

# Harmonized workflows for non-urban areas

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## A. Purpose of the workflow

The GeoPLASMA-CE project will produce a transnational web-based platform presenting geothermal risk and potential maps for six pilot areas in Austria, Czech Republic, Germany, Poland, Slovakia and Slovenia. **Figure 1** and **Table 1** provide an overview of the pilot areas.



**Figure 1: The pilot areas of the GeoPLASMA-CE project.**

**Table 1: Brief characteristics of the pilot areas.**

Pilot area	Urban/ non-urban	Thematic focus	Scale
Vogtland/ W-Bohemia	non-urban	Land-use conflict with thermal and curative water protection	1: 50 000
Wałbrzych/ Broumov	non-urban	Improvement of air quality by using emission-free shallow geothermal energy	1: 50 000
Krakow	urban	Improvement of air quality by using emission-free shallow geothermal energy	1: 10 000
Bratislava/ Hainburg	urban	Evaluate energy market, regulation, support and consumer behaviour in an international region	1: 50 000
Vienna	urban	Use of open loop systems in an aquifer with many shallow geothermal applications	1: 20 000
Ljubljana	urban	Development of energy management strategies for the city	1: 10 000



Some pilot areas cover rural areas with decentralized heating, some pilot areas comprise urban areas with an intensive usage of the subsurface which may be in conflict with the production of shallow geothermal energy. Some pilot areas are well suitable for the use of open loop systems because they host aquifers. Closed systems can be installed everywhere, also if no aquifer is present. Therefore, some pilot areas without large aquifers, e.g. situated on crystalline rocks, are especially suitable for closed loop systems. Some pilot areas are already advanced in the usage of shallow geothermal energy and have to deal with conflicting usage; other pilot areas are following with plans to emission-less energy and have to collect information on their geothermal potential.

During the work in the pilot areas, the partners will use harmonized workflows for developing geological 3D models as a basis for geothermal potential and conflict maps. Since the data, the classification schemes, the scale and level of detail, the legal regulations and the modelling software may vary among the project partners, comparable modelling results can only be obtained if as many work steps of data interpretation, processing and modelling as possible are standardized. Therefore, the project partners agreed on mandatory specifications and rules. Since not all work steps can be standardized, the workflow also contains recommendations and flexible parts which are performed by the partners according to their specific requirements.

This report is the guideline for mapping the geothermal potential, risk and conflict factors for shallow geothermal use in non-urban areas. Two pilot areas, Vogtland/W-Bohemia and Wałbrzych/Broumov are located in rural areas and will follow this workflow. It includes general harmonization rules as well as detailed descriptions of workflow steps. The deliverable also specifies the standardized final outputs that have to be produced by the project partners.

First of all, the project partners specified the outputs they will produce on the basis of a stakeholder query of D.T2.1.1, such that the provided workflow can meet the needs of each pilot area.

## B. Aspects of shallow geothermal use in non-urban areas

Rural areas are characterized by a much smaller density of population than cities. In Central Europe, most rural areas are agricultural sites which may include small industrial plants, forests and natural protection zones. The population lives in small towns or villages or even in isolated farms. Since a connection of small villages or farms with district heating is either complicated or not possible, geothermal installations may provide an important source for heating and warm water supply in family and green houses.

In rural areas, the ground surface is mainly unsealed. The thermal emission from heated buildings and the density of pipelines and tunnels is much smaller than in cities; and natural factors control the temperature of the shallow subsurface, like the solar insulation, the aspect of the slopes and the vegetation. Therefore, the temperature of rock and groundwater follows the natural annual cycle and is warmest in early autumn and coldest in winter. The geothermal gradient of the shallowest parts of the subsurface is also following a natural cycle down to a neutral zone. Below this zone, the geothermal gradient is controlled by geological factors. The geothermal regime in rural areas can therefore be considered to be undisturbed and to be controlled by the rock composition and groundwater flow.

Therefore, mainly natural factors have to be considered by a workflow specifying the geothermal potential and their conflict and risk factors of a non-urban region.

The rural regions often are several 100 km<sup>2</sup> large. Therefore a structural model describing the subsurface has to comprise many modelled objects (40-60 geological units).

Input parameters controlling the shallow geothermal potential are:



- The mean annual ground surface temperature,
- The geothermal gradient,
- The thermal conductivity of the rocks.

Anthropogenic activities like heating of buildings or existing thermal installations can be mainly neglected. However, drainage of agricultural areas and the use of groundwater for agricultural farms may influence the depth of the groundwater table and result in reduced thermal conductivities and heat extraction capacities of the rocks.

Rural regions provide specific risk and conflict factors for shallow geothermal usage:

- Protection zones like natural reserves or water protection zones are important national goods and must not be influenced by geothermal installations.
- Specific geological structures may provide risk factors, e.g. karst, fault zones, swellable rocks, quicksands or steep slopes.
- Shallow gas leakage may cause eruptions while drilling or health damage (e.g. radon).
- Old mines or cavities may cause instabilities of the boreholes and bad conditions for heat conduction (if they are filled with air).

## C. Action plan for the implementation of methodical workflows in non-urban pilot areas

### C.1 Purpose of the action plan

The action plan was developed in order to provide an overview of the outputs which have to be produced for each pilot area. The base for this decision was the stakeholder survey of D.T2.1.1, which was performed in order to investigate which information and products (maps, online-platforms) the stakeholders working in the field of shallow geothermal energy are interested in. The most important stakeholder groups, licensing authorities, political stakeholders, designers/consultants of geothermal plants, drilling companies, equipment producers and others, were asked to participate. A set of 65 parameters concerning different aspects of the use of geothermal energy was registered. The results are presented in the catalogue of requirements (D.T2.1.2) and provide the basis for deciding which outputs should be produced during the project. The desired outputs, the data and software as well as the workflows needed to produce these outputs are presented in the following chapters.

### C.2 Pilot Area Vogtland / W-Bohemia

#### C.2.1. Specification of the pilot area

The pilot area Vogtland/W-Bohemia (Germany, Czech Republic) is especially suitable for using geothermal energy since the Eger valley corresponds to a lithospheric uplift which causes geothermal gradients twice as high as in the surrounding regions. The deeply circulating water in this tectonically active region forms thermal and mineral springs. The usage of this balneal water is in conflict with the geothermal usage, such that a detailed study of land-use conflicts is necessary for the establishment of a strategy for geothermal energy supply. The central part of the pilot area close to the international border consists of a mountain



range. In its foothills, many small towns and villages are located on the both sides of the border. The infrastructural development of this region can benefit significantly from the usage of shallow geothermal energy.

## C.2.2. Stakeholder requirements and aimed outputs

The stakeholder query (D.T.2.1.2) showed that stakeholders are interested in the following information on the geothermal potential as well as the land-use and risk potential:

- suitability of forms of geothermal energy,
- risk and land-use-conflict maps,
- geology,
- geothermal potential maps,
- temperature,
- specific thermal conductivity,
- local map scale,
- detailed information on groundwater and aquifers,
- drinking water protection zones,
- hydraulically separated aquifers,
- confined aquifers,
- existing use,
- cavities.

The suitability of geothermal systems will be presented by traffic-light maps for open and closed loop systems. The geothermal potential will only be modelled for closed loops systems and will be specified by the thermal conductivity. In addition to the stakeholder requirements, the project partners agreed on describing the geothermal potential by the heat extraction rates, which provides a brief overview on the potential of a location for public users like house-owners. In order to provide important information for the expert platform produced by the GeoPLASMA-CE project, the partners agreed on modelling or/and displaying the ground surface temperature and the geothermal gradient. Additionally the thermal conductivities in different depth intervals will be calculated.

In contrast to the stakeholder requirements, confined and artesian groundwater will not be modeled, since no confined aquifers are known in the pilot area. Instead and in addition to the stakeholder requirements, natural reserves, shallow gas leakage, fault zones and contaminated sites will be presented as conflict potentials. These factors are important in the pilot area, which may not be known by the stakeholders. By including these factors, the GeoPLASMA-CE partners provide important information to users of shallow geothermal energy in the pilot area.

## C.2.3. Geological 3D modelling

The geology of the pilot area Vogtland/W-Bohemia is very complex; therefore, a structural 3D model is necessary as basis for the modelling of the geothermal potential and of the land-use conflict and risk potential. 48 units ranging from Paleozoic to Quaternary have to be modelled with the 3D modelling software Paradigm SKUA-GOCAD™. Input data are geologic maps and drilling data provided by the Saxon and Czech geological surveys. The model will comprise the boundaries of geological bodies as triangulated surfaces.

## C.2.4. Suitability maps

Suitability maps will be produced for all pilot areas. The suitability maps give an overview over the systems of geothermal plants which are suitable for a particular location. The maps will be produced separately for open and closed loop systems. They will be provided as traffic-light maps giving an overview on where the use of a particular geothermal system is possible or not. **Table 2** gives a general overview of the input data needed to generate the suitability maps.

**Table 2: Input data necessary for the calculation of the suitability maps.**

pilot area		suitability maps	
		traffic light map closed loop system	traffic light map open loop system
Vogtland / W-Bohemia	catalogue of requirements Vogtland	x	x
	catalogue of requirements W-Bohemia	x	x
	presentation Vogtland (X = yes)	x	x
	presentation W-Bohemia (X = yes)	x	x
necessary INPUT DATA			
parameter	unit		
Full geological 3D-model		x	x
geological maps	map	x	x
Water level (normal water table)	m sub sl		x
Water level (high water table)	m sub sl		x
Water level (low water table)	m sub sl		x
Maximum pumping rate	l/s		x
Maximum daily pumping rate	m <sup>3</sup> /d		x
Maximum annual pumping rate	m <sup>3</sup> /yr		x
Grain size distribution	%		x
Hydraulic conductivity (derived from grain size distribution)	m/s		x
Effective porosity of aquifer derived from pumping test	%		x
Hydraulic conductivity derived from pumping tests	m/s		x
Gross aquifer thickness	m		x
Net aquifer thickness (related to normal water level)	m		x
groundwater: Total dissolved solids (TDS)	mg/l		x
groundwater: Content of NaCl	mg/l		x
groundwater: Content of NO3-	mg/l		x
groundwater: Content of SO42-	mg/l		x
groundwater: Content of Fe2+	mg/l		x
groundwater: Content of Fe (total)	mg/l		x
groundwater: Content of Mg2+	mg/l		x
groundwater: Content of K+	mg/l		x
groundwater: Content of Ca2+	mg/l		x
groundwater: Content of Mn	mg/l		x
groundwater: Content of HCO3-	mg/l		x
groundwater: pH value			x
groundwater: Content of O2	mg/l		x
groundwater: Electrical conductivity of water sample	µS/cm		x
water protection areas (curative, drinking water)	map	x	x
natural reserves / protection areas	map	x	x
tectonics/ faults	map	x	x
cavity, mining maps	map	x	x
landslides map	map	x	x
shallow gas leakage data	map	x	x
anthropogenic lines (electricity, gas,...)	map	x	x
landfills, contaminated area map	map	x	x
Outline of relevant groundwater bodies suitable for shallow geothermal use (combined output with conflict of use maps)	map		x
Outline of groundwater bodies with problematic chemistry (scaling, corrosion, anthropogenic contamination)	map	x	x
necessary calculation software		ArcGIS	ArcGIS
necessary workflow		conflicts	conflicts



### C.2.5. Land-use conflict and risk factors for geothermal use

The pilot area is characterized by hydrothermal and post-volcanic activity. Therefore, the conflict potential of curative water protection zones, shallow gas leakage and fault zones has to be qualified. Also natural reserves, anthropogenic lines and past mining districts are in conflict with the shallow geothermal use. Since the pilot area has been an industrial area for centuries, contaminated sites have to be taken into account for the protection of the ground water.

**Table 3: Factors of land-use conflict and risk for the use of shallow geothermal energy in the pilot area Vogtland/W-Bohemia.**

pilot area		maps of conflict and risk factors							
		water protection areas (curative, drinking water)	natural reserves / protection areas	tectonics/ faults	cavity/ mining areas	landslides	shallow gas leakage	anthropogenic lines (electricity, gas,...)	landfills, contaminated areas
Vogtland / W-Bohemia	catalogue of requirements Vogtland	x			x				
	catalogue of requirements W-Bohemia	x			x				
	presentation Vogtland (X = yes)	x	x	x	x		x		x
	presentation W-Bohemia (X = yes)	x	x	x	x	x		x	
necessary INPUT DATA									
	parameter	unit							
	boreholes: Coding of bore holes (geological codes - LUT)						x		x
	boreholes: Location (harmonized coordinate system including elevation)						x		x
	boreholes: Final depth (TVD)	m					x		x
	boreholes: Final depth (MD)	m					x		
	boreholes: Lithological borehole profile						x		x
	boreholes: Stratigraphic borehole profile						x		x
	Petrographical rock descriptions (LUT)						x		x
	Standardized, harmonized lithological profile								x
	Standardized, harmonized stratigraphic profile								x
	Full geological 3D-model			x	x				x
	geological maps	map		x	x				x
	water protection areas (curative, drinking water)	map	x						
	natural reserves / protection areas	map		x					
	tectonics/ faults	map		x					
	cavity, mining maps	map			x				x
	landslides map	map				x			
	shallow gas leakage data	map					x		
	anthropogenic lines (electricity, gas,...)	map						x	
	landfills, contaminated area map	map							x
	Outline of groundwater bodies with problematic chemistry (scaling, corrosion, anthropogenic contamination)	map							x
	necessary calculation software		ArcGIS	ArcGIS	ArcGIS	ArcGIS	ArcGIS	ArcGIS	ArcGIS
	necessary workflow		conflicts	conflicts	conflicts	conflicts	conflicts	conflicts	conflicts



## C.2.6. Calculation of the geothermal potential for closed loop systems

Due to the geological conditions, closed loop systems are most important for this pilot area. Therefore, all outputs referring to borehole heat exchangers will be produced. In order to generate the outputs, a full 3D structural model and the data and software listed in **Table 4** is required. The outputs can be produced following the harmonized workflows for 3D modelling and closed loop systems.

**Table 4: Desired outputs, necessary software, input data and harmonized workflows for describing the geothermal potential of closed loop systems in the pilot area Vogtland/W-Bohemia.**

pilot area		closed loop systems			
		thermal conductivity maps (W/m·K)	heat extraction maps (W/m)	surface temperature maps (°C)	temperature gradient maps (K/100 m)
Vogtland / W-Bohemia	catalogue of requirements Vogtland	x	x	not recorded	not recorded
	catalogue of requirements W-Bohemia	x	x	not recorded	not recorded
	presentation Vogtland (X = yes)	x	x	x	x
	presentation W-Bohemia (X = yes)	x	x	x	x
	Bulk thermal conductivity (distributed TC profile)	(W/m·K)	x	x	
	Thermal conductivity of dry rock sample	(W/m·K)	x	x	
	Thermal conductivity of saturated rock sample	(W/m·K)	x	x	
	Bulk thermal conductivity map	map/grid		x	
	Mean annual surface temperature	°C			x
	Groundwater temperature (series, single depth point)	°C			x
	Groundwater temperature (series, multiple depth points)	°C			x
	temperature profiles derived from TRT	°C			x
	Water level (normal water table)	m sub sl	x	x	
necessary calculation software		Skua	Skua	ArcGIS	ArcGIS
		ArcGIS extension	ArcGIS extension		
necessary workflow		3D modelling closed loop	3D modelling closed loop	closed loop	closed loop

## C.2.7. Calculation of the geothermal potential for open loop systems

Potentials for open loop systems will not be modelled since the natural conditions are not sufficient and existing conflicts with balneology usages occur in the pilot area.



## C.3 Wałbrzych / Broumov

### C.3.1. Specification of the pilot area

The transboundary pilot area Wałbrzych / Broumov (Poland, Czech Republic) was once a coal mining industrial district, which is today focusing on tourism based on local landscape attractions and clean air. Measurements of air pollution in the Wałbrzych area conducted in recent years indicate significant exceedance of the normal values caused by dust suspensions, which are known to be harmful to human health and the environment. The main cause of this situation is burning of fossil fuels for heating. These conditions imply enhanced utilization of ground source heat pumps as energy sources in the investigated area. The objective of the GeoPLASMA-CE project is to elaborate a 3D geological model and a map of the shallow geothermal energy potential which allows identifying the specific locations with favourable conditions for shallow geothermal use. Additionally, information activities are planned to familiarize and convince local authorities and residents of the Wałbrzych/Broumov area with large ecological and economic benefits related to the practical use of geothermal heat pumps.

From the geological point of view, the Wałbrzych / Broumov area belongs to the Central Sudety Mts. block and includes several sub-units. About two thirds of its territory is built by the transboundary geological unit of the Intra-Sudetic Basin which is filled with sedimentary and volcanic rocks. Along the northern edge of the area there is a small belt of the Kaczawa Mts. metamorphic complex and the Świebodzice Basin in its NE corner. The eastern part of the area is made by a fragment of the Sowie Mts. gneiss complex. The listed geological units are characterized by complicated tectonic structure and by high diversity of the lithostratigraphic rock formations, ranging in age from Lower Paleozoic reported in the basement, metamorphic complexes and Świebodzice Basin to Upper Paleozoic and Mesozoic in the Intra-Sudetic Basin.

### C.3.2. Stakeholder requirements and aimed outputs

The stakeholder query (D.T.2.1.2) showed that stakeholders are interested in the following information:

- suitability of forms of geothermal energy,
- risk and land-use conflict maps,
- geology,
- geothermal potential maps,
- temperature,
- heat extraction capacity,
- local map scale,
- detailed information on groundwater and aquifers,
- drinking water protection zones,
- curative water protection zones,
- hydraulically separated aquifers,
- confined aquifers,
- existing use,
- cavities,
- faults,
- karst,
- pipelines,
- limitation of drilling depth.





The suitability of geothermal systems will be presented by traffic-light maps for open and closed loop systems. The geothermal potential will only be modelled for closed loop systems and be specified by the thermal conductivity. In addition to the stakeholder requirements, the project partners agreed on describing the geothermal potential by the heat extraction capacity, which provides a brief overview of the potential of a location for public users like house-owners. In order to provide important information for the expert platform produced by the GeoPLASMA-CE project, the partners agreed on modelling or/and displaying the ground surface temperature and the geothermal gradient.

In contrast to the stakeholder requirements, limitations of drilling depth and the occurrence of karst will not be modelled since they are not known in the pilot area. Instead and in addition to the stakeholder requirements, natural reserves, confined and artesian groundwater as well as landslides are considered to be important issues for assessing the conflict potential of shallow geothermal use.

### C.3.3. Geological 3D modelling

The geology of the pilot area is very complex; therefore, a structural 3D model is necessary as basis for the modelling of the geothermal potential and of the land-use conflict and risk potential.

Units ranging from Paleozoic to the Quarternary have to be modelled with the 3D modelling software Paradigm SKUA-GOCAD™. Input data are geologic maps and drilling data provided by the Polish and Czech geological survey. The model will comprise the boundaries of geological bodies as triangulated surfaces.

### C.3.4. Suitability maps

Suitability maps will be produced for all pilot areas. The suitability maps give an overview of the systems of geothermal plants which are suitable for one location. The maps will be produced separately for open and closed loop systems. They will be provided as traffic-light maps giving an overview on where the use of one geothermal system is possible or not.



**Table 5** gives a generally overview over the input data that are needed to generate the suitability maps.

### C.3.5. Land-use conflict and risk factors for geothermal use

The main factor for economic development was black coal mining, therefore conflict factors such as the location of past mines and contaminated industrial sites as well as landslides are important. More than 90% of the Czech part is nowadays a protected landscape area. The Polish part is also an important natural and touristic region. Therefore, natural reserves have to be mapped as conflicts to shallow geothermal use. Groundwater mostly occurs in the near - surface layers of strongly weathered and fissured rocks. Confined groundwater occurs in the region of Wałbrzych. However, water protection zones are conflicting with shallow geothermal use, since they are located at a shallow depth level. The complicated tectonic structure of the pilot area requires mapping of fault zones as risk factor.

**Table 5: Input data necessary for the calculation of the suitability maps.**

pilot area		suitability maps	
		traffic light map closed loop system	traffic light map open loop system
Broumov / Wałbrzych	catalogue of requirements Broumov	x	x
	catalogue of requirements Wałbrzych	x	x
	presentation Broumov (X = yes)	x	x
	presentation Wałbrzych (X = yes)	x	x
necessary INPUT DATA			
parameter	unit		
Full geological 3D-model		x	x
geological maps	map	x	x
Water level (normal water table)	m sub sl		x
Water level (high water table)	m sub sl		x
Water level (low water table)	m sub sl		x
Maximum pumping rate	l/s		x
Maximum daily pumping rate	m <sup>3</sup> /d		x
Maximum annual pumping rate	m <sup>3</sup> /yr		x
Grain size distribution	%		x
Hydraulic conductivity (derived from grain size distribution)	m/s		x
Effective porosity of aquifer derived from pumping test	%		x
Hydraulic conductivity derived from pumping tests	m/s		x
Gross aquifer thickness	m		x
Net aquifer thickness (related to normal water level)	m		x
groundwater: Total dissolved solids (TDS)	mg/l		x
groundwater: Content of NaCl	mg/l		x
groundwater: Content of NO3-	mg/l		x
groundwater: Content of SO42-	mg/l		x
groundwater: Content of Fe2+	mg/l		x
groundwater: Content of Fe (total)	mg/l		x
groundwater: Content of Mg2+	mg/l		x
groundwater: Content of K+	mg/l		x
groundwater: Content of Ca2+	mg/l		x
groundwater: Content of Mn	mg/l		x
groundwater: Content of HCO3-	mg/l		x
groundwater: pH value			x
groundwater: Content of O2	mg/l		x
groundwater: Electrical conductivity of water sample	µS/cm		x
water protection areas (curative, drinking water)	map	x	x
natural reserves / protection areas	map	x	x
confined/artesian groundwater areas	map	x	x
tectonics/ faults	map	x	x
cavity, mining maps	map	x	x
landslides map	map	x	x
anthropogenic lines (electricity, gas,...)	map	x	x
Outline of relevant groundwater bodies suitable for shallow geothermal use (combined output with conflict of use maps)	map		x
Outline of groundwater bodies with problematic chemistry (scaling, corrosion, anthropogenic contamination)	map	x	x
necessary calculation software		ArcGIS	ArcGIS
necessary workflow		conflicts	conflicts

**Table 6: Factors of land-use conflict and risk for the use of shallow geothermal energy at pilot area Walbrzych / Broumov.**

pilot area		maps of conflict and risk factors							
		water protection areas (curative, drinking water)	natural reserves / protection areas	confined/ artesian groundwater	tectonics/ faults	cavity, mining areas	landslides	Location of existing geothermal plant	anthropogenic lines (electricity, gas,...)
Broumov / Walbrzych	catalogue of requirements Broumov	x		x		x		not recorded	
	catalogue of requirements Walbrzych	x		x	x	x		not recorded	x
	presentation Broumov (X = yes)	x	x		x	x	x		x
	presentation Walbrzych (X = yes)	x	x	x	x	x	x	x	x
necessary INPUT DATA									
parameter	unit								
boreholes: Coding of bore holes (geological codes - LUT)				x					
boreholes: Location (harmonized coordinate system including elevation)				x					
boreholes: Final depth (TVD)	m			x					
boreholes: Final depth (MD)	m			x					
Full geological 3D-model				x	x	x			
geological maps	map			x	x	x			
Water level (normal water table)	m sub sl			x					
Water level (high water table)	m sub sl			x					
Water level (low water table)	m sub sl			x					
Effective porosity of aquifer derived from pumping test	%			x					
Hydraulic conductivity derived from pumping tests	m/s			x					
Gross aquifer thickness	m			x					
Net aquifer thickness (related to normal water level)	m			x					
water protection areas (curative, drinking water)	map	x							
natural reserves / protection areas	map		x						
drilling limitation layer	map			x					
swellable rock map	map								
confined/artesian groundwater areas	map			x					
tectonics/ faults	map				x				
cavity, mining maps	map					x			
landslides map	map						x		
Location of existing geothermal utilizations								x	
anthropogenic lines (electricity, gas,...)	map								x
Outline of relevant groundwater bodies suitable for shallow geothermal use (combined output with conflict of use maps)	map							x	
necessary calculation software		ArcGIS	ArcGIS	ArcGIS	ArcGIS	ArcGIS	ArcGIS	ArcGIS	ArcGIS
necessary workflow		conflicts	conflicts	conflicts	conflicts	conflicts	conflicts	conflicts	conflicts

### C.3.6. Calculation of the geothermal potential for closed loop systems

Due to the geological conditions, closed loop systems are most important for this pilot area. Therefore, all outputs referring to borehole heat exchangers will be produced. In order to generate the outputs, a full 3D structural model and the data set listed in **Table 7** are necessary. The outputs can be produced following the harmonized workflows for 3D modelling and closed loop systems.

**Table 7: Desired outputs, necessary software, input data and harmonized workflows for describing the geothermal potential of closed loop systems in the pilot area Wałbrzych / Broumov.**

pilot area		closed loop systems			
		thermal conductivity maps (W/m·K)	heat extraction maps (W/m)	surface temperature maps (°C)	temperature gradient maps (K/100 m)
Broumov / Wałbrzych	catalogue of requirements Broumov	x	x	not recorded	not recorded
	catalogue of requirements Wałbrzych	x	x	not recorded	not recorded
	presentation Broumov (X = yes)	x	x	x	x
	presentation Wałbrzych (X = yes)	x	x	x	x
necessary INPUT DATA					
parameter	unit				
boreholes: Coding of bore holes (geological codes - LUT)		x	x		
boreholes: Location (harmonized coordinate system including elevation)		x	x		x
boreholes: Final depth (TVD)	m	x	x		x
boreholes: Final depth (MD)	m	x	x		x
boreholes: Lithological borehole profile		x	x		
boreholes: Stratigraphic borehole profile		x	x		
Petrographical rock descriptions (LUT)		x	x		
Standardized, harmonized lithological profile		x	x		
Standardized, harmonized stratigraphic profile		x	x		
Full geological 3D-model		x	x		
Geothermal gradient	K/m				x
Bulk thermal conductivity (single, average value)	(W/m·K)	x	x		
Bulk thermal conductivity (distributed TC profile)	(W/m·K)	x	x		
Thermal conductivity of dry rock sample	(W/m·K)	x	x		
Thermal conductivity of saturated rock sample	(W/m·K)	x	x		
Bulk thermal conductivity map	map/grid		x		
Mean annual surface temperature	°C			x	x
Groundwater temperature (series, single depth point)	°C				x
Groundwater temperature (series, multiple depth points)	°C				x
temperature profiles derived from TRT	°C				x
Water level (normal water table)	m sub sl	x	x		
necessary calculation software		Skua ArcGIS extension	Skua ArcGIS extension	ArcGIS	ArcGIS
necessary workflow		3D modelling closed loop	3D modelling closed loop	closed loop	closed loop



### C.3.7. Calculation of the geothermal potential for open loop systems

Potentials for open loop systems will not be modelled since the natural conditions for them are not sufficient in the pilot area.

## D. Harmonized workflow for 3D modelling

### D.1 The workflow - a brief description

The 3D structural model is a representation of the subsurface geometry in 3D dimensions. The 3D models provide information on the location, thickness, and structure as well as neighbourhood relations of geologic units. The basis of the 3D modelling is a conceptual model which is used to interpret the geologic data available in the region. The 3D model provides a consistent, unambiguous compilation of this geologic data.

Since the data, the rock classification schemes, the scale and level of detail, the geologic interpretation and the modelling software may vary among the project partners, a comparable modelling result can only be obtained if as many modelling steps as possible are harmonized or standardized. In subsequent steps, the 3D model will be used for the calculation of the geothermal potential. The results of the potential and conflict potential mapping in the pilot areas can only be comparable when the steps of data interpretation, processing and modelling are harmonized.

