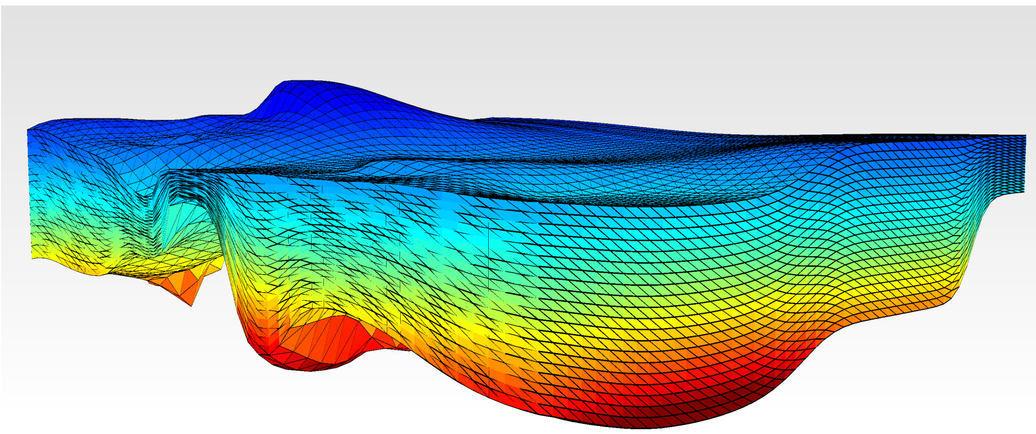
User Manual and Tutorial for GeoReVi

Geological Reservoir Virtualization

Date: November 1, 2019



Foreword

This manual is under preparation and subject to future changes.

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Version 2, June 1991

Preamble

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Finally, any free program is threatened constantly by software patents. We wish to avoid the danger that redistributors of a free program will individually

obtain patent licenses, in effect making the program proprietary. To prevent this, we have made it clear that any patent must be licensed for everyone's free use or not licensed at all.
The precise terms and conditions for copying, distribution and modification follow.

Reporting issues

Unfortunately projects of the GeoReVi's size are not completely bug free. If you find bugs, we would be grateful if you report them either directly to the author under contact@georevi.com or on our GitHub repository (https://github.com/ApirsAL/Ge

2 Introduction

GeoReVi is a software developed for geoscientific information management and knowledge discovery. GeoReVi can deal with many types of subsurface characterization yet being specialized on geothermal reservoir characterization. The software is developed under the MIT license making it free to use and open source.
The software is split up into two components. One component is the client application, the user interacts with, and the other component is the so called back end located either on an accessible server or on local machines. The font end uses a communication framework to access the database located in the back end.

2.1 Built with

- Entity Framework 6 - Database access
- HelixToolkit.WPF - Providing the 3D components
- Managed Extensibility Framework - Providing the modular structure of GeoReVi
- Accord.NET - Linear Algebra and Machine Learning framework
- Windows Presentation Foundation - Framework for creating Windows Desktop Applications
- Caliburn.Micro - Framework for MVVM development in XAML platforms
- FontAwesome.WPF - Providing nice icons
- DotSpatial - Spatial algorithms
- GeoAPI - Coordinate Conversion
- ProjNET - Coordinate Projection

- LiteDB - Embedded NoSQL database
- MoreLinq - Query helper
- Extended WPF Toolkit™ - Providing nice UI controls

2.2 Authors and Contributors

Adrian Linsel, Technische Universität Darmstadt, contact@georevi.com

2.3 Hard- and software requirements

GeoReVi is built with the .NET Framework. This makes the software executable on every machine with Windows XP and newer OS. Since GeoReVi is a desktop database application, a valid connection to the database server has to be provided. When GeoReVi is used internally, please contact your admin for further assistance or use the software in local mode.
The software is tested under the following hard- and software configurations:

Hard-/Software	Database	User interface
OS	Windows Server 2012 R2	Windows 10
CPU	Intel Xeon CPU E3-1276	Intel Core i5-7200U
	v3 @ 3.6 GHz	2.5 GHz
RAM	24 GB DDR4	16 GB DDR4

2.4 Installation

Download the GeoReVi.exe file from GitHub (https://github.com/ApirsAL/GeoReVi) and perform the installation.
To initiate a client-server architecture, a more advanced installation has to be performed. Researchers interested to establish a multi-user environment at their institute should feel free to contact us under contact@georevi.com via Email.

3 Quick start

This section will not cover any theory or background information on how any functionality works in detail. The reader will be guided with the help of the tutorial data set that can be found under

https://github.com/ApirsAL/GeoReVi/tree/master/docs/Tutorial

completely from making basic statistical analysis to the final yet simple reservoir property model. First download the complete **Tutorial** folder from GitHub and save it anywhere on your hard drive. Start GeoReVi and enter the **Local mode** in the login screen.

3.1 Importing a local data set

Under **Data** → **Measurements** we enter the measurements screen. Now we navigate to the **Data analysis** tab. There, under **Univariate** click on **Mesh action** → **Import mesh**. Select **.gmsh** as file extension and navigate to the downloaded **Tutorial** folder and there to **FieldParameters**. Select the *ThermalConductivity.gmsh* file and click open. This file contains thermal conductivity measurements from samples taken from six drill cores penetrating the Rotliegend formation in southwestern Germany. Alternatively, individual data sets from common spreadsheet files can be imported. Therefore, we import another mesh in the same folder called *ThermalConductivity.csv*. When importing spreadsheet files, a dialog will pop up where the user must define, which column should be mapped to which entity. We will produce following mappings between the **Imported headers** and the **Database headers**

1. Thermal conductivity → Value
2. x [m] → X
3. y [m] → Y
4. elevation [m] → Z
5. Date → DateTime
6. Name → Name

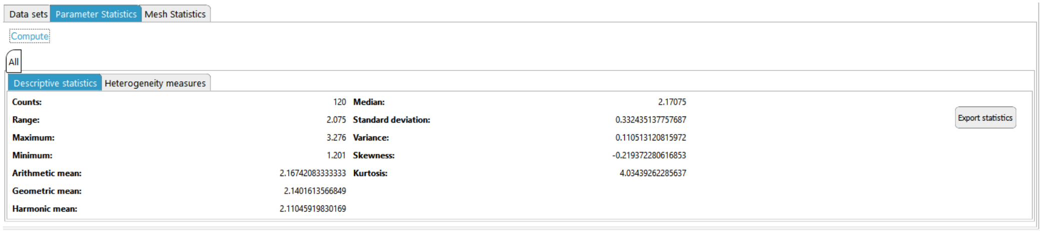

Figure 1: Basic statistics result.

When clicking **Import** the data set will be added to the **Data sets** with the name *New data set*. When we want to remove a data set, we can perform **Mesh action** → **Remove dataset**. After deploying the command the selected mesh will be removed.

The measurement results can be seen under **Univariate** and **Data set**. The first column shows the actual value of the measurement. Thermal conductivity is provided in the SI unit $W/m \cdot K$. The second column shows the x coordinate or longitude respectively. The third and fourth column display y/latitude and z/elevation respectively. The uploaded values are provided as metric x,y and z coordinates in the UTM coordinate system. The fifth column shows the data and the sixth column the name of the individual sample.

The name *All* of the imported mesh is meaningless. So we will change the name to something more meaningful. Therefore, open the expander left from the data table by clicking on it. Open the topmost expander called **Display**. Here, the selected mesh name can be changed. The selected mesh is always the tab selected in the **Data sets** view. Type in "Thermal conductivity Rotliegend" into the textbox and click **Save** left beside it.

3.2 Univariate statistics

To get a first overview over the statistics of the measurement, got to **Univariate** and there to **Parameter statistics**. When clicking on **Compute** the basic parameters of the distribution will be calculated. The result should look like the results shown in fig. 1.
Results from the basic statistics analysis can be exported as .CSV file. Results presented are the statistics of all sample values of the particular data set. The provided measures are the total count of the samples, the *range*, *maximum*, *minimum*, *arithmetic mean*, *geometric mean*, *harmonic mean*, *median*, *standard deviation*, *variance*, *skewness*, *kurtosis*, *coefficient of variation* and *Dykstra-Parson coefficient*.

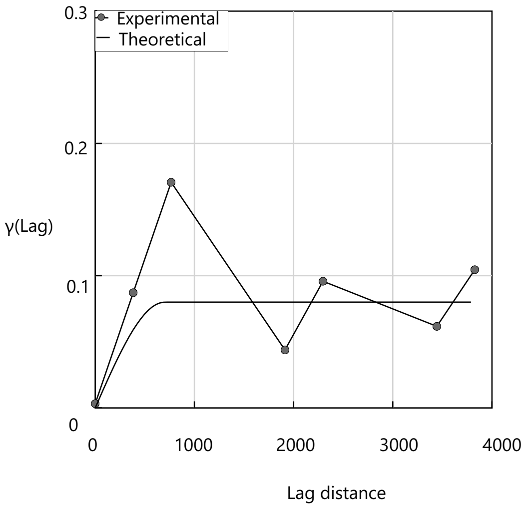

Figure 2: Semivariogram of the thermal conductivity measurement.

3.3 Variography

To analyze the spatial correlation of the data set we can conduct a variographic analysis. Therefore, return to the **Data sets** and **right-click** on the mesh *Thermal conductivity Rotliegend* and press **Add data set to variogram chart**. Now we navigate to the **Charts** tab and then to the **Variogram**. Here, navigate to **Semi-variogram** and open the expander on the left side. In the **Editor** → **Editing** expander menu you will find our data set that was added to the chart in the last step. When you press the button in the left upper side of the chart that shows the tooltip **Refresh** the chart will be created. The x axis shows the lag vector distance and the y axis shows the cumulative semivariance. We want to consider the semivariance in three-dimensional space. Accordingly, **Model** → **Parameters** → **Direction** we have to switch the direction from *Z-direction* to *XYZ-direction*, we insert 0.08 in the **sill** and 700 in the **range** textbox and we will increase the number of **Bins** to 15 . Under **Chart style** → **Axes** → **X axis** insert *4000* in the **X max**, *1000* in the **X tick**, *0.5* in the **Y max**, *0.1* in the **Y tick** textboxes and refresh the chart.

3.3.1 Exporting a chart

By **right-click** → **Export chart** a chart can be exported as .png, .bmp, .pdf or .emf file. Latter one is a vector format that can be opened with popular vector graphic programs like CorelDRAW or Inkscape. When you export the chart from the **Variography** section it will look like fig. 2)

3.4 Empirical distribution

4 Getting started in depth

Following section contains comprehensive descriptions on the data, algorithms and the software structure of GeoReVi.

4.1 Obtaining a Bing Maps Key

In order to use the full functionality of GeoReVi the user has to obtain a Bing Maps Key under https://docs.microsoft.com/en-us/bingmaps/getting-started/bing-maps-dev-center-help/getting-a-bing-maps-key. The key has to be inserted in the K.csv file located in the installation folder under /Media/Data.

4.2 Sample data

We provided a sample data set for the first use of GeoReVi. In the GitHub directory many samples can be found that serve as input data for GeoReVi. A comprehensive data set is provided in the Disibodenberg folder. Here, we produced a comprehensive case study to validate the software. The rock samples and measurements are already documented in the local database when GeoReVi is installed.
Additionally, we provide 3-D models of rock cubes and the entire outcrop that were generated with GeoReVi. Those files can be imported and directly visualized. In the following sections, we will often come back to the Disibodenberg sample data set and exemplary perform workflows with this data set.

4.3 Data management

Data produced in subsurface studies include various geoscientific domains like (petro)physics, sedimentology, hydrogeology, instrumental analytics or geophysics. GeoReVi facilitates the user to manage data sets from all of these entities. Entities like chronostratigraphy or petrography are supplied according to international standards like chronostratigraphic units from the International Chronostratigraphic Chart 2017 (ICC, 2013; updated) and the petrographic terms mostly by definitions from the British Geological Survey (BGS) or American Geological Institute (AGI).
Entities that are not standardized internationally were tried to be reduced on the most normalized level. Lithostratigraphy for instance provides a more or less internationally applied standard to subdivide units hierarchically like following:

1. Group
2. Subgroup
3. Formation
4. Subformation/Member

This schema was transferred into GeoReVi. Nevertheless, in contrast to the chronostratigraphic units, a user also has to be able to adapt information of a lithostratigraphic unit. Generally, data sets can be inserted, updated and deleted manually in accordance to common **CRUD** standards *(Create, Retrieve, Update, Delete)*. A user always works on one of the projects where subscription is provided. Every data set is equipped with the ID of the user who generated the data set. Only this user is allowed to update or delete associated data sets. Users with project subscription may retrieve data sets.

4.3.1 Supported data types

Data from various geoscientific disciplines is supported in the GeoReVi databases. Many types of information necessary for geothermal reservoir rock characterization are accomplished and rationalized in a multidisciplinary data model. Following information can be processed by the databases:

1. **Lithology**
   (a) lithofacies
   (b) architectural elements
   (c) genetic units
   (d) lithological logs
2. **Geological objects of investigation:**
   (a) outcrops
   (b) drillings/wells
   (c) geophysical transects
   (d) hydro(geo)logical objects
3. **Field/drill core samples**
   (a) cylinders/plugs

   (b) cuboids
   (c) handpieces
   (d) thin sections
   (e) powders
   (f) soils
   (g) sediments

4. **Analytical instruments**

5. **Laboratory measurements**
   (a) grain density
   (b) bulk density
   (c) effective/total porosity
   (d) apparent/intrinsic permeability
   (e) (saturated) thermal conductivity
   (f) thermal diffusivity
   (g) (saturated) p- and s- wave velocity,
   (h) bulk geochemistry (oxides and trace elements)
   (i) isotopes
   (j) electrical resistivity
   (k) rock strength (uni- and triaxial)
   (l) grain size

6. **Field measurements**
   (a) spectral γ-ray
   (b) total γ-ray
   (c) magnetic susceptibility
   (d) palaeo flow
   (e) bedding
   (f) lineaments
   (g) joints
   (h) temperature

   (i) sonic log
   (j) rock quality designation index
   (k) hydraulic head
   (l) bounding surface locations

7. **Stratigraphy**
   (a) lithostratigraphic units
   (b) basins

All those entities include meta-information like measurement conditions, subtype definitions or detailed descriptions. However, the visualization and analysis functionality of GeoReVi can be used with local data of any kind as well. Users are encouraged to send us suggestions for data, they would like to have available in GeoReVi too. Please address your requests to contact@georevi.com. We will try to answer your requests as soon as possible.