The presented workflow provides the base for the production of a standardized 3D model for GeoPLASMA-CE. The workflow for generation of the 3D model comprises steps of data preparation, the geometry modelling and the post-processing of the model (**Figure 2**).

During the data preparation step, all data have to be transformed into the same georeference system. The data have to be interpreted according to the project aim and the desired level of detail. Due to these criteria, a modelling domain has to be specified. For details of this specification see D.3.2. Rules for the delimitation of special lithological bodies have to be specified. A standard geologic column comprising all lithological objects to be included in the object has to be worked out. In addition, the contact relationship between the lithological units specified in the standard geologic column has to be determined. The standard geologic column and the contact relationships are combined to the scheme of lithological units, which is the conceptual model forming the logical basis of the 3D modelling. A harmonized fault network has to be constructed. For details of these specifications see chapter 5. Then the geologic raw data have to be interpreted, respecting the scheme of lithological units and the harmonized fault network as well as the rules for delimitation. The input data have to be processed, such that a harmonized input data set is produced which has to be imported to the 3D modelling software. After the data import, a consistency check is necessary (detailed steps are given in D.3.8).

The 3D model is created by interpolation between the input data. First, the fault network has to be modelled. Then, the lithology inside of the fault blocks can be modelled. Since all GeoPLASMA-CE partners use different modelling software, the interpolation algorithm cannot be standardized, but has to be performed as predefined by the 3D modelling software. A top-downward modelling workflow is recommended, since the data density is usually highest near the surface and inconsistencies might arise if units with few input data are modelled prior to units described by many data. Modelling of the unit tops is also recommended, since an approach specifying tops always makes sure that all parts of the model are “known” or specified.



If the pilot area contains an international border, a buffer zone has to be specified, which has to be a minimum of 2 km wide on each side of the border since discontinuities in the model will occur otherwise. The data in the buffer zone have to be exchanged among the partners, and the geologic units are modelled collectively. After a consistency check and finalization of the 3D model in the buffer zone, this model has to be fixed and modelling has to be extended to the whole pilot area. A final consistency check is necessary. The accuracy of the model depends on the density of the input data, on the conceptual expert knowledge about the modelled geology and on the complexity of geologic situation.

A standardized final 3D model output has to be produced. This model represents the geologic units by their top boundaries in a 2D raster data structure. The grid points are specified by a mandatory master grid. The parameters of the master grid are presented in deliverable D.T2.3.1 (harmonized data management infrastructure). The standardized 3D model will be stored in the GeoPLASMA-CE database.

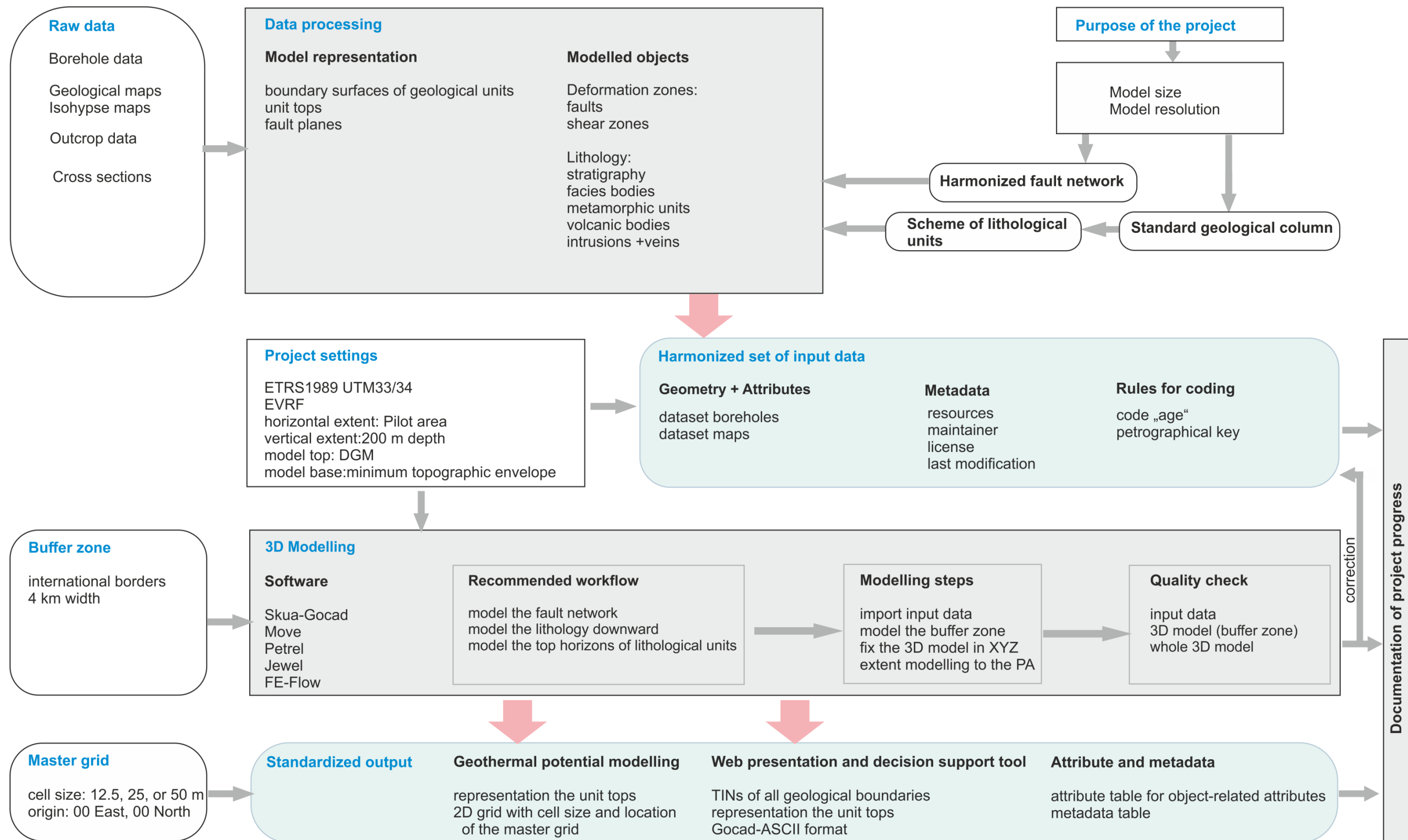


Figure 2: GeoPLASMA-CE workflow for 3D modelling.





The following list provides an overview over the important rules, specifications and workflow steps for 3D modelling. The toolkit in chapter D.3 gives a detailed description of each step.

## 1. Documentation of the project

## 2. Model specification

### Specifications for the modelling domain

Spatial reference system	ETRS1989-TM 33 / ETRS1989-TM 34 meters
Elevation reference system	EVRF2007
Horizontal extent	Pilot areas
Vertical extent	200 m
Model top	digital elevation model
Model base	minimum topographic envelope
No data domain	is possible inside of the model
Model scale	1:10 000 for urban pilot areas 1:50 000 for regional pilot areas
Buffer zones for transnational pilot areas	4 km width

### Specification of the modelled objects

Sedimentary units	Stratigraphy Facies bodies
Metamorphic units	
Magmatic bodies	Intrusions Volcanic units Veins

### Specification of the model representation

Boundary surfaces
Horizon top surfaces
Fault surfaces



### 3. Model input

#### Rules and Concepts

- Standard geologic column
- Structure and depositional relationship
- Scheme of lithological units
- Harmonized fault network

#### Raw data and raw data processing

- Outcrop data
- Borehole data
- Geologic maps
- Cross sections
- Isohypse maps

#### Quality check

- Outcrop data
- Borehole data
- Geologic maps
- Cross sections
- Isohypse maps

#### Harmonized set of input data

### 4. 3D modelling

- 3D Modelling workflow
- Quality check

### 5. Standardized 3D model output

- 3D Web viewer: Triangulated network (TIN)
- Workflow for mapping of the geothermal and conflict potential: 2D Grids of the tops of geologic bodies
- Attribute table with age and petrography codes per unit
- Metadata table for the whole 3D model



## D.2 Rules and mandatory specifications - a checklist

Spatial reference system	ETRS1989-TM 33 / ETRS1989-TM 34 meters → See D.T2.3.1 for specification
Elevation reference system	EVRF2007 → See D.T2.3.1 for specification
Project documentation	template for the documentation of the project progress → See D.T2.3.1 for specification
Vertical extent	≥200 m
Model base	minimum topographic envelope
Buffer zones for transnational pilot areas	4 km width
Model representation	boundary surfaces tops of lithological units fault surfaces
Harmonized set of input data	Stay in line with the joint list of attributes → See D.T2.3.1 for specification Specify code for “age” and “petrography” Fill the metadata table for each data set
3D structural modelling	The buffer zone has to be modelled first along political borders (2 km on each side of the border). After a quality check and correction, this model is kept fixed and extended to both sides of the pilot areas.
Harmonized 3D model output data	2D Grids of the geologic boundary surfaces Metadata table for the whole model Attribute table with age and petrography codes → See D.T2.3.1 for specification



## D.3 Tool kit for 3D modelling - detailed description of the workflow steps

### Project documentation

#### D.3.1. Project documentation

##### General remarks

The documentation contains information which is important for the use of the model at any time after the project end by any person. The project documentation has to give an overview of the modelling steps, the input data, the modelling steps, and the project agents. Since the documentation is necessary to validate the model, it should also contain information on the interpretation and correction of the primary data.

##### Description of workflow steps

The project documentation template is given as an EXCEL spread sheet in deliverable D.T2.3.1 (harmonized data management infrastructure) as processdocu.xlsx (**Figure 3** Fehler! Verweisquelle konnte nicht gefunden werden.).

<b>Project Title</b>	GeoPLASMA-CE									
<b>Project area</b>	Pilot area 1 Vogtland- W-Bohemia									
<b>Last modification</b>	20.05.2017									
<b>by</b>	Ines Götz									
<b>status</b>	data preparation in progress									
<b>Project type</b>	shallow geothermal									
Geological 3D model	structure of lithological units									
Parameterized 3D model	permeability									
	specific heat capacity									
Geothermal potential model	specific heat extraction capacity									
	temperature gradient									
land-use conflict maps	swellable rocks									
	karst units									
<b>Project settings</b>										
spatial reference system	ETRS1989 UTM 33 N									
elevation reference system	EVRF 2007									
coordinates lower left corner	X: 28658 m						Y: 5548730 m			
coordinates lower right corner	X: 322651 m						Y: 5548730 m			
coordinates upper left corner	X: 28658 m						Y: 5609540 m			
coordinates upper right corner	X: 322651 m						Y: 5609540 m			
depth	200 m beneath ground surface									
<b>Processing</b>										
<b>work step</b>	<b>data category</b>	<b>objects</b>	<b>processing</b>	<b>software</b>	<b>source</b>	<b>maintainer</b>	<b>processed by</b>	<b>Date</b>	<b>comments</b>	<b>status</b>
Data preparation	well data	B51, B52, B41, B42, B43, B51, B52, B53, B54, B61, B62, B63, B64, B65, B66, B67, B68, B69, B71, B72, B73, B74, B75, B76, B77	conversion into ETRS1989 UTM 33	ARCGIS 10.4	Saxon drilling and outcrop database	LFLUG (Tobias Duteloff)	Ines Götz	17.05.2017	transformation on the fly	ready

**Figure 3: Screenshot of the processdocu.xlsx template.**

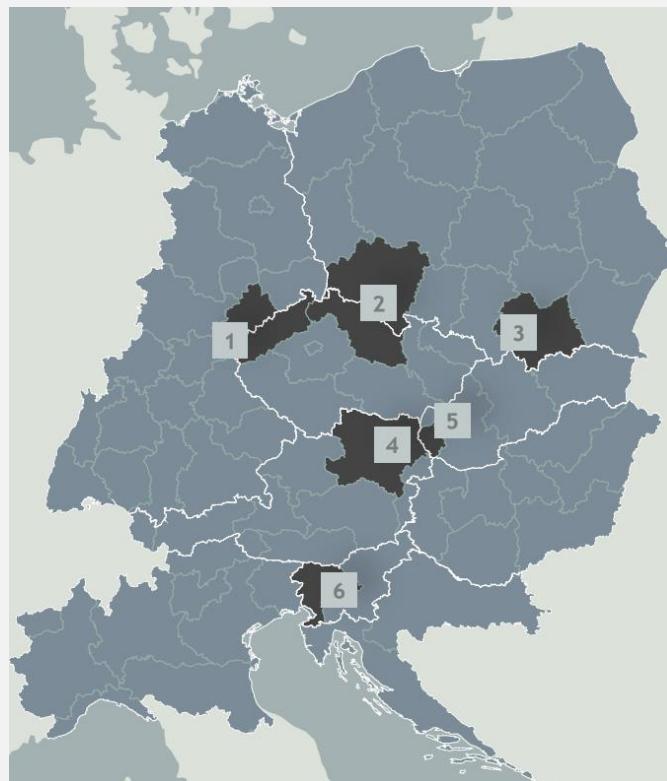
## Specification of project settings

### D.3.2. Modelling domain

#### D.3.2.1. Six pilot areas

##### General remarks

A pilot area is a region that was chosen to participate in the project because of its special geologic or geothermal characteristics or because of its great interest in developing concepts for the use of geothermal energy. The GeoPLASMA-CE project comprises 6 pilot areas which are defined as polygon shapes. **Figure 4** gives an overview of the GeoPLASMA-CE pilot areas.



**Figure 4: Overview of the GeoPLASMA-CE pilot areas.**



## Specification of project settings

### D.3.2.2. Buffer zones at international borders

#### Description of workflow steps

The buffer zone of 4 km width is modelled first by both partners working in the transnational pilot area. A harmonized lithological legend and a harmonized fault network have to be specified prior to data processing. Geologic data sets are exchanged among the partners.

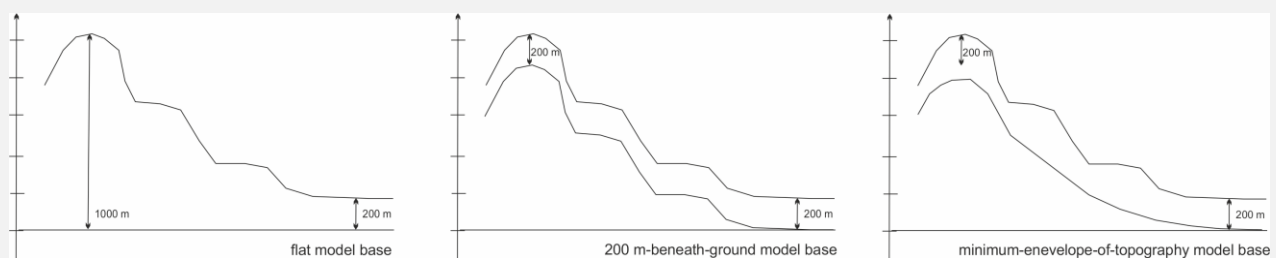
After finalization of the 3D model in the buffer zone, the units are kept unchanged and the 3D model is extended to both sides through the whole pilot area.

## Specification of project settings

### D.3.2.3. Model base 200 m below ground surface

#### General remarks

In order to avoid too large a variation in the modelling depth in regions with topographic changes and to obtain a smooth model base, the minimum topographic envelope is used for specifying the model base (**Figure 5**).



**Figure 5: Possibilities for specifying the model base.**

#### Description of workflow steps

##### Determination of the minimum topographic envelope

Morphological operations are a collection of non-linear operations related to the shape or morphology of objects in a raster image. In ArcGIS, the Focal Statistics tool performs morphological operations that compute an output raster where the value for each output cell is a function of the values of all the input cells that are in a specified neighbourhood around that location. The structural elements specify the cells that are included in the morphological operation. Calculate the minimum envelope by performing an erosion. The size of the structural element specifies how smooth the envelope is.

*Spatial analyst tools → Neighborhood → Focal statistics → circle, 3 cells → minimum*

##### Alternative

Alternatively, the DEM can be resampled to a 1000 m x 1000 m resolution and the average elevation minus 200 m be used to represent a smooth model base parallel to the topography.

## Specification of project settings

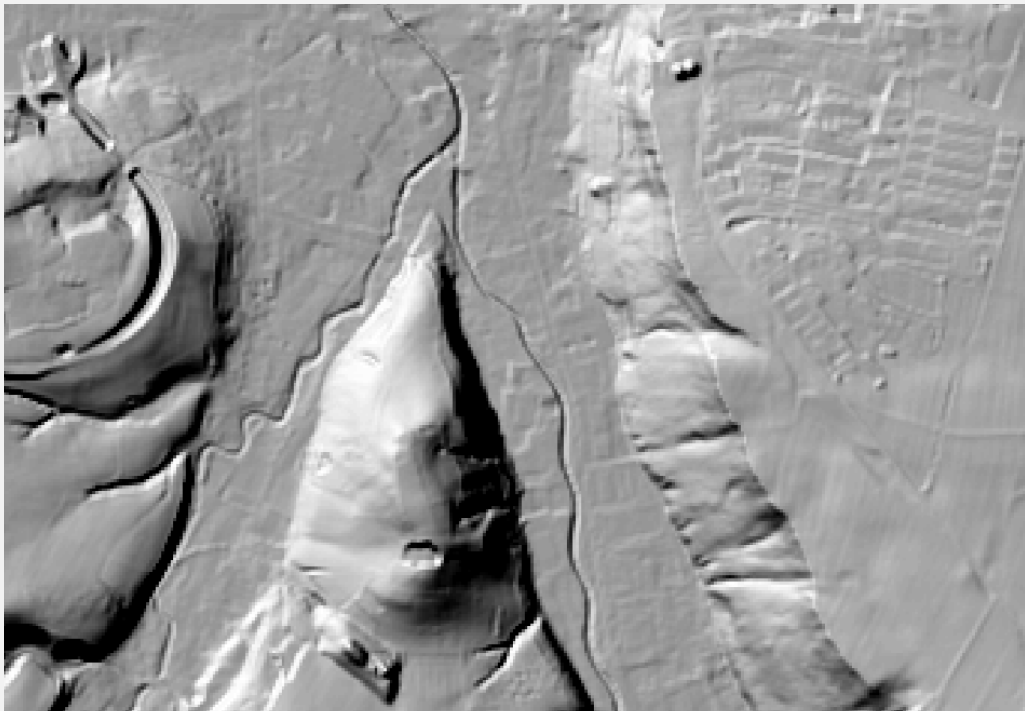
### D.3.2.4. Model top: Digital elevation model of the desired output resolution

#### General remarks

A digital elevation model is a 3D representation of the terrain surface. It forms the upper boundary of all geologic units and is therefore the top unit that has to be included in the 3D subsurface models. DEMs can be represented by raster or vector surface data structures.

DEMs are commonly built using data collected using remote sensing techniques, where two satellites emit radar waves and register the reflected signal. Since the radar waves also reflected by non-geologic objects like houses, roads, dams, the digital elevation model has to be processed prior to its usage in geologic 3D modelling.

#### Description of workflow steps



**Figure 6: Digital elevation model with anthropogenic objects: Waste deposit in the South, roads in the North-East.**





## Resolution of the DEM

Digital elevation models are available with various resolutions (2m, 5m, 10m, 30m, 50m,...). A suitable DEM has to be selected, after the resolution of the standardized output model has been specified. The resolution of the DEM used for 3D modelling should be a bit finer than that of the output model, but not too fine, since DEM with a high resolution need more storage and contain more non-geologic objects.

## Processing of the DEM

Each DEM contains objects which are non-geologic, such as bridges, dams or water surfaces ( **Figure 6** ). If drilling data are linked to a DEM representing one of these objects, the depth of the geologic boundaries represented by the drilling may be wrong. Therefore, the DEM has to be correct prior to loading the drilling data.

### *Correction of water surfaces*

Water bodies are represented in the DEM by the water table. Therefore, they have to be processed in order to show the correct geologic boundary, which is the bottom of the water body. We suggest to correct lakes bigger than 1 ha. The outline of the lakes can be taken from a topographic map. The depth of the lake can be either provided by the state surveys or has to be estimated. The elevation of the DEM has to be subtracted by the depth of the lake.

Rivers should not be corrected, as long as they are narrower than 2 raster cells.

*Create a polygon shapefile "lake" with an attribute "ground\_elevation" → load the shapefile to ArcGIS (+ add data)*

Specify the area that has to be corrected:

*Right-click on the layer "lake" → edit feature → digitize the outline of the deposit*

Generate several buffer rings inside of the polygon and assign realistic value for the elevation of the lake ground:

*ArcToolboxes → Analysis Tools → Proximity → Buffer → create buffers inside of the lake polygon with increasing distance → specify the values for the lake ground elevation in the attribute table*

*ArcToolbox → conversion tools → to raster → polygon to raster → value field "ground\_elevation" → specify the cell size of the DEM*

*ArcToolbox → Spatial analyst tools → map algebra → raster calculator → Con("lake"<Maximumdepth, ground\_elevation, DEM)*

### *Correction of technical and infrastructural objects*

Technical and infrastructural objects have to be identified and specified by polygons. NULL values can be assigned to the parts of the DEM inside of the polygons. The holes can be filled using morphological operations like closure (an erosion followed by a dilation).

*Create a polygon shapefile "deposit" → load the shapefile to ArcGIS (+ add data)*

Specify the area that has to be corrected:

*Right-click on the layer "deposit" → edit feature → digitize the outline of the deposit*



Convert into a raster:

*ArcToolbox → conversion tools → to raster → polygon to raster → specify the cell size of the DEM*

Reclassify the raster:

*ArcToolbox → Spatial analyst tools → Reclass → Reclassify*

Give the same value (e.g. 1) to all polygons, i.e. to the entire range of values, and assign the value 0 to “no data” cells. Note: In the following step, the raster calculator will not work in areas where one or more layers contain “no data” cells, therefore the numerical value 0 is required to preserve the full extent of the layer.

Correct the elevation of the DEM in the region of the deposit:

*ArcToolbox → Spatial analyst tools → map algebra → raster calculator → SetNull("deposit", "DEM", "VALUE =1")*

This will cut “holes” into the DEM since the elevation of the digitized features will be set to “no data”.

Fill the “holes” with data interpolated from surrounding cells by choosing an appropriate value for the diameter of the neighbourhood (100 cells in this example):

*ArcToolbox → Spatial analyst tools → map algebra → raster calculator → Con(IsNull("DEM"), FocalStatistics("DEM", NbrCircle(100, "CELL"), "MEAN"), "DEM")*

Note: In later ArcGIS versions, the

*ArcToolbox → Spatial analyst tools → surface functions → elevation void fill*

function may be utilized instead.



## Specification of project settings

### D.3.3. Model scale

#### Description of workflow steps

The model scale determines the level of detail of the model, which is specified in the harmonized legend, the harmonized fault network and the minimum areal extent and thickness of geologic units reproduced in the 3D model.

Scale for the GeoPLASMA-CE pilot areas:

Vogtland / W-Bohemia	1 : 50 000	
Wałbrzych / Broumov	1 : 50 000	
Krakow	1 : 50 000	
Bratislava / Hainburg	1 : 50 000	
Vienna	1 : 25 000	1 : 10 0000
Ljubljana	1 : 10 000	



## Specification of the modelled objects

### D.3.4. Geologic bodies presented in the 3D-model

#### D.3.4.1. Lithological units

##### General remarks

Units that should be modelled, if they are present in the modelling domain:

- Hydrogeological units,
- Sedimentary units:
- Stratigraphy,
- Facies bodies,
- Metamorphic units,
- Magmatic bodies:
- Intrusions,
- Volcanic units,
- Veins.

A **standard geologic column** specifies which units are modelled in each pilot area. Small units or units with similar geothermal properties can be merged.

##### Specification recommended for 1: 50 000 regional models

A unit is included in the model if its horizontal extent is larger than 10 000 m<sup>2</sup> and if they are thicker than 2 m. Exception: Thermally highly relevant units like quartzite veins or clay layers controlling the dynamics of an aquifer.

##### Description of workflow steps

An interpretation of the geologic data with respect to the modelled process or potential is necessary. For GeoPLASMA-CE, this means that rock units with varying geothermal potential have to be represented in the model. Structures like folds in a rock with similar thermal properties can be neglected.

In addition to representing the geothermal-hydrological units, it is recommended to model important marker horizons or units if these can be easily determined in the geologic data set and aid in setting up the 3D structure of the modelling domain.



## Specification of the modelled objects

### D.3.4.2. Wet and dry lithological units

#### General remarks

Rocks with high water content have a different specific thermal conductivity than dry rocks. The water can be related to pores or fractures. If a dense rock is strongly fractured or decomposed, it can be wet and this decomposed or fractured portion of the rock then has different thermal properties than the dry rock. Therefore, dense and decomposed or fractured rocks have to be modelled as separate rock units, such that varying thermal parameters can be assigned to the units.

#### Description of workflow steps

For modelling the potential of closed loop systems, it is necessary to delimit porous, fractured and weathered rock units from dense rocks, when interpreting the well data and generating the standardized geologic column. The reason for this is that the thermal conductivity in each geologic unit will be averaged. If a weathered and a fresh rock are not modelled separately, the whole rock unit will be represented by the average of the thermal conductivities. If the weathered zone with small thermal conductivity shall be represented in the model, it has to be delimited as a separate unit. In addition, the thermal conductivity for water saturated and dry rocks will be assigned to the model. If a porous rock is not delimited from a dense rock, this differentiation is not possible in the model.

## Specification of the modelled objects

### D.3.5. Geologic surfaces presented in the 3D-model

#### D.3.5.1. Deformation zones

##### General remarks

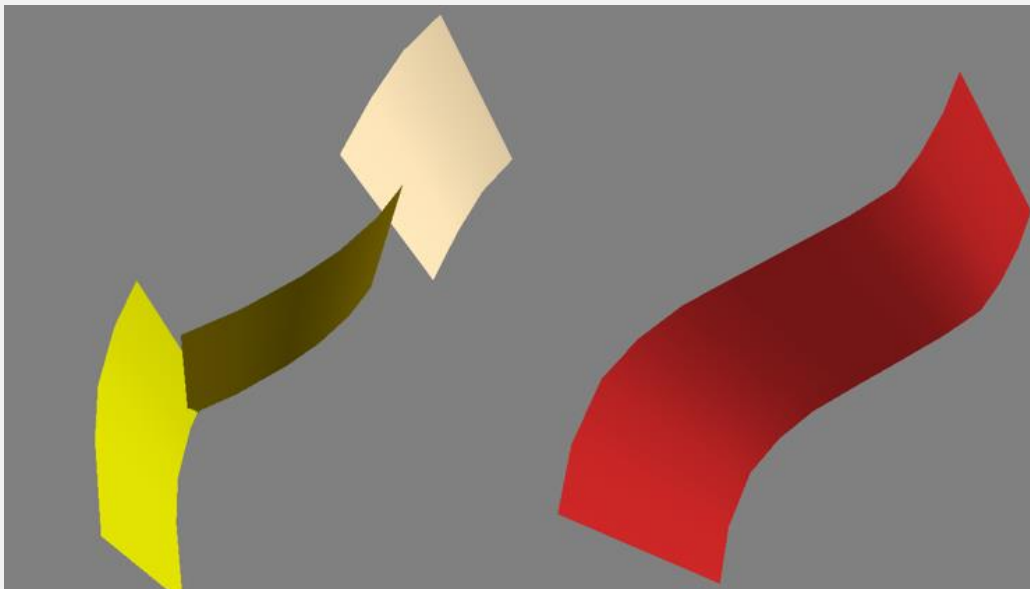
- Fault planes;
- Fault zones;
- Detachment zones;
- Shear zones.

##### Description of workflow steps

Deformation zones have to be included into the model if they displace or cut off important lithological units and if they are hydraulically active.

The fault surface and the horizon top have to be combined to the boundary of one geologic body.

The level of detail of the modelled fault zone has to be specified according to the scale of the model and to the hydraulic properties of the deformation zone (**Figure 7**).