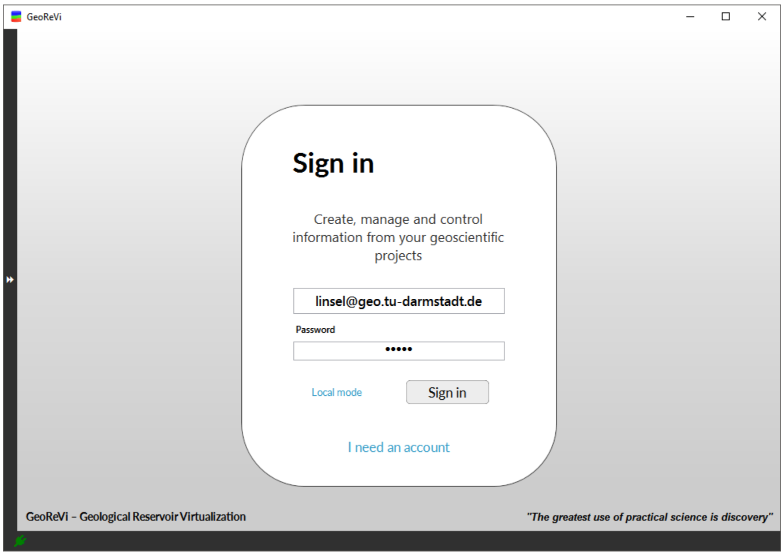

Figure 3: Login view.

4.3.2 Provided data set

In the local application we provided a data set from one of our publications (Linsel et al. 2019). The data set is located in the "Disibodenberg" project. Here you find 41 rock samples (plugs) taken from the outcrop "Sandstone Quarry Obersulzbach". Additionally, you find

4.3.3 Starting the application

First, the user will see the *Login* screen.
If a connection to the server database is established, the text block in the lower left corner is displayed in green color. Otherwise, the text block indicates a missing connection through showing a red color and associated text. If you are not registered in your institutional database yet go to the "Register and Sign In" chapter. Alternatively, you can work on a local database by clicking on "Local mode". When you work on your local database make sure that you update your database by clicking **Start** → **Update LocalDB** to get the domain data for chronostratigraphy, petrography and facies analysis. After login, the user finds the main navigation menu in the top part of the main screen.
The general structure is

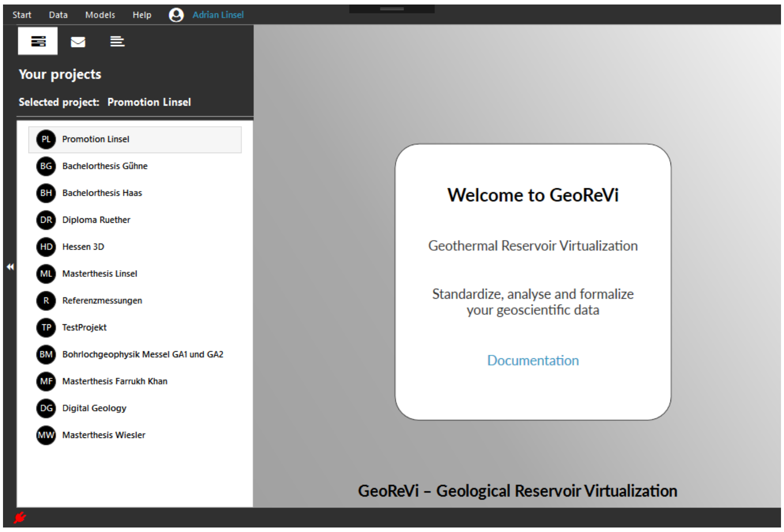

Figure 4: Home view with projects sidebar.

Start	**Data**	**Map**	**Help**
Home	Geological objects	Global Map	Documentation
Projects	Lithology		About GeoReVi
	Rock Samples		
	Measurements		

4.3.4 Registration and Sign in

After installation of the server database, the user can create an individual account to access data from GeoReVi. Therefore, the user has to create an account by providing information. Other users will see the email address and affiliation provided in the registration when inviting users to their projects. The information will be encrypted and stored in the database. The account can be deleted or user information can be changed under *My Account*.

Please, be aware, that all information you provided in GeoReVi won't be accessible anymore when you delete your account!

Your projects and its related data will exist further on and subscribed users will have access to the projects related data unless those are transferred to another project or deleted, too.
After successful registration, the user can sign in by the provided user name and password. At the beginning, the user doesn't have access to any projects but he can see objects of investigation for planning studies and field campaigns.

Projects, the user participates at, will be loaded after sign in and can be selected in the drop-down box next to the main navigation menu. After selection, the user will work on the selected projects and has access to data related to that. Most times, many people will work on one specific project. Therefore, only the uploader and the project creator will have writing-access to the data sets to avoid unwanted data manipulation.

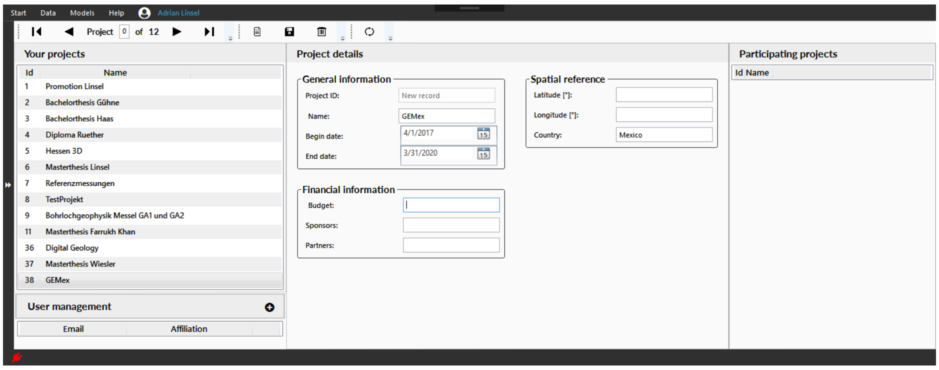

Figure 5: Projects view with a newly added project.

4.3.5 Project Management

Projects can be managed and created in the *Projects* menu. To improve the overview, duplicate project names are forbidden. Duplicate project names will be changed during registration and the user will be informed about it.
After creating a project, the creator can add or remove users. By clicking on '+' in the user management frame a user can be added via dialog service. '-' will unsubscribe the participating user. A user can also unsubscribe from the project by clicking the '-' button in the 'Participating projects' frame.

4.3.6 Objects of investigation

Objects of investigation are all object that can be investigated in a geoscientific context. You can get to the objects form via **Data** → **Geological objects**. In GeoReVi you can differentiate between "Outcrop", "Drilling", "Transect" and "Water body".
Objects of investigation are visible to all users working on the same database. Therefore, an object of investigation has to provide an unique name what is tested when entering it. If the name is already given to another object, you will have to change it accordingly.

4.3.7 Lithologies

Lithologies can be stored according to the lithofacies concept after Miall (1985). Here, geological units are subdivided into three classes namely lithofacies types, architectural elements and genetical units. Here applies

$$lithofaciestype \subset architecturalelement \subset geneticalunit \tag{1}$$

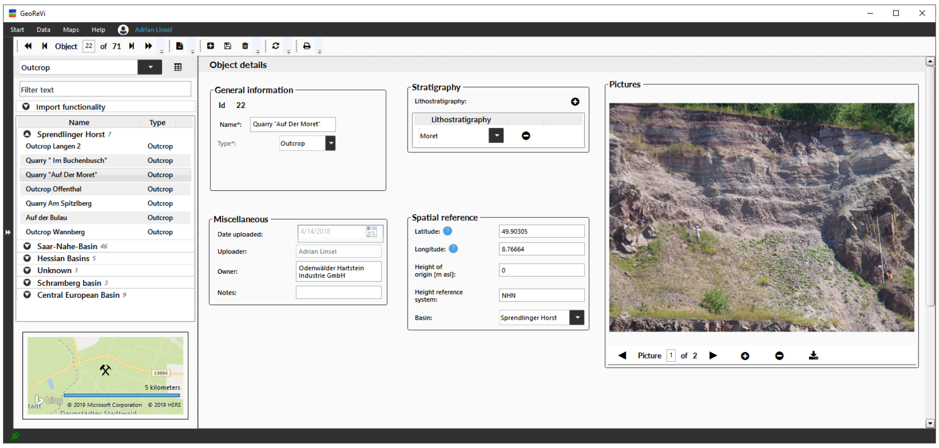

Figure 6: Objects of investigation form.

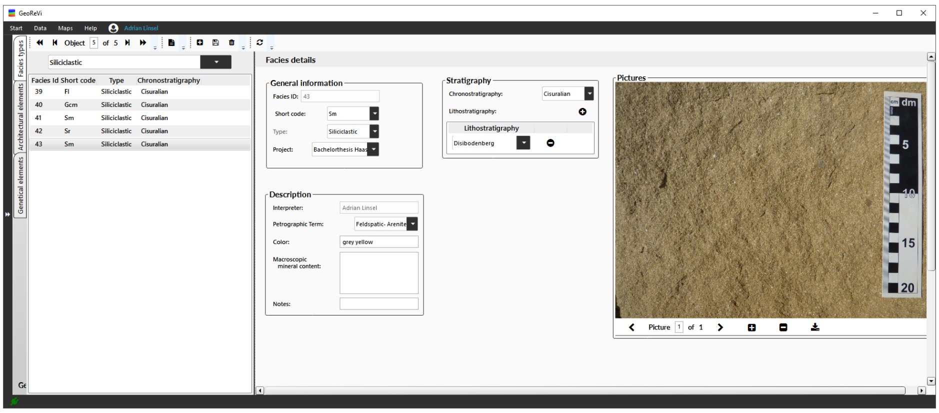

Figure 7: Lithologies form.

Lithologies can be updated in the "Lithologies" menu. When entering this menu you will find a tab-item with the names "Facies", "Architectural elements" and "Genetical units". General information can be documented in the main forms. To store details the user can open the "Details" window.

4.3.8 Rock samples

Rock samples taken from the field can be recorded in the "Rock samples" form. Again the name of a rock sample must be unique across the entire database. An algorithm ensures this while inserting the name of the rock sample and provides an alternative if a sample name is already in use. To avoid this, we recommend to report all samples in the System for Earth Sample Registration (http://www.geosamples.org/). This will provide each sample an individual International Geosample Number (IGSN) that can be used globally.
Samples can be either recorded in the provided data form one by one or loaded in bulk using the import section. Therefore, a .CSV or .XLSX file containing the individual rock samples must be dropped in the "Import" field.
Details can again be documented in the "Details" window.

4.3.9 Measurements

When you navigate to the 'Measurements' view, you will find two types of measurements in two separate views. Laboratory measurements are measurements related to a rock sample. When you open that view you can find the documented objects of investigations in the list on the left side. There you can select the rock sample where you want to archive a new measurement or from which you want to analyze the data. When selecting the rock sample, all types of measurements produced on that rock sample will be loaded and displayed in the list in the central part of the form.
Field measurements are measurements directly generated in or on an object of investigation. You can archive measurements such as well logs or structural measurements here. In the list on the left side you will find again all objects of investigation you documented beforehand. When selecting an object, all measurement related to that object are loaded in the list in the central part. To add measurements to a sample or to an object you can click the '+' button above the list view or you right-click on the list and select 'Add measurement'. A measurement of undefined type will be added to the list. To archive further information you will have to define the particular type of measurement under 'Type'. After saving the changes you can enter further information

in the tab item 'Parameter'. If you want to import a set of measurements please refer to the chapter 4.3.10. To delete a set of measurement you can select multiple measurements in the list, right-click and select 'Delete selected measurements'. Confirm the order to delete the selected measurement and all of those will be deleted from the database.

4.3.10 Import to the database

Data can be imported from spreadsheet files. For import .XLSX and .CSV files with one header row are accepted. We recommend .CSV for import. Most data forms provide an import field in the left upper corner. This field can be expanded and the preferred import objects can be selected. Please ensure, that the .CSV cells provide the correct format (number, string, date, etc.). For file-import, the file containing the data has to be dropped into the border of the field. A file-import dialog will show up immediately, where the imported data columns have to be mapped to the existing database headers. Therefore, single headers from the import file and from the database can be selected and mapped together with the map button. Headers can also be mapped automatically by using the mapping wizard. This algorithm checks for similar headers and maps them automatically.
Some database tables require redundancies for import. For instance, a plug must contain the sample name twice, since two tables are connected via this name to each other. Hence, two columns containing the sample name have to be included into the import spreadsheet. Also, following entities contain **obligatory** fields, where a value has to be provided:

1. Rock samples
2. Objects of investigation
3. Measurements

Please check beforehand, that the provided cells in the selected file have the adequate data format for the imported entity.
Exemplary proceeding

1. Open the rock sample form under **Data** → **Rock samples**
2. Expand the import field by clicking on the **Import functionality** expander
3. Select the type of object you wish to import, in our case, this is the **Plug** sample type

4. Drag & Drop your .XLSX or .CSV files with the rock sample information on the import field

5. In the import form, corresponding headers have to be mapped. This can be done one after another by selecting the headers in the select and by clicking the right-arrow. The mapping will show up in the right mapping-list. An automatic mapping can be done by clicking the "Auto connect" button. This will map headers with identical names together and adds the connection to the mappings list. It is recommended to use the .CSV lists from the data exports since those provide the same headers as required in the import form.