**Figure 7: Different levels of detail of a fault model.**

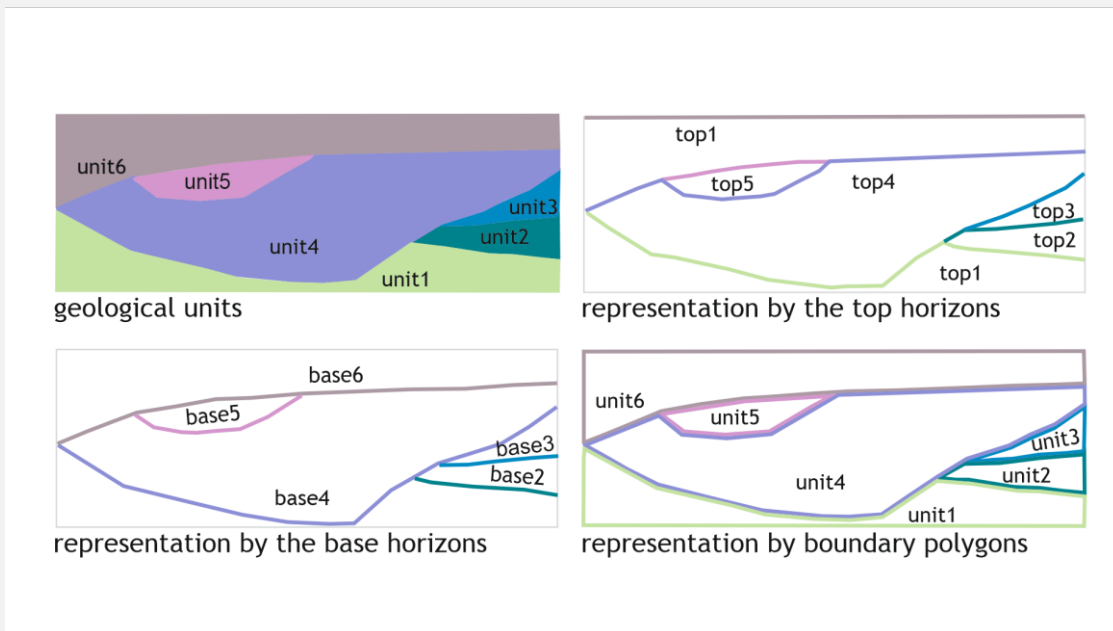
Specification of the model representation

**D.3.5.2. Lithological units: Horizon top surfaces**

**General remarks**

Lithological bodies can be represented in the model either by their volumes or by their boundary surfaces. All GeoPLASMA-CE partners use software working with boundary surfaces. This representation has the advantage that it is storage-efficient. Lithological units can be represented by their top surfaces, base surfaces or by their envelopes (Figure 8). In order to generate comparable modelling results, one uniform representation of objects is mandatory for the GeoPLASMA-CE project.

Modelling approaches modelling the tops are realized in Skua and in Petrel. This modelling approach is especially well suitable, since a model specified by top horizons is completely known and can be modelled from top downward. Since most data are available near the surface, atop down modelling approach avoids inconsistencies in the model.



**Figure 8: Various representations of lithological units by boundary surfaces.**

**Description of workflow steps**

As final representation, a model of the horizon tops is required. The modelling workflow itself cannot be specified, since the GeoPLASMA-CE partners work with various data sets and software systems. However, it has to be pointed out that modelling top or base horizons requires different processing of the input data, such that the data set becomes consistent with the modelling approach used.



## D.3.6. Harmonization rules

### D.3.6.1. Standard geologic column

#### General remarks

The standard geologic column is a composite diagram showing, in vertical sequence, geologic strata underlying a given area down to the model base, with the names of the various rock formations indicated in the column. The standard geologic column comprises information on the petrology and stratigraphy of the pilot area. Since continuously varying lithologies in nature have to be delimited as homogeneous lithological bodies in the model, the standard geologic column provides the guideline for the assignment of a rock to one specific modelled rock body. It is a theoretical classification scheme which combines rocks with similar lithology, geothermal and hydrogeological properties to one geologic unit. Each rock unit represents one row in the column.

#### Description of workflow steps

##### How to generate the standard geologic column

Usually, the geologic maps of a pilot area provide a good starting point for developing a standard geologic column, because the map units are already classified and stratified, while drilling data are usually documented in a more continuous and detailed way with less interpretation.

However, depending on the author, geologic maps display different petrological classification schemes and levels of detail and may apply different classification criteria. These different interpretations give an impression about the variability of rock types mapped and have to be harmonized.

##### 1. Which rocks do exist?

First, the lithological units of the pilot area have to be registered.

##### 2. Which rock groups do exist?

I.e., in the standard column of the TransGeoTherm project, various descriptions of low moor sediments had to be registered and harmonized (**Table 8**):

**Table 8: Different names for similar geological units in Saxony.**

Rock group	unit code	Map Pleistocene	Map Niesky	Map Görlitz
Low moor sediments		Peat, low-moor	Muck	Limnic formation (low moor)

For the geothermal mapping, also criteria like hydrogeologic or geothermal properties have to be considered for the classification. Therefore, a 50 cm thin clay layer with an areal extent of some kilometers needs to be modelled, since it controls the flow of the groundwater, while a large 500 m thick “porphyric” granite and “coarse-grained” granodiorite can be classified in the same group.





### 3. Shall the rocks of one petrological group be represented in the model / in the column?

This is a subjective decision of the project agents and depends on the modelling purpose and on the desired level of detail.

- *Importance criterion*

This is the criterion with the highest priority. If one rock has specific properties controlling the whole system, it has to be included into the column. This may be the hydraulic property of a thin large clay layer or the large specific thermal conductivity of salt rocks.

- *Areal criterion*

The resolution of a model is the size of the raster cells of the output model. Smaller objects cannot be represented.

Make a decision, which minimum number of raster cells has to belong to one geologic unit. I.e., in the TransGeoTherm project, the minimum lateral extend of modelled units was set to 10,000 m<sup>2</sup>. This corresponded to 16 raster cells, since a 25 x 25 m raster was used.

- *Thickness criterion*

In general, a minimum modelled thickness of 2m is used for 3D modelling in regional models in Saxony. However, do not forget to check the importance criterion!

- *Are enough data available to describe the geometry in 3D?*

Not just the geometry, but also the contact of one body to the next has to be modelled. A minimum of 3 data points is needed for 3D modelling of undeformed sedimentary rocks with constant thickness and dip. However, since variability in thickness and dip is typical for geologic units, use as many data as possible! For complicated structures like a salt diapir, two intersecting pairs of seismic section are needed at minimum.

Check small geologic bodies like lenses or intrusions with irregular geometries and contacts, whether you can construct their 3D geometry to get a feeling how many data are needed.

If a rock unit will *not* be represented in the 3D model, it has to be accumulated by its surrounding rocks. Take care that no inconsistencies form at borders of geologic maps or political districts, when you merge rock units.

### 4. In which sequence do the rock units occur?

The neighborhood relationship and the sequence of the rock groups and, in case of sedimentary units, the relative age are described by the order of the units in the standard geologic column. After you have decided which rock units are included into the standardized stratigraphic column, you have to bring them in the sequence of their relative age. The oldest unit is displayed in the bottom row of the column.

### 5. Assign the code "age" to each rock unit in the standard geologic column.

Later, during processing of the input data, this code will be assigned to all well, map and outcrop data to indicate, that they belong to the same model body. The coding is explained in the next tool kit.

### D.3.6.2. Structure and contact relationships

#### General remarks

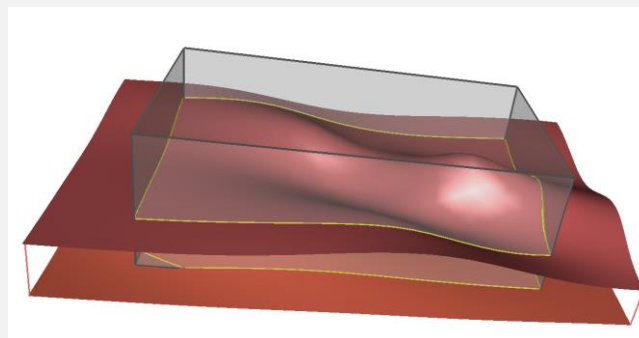
The structure in 3D modelling specifies the geometry and topology of the boundary surfaces which subdivide the volume of the modelling domain. The general geologic structural style should be represented by the model (undeformed sediments, fold-and-thrust-belt, graben structure,...). The model has to consist of consistent bodies. The structure specifies the boundaries between rock units - depositional contacts, intrusive contacts and tectonic contacts- as well as deformational geometries like fault blocks, folds or nappes. Internal structures like foliation are usually neglected in geometrical 3D models.

#### Description of workflow steps

The structure of a pilot area has to be determined by delimiting various rock types in the 3D data set. Geologic concepts and expert knowledge about the region can aid in developing a structural concept which describes the data set in a consistent and unambiguous way.

##### “Layer cake” - conformable and unfaulted structure

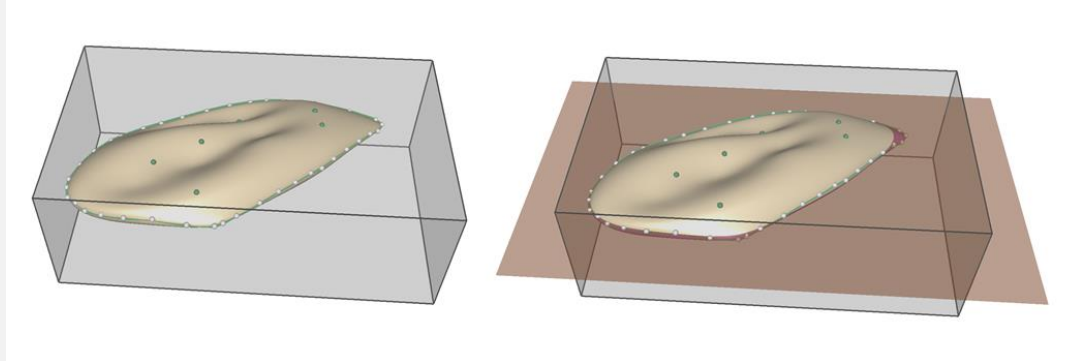
This is the simplest structure that can be modelled (**Figure 9**). In this case, the geologic objects are bigger than the modelling domain and no body ends inside of the modelling domain. The boundary surfaces of the objects are only bordered by the modelling box. No boundary surfaces cut or intersect, although the thickness of the rock bodies may vary.



**Figure 9: The two conformable boundary surfaces of a geologic unit have borders which are specified by the intersection lines with the model box (yellow). There are no internal borders.**

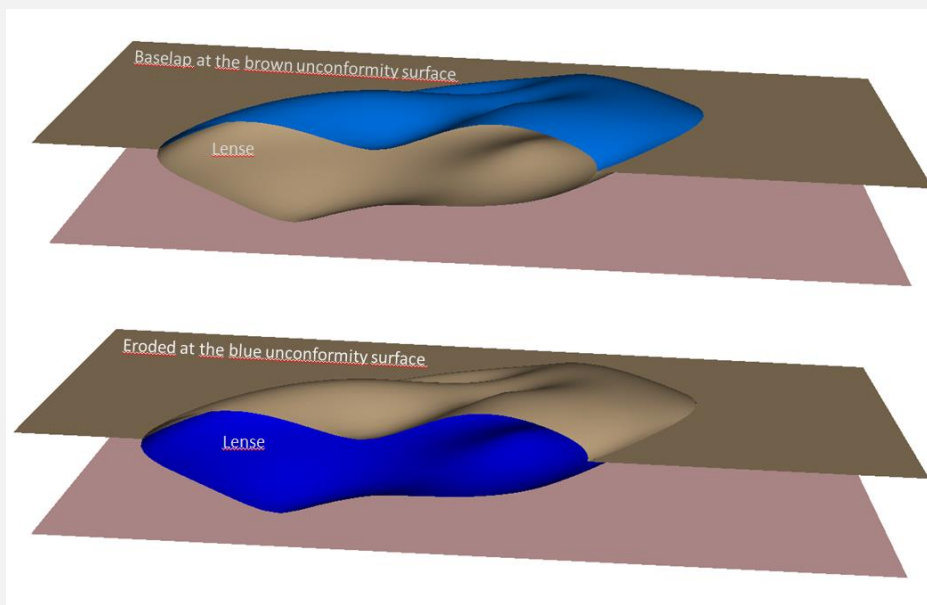
Faults and unconformities and cross-cutting intrusive boundaries are either not known or ignored for simplification reasons. Examples for this structure are undisturbed marine sedimentary deposits or a metamorphic nappe structure. All data points used for 3D modelling are “picks”. This means, that they describe that a boundary is present at the data point. However, it is known that the boundary is also present outside of the data points (in contrast to a deposition outline).

“Lens” or “Blob” - object boundary is completely inside of the modelling domain



**Figure 10: A geologic unit with a boundary surface completely located inside of the model box can be described by two types of data: Outlines specifying the end of the lateral extension of the body (green line-left), and picks specifying the location of the boundary surface (green points –left). If the boundary surface of a lens coincides with another unit boundary, it specifies an unconformity.**

In this case (**Figure 10**), the boundary of a geologic object is completely located inside of the modelling domain. The geologic data referring to it may either represent an outline (like the green line with white dots in the left image: A deposition outline), indicating that the border is ending along the data points. Or they may be picks, just indicating that the object was traced at the data point (green points at the left image). If the border of an inner boundary surface ends at another boundary surface, this is called unconformity in sedimentary environments. The unconformity can be erosional - this means that the bottom surface of the geologic object is cut off by the top boundary surface. The unconformity can be baselap, this means that the top boundary surface is cut off by the bottom boundary surface. Whether a lens is described by baselap or erosion is the agent’s interpretation. However, the modelling results are different depending on the chosen interpretation. In cross-border pilot areas, a uniform interpretation has to be used in order to avoid inconsistencies along the border.



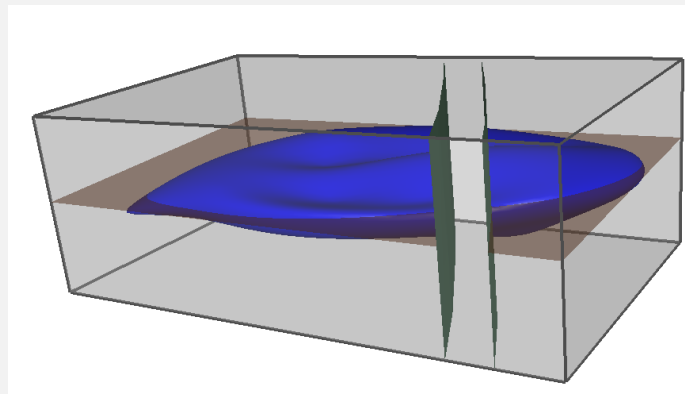
**Figure 11: Baselap and erosional unconformities can be distinguished depending on whether the base surface of a body is cut off by its top surface or vice versa.**

### Object boundary is partially inside of the modelling domain

In this case (**Figure 11**), a boundary surface can be partially bordered by the model box and partially inside of the modelling domain. The contact relationships are the same as for “lenses”.

### Intrusive boundaries

Intrusive rocks cut through their host rock (**Figure 12**). The boundary surfaces of the youngest intrusive bodies are continuous; the boundary surfaces of older rocks are cut off successively by younger intrusions.



**Figure 12: The boundary surfaces of intrusive bodies cut off the boundary surfaces of their host rock units. Older units are cut off by younger ones (brown by blue and green, blue by green).**

### Object boundaries displaced by fault or shear zones

Faults and shear zones are boundaries between rock units which accumulated a displacement. Faults are indicated in the 3D data set by sudden changes in the depth or thickness of rock boundaries and the local absence or duplication of rock units in wells. Shear zones may be broader than faults and can be delimited as separate rock units if necessary. Metamorphic rock units are usually bordered by faults or shear zones.

Model input - rules and concepts

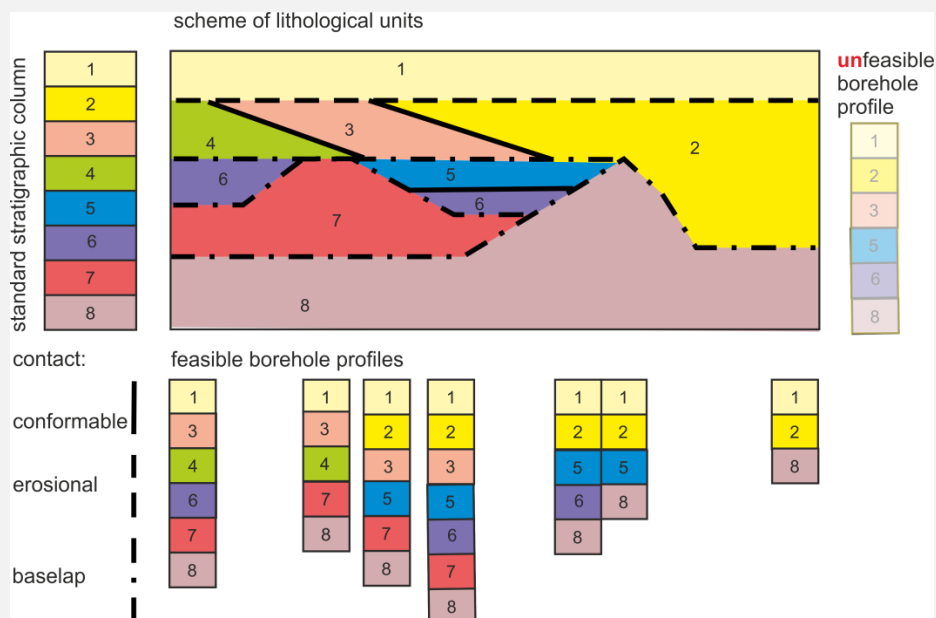
**D.3.6.3. Scheme of lithological units**

**General remarks**

The scheme of lithological units is a combination of the standard geologic column and the contact relationship between the units represented in the column. It specifies the relative position and the contact relations of all rocks to be modelled. **The scheme of lithological units provides the conceptual model and is therefore the basis for the structural modelling.** Additionally, it provides a correlation scheme between various lithologies of the same relative age. It is one of the most important tools in structural 3D modelling, since it can explain the varying sequence of units in borehole profiles which are all consistent with the same standard geologic column. The scheme of lithological units is important for the quality check of the borehole profiles (toolkit D.3.8.2) and for the quality check of the 3D model.

**Description of workflow steps**

A scheme of lithological units has to be produced for all pilot areas. It is a scheme which combines the standard geologic column with the structure and contact relationships and the spatial occurrence of the lithological units (**Figure 13**). The input data and the result of the 3D modelling have to be consistent with this scheme.



**Figure 13: Scheme of lithological units in comparison to the standard stratigraphic column, feasible and unfeasible borehole profiles.**

Model input - rules and concepts

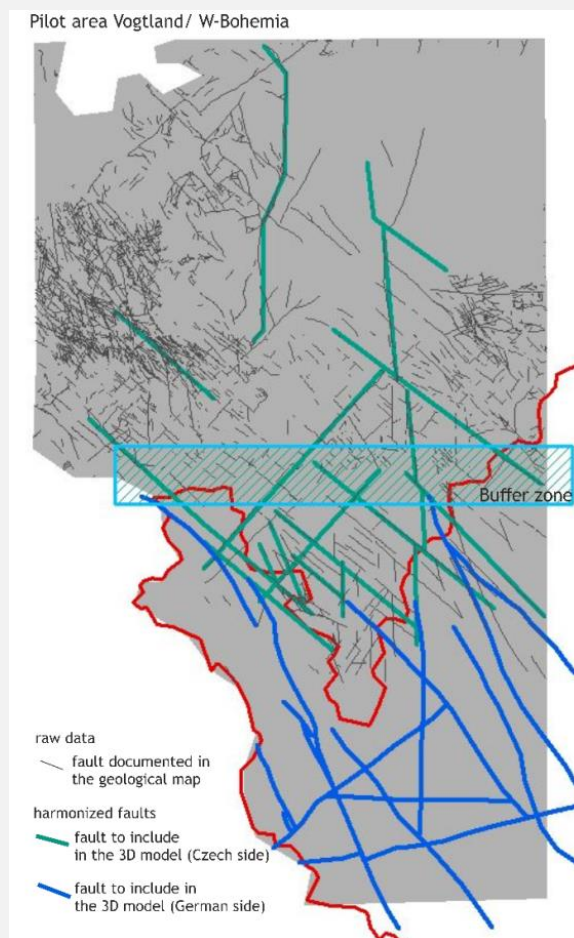
### D.3.6.4. Harmonized fault network

#### General remarks

The harmonized fault network is a set of fault data with the same level of detail or resolution and is used for the combination of different geological maps. If a fault is extending to the edge of the map, it will only be part of the harmonized fault network if it is also traceable on the neighboring geologic map. Lateral offsets along the map edges have to be corrected.

#### Description of workflow steps

The harmonized fault network should include structurally and geothermally important faults on the simplest possible level of detail (**Figure 14**). It should be kinematically reasonable.



**Figure 14: Harmonized fault network in the pilot area Vogtland/W-Bohemia.**



Model input - raw data

## D.3.7. Raw data and raw data processing

### D.3.7.1. Outcrop data

#### General remarks

Outcrop data is geologic data directly determined by a geologist at the Earth's surface or in a mine. This may be point or line data.

#### Description of workflow steps

Outcrop data is the most reliable data in geology. In addition to petrography and stratigraphy, outcrop data may provide important structural data. **The structural concept of a 3D model usually is consistent with outcrop data in the model region.** However, the level of detail usually much higher than the level of detail of a regional 3D model.



Model input - raw data

### D.3.7.2. Borehole profiles

#### General remarks

Well data comprise information on the location of the well head, on the well path and on the lithology documented along the well path. Usually, they comprise a detailed petrographic description. This has to be classified according to the rock groups of the standard column. Additionally, the rock groups have to be stratified, which means that the stratigraphic location of each rock group has to be qualified. After classification and stratification, petrographic data in the well receive a code which specifies to which unit in the scheme of lithological units a data point belongs to.

#### Description of workflow steps

##### Example

The example shows the lithological attributes of a well documentation from Saxony (**Table 9**). The well data are interpreted due to their hydrogeological properties. A general subdivision in aquifers and aquitards is used. If two aquifers are located directly on top of one another, they may be merged in one model body. This is the case for Cenomanian sandstone and conglomerate.

In case of model bodies 2 and 3 the two aquitards were kept as separate model bodies, because one is a continuous layer and the other a lens, both having a different function in the hydrogeological system.

The Cenomanian marlstone and its altered cap were merged to one model body, since both rock units act as aquitard (model body 6). In contrast, the gneiss and its altered cap have different hydrogeological properties: The sandy silt acts as aquifer in contrast to the dense gneiss which is impermeable. Therefore, the rocks are assigned to two different model bodies: The altered gneiss is model body 8, the dense gneiss is model body 9.

After the decision was made, which rocks are merged or kept separately, all wells have to be interpreted in a consistent way.

For the specification of the “groups” of the output model, only a subdivision in aquifer (01) and aquitard (02) was taken.





**Table 9: Example for coding of a drilling data set.**

Well data		Processing			Assignment to model bodies		
Petrology	Verbal description	Interpretation	Lithological group	Stratigraphy	Model body	Project-internal code	Age code
sand	strongly silty with gravel	slope wash	Loam lense aquifer	Holocene	Holocene-aquifer	1	001 01 01 01 01
silt	strongly sandy with clay	slope wash loam	loam lense aquitard	Holocene	Holocene-aquitard	2	001 01 01 01 02
silt	uniformly silty	loess	loam continuous aquitard	Holocene	Holocene-loess	3	001 01 01 01 02
sand	fine lamination of dark and yellow fine sand layers	basin fill	sand continuous aquifer	Pleistocene	Pleistocene-aquifer	4	001 01 02 02 04
sandstone	dense and hard banks	marine sediment	sandstone continuous aquifer	Cenomanian	Cenomanian-aquifer	5	002 01 01 32 01
gravel stone	fine gravel, sandy	marine sediment	conglomerate aquifer	Cenomanian	Cenomanian-aquifer	5	002 01 01 32 01
silt	decomposed marlstone	marine sediment, altered	lloam continuous aquitard	Cenomanian	Cenomanian-aquitard	6	002 01 01 32 02
marlstone	banked	marine sediment	marlstone continuous aquitard	Cenomanian	Cenomanian-aquitard	6	002 01 01 32 02
sandstone	banked with silt layers	marine sediment	sandstone aquifer	Cenomanian	Cenomanian-aquifer	7	002 01 01 32 01
silt	sandy l with fine feldspar gravel and biotite	altered gneiss	loam aquifer	Cambrian	Cambrian-aquifer	8	004 32 00 00 01
gneiss	biotite gneiss	gneiss	gneiss aquitard	Cambrian	Cambrian-aquitard	9	004 32 00 00 02

Model input - raw data

### D.3.7.3. Geologic map

#### General remarks

Geologic maps are projections of the outcrop of geologic bodies to a horizontal plane. A geologic body is usually represented by a polygon describing its intersection surface with the Earth's surface. The polygon is specified by an outline delineating the border of the geologic body at the Earth's surface.

A line in a geologic map represents the intersection of a geologic surface with the Earth's surface. Line objects are usually used to represent geologic surfaces without their relation to a specific geologic body, like faults.

Points in geologic maps usually represent points of measurement of the orientation of a surface.

#### Description of workflow steps

##### Project the map data to the DEM

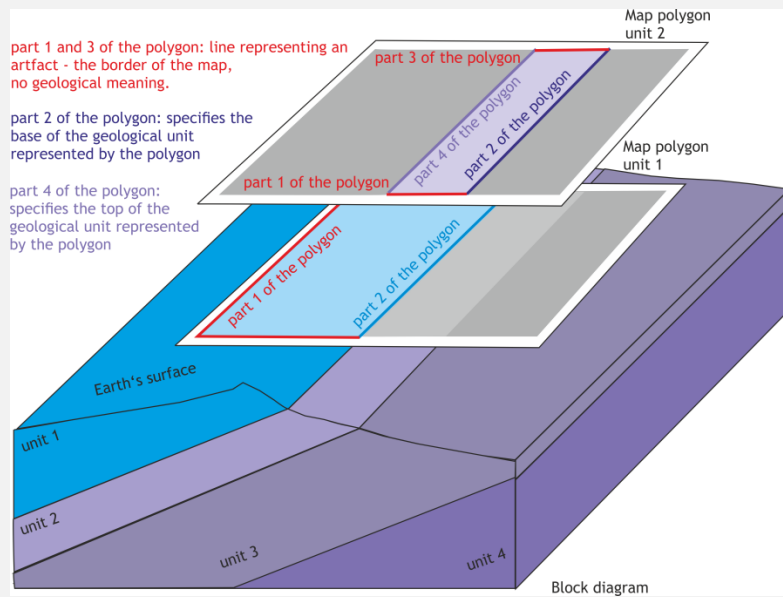
The geologic body was mapped by a geologist moving along the Earth's surface with its topography. The geologic map is a horizontal plane which is not describing the Z-values of the mapped boundary lines. In order to correct this and to bring the geologic boundaries in a correct position in 3D, all map data have to be projected in vertical direction onto the DEM surface.

##### Classification of polygon data

The feature most relevant for 3D modelling is the polygon, since it represents the outline of geologic bodies at the Earth's surface. However, care has to be taken since the geologic meaning of a polygon boundary may not be clear or may be different for different parts of the polygon:

If the boundary of a **geologic object is only partially inside of the modelling domain**, the polygon boundary consists of the intersection of the geologic boundary with the Earth's surface and of the map border. The map border has no geologic meaning. If the polygon part representing the map border is projected to the ground surface and used for 3D modelling, this produces errors, since the real position of the geologic boundary is in the subsurface (**Figure 15** map polygon unit 1). Therefore, each map polygon has to be split in parts representing the geologic boundaries and in parts representing the map boundaries.

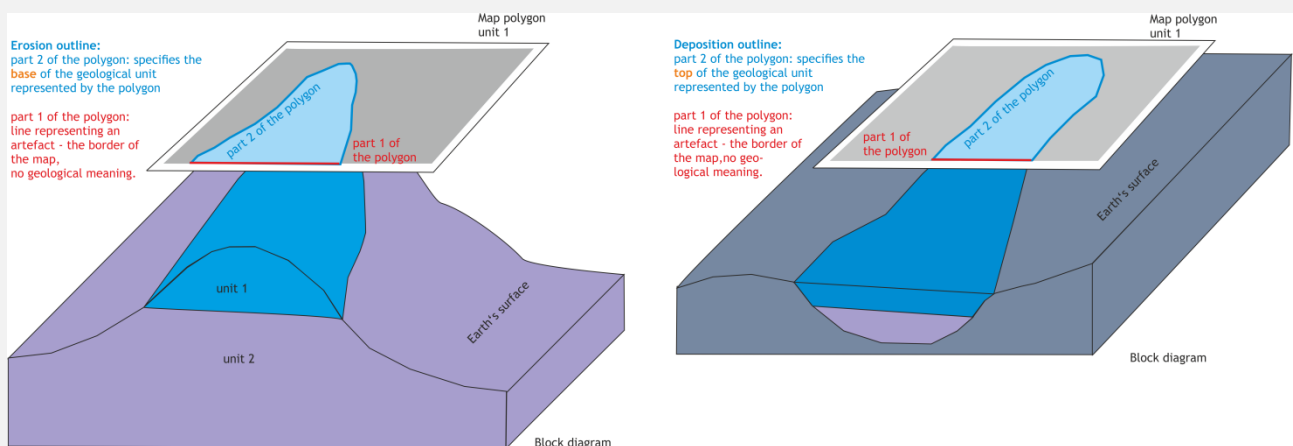
In some cases, the polygon can represent the top and the base boundary of a stratigraphic unit and has to be split into parts which have to be assigned to the proper model boundary surfaces (**Figure 15** map polygon unit 2).



**Figure 15: Relation of objects on a geological map to objects in a 3D model in conformable sedimentary rocks.**

If a geologic boundary is completely inside of the map, erosion and deposition outlines have to be distinguished (**Figure 16**):

A deposition outline describes the top of a geologic unit. An erosion outline describes the base of a geologic unit. If horizon tops are modelled, the erosion outline in **Figure 16** has to be specified as top of unit 2 although, in the map, it is shown as outline of unit 1. So: Be careful with classifying map data to the proper model boundary surfaces!



**Figure 16: Relation of objects on a geological map to objects in a 3D model in sedimentary rocks with unconformities.**



Model input - raw data

#### D.3.7.4. Cross sections

##### General remarks

Geologic cross sections are interpreted data providing a vertical model of the geologic structure along a line. The boundaries of geologic units and faults are represented as lines in the cross sections. Cross sections have to be used with care because they are usually inconsistent in 3D.

##### Description of workflow steps

Cross sections are useful tools for interpretation of the geologic raw data. They aid in developing an imagination, which data belong to a geologic body, which size and structure it has. The geologic data can be interpreted with various conceptual models, i.e. differences in the depth of one boundary may be explained by sedimentation, folding, faulting. The cross section has to explain all available data in a consistent way by checking the possible structural concepts.

Cross sections should be drawn perpendicular to the strike of the geologic units, since then the apparent dip is coincident with the real dip.



Model input - raw data

### D.3.7.5. Isohypse maps

#### General remarks

An isohypse map is a map contouring constant depth levels of a geologic boundary surface (horizon or fault). It is interpreted data generated by interpolation. It provides picks where the position of one horizon is known, but not an outline.

#### Description of workflow steps

Isohypse maps have to be carefully checked against the borehole data set. If deviations to several wells are found, the isohypse data can either be neglected or shifted by a constant amount (difference to the well marker).



Model input - raw data

## D.3.8. Quality check

### D.3.8.1. Outcrop data

#### General remarks

This is a process reviewing the quality and correctness of all data used. The XYZ coordinates and the geologic information of the data has to be checked especially in the context of other data in order to obtain a consistent and geologic reasonable data set.

#### Description of workflow steps

Outcrop data have to be considered most reliable. However, different geologists may use different interpretations of field evidence. Therefore, outcrop data have to be validated in the sense of the geologic concept used for 3D modelling.

In addition, location errors like erroneous XYZ coordinates may occur.



Model input - raw data

### D.3.8.2. Borehole profiles

#### General remarks

The quality check of the input data includes a check of proper import of the boreholes (location, missing information) as well as a consistency check of the imported geologic boundaries.

#### Description of workflow steps

##### Check of the drilling location

Errors may occur in the XY coordinates and in the Z-value. First, check whether digits are missing or duplicated in the X Y coordinates. Then, check the differences of the Z-values of the well heads against the DEM. Differences of <1 m can be neglected. Possible sources of errors:

- The well has an ellipsoid-referenced Z-value (GPS measurement). In this case, the deviation is 30-40 m and has to be corrected as described in D.T2.3.1.
- The DEM is erroneous (represents a spike / building) → correct the DEM as described in D.3.2.4.
- The DEM has changed due to an anthropogenic deposit or excavation → if the difference is feasible, keep the drilling head.
- The drilling head is erroneous → project it to the DEM and move the whole drilling path respectively.

##### Check for errors in stratigraphy

A wrong stratigraphic assignment can be detected by a shift of the Z-value of one well marker, by local changes in the unit thickness, by changes in the sequence of the units.

- Correct a wrong stratigraphy in the well documentation
- Refine the stratification, if necessary, in the well documentation
- Do **not** correct to fine stratigraphy in the well documentation. This is only done in the coding step of the well data processing in order to not lose information.

##### Check for missing well markers

If a well marker is missing, this can have various reasons:

- The unit exists, but was missed and not documented in the borehole.
- The unit exists, but the borehole is too short to reach it.

In both cases, the unit has to be modelled at the location of the borehole.

- The unit was faulted out along a normal fault. No unconformity exists, but the borehole is intersecting the “hole” in the unit produced by faulting.
- The unit is absent due to an unconformity. The modeler has to decide whether this is a baselap or an erosion.



### Check for errors in petrography

Since well data are registered by various persons with various levels of knowledge and often by non-geologists, at different times, the description of the well data may be heterogeneous. Inconsistencies in the petrographic description may already occur in the field. Later, errors during the digital registration and classification may occur.

- Check original well documentation,
- Check the neighboring drillings and harmonize the inconsistent one, if reasonable.

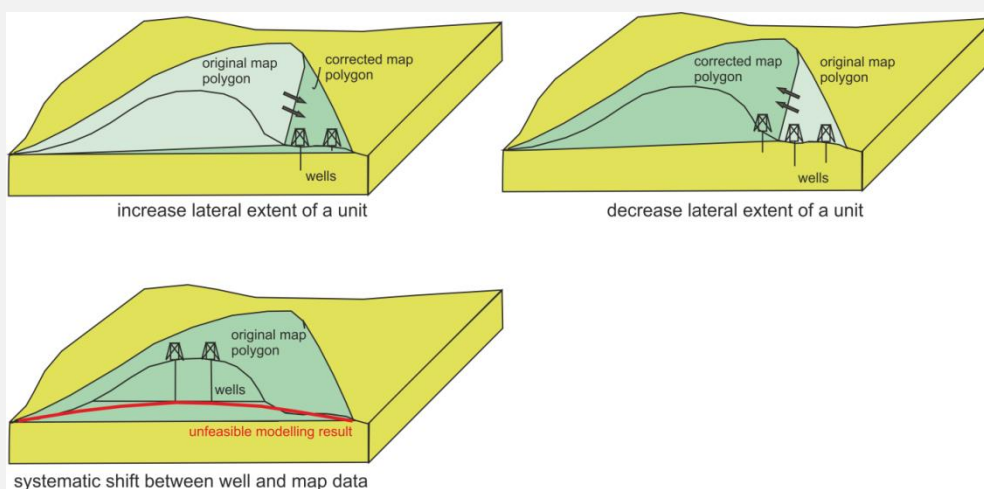


### D.3.8.3. Geologic maps

#### General remarks

The quality check of map data mainly includes a consistency check against borehole and outcrop data.

#### Description of workflow steps



**Figure 17: Change of the lateral extent of a map unit after comparison with drilling data.**

If the lateral extent of a geologic unit was not mapped correctly, this can be detected by wells which have traced the geologic unit outside of the map polygon. The map polygon has to be corrected in such a way that it includes all wells with the geologic unit (Figure 17).

If wells that reach the depth level of a geologic unit do not contain a geologic unit, although they are located inside of the map polygon, the lateral extent of the geologic unit has to be reduced.

Sometimes, a systematic error of the Z-values of the well data and map data can be observed. In this case, the map data have to be considered as less reliable. If in this case both well and map data are used for 3D modelling, large sedimentary horizons will get a convex or concave shape, which cannot be explained by processes of their formation. The shape of the modelling result will rather correspond to the morphology of the Earth's surface, which is younger than the geologic unit. In this case, the extent of a polygon has to be re-digitized completely.



Model input - raw data

#### D.3.8.4. Cross sections

##### General remarks

Cross sections usually do not match the 3D geometry properly. A quality check is very important!

##### Description of workflow steps

###### Inconsistencies of cross sections

###### *Changes in apparent dip*

If the base line of the cross section has a kink, this is not directly seen in the cross section, since this is drawn on one plane. However, the apparent dip of a geologic unit changes at the kink, such that the user gets the impression that the dip itself is changing.

###### *Proper points of intersection of units drawn in different cross sections*

If two sections cross one another, but the lines tracing the borders of geologic surfaces do not intersect, this has to be corrected by shifting, stretching, rotating of one of the cross sections. If the result is not getting better while using these operations, the lines may be interrupted in the vicinity of their crossing, such that the inconsistency is not digitized.

###### Inconsistencies with map and well data

If a cross section is inconsistent with map data, this has to be corrected by shifting, stretching, rotating of one of the cross sections. If the result is not getting better while using these operations, the lines may be interrupted in the vicinity of their crossing, such that the inconsistency is not digitized.



Model input - raw data

### D.3.8.5. Isohypse maps

#### General remarks

The quality check mainly includes a consistency check against the borehole data.

#### Description of workflow steps

If the isohypse map is old, it usually has a bad not consistent with the well data.

- A systematic error can be corrected by shifting the isohypses.
- A local systematic error can be corrected by shifting parts of the isohypses and leaving spaces to the unshifted parts which are big enough to avoid kinks and irregularities in the modeled object.



Model input - harmonized set of input data

### D.3.9. Harmonized sets of input data

#### General remarks

Harmonized input data sets meet the following requirements:

- They directly feed into the elaboration of harmonized output datasets.
- They are available in a digital data format having a geographical reference.
- They are in line with a harmonized list attributes and parameters, which organizes the thematic content and the physical units.
- They use the joint coding of age and pilot area number.
- Each data set is accompanied by a metadata sheet.

#### Description of workflow steps

The rules for producing the harmonized set of input data can be found in the deliverable D.T2.3.1 „Set-up of harmonized data management infrastructure for GeoPLASMA-CE“.

For each set of input data, a data and metadata set has to be produced, e.g., one for all borehole data, one for all map data, one for all fault data.



## 3D structural modelling

### D.3.10. 3D modelling

#### D.3.10.1. Modelling workflow

##### General remarks

The term 3D structural modelling comprises all mathematical and computer-scientific methods allowing the uniform mapping of topology, geometry and properties of geologic objects while taking into account all kind of data related to these objects. The result of 3D structural modelling is a set of geometrically feasible and geologically reasonable objects representing the structure of the subsurface on a certain level of simplification.

##### Description of workflow steps

3D modelling is performed by every partner with its own software and interpolation algorithm.

##### International boundaries

Partners in international pilot areas have to take care to generate a consistent 3D model along the political boundaries. Therefore, a buffer zone of 2 km width on each side of the border has to be specified. The 3D model is first generated inside the buffer zone by both partners in common. After this model has been generated and quality-checked, it will be fixed and not changed again. Then, the 3D model is extended to both sides of a pilot area.

##### Geologic concept

The first step in 3D modelling is to **generate a conceptual model** about the structure of the pilot area. This has to be done by respecting the most recent geologic knowledge and can be supported by constructing cross sections.

##### Construction of the 3D bodies

**The fault network has to be modelled first**, because it displaces lithological bodies. **Then, the lithological units are modelled.** Finally, **the ground water level can be modelled crossing all lithological boundaries.**

**Modelling top downward** is strongly recommended since most data is available near the ground surface. Therefore, most details will also be modelled near the ground surface. For deeper units, fewer details are known, such that these units can respect geometric constraints set by the upper units without getting inconsistent with the data. This is often not the case, when upward modelling is performed. Then, inconsistencies are produced.

Volumes cannot yet be displayed in the Web by GiGa. Therefore, **boundary surfaces** have to be modelled. It is recommended to model **the tops of the lithological units**, since these are needed as input for the calculation of the thermal conductivities and heat extraction capacities.



## 3D structural modelling

### D.3.10.2. Quality check

#### Description of workflow steps

##### Do you see intersections with the DEM not represented in the geologic map?

In regions where not many data are available, the horizons may cross the DEM representing the upper boundary of the model. This is not feasible. There are two ways how to handle this sort of inconsistencies:

- Cut the crossing horizon at the DEM and delete the part above the ground surface. This will produce an erosional structure and is only allowed if it is geologically feasible.
- Move the inconsistent part of the horizon below the ground surface, if this is geologically feasible.

##### Are all important structures present in the 3D model?

##### Are horizon intersections feasible?

Horizons of conformable sedimentary units must never cross. If they do so in the model, the horizon representing the base of one unit has to be moved below the horizon representing the top of the same unit.

If the unit is unconformable, a horizon intersection has to occur. If the unconformity is erosional, the base horizon of one unit has to be cut off by the top horizon of the unit. If the unconformity is baselap, the top horizon of one unit has to be cut off by the base horizon of the unit.

##### Is the number of unconformities correct?

##### Are there sudden and local thickness changes? This may indicate:

- Faults,
- Political boundaries or map boundaries,
- Erroneous input data.

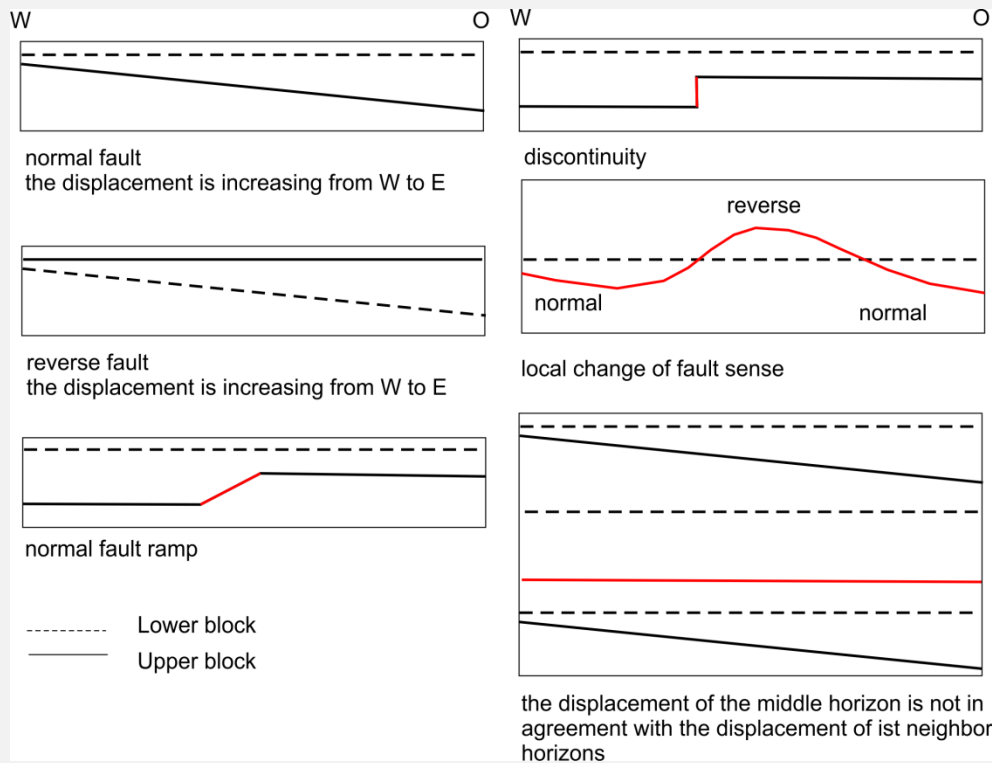
##### Are the fault blocks consistently modelled?

In a completely brittle environment the fault blocks have to be completely confined by faults and the fault displacement has to be kinematically feasible.

If ductile deformation is known in the region, faults may appear only locally and a consistence check is more difficult. However, the conceptual model will aid in analyzing whether the fault orientation and the soft linkage zones are represented in a geologically feasible way.

##### Is the fault displacement feasible?

The analysis of the fault displacement can be performed using Allan's diagram plotting the horizon-cutoffs along the fault plane (**Figure 18**). Inconsistencies may be indicated by a local shift from normal to reverse faulting or by discontinuities.

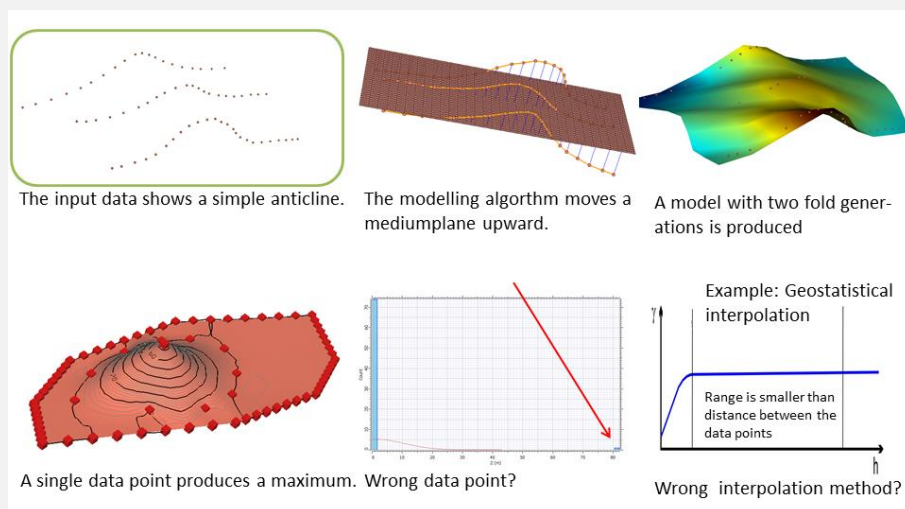


**Figure 18: Quality check of fault displacement in a 3D model.**

Is the fold structure coincident with the conceptual model and the input data?

Additional fold generations may be artefacts produced by the modelling algorithm (at least in SKUA-GOCAD™).

Which structures in the 3D model are not constrained by data? Are they artefacts (**Figure 19**)?



**Figure 19: Examples for artefacts in a 3D model.**



## Standardized 3D model output

### D.3.11. Standardized set of output data

#### D.3.11.1. Triangulated irregular network for 3D visualization and decision support tool

##### General remarks

Harmonized output data sets have to meet the following requirements:

- They are in line with the harmonized lists of attributes, parameters and coding, which organizes the thematic content and physical units.
- They have to be delivered in a **harmonized format** and at a **harmonized spatial reference system**.
- They are displayed on the web portal.

##### Description of workflow steps

- The TIN objects have to be delivered in GOCAD\_ASCII format.
- A table with the age and petrography coding for all units of one pilot area has to be delivered.
- A metadata table has to be filled for the full 3D model.





Standardized 3D model output

### D.3.11.2. 2D grid orthogonal raster for potential mapping

#### General remarks

Harmonized output data sets have to meet the following requirements:

- They are in line with the harmonized lists of attributes, parameters and coding, which organizes the thematic content and physical units.
- They have to be delivered in a **harmonized format** and at a **harmonized spatial reference system**.
- They are displayed on the web portal.

#### Description of workflow steps

Representation of the tops of geological units in a raster format is necessary for mapping of the geothermal potential for closed loop systems. Overturned units have to be represented piece-by-piece. Simplify this sort of structures, if possible.

- If the top of a geological body is formed by a fault, the Z-value of the stratigraphic unit will be -9999 in this region. You have to copy the Z-values of the fault to this region in order to describe the whole boundary of the geological body.
- The 2D grid has the spatial reference system, location, resolution and extent of the master grid. Additionally, one table with the age and petrography coding for all units of one pilot area has to be delivered.
- One metadata table has to be filled for the full 3D model.



## E. Harmonized workflow for mapping land-use conflicts and risk factors

### E.1 The workflow - a brief description

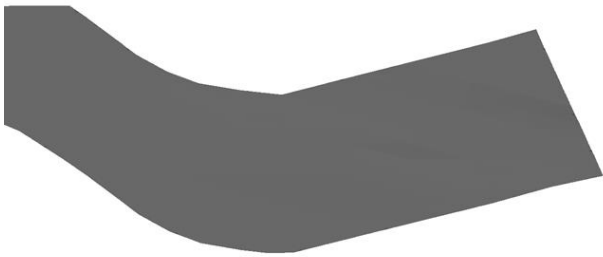
Geothermal energy is clean, emission-free and sustainable. However, every intervention in the subsurface has consequences which may eventually cause hazards or damages. Therefore, a proper professional installation of geothermal plants taking into account risk factors is important for the development of energy concepts using shallow geothermal energy. On the other hand, some geological conditions or anthropogenic interventions may reduce the efficiency of a geothermal plant or cause health problems or injury.

Existing conflict and risk factors can be presented as a:

- **Conflict layer:** A conflict layer is a thematic map representing one conflict factor without interpretation of its impact on a land-use like shallow geothermal energy. This kind of uninterpreted representation is well suitable for experts who know the impact of on a land-use like shallow geothermal energy.
- **Extent layer:** The extent layer provides information on where the data set specifying one conflict is available. If in a conflict layer a location is not marked, this can mean that there is no conflict or it can mean that no data set was available and that it is not clear, whether a conflict exists. Both cases have to be distinguished! Therefore, each conflict layer has to be combined with an extent layer. The extent layer is also considered for processing the traffic light map. A no-data region has to be included with the yellow light because this indicates that it is not known whether there is no conflict or whether shallow geothermal use is forbidden. This has to be clarified by an individual case check.
- **Conflict map:** The conflict map is a combination of a conflict layer and an extent layer. It will be produced for each conflict factor relevant for a pilot area.
- **Traffic light map:** A traffic-light map in the project's context is an interpreted thematic map which combines various data sets in order to give a short overview of the use of shallow geothermal energy. It consists of 3 categories: Shallow geothermal plants are generally possible (green), attention: more information needed (yellow), shallow geothermal plants are generally prohibited (red). It is an interpreted map where the conflict factors leading to the assignment of each point to a particular category is not obvious anymore. The traffic light map is especially useful for public users who want to get information on whether geothermal use is possible in their region. The traffic-light maps will be produced for open loop and closed loop systems separately.

The first step of mapping land-use conflicts and hazard risk is to develop an inventory of possible risk and conflict factors. After investigating which land-use conflict and risk factors are relevant for each pilot area and after collecting the data describing the factors, the input data concerning the data structure has to be analysed (**Figure 20**). A table helps to sort data describing the conflict factors by the aspects of property group, feature class and data model, because the following workflow is the same for objects of the same data structure regardless on whether the factor is anthropogenic or geogenic. The structure of data describing any factor may be different from pilot area to pilot area and from country to country. Therefore, each partner has to sort his conflict layers according to his needs and input data.

The workflows to generate conflict maps and traffic light maps are provided for raster and vector data (**Figure 21**). If input data are mixed concerning these data models, all data have to be converted to the same data model. If the workflow for raster data is used, inaccuracies due to the raster size will occur. Therefore, if the input data are mainly available in vector data models, it is recommended to use the workflow for vector data. If the input data are mainly available as raster data, the inaccuracies exist from the very beginning and the workflow for raster data can be used, which saves the data transformation steps.



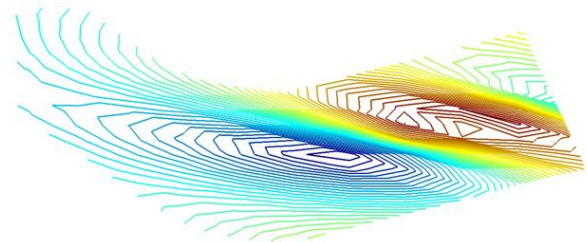
property: binary- data model: vector - feature class: polygon



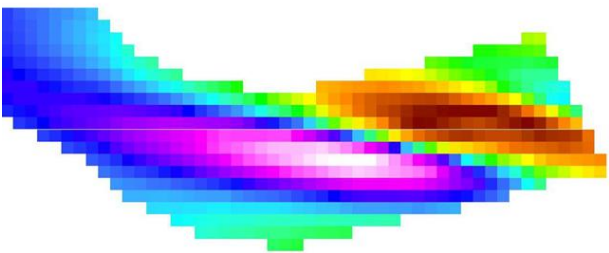
property: continuous- data model: vector - feature class: point



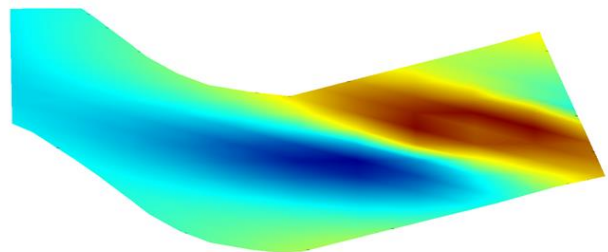
property: categorial- data model: vector - feature class: polygon



property: continuous- data model: vector - feature class: line

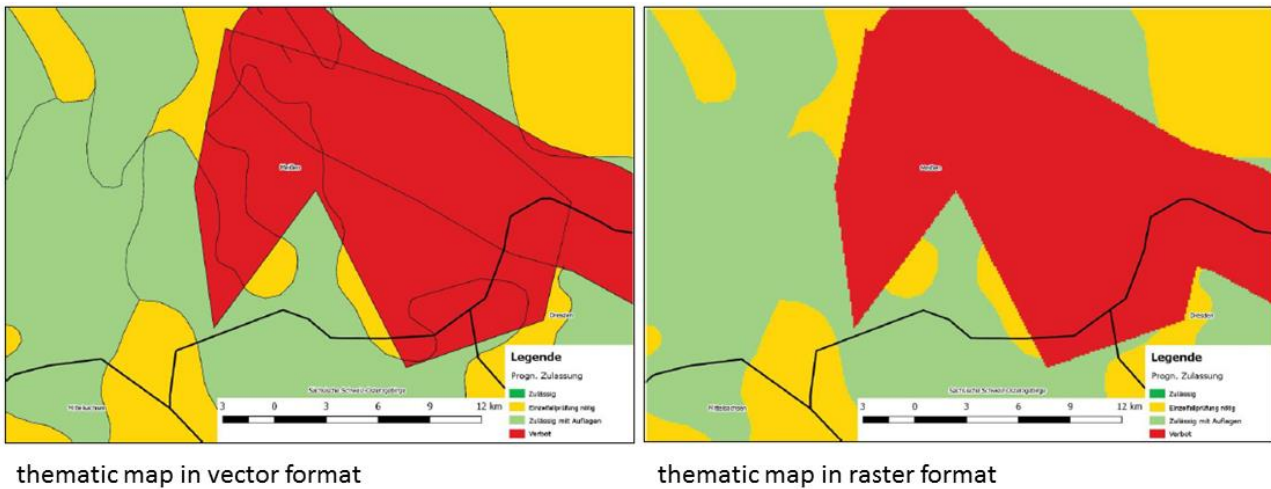


property: continuous- data model: raster - represented: polygon



property: continuous- data model: vector - feature class: polygon

**Figure 20: Various representations of the same unit of swellable rocks. The unit can be represented just by its presence (binary property), by categories like limitation of drilling depth (categorical property), by the depth of its top (continuous property). The depth of the top can be represented by a raster or a vector data model. In case of using a vector data model, it can be represented by point, line or polygon features. The processing of the data for a conflict map or a traffic-light map depends mainly on the data structure of the available data set describing each conflict factor.**



**Figure 21: Comparison of a map represented in the vector data model (left) and raster data model (right).**

After collecting the data for all relevant conflict factors, an extent layer has to be generated for each factor. This extent layer shows areas where no data are available. In order to prepare the conflict layers, all objects need an attribute describing their conflict or land-use risk. The conflict map is calculated by combining both layers.