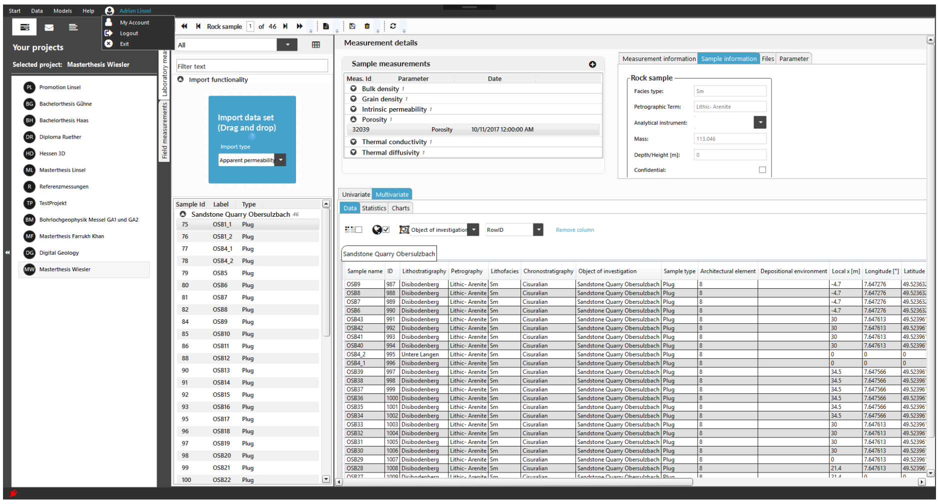

Figure 8: Measurements form with an import area where .CSV and .XLSX files can be dropped for import..

4.4 Data analysis and visualization

Data analysis and visualization takes place in the 'Measurements' view. The form is built up by two components namely "Measurements" and "Data analysis". First one contains measurements according to section 4.3.9. The "Data analysis" component is built up by data sheets, statistic forms and charts where you can analyze and visualize your data.

4.4.1 Univariate data analysis

To load a set of univariate, spatially referenced measurements click the black 'Load univariate data set' button above the "Univariate" tab. This will download all measurements from the selected type from all samples where the selected sample belongs to. For example when you have the 'Porosity' measurement of a sample called 'OSB1' selected and you click the button, all data of the selected combo box property from all rock samples belonging to the associated outcrop will be loaded in the univariate data sheet.

In the tab "Parameter statistics" the user can retrieve basic descriptive statistic measures. Basic statistical parameters including *arithmetic mean*, *geometric mean*, *harmonic mean*, *sample standard deviation*, *sample variance*, *n^{th}-quartile*, *n^{th}-percentile*, *median*, *maximum*, *minimum*, *range*, *counts*, *skewness* and *kurtosis* can be computed from a data set. Physical and lithological heterogeneity has a strong influence on both the predictability of reservoir properties in a target formation and the lifetime and recovery rate of any type of geological reservoirs Ailin 2012; Crooijmans et al. 2016. Fitch et al. 2015 present a set of quantitative heterogeneity measures of a univariate field parameter data set. These measures, that indicate the dispersion of a univariate data set $\mathbf{x}$, include the coefficient of variation c_v, which can be calculated as $c_v = \sigma \cdot \overline{x}^{-1}$, with σ as the empirical standard deviation and $\overline{x}$ as the arithmetic mean and the Dykstra-Parsons coefficient c_{dp}, which can be calculated as $c_{dp} = (p_{84} - p_{50}) \cdot p_{50}^{-1}$, with p_n as the nth percentile.

Variography

Originally defined by Matheron 1963, the semivariogram describes the spatial dependence of a random field variable in space. Variability of a regionalized field parameter z is computed at different scales by calculating the dissimilarity between pairs of data values $z(x_\alpha)$ and $z(x_\beta)$ at the locations x_α and x_β in the spatial domain. As a measure for dissimilarity $\gamma_{\alpha\beta}$ is calculated as $\gamma_{\alpha\beta} = 0.5 \cdot \big(z(x_\alpha) - z(x_\beta)\big)^2$. Since x_α and x_β can be expressed as points separated by a lag vector $\mathbf{h}$, dissimilarity can also be formulated as:

$$\gamma_{\alpha\beta}(\mathbf{h}) = \frac{1}{2} \cdot \big(z(x_\alpha + \mathbf{h}) - z(x_\alpha)\big)^2 \in [0, \infty] \tag{2}$$

Semivariogram calculation results in a set of points representing the cumulative dissimilarity γ of point-pairs with the Euclidean distance of $|\mathbf{h}|$ in the domain. The experimental semivariogram, however, represents the cumulative dissimilarity of a discrete set of point-pairs x with n_c representing the count of point-pairs within the distance classes h_k of identical distance increments (eq. 3).

$$\gamma(\mathbf{h}) = \frac{1}{2n_c} \sum_{\alpha=1}^{n_c} \big(z(x_\alpha + \mathbf{h}) - z(x_\alpha)\big)^2 \in [0, \infty] \tag{3}$$

The continuous counterpart, represented by the theoretical semivariogram, is an approximation to the experimental semivariogram assuming $z(\mathbf{x})$ to be a stationary random field Wackernagel 2003. A theoretical variogram γ_{theo} is represented by a covariance function C with the relationship $\gamma_{theo}(\mathbf{h}) = C(0) - C(\mathbf{h})$, where C is a positive definite, even function. If a nugget effect is observable, the theoretical semivariogram is translated by the magnitude of the nugget (n) on the ordinate. Six covariance models are mostly used to fit the experimental semivariogram namely the spherical, gaussian, exponential, power, kardinal sine and linear model Armstrong 1998; Ringrose and Bentley 2015. In order to calculate the covariance function, the variables nugget (n), range (a) and sill (b) must be determined.
Semivariograms can be used to quantify the spatial or time correlation of a

random field parameter Ringrose and Bentley 2015; Gu et al. 2017; Rühaak et al. 2015. Further on, the differences in range and sill in dissimilar directional semivariograms can quantify the geometric anisotropy of a field parameter Ringrose and Bentley 2015. The resulting semivariogram and covariance functions are input variables for kriging analyses.

To produce a semivariogram analysis you have to add a mesh to the semivariogram chart with **Right click → Add to semivariogram chart**. There the user has to update the chart with the button in the top left corner. Sometimes, the distance (x axis) and variance (y axis) are exceeding the predefined range of 10 and 10 respectively. So, the user has to adapt the axes. Under "Model" the user can adapt the properties of the experimental and theoretical semivariogram.

4.4.2 Mesh generation

All data that is loaded in the univariate data sheet will be treated as a 'Mesh'. A mesh is a structure with vertices or nodes, faces and cells. When you load a data set it is a set of scattered, unconnected vertices. You can add the selected data sets to chart objects by right-clicking on the sheet and selecting the wanted option. If you want to create for instance a depth log of a property you have to right-click and select 'Add to line chart'. Then navigate to the line chart by 'Charts → Line chart' and select 'Z-direction'. When clicking the 'Refresh' button in the upper right corner, the graph will be drawn.
Each data set handled in the measurements view is a mesh. Meshes in GeoReVi consist of nodes (vertices), faces and cells. Additionally, a datatable is associated with each mesh that holds the measurement values. Data sets loaded from the database or from a .CSV, .XLSX or .XLS file are imported as discrete points into the data table without nodes, cells or faces. You can edit or remove single values in the data table displayed.