While the standardized output of conflict maps for web-visualization is a raster data model, the conflict and extent layers produced in the vector-data workflow have to be used for the compilation of the traffic light map.

The workflow generating the traffic light map uses the conflict layers and the extent layers prepared in the previous step. Since some of the conflict layers may consist of point or line features while the extent layer will always consist of polygons, all point and line features have to be converted into polygons either by buffering or by calculating a convex hull around the data set.

All attributes present in any conflict layer have to be reclassified to one of the three categories of the traffic light map:

- Generally possible (1-green),
- Attention: Additional information needed (2-yellow),
- Generally not allowed (3-red).

This interpretation and reclassification has to be performed by the project agent since the interpretation may be different from pilot area to pilot area, e.g. drilling may be completely forbidden in a natural reserve in one country, while it is allowed after an individual check in another country. All no-data regions of the extent layers have to be attributed with “2” - individual case check. Point and line features have to be converted into polygon features either by specifying of a buffer zone or by calculation of a convex hull. They have to be classified by the categories of the traffic light map afterwards. After reclassification of all layers, one traffic light map for each open and closed loop geothermal plants can be produced either by union and subtraction of all polygon layers for vector data or by map algebra for raster data. The harmonized output is a raster data set coinciding with the master grid.



The workflow was written for ArcGIS. Version 10.2.2 for Desktop (basic license) was used for compiling the workflow. Additionally, the following are required for the preparation of conflict maps and traffic light maps:

- Spatial Analyst
- Geostatistical Analyst
- An Advanced ArcGIS Licence is required if the Vector Data Workflow is to be used for the creation of traffic light maps (“erase” tool), but not for the Raster Data Workflow

The following points provide an overview of the workflow steps (compare with **Figure 22**):

## 1. Documentation of the project

## 2. Data preparation

Preparation of a list with relevant factors of land-use conflict and risk

Collection of input data

Analysis of the data structure of the input data

Decision for either the vector or the raster data workflow

## 3. Generation of conflict maps

Transformation of all input data sets to one data model (vector or raster)

Specification of a data-extent layer for each conflict layer

Assignment of attributes describing the conflict

Combination of conflict and extent layers

Setting the Geoprocessing environment to the master grid coordinates, extent and resolution

Standardization of output for each conflict or risk factor

## 4. Generation of traffic light maps

Interpretation of the conflict data concerning the three suitability categories due to their impact on the use of shallow geothermal energy

Assignment of the attributes of the three traffic-light categories to all conflict layers

Combination of all conflict and extent layers such that the maximum value of all layers is displayed for each location

Setting the Geoprocessing environment to the master grid coordinates, extent and resolution

Standardization of output in raster format

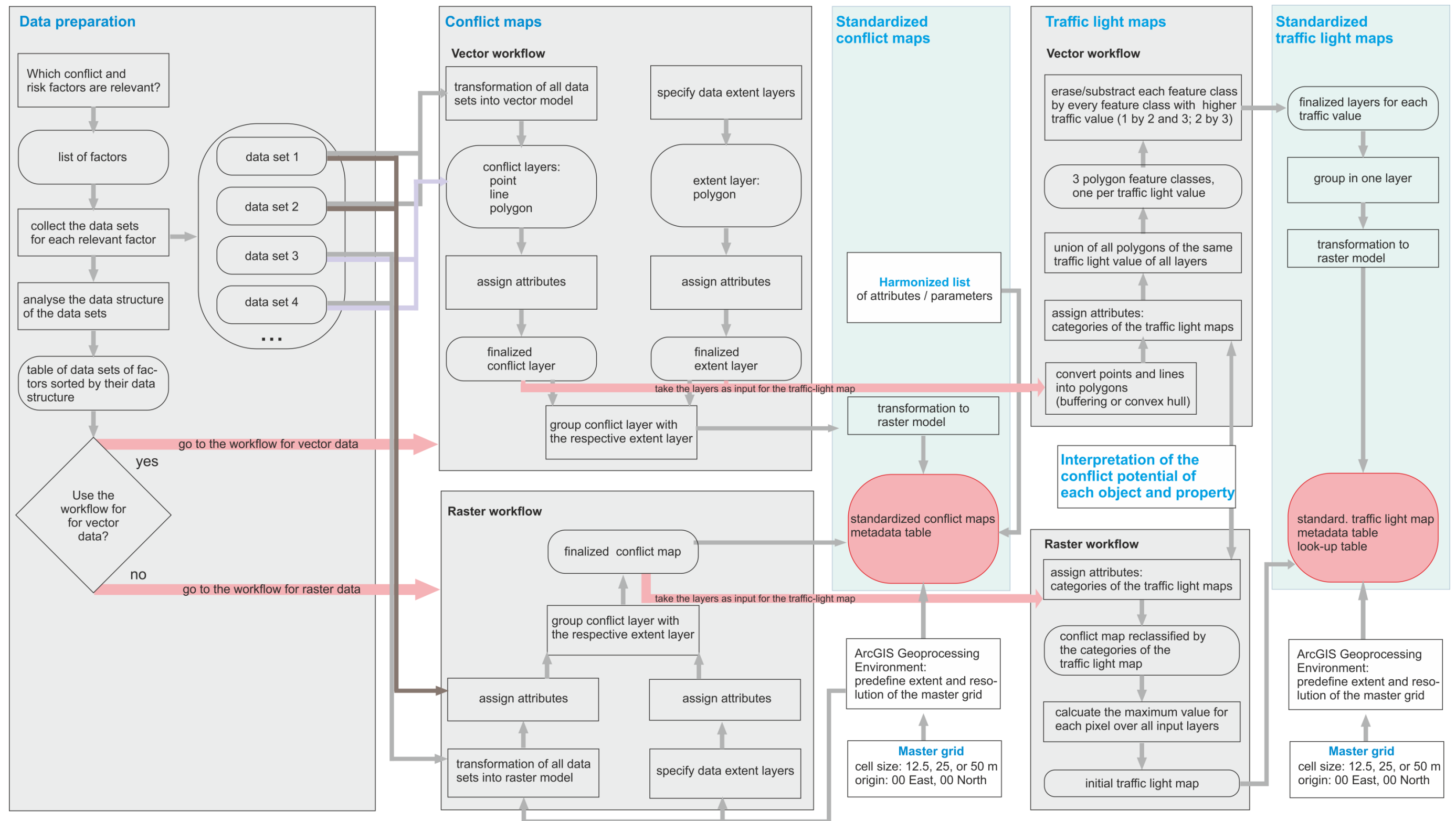


Figure 22: GeoPLASMA-CE workflow for mapping conflicts with shallow geothermal use and generating traffic light maps for the suitability of open or closed loop systems.



## E.2 Rules and mandatory specifications - checklist

Spatial reference system	<p>ETRS1989-TM 33 / ETRS1989-TM 34 meters</p> <p>→See D.T2.3.1 for specification</p>
Elevation reference system	<p>EVRF2007</p> <p>→See D.T2.3.1 for specification</p>
Extent layer	<p>Binary property no_data_cat</p> <ul style="list-style-type: none"> <li>• Attribute for a region with data: 9999</li> <li>• No data value: -9999</li> </ul>
Conflict map	<p>Attributes from the joint attribute and parameter list</p> <p>→See D.T2.3.1 for specification</p>
Traffic light map	<p>Categorical property traffic_va (short integer)</p> <p>1... shallow geothermal installations are generally possible (green)</p> <p>2... attention: more information required (yellow)</p> <p>3... shallow geothermal installations are generally prohibited (red)</p>
Transfer the raster data to the master grid	<p>Grid resolution: 12.5, 25 or 50 m</p> <p>Borders of the grid cells at (00,00) coordinates</p> <p>→See D.T2.3.1 for specification</p>
Export data format of all raster data	<p>.adf -ESRI grid</p>
Completed metadata template	<p>Metadata table for conflict layers</p> <p>Metadata table for traffic light maps</p> <p>Look up tables connecting the attributes of the conflict maps with the traffic light maps</p> <p>→See D.T2.3.1 for specification</p>
Project documentation	<p>Table for the documentation of the project progress</p> <p>→See D.T2.3.1 for specification</p>



## E.3 Tool kit for mapping land-use conflict and risk factors for shallow geothermal use

Input data

### E.3.1. Analysis of relevant land-use conflict and risk factors

#### General remarks

A conflict is a disagreement of aims. In context of shallow geothermal use, it means a land-use conflict, which may arise when one portion of land or of the subsurface is exposed to more than one uses.

Each activity has consequences. Some consequences are wanted and expected; other consequences are unwanted and are considered to be negative. Some of these negative consequences may cause damage, harm or injury. A risk is the possibility of loss, damage or injury. A risk factor is a variable associated to an increased risk.

Shallow geothermal use can be inefficient, dangerous or forbidden (e.g. due to land-use conflicts). In order to plan a geothermal plant, the risk and land-use conflict factors have to be known by the user, planning office, drilling company and authority.

A conflict layer displays a single existing land-use conflict or risk factor.

#### Description of workflow steps

Identify conflict and risk factors relevant for your pilot area (compare to **Table 10**).





**Table 10: Risk and conflict factors for shallow geothermal use.**

Group	Factor	Effect/impact
Protection zones	Drinking water protection zone	Ground water could be contaminated by drilling activity or by fluids emitted by the geothermal plant
	Curative water protection zone	Ground water could be contaminated by drilling activity or by fluids emitted by the geothermal plant
	Drinking/curative water well	Ground water could be contaminated by drilling activity or by fluids emitted by the geothermal plant
	Industrial water well (mineral water, breweries, chemical and textile industries)	Ground water could be contaminated by drilling activity or by fluids emitted by the geothermal plant
	Floodplain	Area restricted for settlement
	Natural reserve	Region which should develop independently of human influence of any kind
Geology	Mineral formation and transformation, e.g. swellable rocks (anhydrite, clay)	Water injected by a geothermal plant could initiate mineral transformation and lead to damage of houses and infrastructure
	Aquifer is existing (minimum thickness and yield)	Installation of an open loop system is possible
	Significant change of groundwater table	Could initiate ground motions due to hydrostatic changes caused by open loop systems, which might cause damages in the surroundings of the geothermal plant
	Confined or artesian aquifer	Could cause water eruption in the drilling hole, leading to difficulties in sealing the borehole heat exchanger properly
	Hydraulically separated aquifers	Drilling into hydraulically separated aquifers could connect them and change the hydraulic system and could cause salinization of fresh water aquifers
	Groundwater mineralization like sulfate containing groundwater	Mineralization can obstruct and destroy open loop systems, grouting material may be altered or destroyed by the mineralized water, efficiency of the heating system decreases
	Karst	Problems for closed loop systems if grouting cannot be conducted properly and cavities remain, impeding heat and fluid exchange of the geothermal plant
	Shallow gas leakage, CO <sub>2</sub> , radon, methane	For gas saturated water: While drilling, blow out might occur and cause water or sediment eruptions Radon and CO <sub>2</sub> : Health damage possible while drilling and the well bore might create migration paths for the gas Methane: Danger of explosion
	Fault and fracture zones in crystalline rocks	Geotechnical problems could occur while drilling, problems with grouting material are possible
	Quick sand	Well bore is not stable
	Slope of the ground surface	Geotechnical problems possible (the sequence of geological strata, e.g. the existence of clay layers and the dip direction are also important)
Anthropogenic intervention	Existing shallow geothermal use in the neighborhood	This might reduce the efficiency of a heat plant
	Distance to borders (property, protection zone)	Legal restrictions Probably not important for the GeoPLASMA-CE raster size
	Requirement to use district heating	No geothermal plants are allowed by regulation
	Pipelines	Pipelines could be destroyed by drilling activity
	Subway lines	Disturbance of traffic possible, problems with grouting may occur
	Public property	Geothermal use could be prohibited
	Mining concession or licenses	Geothermal use could be prohibited
	Past mining activities and artificial cavities	Problems during grouting are possible
	Contaminated sites	Migration of the contamination possible, surrounding subsurface and groundwater may be contaminated by drilling activity, the well bore might create migration paths
	Old deposits	Migration of the contamination possible, surrounding subsurface and groundwater may be contaminated by drilling activity, the well bore might create migration paths
	Governmental requirements	E.g. limitation of the drilling depth for specific geologic units



## Input data

### E.3.1.1. Order the relevant conflict and risk factors by their data structure

#### General remarks

The work steps described in the workflow are valid for all conflict layers of the same data structure. Each land-use conflict or risk factor can be described by different data structures.

The property type displayed in a conflict layer can be:

- Binary: The conflict layer shows whether a particular factor is present or not, e.g. natural reserves are present or not.
- Categorical: The conflict layer shows various groups of objects, e.g. a layer with anthropogenic lines is composed of the groups electric line, telephone line, water pipeline, gas pipeline.
- Sequential: The conflict layer shows categories which are ordered by a sequence, e.g. groundwater protection zone S1, S2, S3a, S3b. You know that S1 is more protected than S2 and S2 is more protected than S3.
- Continuous: The conflict layer displays a variable which is usually a real number and can take any value at each location, e.g. the depth of a unit of swellable rocks or the slope of the ground surface.
- Discrete: A discrete property is similar to a continuous property, however, only natural numbers are possible, e.g. the number of existing geothermal plants per pixel.

Dimensionality of objects displayed in a conflict layer:

- Point: 0-dimensional,
- Line: 1-dimensional,
- Polygon: 2-dimensional.

Data model used:

- Raster data model: A raster data model is based on a square-based tessellation of the 2D plane into cells. Each raster cell is associated with numbers quantifying the observed attribute.
- Vector data model: A vector data model is a representation of the world using points, lines, and polygons. All of these objects consist of points, and sometimes (in case of lines and polygons) of segments connecting them. Each point is specified by the coordinates of its position vector.



## Description of workflow steps

Each conflict factor can be represented by different property groups. In the example in **Figure 20**Figure 20, a swellable rock unit is represented just by specifying where it is located (binary), by specifying different categories: Absent (green), drilling allowed with limitation of the drilling depth (yellow), drilling forbidden (red), and by a continuous variable specifying its Z-value.

All three of the representations can be provided as raster or as vector data. The last data set representing the continuous variable can be available as point, line or polygon feature.

Depending on the data structure, different work steps have to be applied. That's why it is necessary to analyse the data structure of all data sets (**Table 11**).

1.) Which variable type is used for describing the conflict or risk? Is it

- binary,
- categorical/nominal or ordinal/sequential,
- discrete or continuous?

3.) Are the objects available as

- raster data,
- vector data?

2.) Are the specified objects

- points,
- lines or
- polygons?

Make a table to order your data describing the conflict factors concerning these aspects, because the following workflow is the same for objects of the same data structure regardless of the meaning of the conflict factor. The assignment may be different from pilot area to pilot area and from country to country. Therefore, each partner has to order his conflict layers according to his needs and input data.



**Table 11: Possible variable types, features and data models.**

Variable types	Feature	Data model	Conflict layers -examples
binary	point	vector	Location of drinking water production well Location of industrial water production well
		raster	Anonymized points with existing geothermal usage
	line	vector	Mining galleries Pipeline Underground network Fault and fracture zone
		raster	Scanned map of mining gallery
	polygon	vector	Floodplain Natural reserve Extent of a unit with swellable rocks Extent of confined/artesian groundwater Extent of karst Extent of quick sand Extent of public property Extent of contaminated sites Extent of deposits Mining concession or license
		raster	Scanned map containing floodplains
categorical/ sequential	point	vector	Location of water production wells for drinking water, mineral water, curative water Shallow gas leakage (CO <sub>2</sub> , radon, methane)
		raster	Scanned map of water production wells
	line	vector	Anthropogenic lines (electric, gas, water, telephone)
		raster	Scanned map of anthropogenic lines
	polygon	vector	Groundwater protection zones of level 1, 2, 3a, 3b Region with mineralized groundwater concentration (small, medium, high)
		raster	Scanned map of groundwater protection zones
discrete/ continuous	point	vector	
		raster	
	line	vector	
		raster	
	polygon	vector	Groundwater isohypses Aquifer thickness isolines Aquifer yield isolines
		raster	Top of a unit of swellable rocks Depth of confined/artesian aquifer

Vector-data workflow for the conflict maps

## E.3.2. Conflict maps (vector data workflow)

### E.3.2.1. Data-extent layer

#### General remarks

The extent layer is a map showing where the data describing one land-use risk or conflict factor are available or not. This information is very important. If it was not specified, this could generate the impression that no risk is present. However, we simply do not know whether a risk is present or not.

#### Description of workflow steps

##### Create an extent layer

Copy the pilot area polygon for each conflict layer you want to use

*Table of contents (TOC) → right-click on the layer with the pilot\_area → copy*

*TOC → Layers → paste layer*

*Click into the name of the pasted layer in the TOC → give it a new name (e.g. gw\_protection\_extent)*

Create a field: no\_data\_cat: short integer

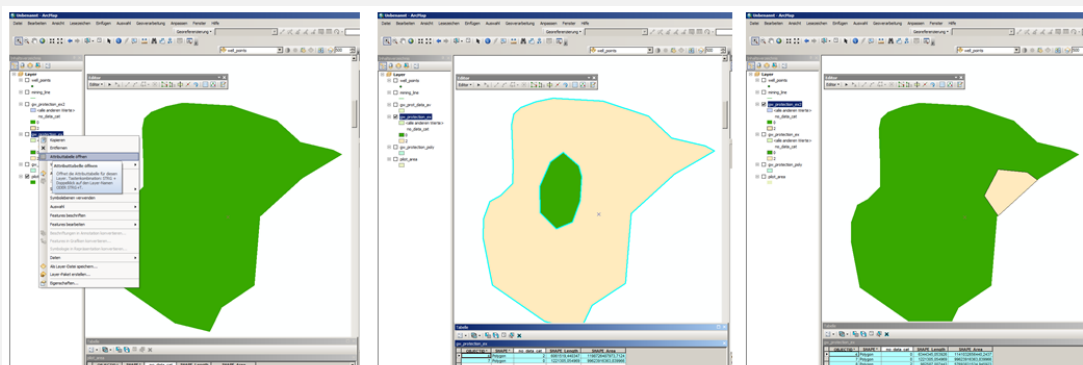
*TOC → right-click on gw\_protection\_ext → attribute table → table options → add field → no\_data\_cat: short integer*

**Assign the no\_data\_cat:**

**9999 ...if data are available**

**-9999 ...if no data are available**

These numbers will be used for combining the extent layer with the conflict layer in order to compile a conflict map. Three cases for specifying the extent layer can be distinguished:



The data set for a conflict layer is available in the whole pilot area.

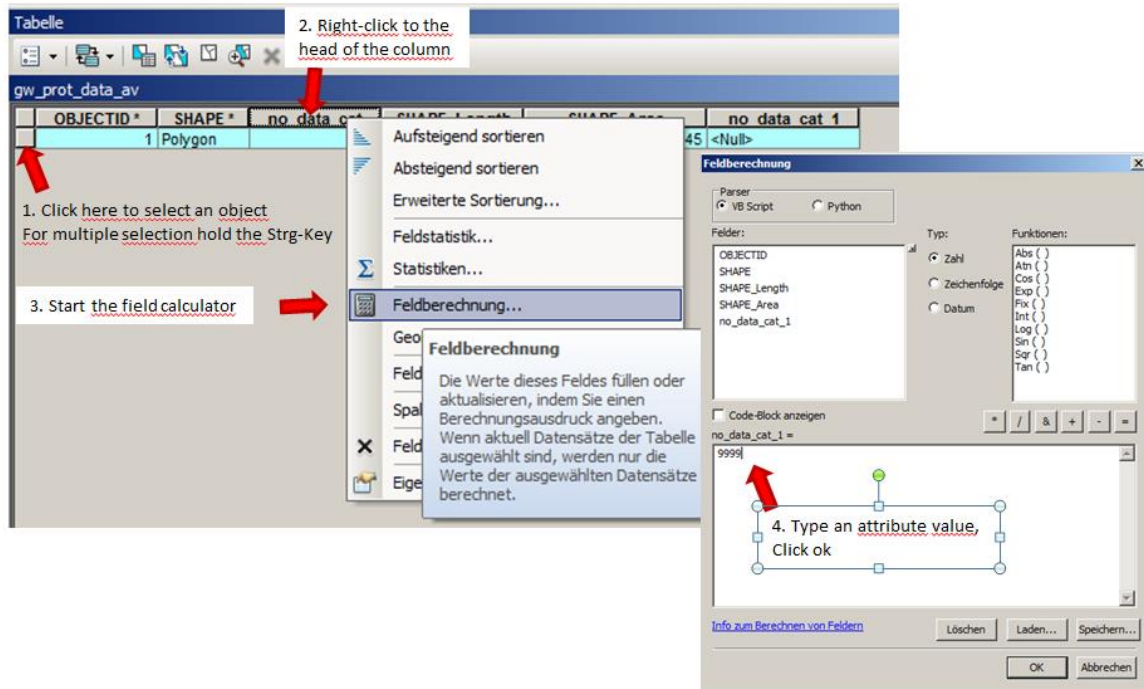
The data set for a conflict layer is available in one region pilot area.

The data set for a conflict layer is not available in one region pilot area.

**Figure 23: Specification of polygons in the extent layer: The large polygon represents a pilot area.**

The data set is valid for the whole pilot area (Figure 23 left).

In this case, you have to assign a 9999 as no\_data\_cat value for the pilot area polygon (Figure 24).



**Figure 24: Attribute table in ArcGIS: How to assign the attributes of the extent layer.**

TOC → open attribute table → Select the polygon by clicking in its row to the left of the first column → right-click into the header of the column no\_data\_cat → select the field calculator → type 9999

The data set is only valid for one polygon inside of the pilot area (Figure 23 middle).

In this case you have to assign the no\_data\_cat value of -9999 for the whole pilot area polygon, to cut a polygon specifying the extent of the data set into the pilot area polygon and assign a no\_data\_cat value of 9999 for this inner polygon.

TOC → open attribute table → Select the polygon by clicking in its row to the left of the first column → right-click in the header of the column no\_data\_cat → select the field calculator → type -9999

TOC → Right-click on the gw\_protection\_extent → edit layer → select the pilot area polygon

Activate the tool “snip / catch at point”



Activate the tool “cut polygons”



Digitize the region that contains the data set, such that a closed polygon is generated

Right-click on the new polygon → attributes → type 9999

*Stop editing and save the edits*

*If you want to use an existing polygon select the trace tool  to digitize the polygon*

*The data set is not available for some regions of the pilot area polygon (Figure 23 right).*

In this case you have to assign the no\_data\_cat value of 9999 for the whole pilot area polygon, cut a polygon specifying the extent of the no-data region into the pilot area polygon and assign a no\_data\_cat value of -9999 for this polygon.

*TOC → open attribute table → Select the polygon by clicking in its row to the left of the first column → right-click in the header of the column no\_data\_cat → select the field calculator → type 9999*

*TOC → Right-click on the gw\_protection\_extent → edit layer → select the pilot area polygon*

*Activate the tool “snip/ catch at point”*



*Activate the tool “cut polygons”*



*Digitize the region that contains the data set, such that a closed polygon is generated*

*Right-click on the new polygon → attributes → type -9999*

*Stop editing and save the edits*

*If you want to use an existing polygon select the trace tool  to digitize the polygon*

## Vector-data workflow for the conflict maps

### E.3.2.2. Transformation of raster data into vector data

#### General remarks

A data transformation converts a set of data from the data format of a source data system into the data format of a destination data system. It is needed if input data are available in different data structures.

#### Description of workflow steps

From the following, select the paragraph which is applicable to the data structure of your conflict layer! In some cases automatic conversion and manual digitizing are described.

##### Binary property -points -automatic conversion (Figure 25):

**This method is inaccurate! Check the location of the points in comparison to the original map!**

Resample the raster with a suitable resolution to ensure that each point is assigned to only one raster cell and therefore can be vectorized as one point::

*ArcToolbox → data management tools → raster → raster processing → resampling → select the input file, the desired resolution and the location for storage of the output file*

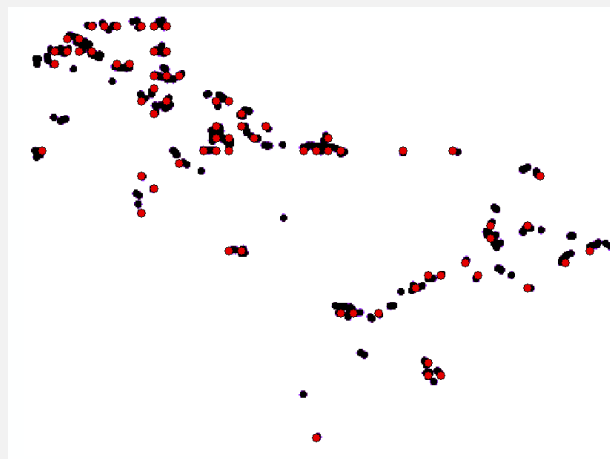
Create a point feature:It can be useful to convert the input raster to a monochromatic raster first, i.e. ensuring that the raster contains only cells of a single constant value and “no data” cells. The background colour can be removed by using the tools “Set Null” or “Reclassify”. After converting the raster into a point feature, the output will only contain valid data points.