Regular mesh generation
Each node in a mesh created in GeoReVi is indexed according to a regular mesh. To create a simple hexahedral mesh in the bounding domain of one or more meshes the user has to expand the menu on the left side of the data set view. Under *Source data sets* you can select the meshes that should serve as source data sets for the meshing process. When you open the *Discretization* expander you can find define the type of mesh that should be created, the boundaries as x, y and z coordinates and the step width in each direction.
You can create one-, two- and three-dimensional meshes. The default setting

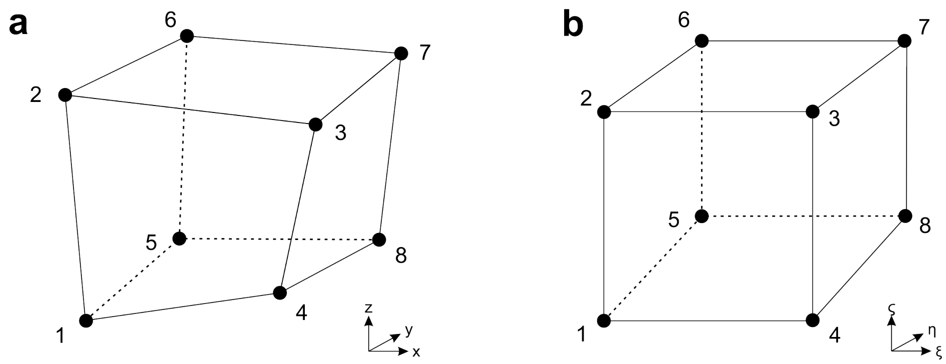

Figure 9: Conceptual representation of a hexahedral grid cell in GeoReVi as irregular shape (a) and with a local coordinate system (b).

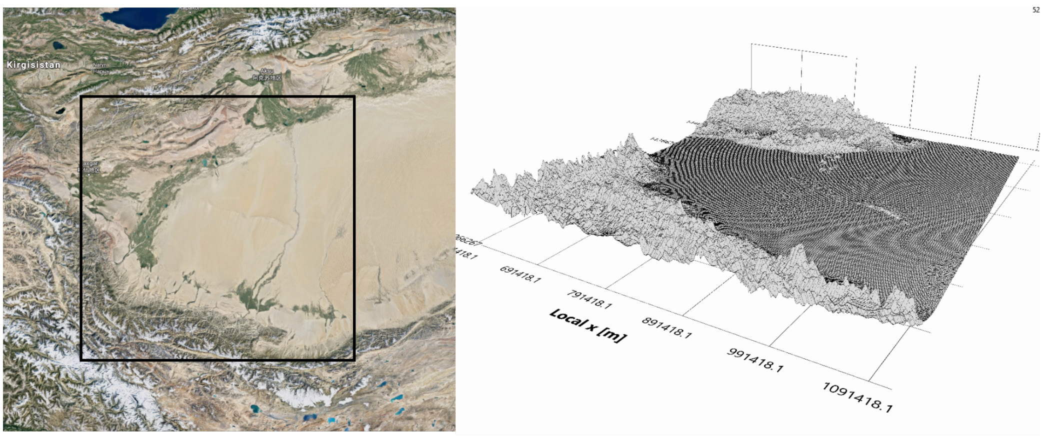

Figure 10: Digital elevation model of the area around the western part of the Xinjiang basin in China (15x exaggerated).

creates a three-dimensional mesh of 20x20x20 cells in the bounding domain of the selected meshes. The dimension of a mesh is controlled by the step width. By selecting a step width of 0 the according dimension will be removed. If, for instance, step width z is reduced to 0, and x and y is kept as 20, a two-dimensional grid with 20 faces in x and 20 faces in y direction will be created. Similar, if two dimensions are reduced to 0, a line grid will be created.

Digital elevation models Based on the API provided by **Bing Maps** a two-dimensional data set can be assigned elevation values. Therefore, create a two-dimensional mesh in the area you want the elevation data from by providing start x, end x, start y and end y coordinates in WGS84 format.

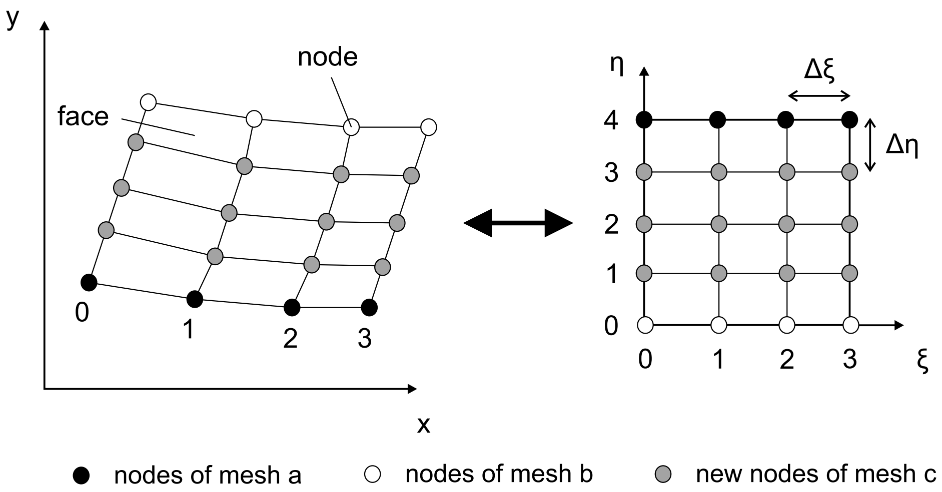

Figure 11: Concept of mesh generation using two contraint meshes of dimensionality d-1 with d as the target dimension.

Gridding two surfaces

When you have two two-dimensional data sets you can create a three-dimensional grid out of those. However, both surfaces must provide identical dimensionality in x, y and z direction and one dimensionality less than the target mesh.
For 3-D mesh creating select the option "From two surfaces" in the "Boundary type" combo box and select those two surfaces that should be used in the "Source data set". When you press "Compute discretization" a 3-D grid will be created. Therefore, the two source data sets are projected from a physical in a local coordinate system (fig. 11. Nodes from the two source data sets serve as boundary nodes for the new mesh. After projection, the points in between the two boundary meshes are created according to

$$\begin{aligned} R &= (i-1)(n_\zeta + 1) + 1 \\ C &= mod((i-1), (n_\iota + 1)) + 1, \end{aligned} \tag{4}$$

$$\begin{aligned} x &= \sum N_k(\zeta, \iota) x_k \\ y &= \sum N_k(\zeta, \iota) y_k \end{aligned} \tag{5}$$

where R is the row and C is the column of a node i, n_ζ is the number of

4.4.3 Mesh statistics

A mesh provides characteristic properties like dimensionality, count of nodes, faces and cells or bulk volume/area. Those statistics can be computes in the

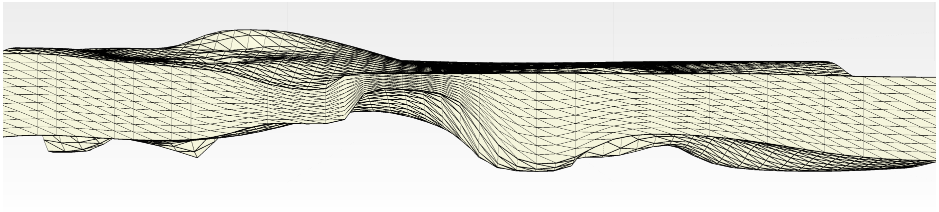

Figure 12: 3-D mesh generated with two bounding surfaces on the top and on the bottom.

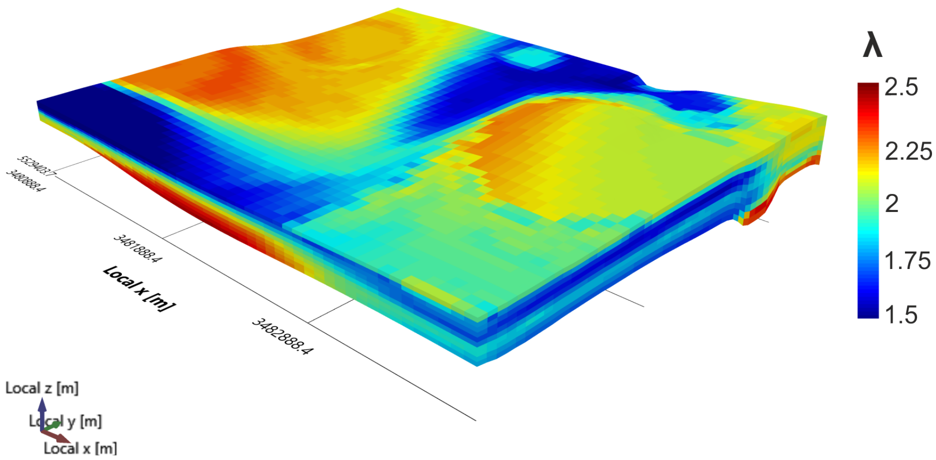

Figure 13: IDW interpolation result for thermal conductivity measurements in the Donnersberg formation located in central Germany.

"Mesh statistics" tab. When the user presses "Compute" he or she will get all that information displayed immediately.

4.4.4 Spatial interpolation and simulation

In the following section, we will explain how to interpolate values from one or more source data sets to a target mesh. To reduce the content in this section, we will cover the most important algorithms with examples. For more details on the theory behind the interpolation and simulation algorithms we will refer to the textbooks of Wackernagel (2003) and Webster & Margaret (2007).
All types of meshes can be used as both input and target of an interpolation. The selected "Source data sets" serve as constraints for the interpolation algorithms. The "Target data set" provides the nodes where the interpolated values will be calculated. The user can interpolate either the value, elevation, latitude/x or longitude/y of a mesh.

Spatial inter- and extrapolation can be generated with deterministic and stochastic techniques. All interpolations are based on the assumption that a known constraint point x_k with a value $z(x_k)$ has a weight on a discrete point x_0 in space with an unknown value $z(x_0)$.

Neighborhood
The number of constraints in each interpolation can be restricted by defining a neighborhood. Therefore, a maximum distance in x, y and z direction can be defined. Also, the total number of constraint can be reduced to a certain count.
Inverse Distance Weighting
For deterministic interpolation we performed inverse distance weighting (IDW), p-value IDW and Shepard's IDW Shepard 1968 interpolations. The IDW interpolation generally calculates an unknown value $z(x_0)$ at point x_0 by weighting the distance of that point to each known value point (x_k)in space. The underlying formula for IDW is:

$$z(x_0) = \frac{\sum_{k=1}^{n} 1/d_k^p \cdot z(x_k)}{\sum_{k=1}^{n} 1/d_k^p}, \tag{6}$$

where d is the Euclidean distance between the the point with the known value x_k and the point with the unknown value x_0 and p is an exponent factor to bias the weights non-linearly. IDW is a reliable and widely applied method to interpolate static field parameters in one to three-dimensional space **RN635**.

Kriging
For stochastic interpolation we used simple kriging (SK), ordinary kriging (OK) and universal kriging (UK). Kriging is a common method to interpolate geological field parameters in space **RN636**; **RN630**. Therefore, the value $z(x_0)$ at an unknown point x_0 is calculated by weighting the neighboring known values and building a linear combination of those like:

$$z(x_0) = \sum_{k=1}^{n} w_k \cdot z(x_k), \tag{7}$$

where w_k is the weight of the known point x_k with the value $z(x_k)$. While eq. 7 applies to SK and OK, UK
The kriging types primarily differ in the derivation of the weight vector. For all systems a set of linear equations has to be solved like it is outlined in the following paragraphs The quality of kriging interpolation is dependent on the theoretical semivariogram and the goodness of fit to the experimental

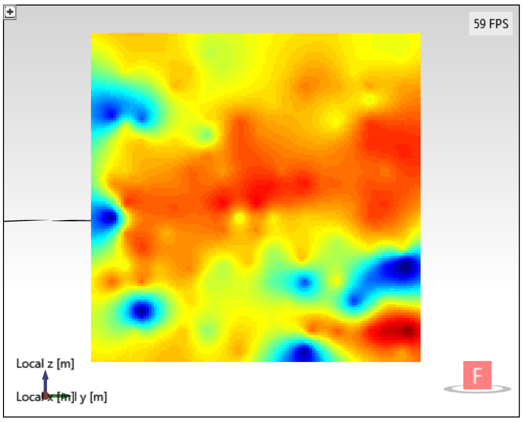

Figure 14: Simple kriging interpolation of the apparent permeability measured on 108 rock plugs on a rock slab of 0.5 x 0.5 m.

values.

Simple Kriging weights

To obtain the simple kriging weights, a set of n equations have to be solved. In matrix notation, this set of equations can be written as:

$$\begin{pmatrix} c(x_1 - x_1) & \cdots & c(x_1 - x_n) & 1 \\ \vdots & \ddots & \vdots & \vdots \\ c(x_n - x_1) & \cdots & c(x_n - x_n) & 1 \end{pmatrix} \begin{pmatrix} w_1^{SK} \\ \vdots \\ w_n^{SK} \end{pmatrix} = \begin{pmatrix} c(x_1 - x_0) \\ \vdots \\ c(x_n - x_0) \end{pmatrix} \tag{8}$$

with c as covariance function, x_n as point with known value Wackernagel 2003.

Ordinary Kriging weights

To obtain the ordinary kriging weights, a set of n+1 equations have to be solved. In matrix notation, this set of equations can be written as:

$$
\begin{pmatrix}
\gamma(x_1 - x_1) & \cdots & \gamma(x_1 - x_n) & 1 \\
\vdots & \ddots & \vdots & \vdots \\
\gamma(x_n - x_1) & \cdots & \gamma(x_n - x_n) & 1 \\
1 & \cdots & 1 & 0
\end{pmatrix}
\begin{pmatrix}
w_1^{OK} \\ \vdots \\ w_n^{OK} \\ \mu_{OK}
\end{pmatrix}
=
\begin{pmatrix}
\gamma(x_1 - x_0) \\ \vdots \\ \gamma(x_n - x_0) \\ 1
\end{pmatrix}
\tag{9}
$$

with γ as theoretical semivariogram, x_n as point with known value and μ as Lagrange parameter Wackernagel 2003.