Alternatively, raster sets containing two or more values (e.g. 0 and 1, or 0 - 255) can be converted to a point feature first and then reduced to the desired data points by using a query expression:

*ArcToolbox → Conversion tools → from raster → raster to point → select the value\_field*

*Selection by attribute → select all points where the [grid\_code] > 'color\_value'*

*Right-click on the point feature → start editing → right-click → delete all selected points*





**Figure 25: Result of automatic vectorization: Original points are black, extracted points are red.**



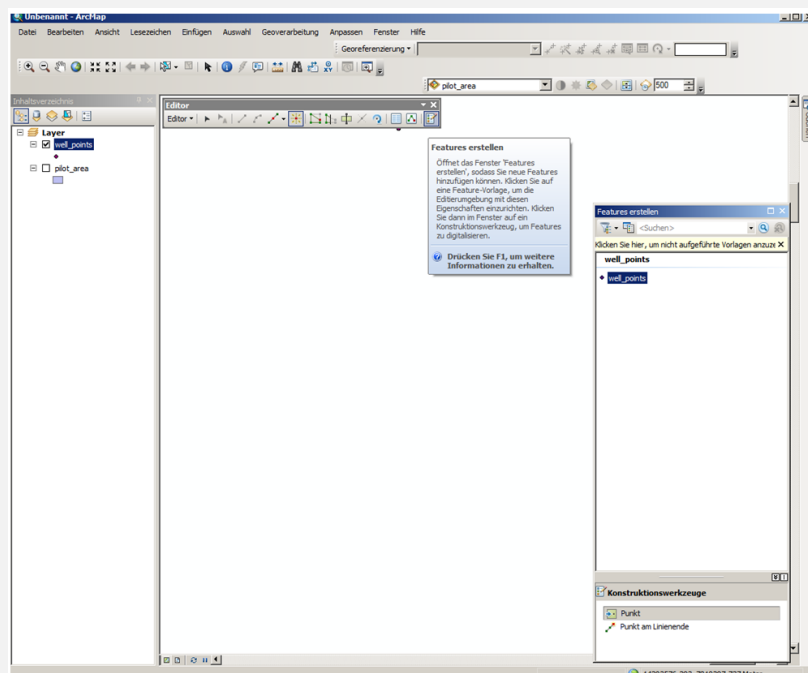
### Binary property -points -conversion by manual digitizing (Figure 26)

Generate a point feature class in ArcCatalogue, e.g. a feature well\_points

Add the feature class to ArcMap → right-click the feature class in the TOC → start editing

→ select the tool “create feature”  → go to the window “create feature” and select “well\_points” → go to the window “construction tools” → select “points” → go to the editor tool bar and digitize the points 

Save the edits and exit the editor toolbar



**Figure 26: ArcGIS digitizing toolbar.**

### Binary property -lines -automatic conversion

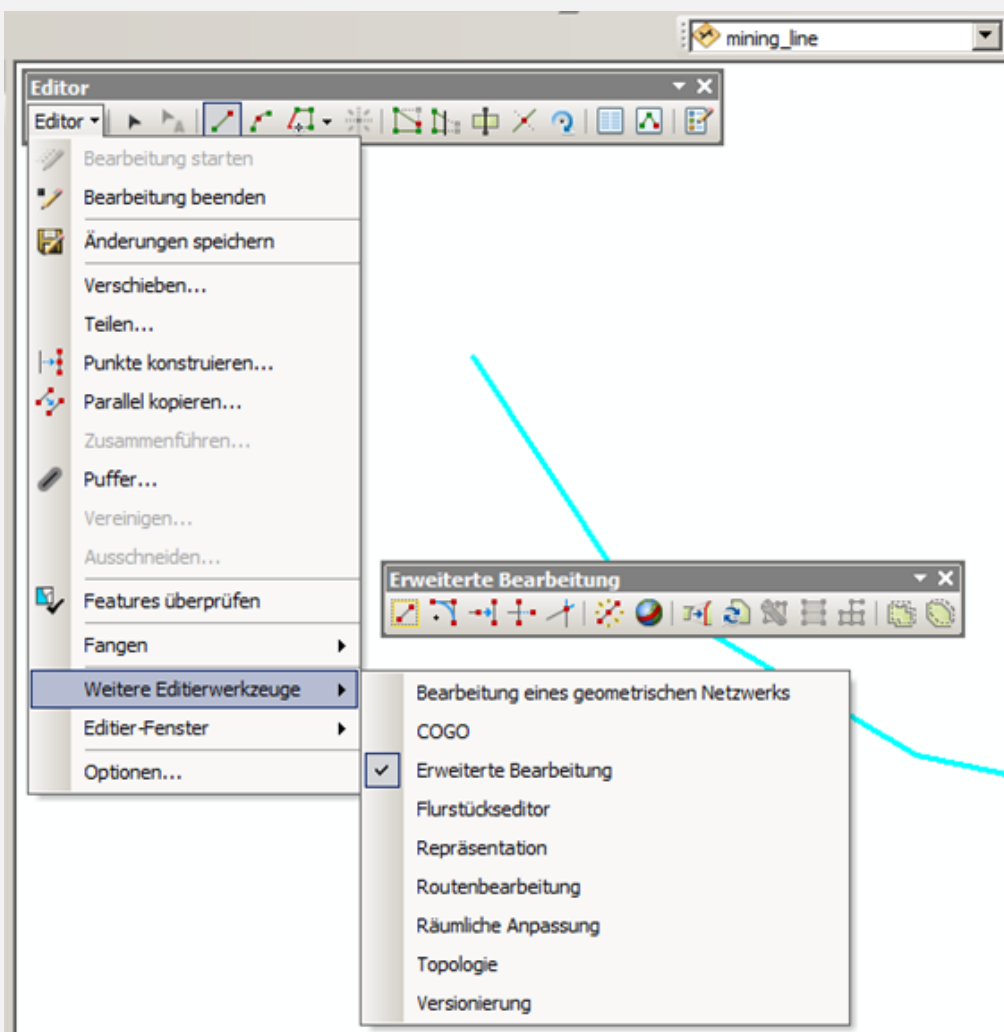
ArcToolbox → Spatial Analyst tools → Reclass → Reclassify → classify → create two classes assign value 1 to the class with the line and NoData to the class of the background around the lines → the result is a raster which contains only the lines

Note: If the input raster is two-coloured (i.e. contains the values 0 and 1), the step above can be omitted and the “no data” value assigned to the background colour during the conversion to a vector file.

ArcToolbox → Conversion tools → from raster → raster to polyline → select the value\_field and set the background value to “zero”.

Smooth the line by using the editor toolbar (Figure 27):

Smooth: Start the Editor toolbar → select the line features → Editor toolbar menu → select the advanced editing toolbar → smooth 



**Figure 27: ArcGIS advanced editing toolbar.**

### Binary property -lines -conversion by manual digitizing

*Generate a line feature class in ArcCatalogue, e.g. a feature mining\_galleries*

*Add the feature class to ArcMap → right-click the feature class in the TOC → start editing*

*→ select the tool “create feature”  → go to the window “create feature” and select*

*“mining\_galleries” → go to the window “construction tools” → select “polyline” → go to*

*the editor tool bar and digitize straight or curved line segments *

### Binary property -polygons -automatic conversion



*ArcToolbox → Spatial Analyst tools → Reclass → Reclassify → classify → create two classes; assign value 1 to the class with the line and NoData to the class of the background around the polygons → the result is a raster which contains only the lines*

*ArcToolbox → Conversion tools → from raster → raster to polygon → select the value\_field*

*Smooth: Start the Editor toolbar → select the line features → Editor toolbar menu → select the advanced editing toolbar → smooth *

### Binary property -polygons -conversion by manual digitizing

*Generate a polygon feature class in ArcCatalogue, e.g. a feature natural\_reserve*

*Add the feature class to ArcMap → right-click the feature class in the TOC → start editing → select the tool “create feature”  → go to the window “create feature” select “natural\_reserve” → go to the window “construction tools” → select “polygon” → go to the editor tool bar and digitize straight or curved line segments *

*Smooth: Start the Editor toolbar → select the line features → Editor toolbar menu → select the advanced editing toolbar → smooth *

### Categorical or sequential property -points -automatic conversion

Resample the raster with a suitable resolution to ensure that each point is assigned to only one raster cell and therefore can be vectorized as one point::

*ArcToolbox → data management tools → raster → raster processing → resampling → select the input file, the desired resolution and the location for storage of the output file*



*ArcToolbox → Spatial Analyst Reclass → reclassify → create new classes according to the categories you have → add the background as NoData class*

Create a point feature:

*ArcToolbox → Conversion tools → from raster → raster to point → select the value\_field*

### Categorical or sequential property - points -conversion by manual digitizing

*Generate a point feature class in ArcCatalogue, e.g. a feature well\_points with the attribute to be specified, e.g. production\_type as string (for text attributes like “mineral water”, “drinking water”, “curative water”).*

*Add the feature class to ArcMap → right-click the feature class in the TOC → start editing → select the tool “create feature”  → go to the window “create feature” and select “well\_points” → select “points” → go to the editor tool bar and digitize the points *

open the attribute table  → assign the attributes for “production\_type”

#### Categorial or sequential property -lines -automatic conversion

ArcToolbox → Spatial Analyst tools → Reclass → Reclassify → classify → create new classes according to the categories you have → add the background as NoData class


→ the result is a raster which contains the lines of different categories in different classes

ArcToolbox → Conversion tools → from raster → raster to polyline → select the value\_field

Smooth: Start the Editor toolbar → select the line features → Editor toolbar menu → select the advanced editing toolbar → smooth 

#### Categorial or sequential property - lines -conversion by manual digitizing

Generate a line feature class in ArcCatalogue, e.g. a feature anthrop\_lines with the attribute to be specified, e.g. line\_type as string (for text attributes like “electric”, “water”, “telephone”).

Add the feature class to ArcMap → right-click the feature class in the TOC → start editing → select the tool “create feature”  → go to the window “create feature” and select “anthrop\_lines” → select “polyline” → go to the editor tool bar and digitize the lines



open the attribute table  → assign the attributes for “line\_type”

#### Categorial or sequential property -polygons -automatic conversion

ArcToolbox → Spatial Analyst tools → Reclass → Reclassify → classify → create new classes according to the categories you have → add the background as NoData class

→ the result is a raster which contains only the polygons


ArcToolbox → Conversion tools → from raster → raster to polygon → select the value\_field

Smooth: Start the Editor toolbar → select the line features → Editor toolbar menu → select the advanced editing toolbar → smooth 

### Categorial or sequential property - polygons -conversion by manual digitizing

Generate a polygon feature class in ArcCatalogue, e.g. a feature *gw\_prot\_zone* with the attribute to be specified, e.g. *protection\_zone\_classification* as string (for text attributes like “S1”, “S2”, “S3a”, “S3b”).

Add the feature class to ArcMap → right-click the feature class in the TOC → start editing

→ select the tool “create feature”  → go to the window “create feature” and select “gw\_prot\_zone” → select “polygon” → go to the editor tool bar and digitize the polygon



open the attribute table  → assign the attributes for “protection\_zone\_classification”

### Discrete or continuous property - polygon - automatic conversion

ArcToolbox → Spatial Analyst tools → Surface → contour line → add contour interval and base

Smooth: Start the Editor toolbar → select the line features → Editor toolbar menu → select the advanced editing toolbar → smooth 

Vector-data workflow for the conflict maps

**E.3.2.3. Example: Layer showing limitations of drilling depth**

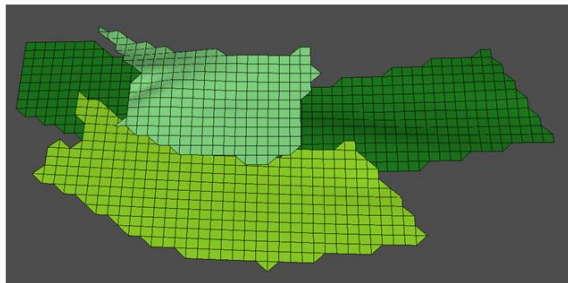
**General remarks**

Limitation of drilling depth is necessary for regions with swellable rocks and artesian groundwater and a set of hydraulically separated aquifers which must not be connected (e.g. a salt and a fresh water aquifer).

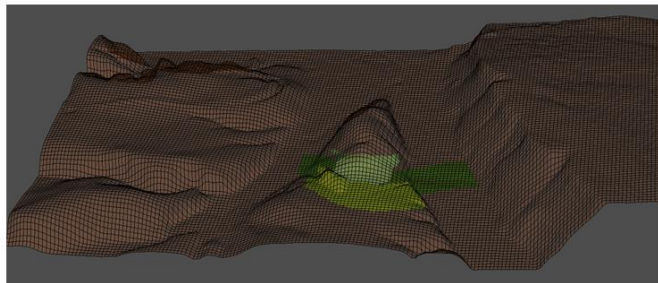
**Description of workflow steps**

The example comprises three 2D grids representing the absolute Z-values of the tops of units which must not be drilled. The geometry of these objects was produced in the 3D modelling software and then exported into ArcGIS. They can represent units consisting of swellable rocks or containing an artesian aquifer. In addition, the digital elevation model is given. A map representing the limitation of drilling depth has to display the relative depth below the ground surface of the shallowest layer with limitation and a “drilling allowed” value outside of the extent of these geologic units. If you want to stay on the safe side, you can add a safety margin. For including the conflict layer in the traffic-light map, you have to transform the data set into a vector model.

The data are given as raster data sets exported from the 3D modelling software (**Figure 28**).



2D grid showing the location of three tops of units which are not allowed to be drilled in the 3D modelling software.



Digital elevation model above the 3 layers.

**Figure 28: 3D view of the tops of three units where drilling is prohibited.**

The workflow for calculation of the limitation in drilling depth comprises the following steps:

**Importing a 2D grid into XYZ format**

In this example, the 2D grids specifying the geologic units were generated in SKUA-GOCAD™. The import may be slightly different from other software. However, it is important to set the coordinates, extent and resolution for all raster data sets to the properties of the master grid.

*Import: data → add data → add XY data → X-field: X → Y: field: Y → Z-field: Z*

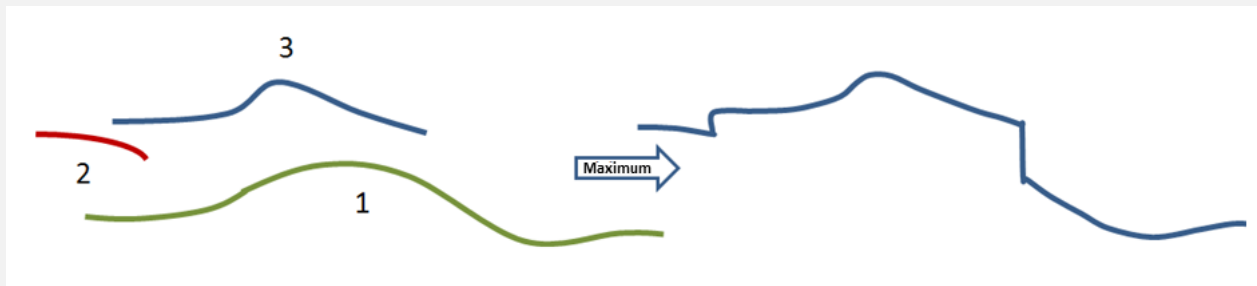
*Geoprocessing → environment → output coordinates → master grid → extent → master grid → resolution → type the resolution specified for the master grid → raster analysis → cell size → ok*

*ArcToolbox → Conversion Tools → in raster → point to raster → value field: Z → mean → cell size as specified in the master grid*

Calculate the minimum depth (maximum elevation) of all horizons with drilling limitations

This calculates the maximum elevation sub sea level of all units which need a limitation of drilling depth (**Figure 29**):

*ArcToolbox* → *spatial analyst tools* → *local* → *cell statistics* →  
*maximum* → *output: maximum\_absolute*



**Figure 29: Schematic visualization of the calculation of the maximum elevation of the 3 horizons.**

Calculate a raster with the allowed drilling depth (from surface) by subtracting the maximum elevation of the horizons with drilling limitation from the elevation of the ground surface.

*ArcToolbox* → *spatial analyst tools* → *Math* → *Minus* → *Raster 1: DEM* → *Raster 2: maximum\_absolute* → *output: drilling\_depth*

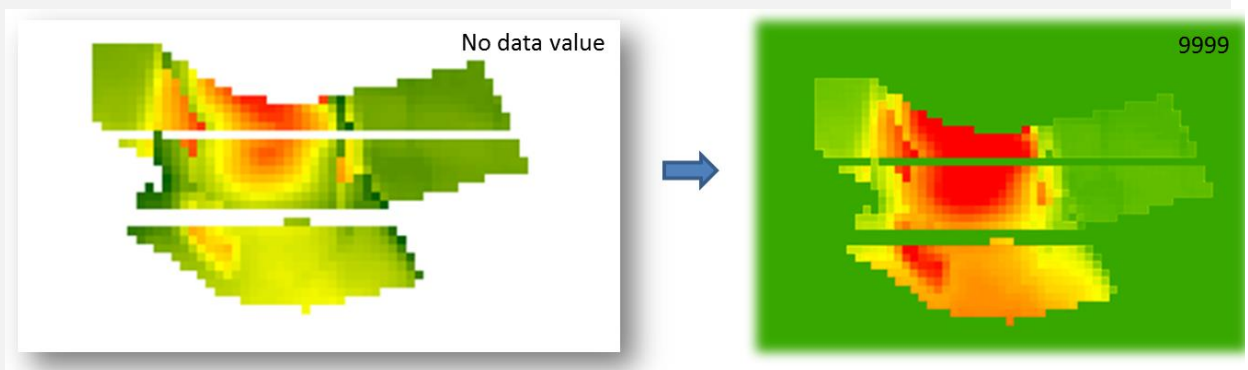
Optional: Add a safety margin (e.g. -10 m)

*ArcToolbox* → *spatial analyst tools* → *map algebra* → *raster calculator* →

`Con("drilling_depth" > 10, Con("drilling_depth" < 9000, "drilling_depth" - 10, "drilling_depth"), "drilling_depth")` → *output: drilling\_depth\_safe*

Set all values outside of the horizons from “no data” to 9999 to indicate that there is no limitation of drilling depth.

*Spatial Analyst Tools* → *Map Algebra* → *Raster Calculator* →  
`Con(IsNull("drilling_depth"),9999,"drilling_depth")`



**Figure 30: Limitations of drilling depth in an area (left). All locations outside of the critical units are specified by a no data value, although it is known that no limitation to the drilling depth is applicable in these locations. Therefore, the no data value is converted into a very large value, indicating that deep drilling is possible (right).**

Calculate contour lines

*ArcToolbox → Spatial Analyst tools → Surface → contour line → add contour interval and base*





## Vector-data workflow for the conflict maps

### E.3.2.4. Attributes of the conflict layers

#### General remarks

Attribute data is that part of geodata which contains thematic information about a spatial object, such as a property or category. Attribute data provides characteristics about spatial data. Attribute data is usually appended in tabular format to spatial features.

#### Description of workflow steps

In most cases, this step has already been completed when you load a data set. Check whether attribution is available for all data sets! If not, follow the workflow.

##### Create a new attribute by adding a field to the attribute table

*Right-click on the conflict layer in the TOC → open attribute table → table options → add new field*

##### Binary property

*Right-click into the header of the new field column → field calculator → type the name/value of the attribute*

##### Categorial and sequential property

Case 1: An attribute exists which can be used for grouping of the categories:

*Main menu bar → selection → by attribute → select the attribute and the value you need from the conflict layer*



*Be aware of the “select from selection” and “add to current selection” options!*

*Right-click on the conflict layer in the TOC → open attribute table → table options → add new field*

*Right-click into the header of the new field column → field calculator → type the name/value of the attribute (this assigns only to the selected features!)*

Case 2: Select by hand in the editor mode

If no attributes are assigned, you have to assign the attributes by hand for each object:

*Right-click the feature class in the TOC → start editing → open the attribute table  → select the feature you want to attribute  → write the attribute into the new field of the attribute table*

**Classify your conflict layers as specified in table 12!**



Water protection zone	Categorical Protection zone	0 -9999 Category	No protection zone No data available Individual classification for each pilot area	255 255 255 200 200 200	
Natural reserve	Binary presence	0 -9999 1	No reserve No data available Natural reserve	255 255 255 200 200 200 000 255 000	
Limitation of drilling depth	Continuous depth	0 -9999 1 2 3 4 5 6 7 8 9 10	No limitation No data available 20 m 40 m 60 m 80 m 100 m 120 m 140 m 160 m 180 m >200 m	255 255 255 200 200 200 227 030 036 247 123 107 247 155 115 254 208 154 252 199 093 254 204 000 250 236 084 255 243 131 255 251 219 221 228 137	
Confined and artesian groundwater	Binary presence	0 -9999 1	No confined/ artesian groundwater No data available Confined/artesian aquifer	255 255 255 200 200 200 114 178 252	
Tectonics /faults	Binary presence	0 -9999 1	No fault No data available fault	255 255 255 200 200 200 025 025 025	
Cavities /mining sites	Binary presence	0 -9999 1	No cavity / mine No data available Cavity /mine	255 255 255 200 200 200 175 151 120	
Landslides	Binary presence	0 -9999 1	No Landslide No data available Landslide	255 255 255 200 200 200 158 090 002	
Shallow gas leakage	Categorical gas	0 -9999 1 2 3	No leakage No data available CO <sub>2</sub> Radon Methane	255 255 255 200 200 200 080 080 080 000 152 070 255 255 102	
Karst	Binary presence	0 -9999 1	No karst No data available	255 255 255 200 200 200 183 120 206	
Hydraulically separated aquifers	Binary presence	0 -9999 1	No separated aquifer No data available Hydraulically separated aquifers	255 255 255 200 200 200 025 044 168	
Existing geothermal utilization	Discrete Number per pixel	0 -9999 1 2 3 4 5 6 7	No utilization No data available 1-3 3-5 6-10 11-20 21-50 51-100 >100	255 255 255 200 200 200 250 221 182 250 193 118 204 118 118 250 128 128 215 053 053 250 000 000 245 112 030	
Electric lines - pipelines	Categorical	0 -9999 1 2 3 4 5	No protection zone No data available Electrical Water Gas Telephone Other	255 255 255 200 200 200	
Contaminated sites	Binary presence		No protection zone No data available Contaminated site	255 255 255 200 200 200 113 115 049	

**Table 12: Standardized classification of cell-related output attributes.**

Vector-data workflow for the conflict maps

**E.3.2.5. Combination of conflict and extent layer**

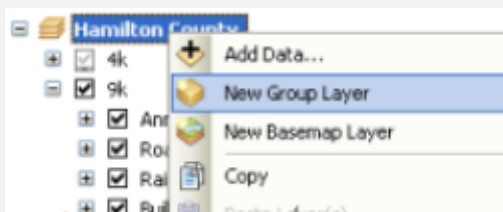
**Description of workflow steps**

Generate empty group layers and add data sets to the project

*Right-click on layer in the TOC and select new group layer*

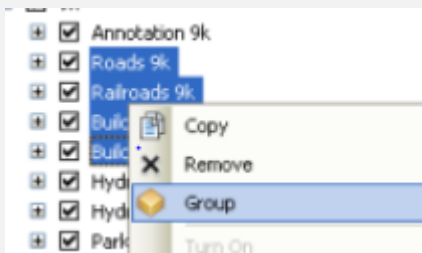
*Repeat for each conflict factor → click into the name “new group layer” and type the name of each conflict factor*

*Add data by right-clicking the name of the group layer → add data*



**Organize existing layers to a group layer**

*Select the layers you want to group by clicking on them while holding the Ctrl-Key → right-click → group*



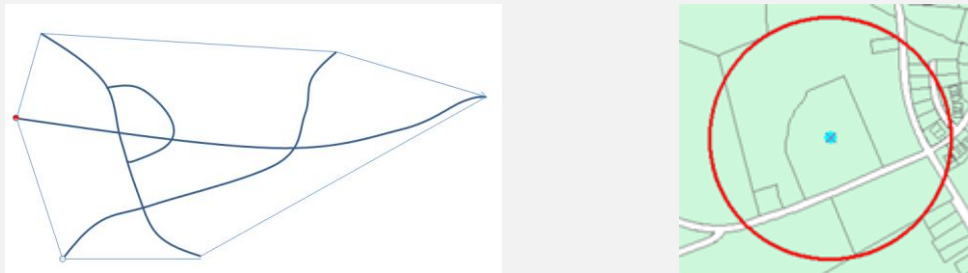
## Vector-data workflow for the traffic light maps

### E.3.3. Traffic light maps (vector data workflow)

#### E.3.3.1. Conversion of point and line features to polygon features

##### General remarks

For calculating a traffic light map, all point and line features have to be converted into polygon features (**Figure 31**). This can be done by constructing the convex hull around all features, which might be reasonable for a mine with many mining galleries, because unknown galleries might exist. Or it can be done by calculating a buffer, which provides a safety distance for each feature present in the conflict layers. This might be reasonable e.g. for wells, such that you construct a safety distance around each well rather than specifying an outline around the full area where wells exist.



**Figure 31: Conversion of points and lines to polygons can be realized either by generating the convex hull or by creating a buffer.**

##### Description of workflow steps

The project's agent has to make a decision about the size of the buffers surrounding point or line data. If you e.g. generate a buffer around a drinking water well where geothermal use is forbidden, you have to respect regulations as well as the groundwater flux. If you generate a buffer around abandoned mines, you should take into consideration knowledge of the inaccuracy of the old mine maps.

##### Convex hull

*ArcToolbox → data management tools → features → minimum bounding geometry → convex\_hull*

##### Create a buffer around a point or line

If the data set contains points or lines of different categories, and different buffer sizes are required for each category, this can be accomplished by assigning the buffer size to each object in the attribute table prior to buffering.

*Open attribute table → add new field → name field "buffer\_size" → perform query selection for each category → right-click into the field header and chose the field calculator → assign the desired buffer size to the selected objects.*

Repeat the query and the assignment of buffer size for each type of object until all objects have a buffer size assigned to them.



*ArcToolbox → Analysis tools → proximity → buffer → input feature class → set distance to “field” and chose the field buffer\_size → select the side type (whether the buffer is generated on the left, right or both sides) → select the end type*

If there is only one type of object, or all objects will have the same buffer size, the buffers can be created directly, without adding a new field to the attribute table:

*ArcToolbox → Analysis tools → proximity → buffer → input feature class → specify the buffer diameter in linear units (m) → → select the side type (whether the buffer is generated on the left, right or both sides) → select the end type*



## Vector-data workflow for the traffic light maps

### E.3.3.2. Classification of the conflict layers according to the categories of the traffic light map

#### General remarks

All features need an attribute which specifies their class/category in the traffic light map. This step requires the interpretation of the project's agent. All attributes available in the conflict layers have to be converted into the categories of the traffic light map depending on the impact of a conflict factor and the governmental regulations valid in each pilot area.

The categories, into which all properties have to be transformed, are:

#### 1... shallow geothermal installations are generally possible

No conflicts and risks known.

#### 2... attention: More information required

At least one conflict is present. Shallow geothermal use is allowed with special obligations such as limitations of drilling depth, special drilling equipment or grouting material. Or: Information is missing, it is not possible to decide whether shallow geothermal installations are generally allowed or prohibited.

#### 3... shallow geothermal installations are generally prohibited

At least one conflict is present that forbids shallow geothermal installations.

#### Description of workflow steps

##### Create a new attribute by adding a field to the attribute table

*Right-click on the conflict layer in the TOC → open attribute table → table options → add new field named traffic\_va as short integer*

##### Binary property

*TOC → open attribute table → table options → Select all*

*Right-click into the header of traffic\_va → field calculator → type the value of traffic\_va*

##### Categorial and sequential property

*Main menu bar → selection → by attribute → "attribute"=x*

*Be aware of the "select from selection" and "add to current selection" options!*

*Right-click on the conflict layer in the TOC → open attribute table → Right-click into the header of the field traffic\_va → field calculator → type the value of traffic\_va (this assigns only to the selected features!)*



### Discrete or continuous property

For this property, a reclassification is necessary prior to assigning the traffic light value.

Example: You have got a set of isohypse contours describing the depth of a swellable rock unit. You want to specify the following categories:

If the top of the swellable rock unit is buried less than 50 m, drilling is completely forbidden (traffic\_va = 3),

If the depth of the unit is greater than 50 meters, an individual case check is necessary (traffic\_va = 2).

If no swellable unit is present, no limitation is necessary (traffic\_va = 1). These locations were attributed with a drilling depth of 9999 in the conflict layer.

*Main menu bar → selection → by attribute → method: new selection → “drill\_depth”<=50*

*Attribute table → Right-click into the header of the traffic\_va → field calculator → type the value of traffic\_va: 3*

*Main menu bar → selection → by attribute → method: new selection → “drill\_depth”<=200 AND “drill\_depth”>50*

*Attribute table → Right-click into the header of the traffic\_va → field calculator → type the value of traffic\_va: 2*

*Main menu bar → selection → by attribute → method: new selection → “drill\_depth”>200*

*Attribute table → Right-click into the header of the traffic\_va → field calculator → type the value of traffic\_va: 1*



### E.3.3.3. Compilation of the traffic light map from the conflict and extent layers

#### Description of workflow steps

The compilation of the traffic-light map consists of two steps:

- Calculate the union of all polygons from all conflict layers with the same traffic-light value,
- Stepwise erase united polygons of a small category by polygons of the greater categories.

#### Calculate the union of all polygons with the same traffic-light value

##### Binary property

A layer with a binary property can be used for the calculation.