Universal Kriging weights

To obtain the ordinary kriging weights, a set of n+1 equations have to be solved. In matrix notation, this set of equations can be written as:

$$
\begin{pmatrix}
\gamma(x_1 - x_1) & \cdots & \gamma(x_1 - x_n) & 1 & f_1(x_1) & \cdots & f_k(x_1) \\
\vdots & \ddots & \vdots & \vdots & \vdots & \vdots & \vdots \\
\gamma(x_n - x_1) & \cdots & \gamma(x_n - x_n) & 1 & f_1(x_n) & \cdots & f_k(x_n) \\
1 & \cdots & 1 & 0 & 0 & \cdots & 0 \\
f_1(x_1) & \cdots & f_1(x_n) & 0 & 0 & \cdots & 0 \\
\vdots & \ddots & \vdots & \vdots & \vdots & \ddots & \vdots \\
f_k(x_1) & \cdots & f_k(x_n) & 0 & 0 & \cdots & 0
\end{pmatrix}
\cdot
\begin{pmatrix}
w_1^{OK} \\ \vdots \\ w_n^{OK} \\ \mu_{OK} \\ \phi_0 \\ \vdots \\ \phi_k
\end{pmatrix}
=
\begin{pmatrix}
\gamma(x_1 - x_0) \\ \vdots \\ \gamma(x_n - x_0) \\ 1 \\ f_1(x_0) \\ \vdots \\ f_k(x_0)
\end{pmatrix}
\tag{10}
$$

with γ as theoretical semivariogram, x_n as point with known value and μ as Lagrange parameter $f_i(x)$ as i^{th} polynomial Webster and Margaret 2007.

4.4.5 Conditional Simulation

Most interpolation techniques do not represent the original statistical parameter distribution adequately and induce a slight smoothing effect into the spatial distribution. Conditional simulations aim to replicate the original statistical parameter distribution through Monte-Carlo simulations. Random numbers were created using the Box-Muller method

4.4.6 Uncertainty Integration

Integrating measurement errors into an interpolation can be achieved by estimating the measurement error precision σ_e with a variance of σ_e^2 and incorporating it into the kriging system of linear equations like:

$$\begin{pmatrix} \gamma(x_1 - x_1) + \sigma_1^2 & \cdots & \gamma(x_1 - x_n) & 1 \\ \vdots & \ddots & \vdots & \vdots \\ \gamma(x_n - x_1) & \cdots & \gamma(x_n - x_n) + \sigma_n^2 & 1 \\ 1 & \cdots & 1 & 0 \end{pmatrix} \begin{pmatrix} w_1^{OK} \\ \vdots \\ w_n^{OK} \\ \mu_{OK} \end{pmatrix} = \begin{pmatrix} \gamma(x_1 - x_0) \\ \vdots \\ \gamma(x_n - x_0) \\ 1 \end{pmatrix}, \tag{11}$$

what is the simple kriging system of linear equations Wackernagel 2003 with error variance. In contrast to the conventional formula, σ_e^2 was added in the diagonal of the matrix.
To perform

4.4.7 Multivariate statistics

Multivariate analyses in GeoReVi comprise k-Means cluster analysis, principal component analysis, multidimensional scaling (Sammon mapping) and correlation analysis. The multivariate analysis can be performed in the "Multivariate" tab in the data analysis window. Here, the user can upload standard spreadsheets and perform basic data transformations on the individual columns. To add a data set to a multivariate analysis the user has to right-click on the selected data set and add it to the particular analysis.

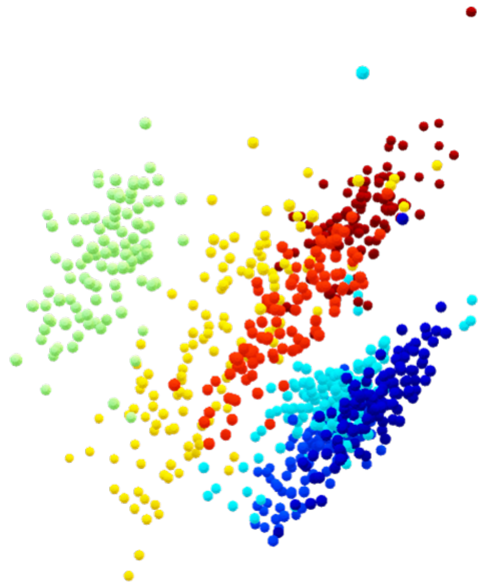

Figure 15: 3D representation of a Principal Component analysis.

4.5 Data visualization

Data visualization can be performed in different types of charts. GeoReVi includes line and scatter charts, bubble charts, ternary charts, histograms, box-whisker charts, semivariograms and 3-D charts. To add a mesh to a chart in the univariate analysis the user has to **right-click** → **Add mesh to chart**. When a mesh is added to a chart type it is displayed individually as a series.

4.5.1 Line-, scatter and bubble chart

4.5.2 Box-Whisker chart

4.5.3 Histogram chart

4.5.4 3-D chart

You can add meshes to the 3-D chart by **right-click** → **Add mesh to 3-D chart**. In the 3-D chart the user can adapt the chart width/height, background, colormap,

Vector field
Vector fields are displayed when the user selects the "Gradient" option. A

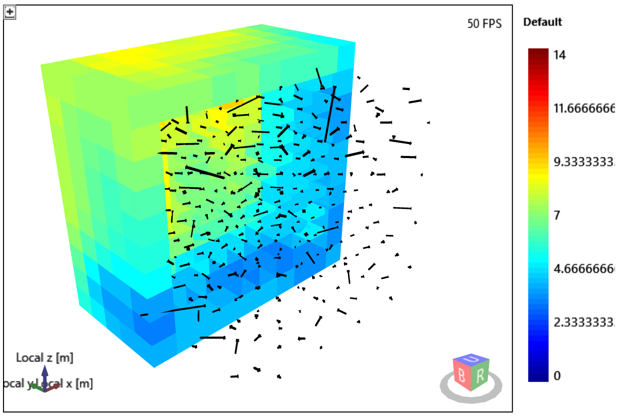

Figure 16: Vector field of the apparent permeability measured on a rock cube and interpolated with simple kriging.

vector field is based on the gradient ∇ of a field parameter f like

$$\nabla f = \begin{bmatrix} \frac{\partial f}{\partial x} & \frac{\partial f}{\partial y} & \frac{\partial f}{\partial z} \end{bmatrix}^T \tag{12}$$

5 Developing Plug-ins

This section is under preparation.

6 Personal data security

The database where GeoReVi stores user information is located on a local server or in the cloud which is dependent on the infrastructure provided by your administration. Passwords and user messages are encrypted and secured in a database management system. For internal communication, the implemented message service can be used. Messages are peer-to-peer encrypted and stored in the database.

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