##### Categorical property

For a layer containing categories, select the traffic\_va you are working with. The union operation is performed only for the selected features. If necessary, generate new layers containing the polygons with one traffic\_va as separated sets.

*Main menu bar → selection → by attribute → method: new selection → [traffic\_va]=1*

*Right-click on the layer in the TOC → data → export data → selected features*

#### Calculate the union

*ArcToolbox → analysis tools → overlay → union → select all layers containing features with traffic\_va=1*

Repeat this for all three categories. Consider choosing “only FID” when selecting the attributes to be preserved during the union. This will reduce file size and processing time.

#### Stepwise erase the polygons

Note: An advanced license is required to utilize the “erase” tool.

*ArcToolbox → analysis tools → overlay → erase → input feature: union of all polygons with the traffic\_va 1 → erase feature: union of all polygons with the traffic\_va 2,3*

The output feature contains polygons with traffic light value 1 in only in those places where there is no traffic value 2 present. Use this output feature as input feature and repeat the step, using the union of all polygons with a traffic\_va of 3 as erase feature.

The output feature now contains polygons with traffic light value 1 only in those places where neither a value of 2 nor a value of 3 is present.





Similarly, create a feature containing polygons with traffic\_va = 2 only in those places where there is no traffic light value of 3 present:

*ArcToolbox → analysis tools → overlay → erase → input feature: union of all polygons with the traffic\_va 2 → erase feature: union of all polygons with the traffic\_va 3*

**Assign the RGB color codes for the classes:**

*Traffic light value: 1 205 245 122 green*

*2 255 255 190 yellow*

*3 255 061 084 red*



## E.3.4. Conflict maps (raster data workflow)

### E.3.4.1. Preparation of the data extent layer

#### General remarks

The extent layer is a map showing where the data describing one land-use risk or conflict factor are available or not. This information is very important. If it was not specified, this could generate the impression that no risk is present. However, we simply do not know whether a risk is present or not.

#### Description of workflow steps

The extent layer is binary with a property `no_data_cat`.

**Assign the `no_data_cat`:**

**9999 ...if data are available**

**-9999 ...if no data are available**

These numbers will be used for combining the extent layer with the conflict layer in order to compile a conflict map.

Preparation of the extent layer consists of two steps:

- Digitizing the polygons of no-data and data regions,
- Conversion to the raster data model.

**For digitizing the extent layer**

**See toolkit E.3.2.1.**

**Conversion to raster data model**

*Geoprocessing → environment → output coordinates → master grid → extent → master grid → resolution → type the resolution specified for the master grid → raster analysis → cell size → ok*

*ArcToolbox → Conversion tools → to raster → polygon to raster → value field: `no_data_cat`*



## Raster-data workflow for the conflict maps

### E.3.4.2. Transformation of vector data into raster data

#### General remarks

A data transformation converts a set of data from the data format of a source data system into the data format of a destination data system. It is needed if input data are available in different data structures.

#### Description of workflow steps

##### Predefine the settings of the master grid as extent and resolution for all rasters you produce

*Geoprocessing → environment → output coordinates → master grid → extent → master grid → resolution → type the resolution specified for the master grid → raster analysis → cell size → ok*

##### Binary property -points

*ArcToolbox → Conversion tools → to raster → point to raster*

*ArcToolbox → Spatial Analyst tools → Reclass → Reclassify → create two classes; assign value = 1 to the class with the points and NoData to the class of the background around the objects*

##### Binary property -lines

*ArcToolbox → Conversion tools → to raster → line to raster*

*ArcToolbox → Spatial Analyst tools → Reclass → Reclassify → create two classes; assign value = 1 to the class with the line and NoData to the class of the background around the objects*

##### Binary property -polygons

*ArcToolbox → Conversion tools → to raster → polygon to raster*

*ArcToolbox → Spatial Analyst tools → Reclass → Reclassify → create two classes; assign value = 1 to the class with the line and NoData to the class of the background around the objects*

**Be careful to select a cell size which does not exceed the resolution of the smallest polygon! Otherwise you will lose information.**



### Categorial or sequential property - points

*ArcToolbox → Conversion tools → to raster → point to raster*

*ArcToolbox → Spatial Analyst tools → Reclass → Reclassify → create new classes according to the categories you have → add the background as NoData class*

### Categorial or sequential property - lines

*ArcToolbox → Conversion tools → to raster → line to raster*

*ArcToolbox → Spatial Analyst tools → Reclass → Reclassify → create new classes according to the categories you have → add the background as NoData class*

### Categorial or sequential property - polygons

*ArcToolbox → Conversion tools → to raster → polygon to raster*

*ArcToolbox → Spatial Analyst tools → Reclass → Reclassify → create new classes according to the categories you have → add the background as NoData class*

### Discrete or continuous property - polygons

Conversion of continuous vector data like contour lines into a raster data set requires a step of data analysis, since various interpolation methods are available in ArcGIS, but not all methods are suitable for every data set. E. g. for interpolation of a variable with trend you have to use a different Kriging method than for variables without trend. ArcGIS provides various tools for data analysis which can be used prior to deciding which interpolation method is appropriate.

*Main menu → customize → extensions → select the geostatistical analyst*

*See the separate ArcGIS tutorial how to work with the geostatistical analyst*



## Raster-data workflow for the conflict maps

### E.3.4.3. Attributes of the conflict layers

#### General remarks

Attribute data is that part of geodata which contains thematic information for one spatial object, such as a property or category. Attribute data provides characteristics about spatial data. Attribute data is usually appended in tabular format to spatial features.

#### Description of workflow steps

For raster data only numerical values can be assigned. Again, you can have binary, categorial or sequential and continuous / discrete properties.

The properties can be assigned either by reclassification or by the raster calculator.

*ArcToolbox → spatial analyst tools → reclass → reclassify → classify → specify the number of classes you need*

*ArcToolbox → spatial analyst tools → map algebra → raster calculator → type a formula in order to assign a property, e.g. Con("miningsite"==1,"miningsite",0)*

**Classify your conflict layers as specified in table 12 in toolkit E.3.2.4!**

Raster-data workflow for the conflict maps

**E.3.4.4. Combination of conflict and extent layers**

**Description of workflow steps**

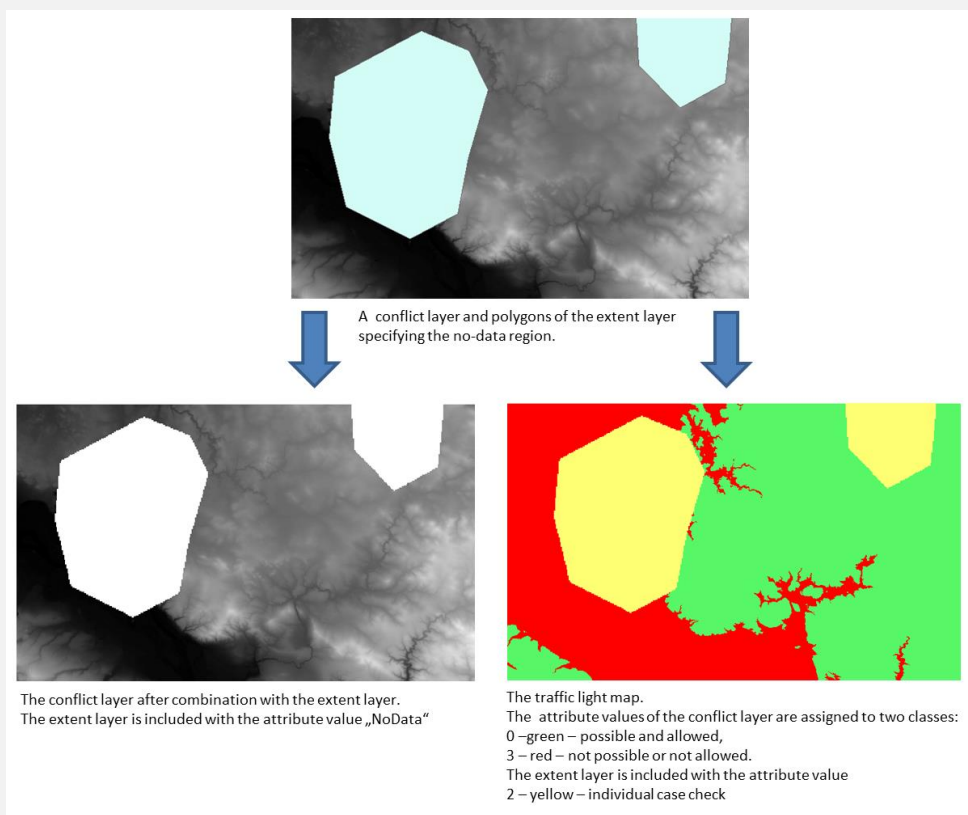
Combine the conflict and the extent layer (Figure 32).

*Geoprocessing → environment → output coordinates → master grid → extent → master grid → resolution → type the resolution specified for the master grid → raster analysis → cell size → ok*

*ArcToolbox → spatial analyst tools → map algebra → raster calculator → Con(“extent\_layer”, “conflict\_layer”, “extent\_layer”)*

With this operation, the conflict map receives

- the values of the conflict layer if the extent layer has the value 1 (i.e. is “true”),
- the no-data value if the extent layer has the value no data (i.e. is “false”).



**Figure 32: Possibilities for combining a conflict layer and a data-extent layer in the raster data format.**



## E.3.5. Traffic light maps (raster data workflow)

### E.3.5.1. Classification of the conflict layers according to the categories of the traffic light map

#### General remarks

All features need an attribute which specifies their class/category in the traffic-light map. This step requires the interpretation of the project's agent. All attributes available in the conflict layers have to be converted to the categories of the traffic-light map depending on the impact of a conflict factor and the governmental regulations valid in each pilot area.

The categories, to which all properties have to be transformed, are:

#### 1... shallow geothermal installations are generally possible

No conflicts and risks

#### 2... attention: more information required

At least one conflict is present. Shallow geothermal use is allowed with special obligations such as limitations of drilling depth, special drilling equipment or grouting material. Or: information is missing; it is not possible to decide whether shallow geothermal installations are generally allowed or prohibited.

#### 3... shallow geothermal installations are generally prohibited

At least one conflict is present that forbids shallow geothermal installations.

#### Description of workflow steps

Reclassify all properties such that the map consists only of the three categories available in the traffic-light map.

#### Binary and categorial properties

*ArcToolbox → spatial analyst tools → reclass → reclassify → go to the column "new value" and replace -9999 of the conflict layer by 2 for the traffic light map*

Replace all other categories by the values needed in the traffic-light map.

#### Continuous and discrete properties

Continuous and discrete properties have to be classified first.

*ArcToolbox → spatial analyst tools → reclass → reclassify → classify → specify maximum 3 classes*



## Raster-data workflow for the traffic light maps

### E.3.5.2. Compilation of the traffic light map

#### General remarks

After assigning the categories of the traffic-light maps to all conflict layers and extent layers, the polygons of all steps have to be combined by taking the maximum value present at each location. This means, if in any layer an attribute 3 (forbidden or not possible) appears, this is selected to represent the location in the traffic-light map. If at one location no layer has the value 3, the next biggest is assigned, e.g. if no data are available for any of the layers. The resulting traffic-light map always displays the maximum risk appearing in any of the layers.

#### Description of workflow steps

The maximum value of all layers for each pixels can be calculated if all layers have the same extent, resolution and cell number.

*Spatial analyst tools → local → cell statistics → maximum*

#### Assign the RGB color codes for the classes:

*Traffic light value: 1 205 245 122 green*  
*2 255 255 190 yellow*  
*3 255 061 084 red*





Output data

### E.3.6. Standardized output

#### Description of workflow steps

Ensure that the conflict, extent and traffic light layers are specified in the master grid coordinates, resolution and extent when a raster data model is calculated in the workflow for the first time. This is done by setting the environment resolution, coordinates and extent to the master grid in

*Geoprocessing → Environments!*

Use the harmonized classification specified in the workflow!



## F. Workflow for modelling the geothermal potential of closed loop systems

### F.1 The workflow - a brief description

Geothermal closed loop systems are in general tubulars of polyethylene inside of a borehole. The annulus is filled up with a mixture of bentonite and cement to give a good bond between the formation and the tubulars. The tubulars are closed and filled up with a mixture of water and antifreeze. A ground source heat pump inside a building circulates this mixture in the pipe loop. Heat from the ground is absorbed into the fluid, and then passes via heat exchanger into the heat pump.

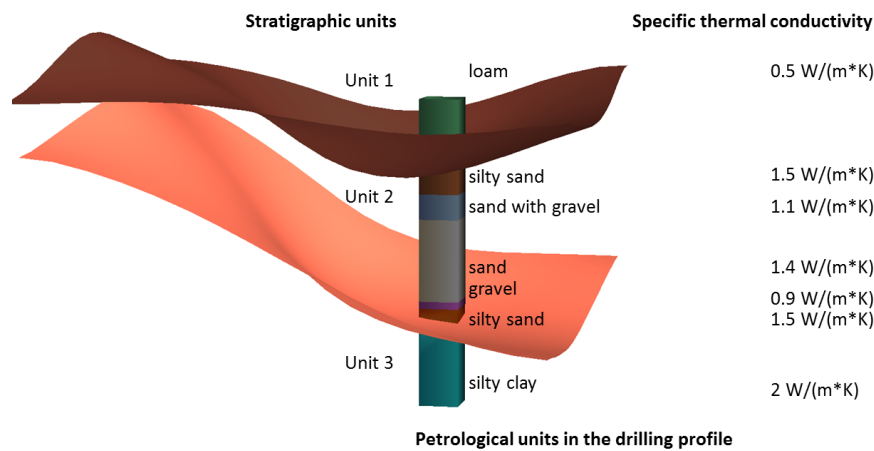
Geothermal mapping of closed loop systems has to consider the specific thermal conductivities of rocks, the availability of groundwater and secondarily the geothermal gradient. Geothermal potentials are represented by the parameters specific thermal conductivity, heat extraction capacity and/or temperature. Together with the thermal conductivity maps, the temperature data provides a base for professional planning of a specific geothermal plant. In contrast to that, the maps of heat extraction capacity in Watts per Meter give a good overview of geothermal potential for public users.

Since comparable maps for all pilot areas can only be obtained if the rock classification schemes, the scale and level of detail and the geological interpretation is the same among the project partners, the modelling steps are harmonized or standardized. In subsequent steps, the geothermal potential maps will be used for a web representation. The presented workflow provides the base for the production of a standardized output.

The workflow comprises steps of data preparation, the calculation of the thermal conductivity considering wet and dry properties of rocks, the calculation of the heat extraction capacity, the compilation of a temperature map and of the geothermal gradient in each pilot area.

The standardized output of the 3D modelling workflow describing the structure of the modelling domain will be used as input in this workflow. A set of geometry 2D grids representing the lithological top surfaces with a resolution of 12.5, 25, 50 m has to be loaded to the ArcGIS software. Additionally, a grid specifying the depth below surface of the groundwater table is required. The software automatically takes the value of the shallowest geological unit as ground surface, such that no digital elevation model has to be loaded.

During the data preparation step, the laboratory and literature data for specific thermal conductivities (wet/dry) collected in the thematic work package (TWP) have to be assigned to the drilling data. In each lithological unit, several petrographic subunits are recorded in the drilling profiles. These subunits describe the variability of the specific thermal conductivity within one stratigraphic unit represented in the model (**Figure 33**). In order to obtain the representative thermal conductivity for each unit, the thickness-weighted arithmetic mean is calculated for each unit as well as both the dry rock and wet rock properties, prior to loading the drilling data into ArcGIS.



**Figure 33: Connection of stratigraphic and petrographic information: A 3D model comprises three units (unit 1, unit 2, unit 3). Each unit has a variable petrography documented in the borehole profiles (unit 2 consists of silty sand, sand with gravel, sand, gravel, silty sand). For each petrography, physical parameters can be specified. A thickness averaged parameter will be assigned to the unit.**

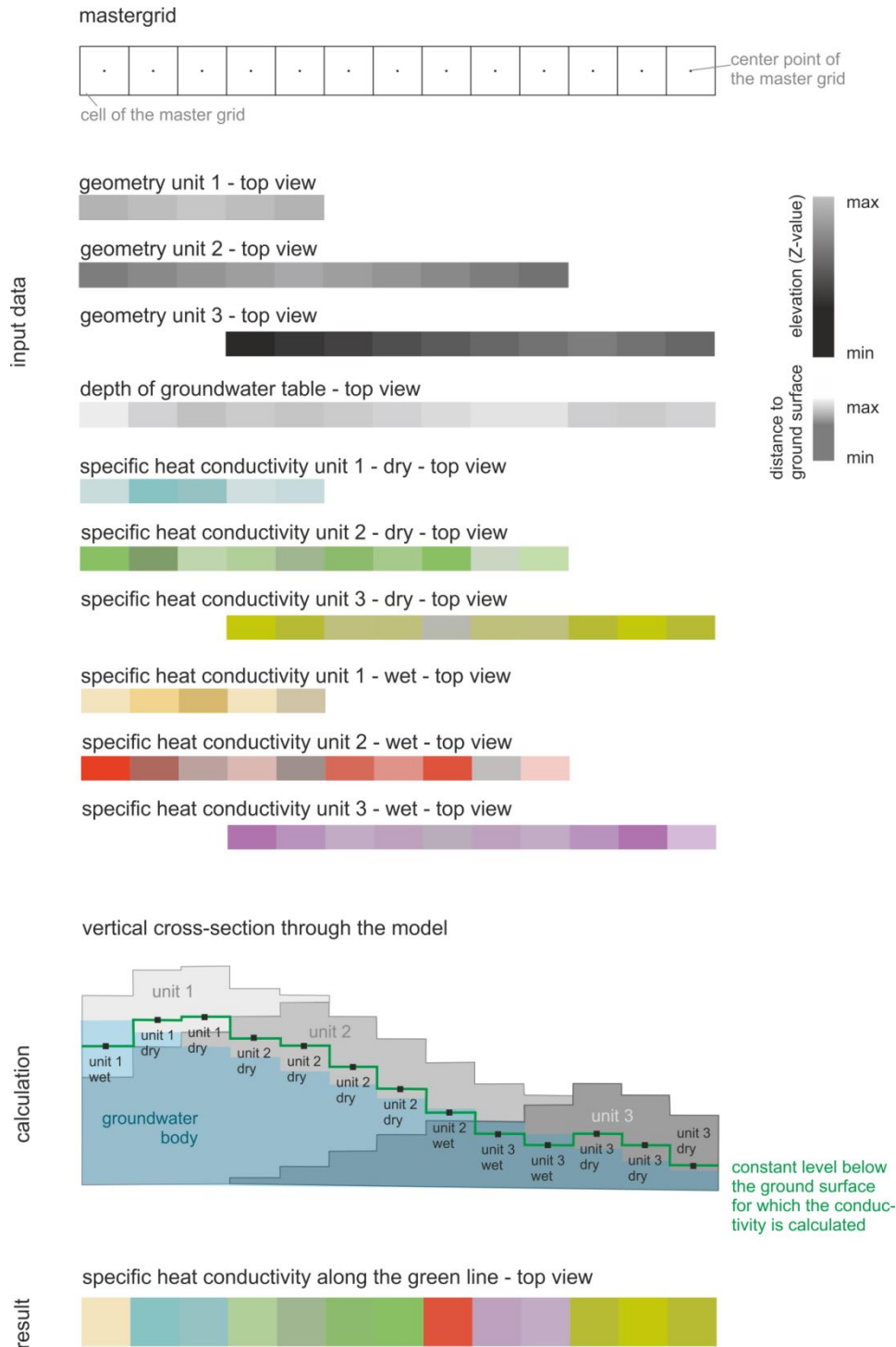
The spatial distribution of the representative thermal conductivity of each unit is interpolated in ArcGIS from the weighted mean values for wet and dry rocks with the Inverse-Distance Method. The results are two raster data sets (wet, dry) describing the thermal conductivity at the top of one unit with the same coordinates, resolution and extent as the raster describing the geometry of the unit. If the density of data points is too small to obtain feasible interpolation results, additional artificial nodes have to be added, a mean value assigned to these newly-added data points, and the interpolation has to be repeated.

The ArcGIS extension “IE Geothermie”, provided by PP04 (LfULG) can be used to calculate the average thermal conductivity for an interval from the ground surface to a given depth level. The ArcGIS extension provides the possibility to calculate the thermal conductivities in 10 m intervals. The calculation of 10 m intervals is necessary for the location query tool on the GeoPLASMA-CE web tool (for a map visualization of these parameters, a few representative levels may be selected, not all 10 m intervals have to be shown). The raster data set describing the geometry of the geologic units, the thermal conductivity for dry rocks, the thermal conductivity for saturated/wet rocks and the raster specifying the depth of the groundwater table below the ground surface are necessary as input data (Figure 34). The ArcGIS extension calculates the average thermal conductivity down to the depth level. For all units above the groundwater table, the dry thermal conductivity is used as input; for all points below the ground water table, the wet thermal conductivity is used.

The heat extraction capacity (HEC) in W/m can also be calculated with the ArcGIS extension using an empirical formula which was determined with simulation software for a standard single-family house with a specified annual heat production time. For the GeoPLASMA-CE project, an annual production time of 2,400 h will be used. **The formula is valid for a double U probe!** It is calculated by applying the formula:

$$HEC = -0.85 \cdot \lambda^2 + 12.39 \cdot \lambda + 26.26 \quad (1)$$

where HEC is the heat extraction capacity in W/m and  $\lambda$  is the thermal conductivity in W/(m·K).



**Figure 34: Schematic illustration of the steps required for calculating the average thermal conductivity for a depth interval below surface. The data are discretized with the cell resolution and location of the master grid of one pilot area. The input data consist of a set of raster data representing the absolute depth at top of the geological units in m sub sea level. Additionally, the distance of the groundwater table to the ground surface is required. The representative thermal conductivities have been calculated for wet and dry material from specific thermal conductivities provided in a harmonized parameter table. They are specified for each geological unit. The average thermal conductivity will be determined for the interval between the ground surface and a constant depth below the ground surface (green line). As the vertical cross-section illustrates, the line transects all three geological units and is in some instances located above, in others below the groundwater table. The respective thermal conductivity is assigned to each grid cell.**



The formula was developed basing on single-case calculations of specific heat extraction capacities with the EED software. Groundwater flow is neglected. The formula is valid for the following parameters of the subsurface and the geothermal plant:

Subsurface Temperature:	8,75 °C
Heat flux:	0,07 W/m <sup>2</sup>
Specific heat capacity:	2,0 MJ (m <sup>3</sup> * K) <sup>-1</sup>
Array:	2 heat exchangers
Distance between wellbores:	6 m
Wellbore diameter:	152 mm
Flow rate per heat exchanger:	0,001 m <sup>3</sup> /s
Borehole heat exchanger type:	Double U-tubes, PE DN 32 PN 10
Center-to-center distance:	0,07 m
Thermal conductivity of grout:	0,7 W (m * K) <sup>-1</sup>
Thermo-vector fluid:	Monoethylene glycol (MEG)
Simulation period:	20 years
Heat exchanger output:	11,8 kW 28,32 MWh/a at 2400 h
Seasonal performance factor:	3,5
Min. fluid temperature:	- 5 °C
Max. fluid temperature:	15 °C
Basis load:	includes some hot water generation

The specific heat extraction capacities presented in the heat extraction maps are only valid for these boundary conditions. If some of the parameters vary, the true specific heat extraction capacity of a geothermal plant will change.

In order to provide an overview map for the geothermal potential of closed loop systems independent on the technical parameters of the plant and on legal regulations, a categorial map of rock properties is provided. This map might be an addition or an alternative to the heat extraction maps. It is produced by reclassification of the average thermal conductivity in 200 m depth by reclassifying it to four categories.

The mean annual temperature can be represented as ground surface temperature or as air surface temperature. Temperature data are provided by the meteorological surveys. Air surface temperatures have to be corrected in order to obtain ground surface temperatures. If temperature maps for a pilot area are available, these should be used. If only point data is available, this can be used for interpolation by geostatistical methods which respect trends and anisotropies in the spatial distribution of the temperature.

The geothermal gradient is generally a difference in temperature in a given distance. Hence a 3D environment, the geothermal gradient is usually referenced to a difference in temperature between two



points defined by their vertical distance, i.e. depth or thickness of the layer as far as temperature is known at a top and base of the horizon.

The geothermal gradient can be directly calculated from temperature logging in boreholes and by calculating the change of temperature over measured length by:

$$g_{th} = \frac{\delta T}{\delta z} = \frac{T_{bot} - T_{top}}{z_{bot} - z_{top}} \quad (2)$$

where:  $g_{th}$  - geothermal gradient,  $T$ - temperature ( $^{\circ}\text{C}$ , K),  $z$ - depth (m), indexes *bot* and *top* indicate bottom (base) and top of the respective borehole section.

Due to daily and seasonal temperature variations at the ground surface, the upper 10 m of the soil and rock (depending on thermal diffusivity it can be more) is affected by diurnal and annual temperature waves. To calculate a geothermal gradient in this shallow zone, it must be compensated for variations in surface temperatures, which requires detailed physical data on rocks and a complicated procedure. Beneath this seasonal zone, a neutral zone follows down to a depth of 30-50 m, which is characterized by an almost constant temperature, before the temperature is increasing downward due to the geothermal heat flow. A justifiable approach is to discard the topmost temperature measurements from the seasonal and neutral zones and to start with a value from the shallowest unaffected measurement specifying  $T_{top}$ . The geothermal gradient will be represented by the unit K/100m.

A discussion among the GeoPLASMA-CE partners showed that too few temperature logs are available in the pilot areas in order to interpolate the geothermal gradients from the boreholes directly. Instead, the model will be applied by using the geological information from the 3D model and the thermal conductivity maps and calculating the geothermal gradients via the heat equation. If the heat production is neglected, the geothermal gradient can be calculated directly from the geothermal conductivity maps produced in this workflow by the formula:

$$g_{th} = - \frac{q_z}{\lambda} \quad (3)$$

where:  $g_{th}$  - geothermal gradient,  $q_z$  is the vertical component of the heat flux in  $\text{W}/\text{m}^2$  and  $\lambda$  is the thermal conductivity in  $\text{W}/(\text{m}\cdot\text{K})$ . The negative sign indicates that the heat flows from regions with higher to regions with lower temperature or, in geological scenarios, from the centre of the earth outward. The temperature log data is used for specifying the boundary condition; this is the heat flux; by multiplying the geothermal gradient in the borehole by the average heat conductivity. The heat flux then is interpolated between the boreholes by the Inverse Distance Method. In a final step, the geothermal gradient is calculated by dividing the heat flow raster by the conductivity raster.

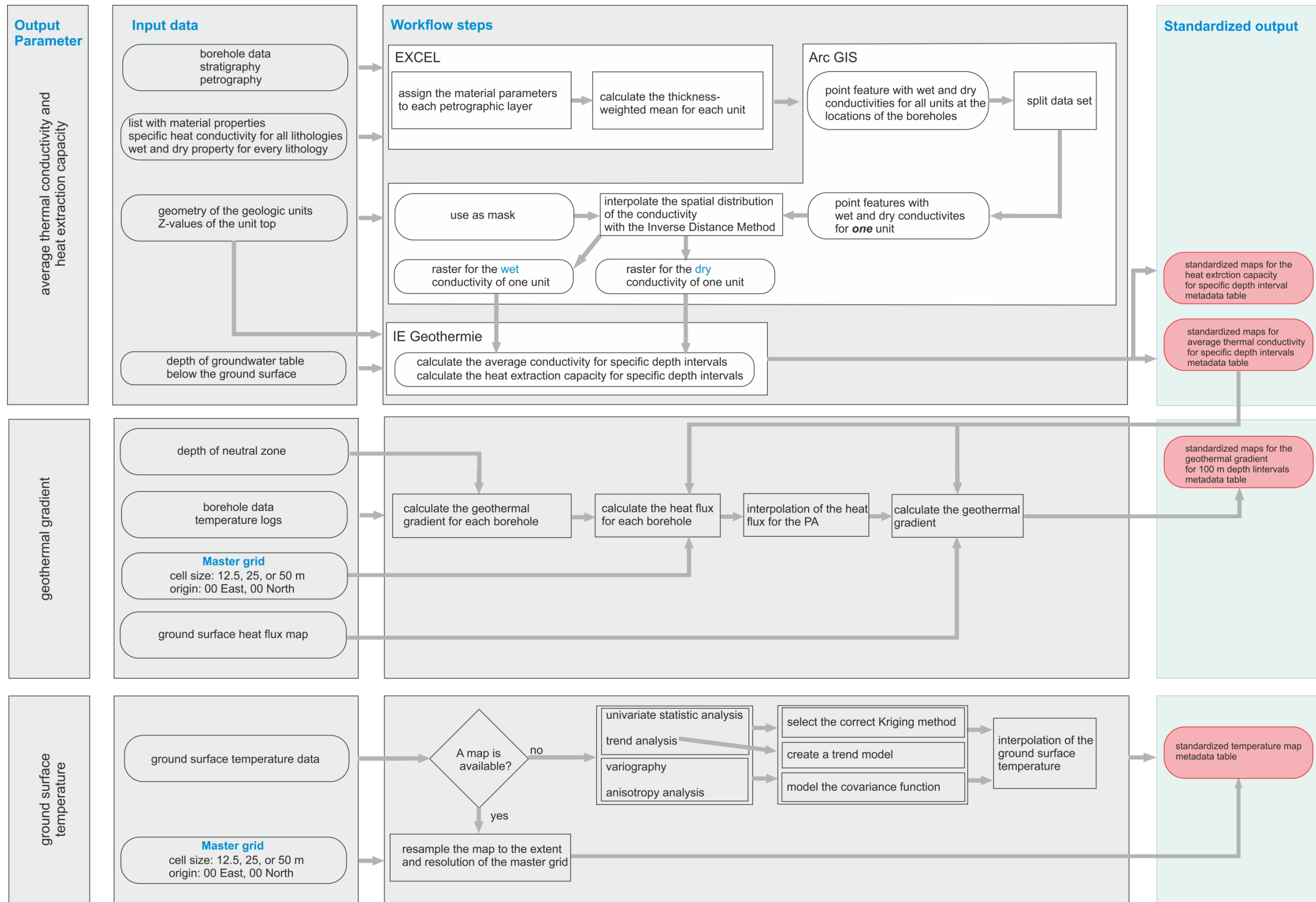


Figure 35: GeoPLASMA-CE workflow for mapping the geothermal potential for closed loop systems.

The workflow is written for ArcGIS. Version 10.2.2 for Desktop (basic license) was used to compile the workflow. In addition to the basic ArcGIS license, the following are required:

- Spatial Analyst
- Geostatistical Analyst
- IE Geothermie

The following points give an overview of the workflow steps (compare with **Figure 35**):

## 1. Documentation of the project

## 2. Thermal conductivity and heat extraction capacity

### Input data

Geometry data for geologic units

Depth of the groundwater table below the ground surface

Borehole data - model units, petrography

List with rock parameters of the specific thermal conductivity for wet and dry rocks with petrographic description

### Processing of the input data

Assign the rock parameters to each petrographic layer of the boreholes

Calculate the thickness weighted mean of the material parameters for each model unit at the boreholes

Load the borehole data to ArcGIS

Split the data set into one separate point feature per model unit

### Quality check the input data

Are all borehole data and the geometry data for this unit coincident?

Are the rock parameters feasible?

### Interpolation of the material parameters for the whole geologic unit

Interpolate one raster data set per unit for the wet specific thermal conductivities with the Inverse Distance Method

Interpolate one raster data set per unit for the dry specific thermal conductivities with the Inverse Distance Method

Use the geometry data from the model unit as mask and snap raster





### Quality check of the interpolation result

- Check whether the interpolation was extended to the whole model unit
- If necessary, digitize additional artificial data points
- Assign the mean rock properties (conductivity dry/wet) to the artificial data points
- Repeat the interpolation

### Calculations

- Calculate the thermal conductivity for various depth levels respecting the location of the groundwater table
- Reclassify the map of the thermal conductivity for the depth level of 200 m as categorial map representing geothermal rock properties
- Calculate the heat extraction capacity for 2,400 h/a

### Standardized output

- One standardized raster data set for each map with the attributes as specified in the deliverable D.T2.3.1
- One attribute table for each group of maps with the relevant depth level for each map
- One metadata table for each group of maps

## 3. Mean annual ground surface temperature

### Input data

- Geometry data for geologic units
- Depth of the groundwater table below the ground surface

### Research for temperature maps from the meteorological surveys

- If you find processed temperature maps, use these
- Get a permit to publish the map on the web!
- Production of the standardized output in raster format

### Interpolation of the ground surface temperature

- Perform a statistical data analysis
- Perform a trend analysis
- Perform a spatial data analysis
- Decide which Kriging method is appropriate for the data set
- Specify a trend model
- Specify an anisotropic variogram model
- Interpolate one raster data set with the Kriging method
- Standardized output in raster format



## 4. Geothermal gradient

### From temperature data

#### Input data

- Borehole temperature logs
- Thermal conductivity maps
- Eventually: heat flux map

#### Processing of the input data

Calculate geothermal gradients in each borehole

If detailed measurements of the specific thermal conductivity density along the borehole exist, calculate geothermal gradient discarding the calculated gradients for the seasonal and neutral zones. Create new related borehole attribute table with the calculated geothermal for each borehole.

Load the borehole data to ArcGIS

Read the average heat conductivity for each borehole

Calculate the heat flux for each borehole

#### Quality check the input data

Are the gradients feasible?

#### Interpolation

Interpolate one raster data set with the heat flux by using the Inverse Distance Weighted Method

Generate a raster data set with the geothermal gradient

Standardized output in raster format



## F.2 Harmonized rules and specifications - checklist

Spatial reference system	ETRS1989-TM 33 / ETRS1989-TM 34 meters → See D.T2.3.1 for specification
Elevation reference system	EVRF2007 → See D.T2.3.1 for specification
Geometry data	Standardized output of the 3D model
Material parameter specific thermal conductivity wet/dry	Use the parameter list of GeoPLASMA-CE produced in TWP 3
Transfer the raster data to the master grid	Grid resolution: 12.5, 25 or 50 m Borders of the grid cells at (00,00) coordinates
Export data format of all raster data	.adf -ESRI grid
Completed attribute table	One attribute table for each group of maps specifying the depth level of each map
Completed metadata table	Metadata table for each group of maps
Project documentation	Table for the documentation of the project progress → See D.T2.3.1 for specification

## F.3 Tool kit for mapping the geothermal potential of closed loop systems

Thermal conductivity and heat extraction capacity - input data

### F.3.1. Thermal conductivity and heat extraction capacity

#### F.3.1.1. Input data - geometry data for the geological units

##### General remarks

The geological units are described by their tops.

For each geological unit, a raster data set is needed which has to coincide with the master grid by the cell location and resolution as well as the extent of the raster. Raster cells outside of a geologic unit are specified by the no-data value (-9999).

##### Description of workflow steps

This data corresponds to the standardized output of the 3D modelling workflow (chapter D).

The data have to be loaded to the ArcGIS software (**Figure 36**).

You can import the data directly as a raster data if the 3D modelling software provides a corresponding export function.

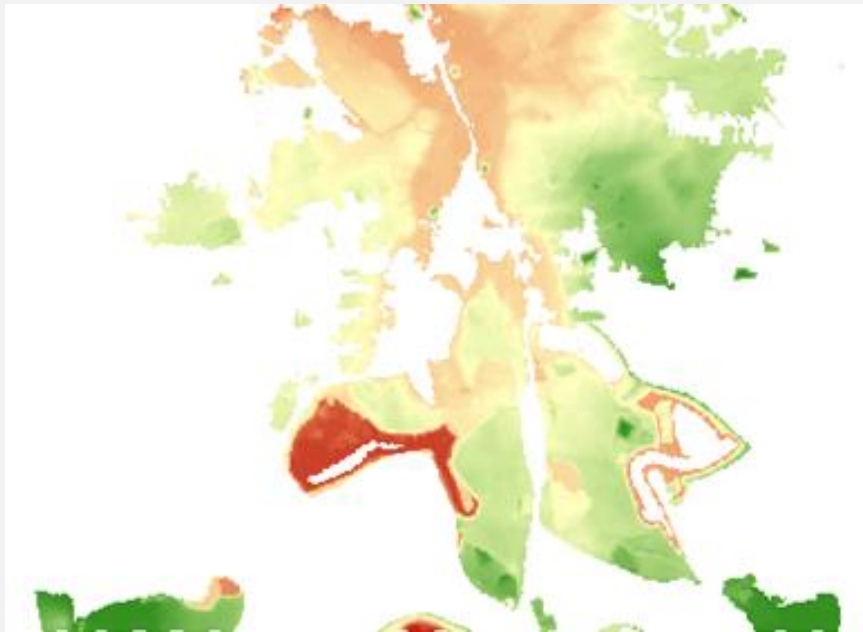
*Main Menu → data → add data*

If no appropriate export function is available in the 3D modelling software, the data can be exported as XYZ file. You can load them as point feature and then convert them into a raster data set.

*Main Menu → data → add data → add XY data → specify the Z-value*

*Main Menu → Geoprocessing → environment → output coordinates → master grid → extent → master grid → resolution → type the resolution specified for the master grid → raster analysis → cell size → ok*

*ArcToolbox → Conversion Tools → in raster → point to raster → value field: Z → mean or nearest → cell size as in the master grid*



**Figure 36: Example for a raster specifying the extent and the depth of the top of a geological unit.**



Thermal conductivity and heat extraction capacity - input data

### F.3.1.2. Input data - groundwater depth below ground surface

#### General remarks

This data set has to be provided as a raster data set coinciding with the master grid by the cell location and resolution as well as the extent of the raster.

If the ground water table was calculated, the ground water depth can be determined as its difference from the ground surface.

#### Description of workflow steps

For the calculation of the groundwater depth, two raster data sets have to be loaded to ArcGIS, the DEM and the ground water table. Both raster data sets have to coincide with the master grid by the cell location and resolution and the extent of the raster.

*ArcToolbox → spatial analyst tools → Math → Minus → Raster 1: DEM → Raster 2: groundwater\_table → output: groundwater\_depth*



Thermal conductivity and heat extraction capacity - input data

### F.3.1.3. Input data - borehole data

#### General remarks

One table for all wells is needed which specifies the thickness of all petrological layers and assigns them to a model body (unit ID) (**Figure 33**).

#### Description of workflow steps

**Table 13** shows the header of a table with borehole data which is needed for the workflow.

**Table 13: Header of a file with borehole data needed for the workflow.**

Borehole ID	Easting	Northing	Thickness	Unit ID	Pet key
-------------	---------	----------	-----------	---------	---------



Thermal conductivity and heat extraction capacity - input data

#### F.3.1.4. Input data - material parameter list

##### General remarks

The specific thermal conductivity is a material property describing how well a material conducts heat. Its unit is  $W/(m \cdot K)$ .

##### Description of workflow steps

The parameter of the specific thermal conductivity has to be either determined by measurements or estimated from literature values. One [list with parameters](#) comprising the thermal conductivity for all rocks (wet and dry) will be worked out in TWP 3. This list can be used by all partners.





Thermal conductivity and heat extraction capacity - processing of input data

### F.3.1.5. Assign the specific thermal conductivity to each petrological layer at boreholes

#### General remarks

The specific thermal conductivity depends on the mineralogical composition, the grain size and the water content of a rock. In each lithological unit, several petrographic layers are recorded in the drilling profiles. These subunits describe the variability of the specific thermal conductivity within one stratigraphic unit represented in the model.

#### Description of workflow steps

The parameter of the specific thermal conductivity has to be assigned for both water saturated and dry rocks since the specific thermal conductivity of porous sedimentary rocks strongly depends on the water contents. If a rock is dense, like granite, the specific thermal conductivity of wet and dry rocks is the same. However, the calculation algorithm requires also specifying the wet and dry specific thermal conductivity for these rocks (**Table 14**).

**Table 14: Header of a file with borehole data after assignment of the specific thermal conductivities.**

Borehole ID	Easting	Northing	Thickness	Unit ID	Pet key	thermal conductivity dry	thermal conductivity wet
-------------	---------	----------	-----------	---------	---------	--------------------------	--------------------------

Extend the table with the drilling data by two fields and assign the specific thermal conductivity for wet and dry rocks to each PET key number.

**A macro-script** will be prepared for the partners to do this automatically.



Thermal conductivity and heat extraction capacity - processing of input data

### F.3.1.6. Calculate the thickness-weighted mean for each geologic unit at boreholes

#### General remarks

The thickness-weighted mean describes the average thermal conductivity along a borehole profile for a geologic unit composed of various petrological layers. Each petrological layer is weighted by its vertical thickness in the drilling profile. A thickness-weighted mean is calculated as representative value for the thermal conductivity for each geologic unit and for each borehole.

#### Description of workflow steps

The thickness-weighted mean is calculated by the following two formulas:

$$\lambda_{layer}^{weighted} = \frac{thickness\ layer}{thickness\ unit} \cdot \lambda_{layer} \quad (4)$$

$$\lambda_{unit} = \sum_{layer} \lambda_{layer}^{weighted} \quad (5)$$

$\lambda$  is the specific thermal conductivity.

A script (Excel-macro) will be prepared for the partners to do this automatically.

A new table will be produced which contains only one entry per geological unit (**Table 15**).

**Table 15: File header after calculating the weighted mean of the thermal conductivity for each unit. In this table, each unit is represented by one row, a petrographic differentiation is not specified anymore.**

Borehole ID	Easting	Northing	Thickness	Unit ID	Weighted thermal conductivity dry	Weighted thermal conductivity wet
-------------	---------	----------	-----------	---------	-----------------------------------	-----------------------------------



Specific thermal conductivity and heat extraction capacity - processing of input data

### F.3.1.7. Split the data set in point features for each geologic unit

#### General remarks

A point feature comprising the representative weighted means of the specific thermal conductivities in all boreholes is needed for each geologic unit. It can be selected from the full data set.

#### Description of workflow steps

Load the table to ArcGIS:

*Main Menu → data → add data → add XY data → specify X field: Easting; Y field: Northing*

The data set consists of many points with the same XY coordinates for a vertical borehole. Split the data set by selecting all geologic units:

*Main Menu → selection → by attributes → drilling data → create new selection → borehole data → "unit"=00108040202*

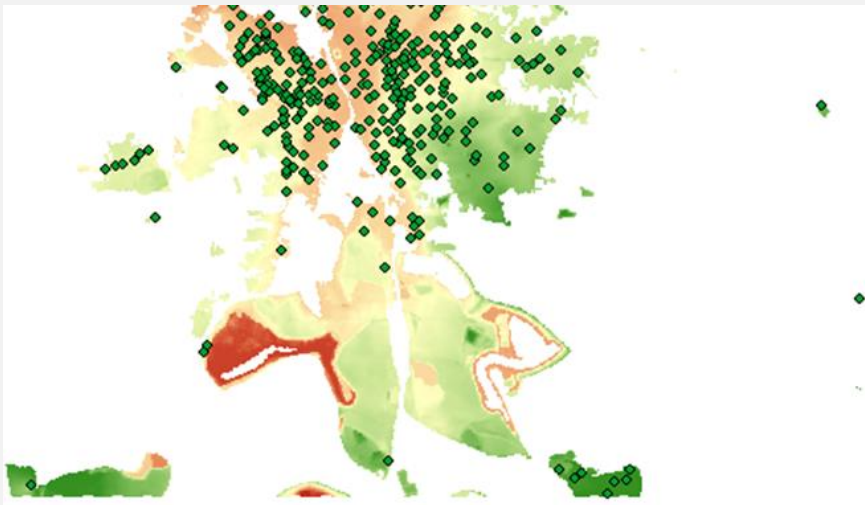
*TOC borehole data → right-click → data → export → selected features*

Thermal conductivity and heat extraction capacity - quality check of input data

### F.3.1.8. Quality check of the location of the drilling data and of the material parameters

#### Description of workflow steps

Check whether all input data of a unit are located inside of the geometry raster of that unit (**Figure 37**).




**Figure 37: Raster with the extent and depth of a geological unit and the borehole data referring to this unit, loaded as point shape in ArcGIS.**

*ArcToolbox → Conversion tools → from raster → raster to polygon → select the value\_field*

Select all points of the point feature:

*Right-click on the conflict layer in the TOC → open attribute table → table options → select all*

Or *Take the selection tool  and draw a square with the mouse including all points of the shape*

*Main Menu → selection → by location → remove from selection → is completely inside → unit polygon feature*

This shows all points outside of the polygons. You can save them by

*TOC borehole data → right-click → data → export → selected features*

Check the data and correct the errors.

#### Check the material parameters

Open the attribute table and check whether fields for the wet and dry thermal conductivity are present. Check whether the values are reasonable.

*Right-click on the conflict layer in the TOC → open attribute table → right-click into the header of the thermal conductivity fields → statistics*

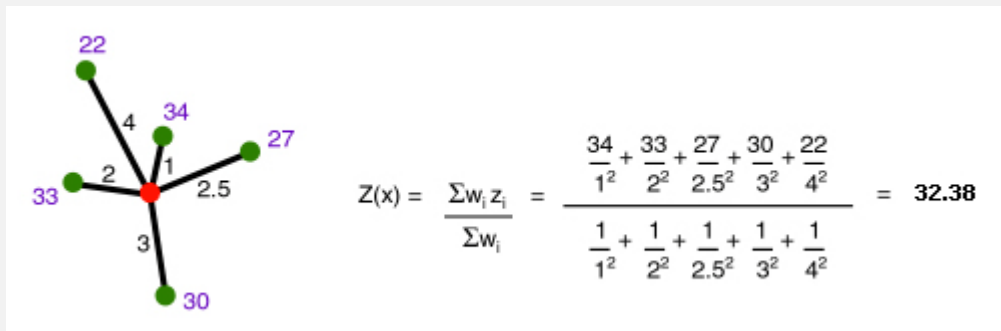
Thermal conductivity and heat extraction capacity - interpolation

### F.3.1.9. Interpolate wet and dry thermal conductivity with the Inverse Distance Method

#### General remarks

The data for wet and dry specific thermal conductivity will be interpolated in order to estimate these parameters at locations where no data are available. The results of this work step are two raster data sets per geologic unit, one raster describing the thermal conductivity for wet rocks and one for dry rocks.

Inverse Distance Weighting (IDW) is a type of deterministic method for the interpolation with a known scattered set of points. The estimated values at unknown points are calculated with the weighted average of the values available at the known points (Figure 38). The weight a particular point is assigned in the calculation depends upon the sampled point's distance to the non-sampled location. The method can be applied for spatially dependent variables which similarity decreases with increasing distance. Anisotropies and trends cannot be respected by the mathematical model. When the exponent  $p = 2$ , the method is called inverse distance squared weighted interpolation. A maximum number of points included in the calculation can be specified. It is 12 per default.



**Figure 38: Illustration of the inverse distance method. The value for one location without data is estimated by the neighbouring data points which are weighted by their distance. If the exponent  $p=2$ , the distance is squared.**

You have to interpolate the wet and the dry material properties for each geologic unit.

#### Description of workflow steps

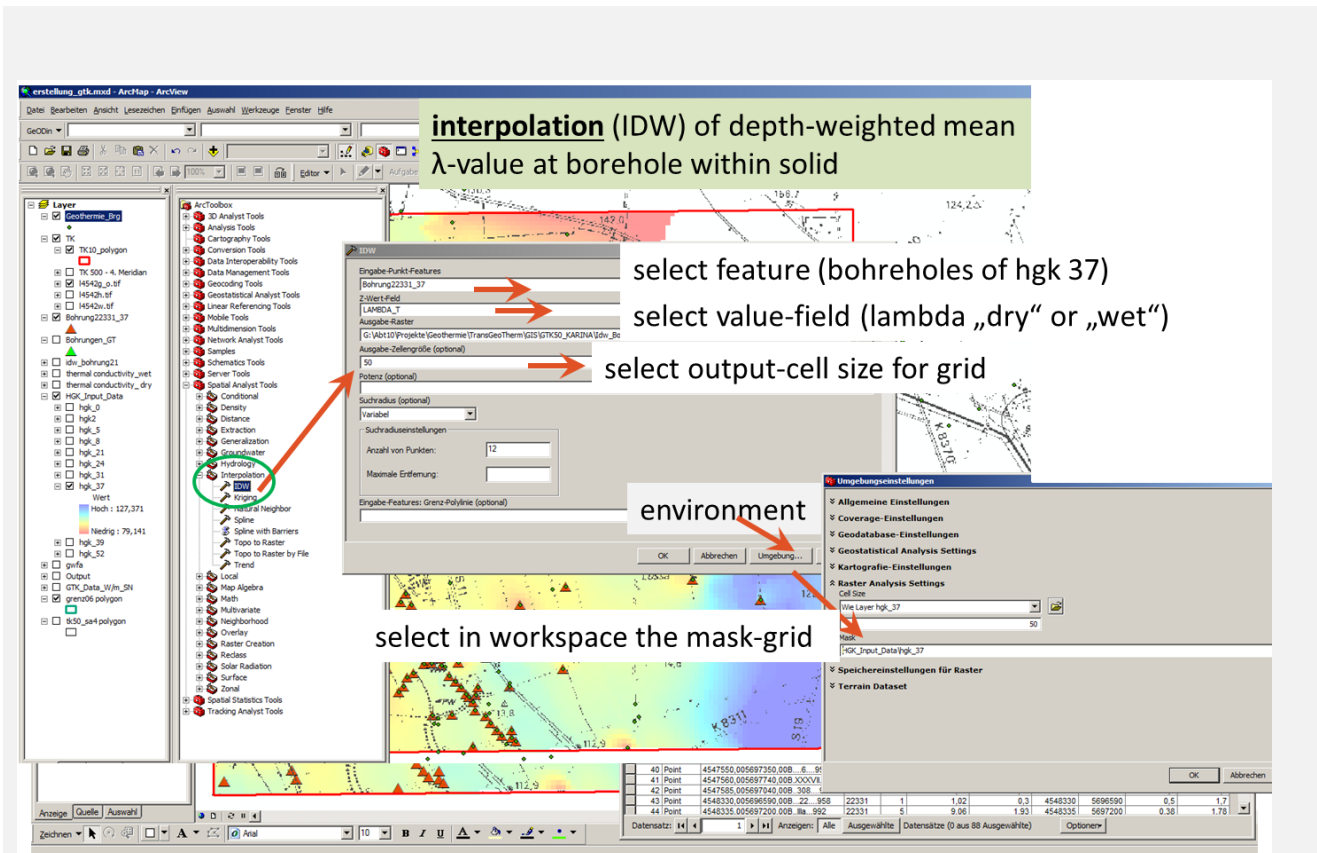
##### Interpolate the specific thermal conductivity for a single unit

Set the coordinates, extent and cell size of the master grid as default in order to produce a standardized output (if you have not done it before).

*Main Menu → Geoprocessing → environment → output coordinates → master grid → extent → master grid → resolution → type the resolution specified for the master grid → raster analysis → cell size → ok*

The interpolation of the thermal conductivity for each geologic unit is performed with the thickness-weighted mean values as input data (Figure 39).

*ArcToolbox → spatial analyst tools → interpolation → IDW*

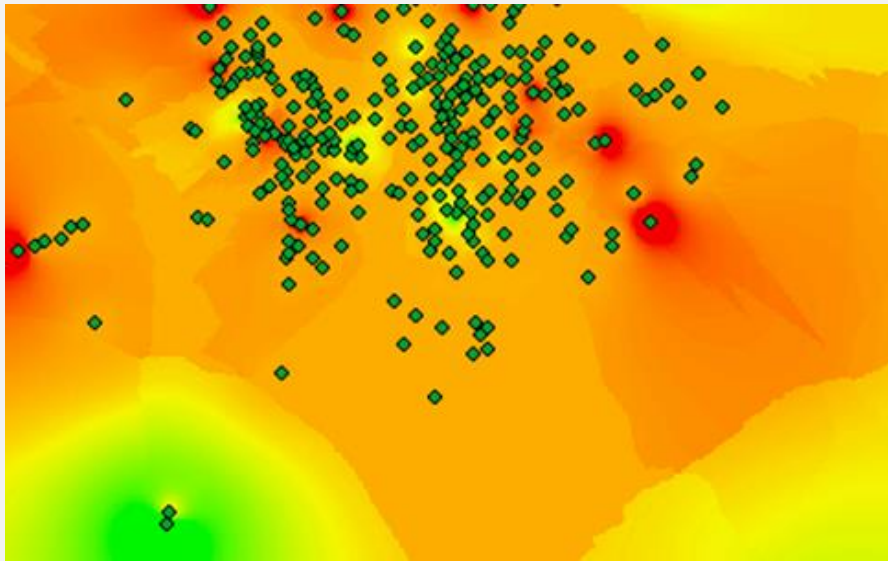


**Figure 39: Spatial Analyst toolbox with the inverse distance weighting tool used for this workflow step.**

A modelling result for the whole pilot area, including the area outside of the geologic unit, is obtained (Figure 40). In order to run the interpolation only inside of the geologic unit, you have to specify the geometry raster of the unit as mask (Figure 41):

*ArcToolbox → spatial analyst tools → interpolation → IDW → environment → raster analysis → mask → select the geometry raster of the geologic unit*

*Processing extent → snap raster → select the geometry raster of the geologic unit*



**Figure 40: Interpolation result without specification of the raster environment.**



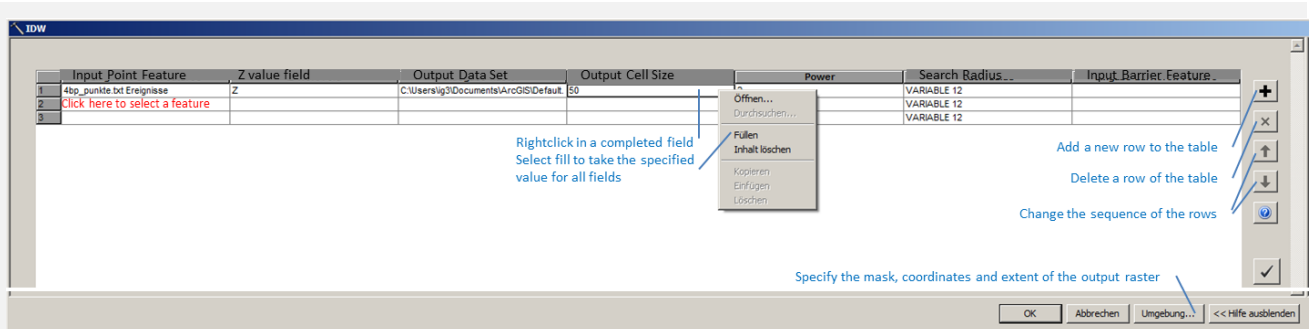
**Figure 41: Interpolation result with specification of the raster environment.**

Use the batch mode to interpolate the thermal conductivity for many units

Start the interpolation tool in the batch mode (**Figure 42**):

*Right-click on the IDW tool in ArcToolbox → spatial analyst tools → interpolation*

*Select batch*



**Figure 42: Specifications for the batch mode.**

*Click on the “+” icon to add new rows to the table*

*Click into a field and select the input feature, the variable that has to be interpolated, the output path, the output cell size, the exponent used for the interpolation and the number of data included into the interpolation*

*If you have many fields, and you want to fill them with the same entry, specify the parameter for the first row, right-click into the filled field and select fill. This completes all fields of the column*

*For specifying the output mask, go to environment → raster analysis → mask → select the geometry raster of the geologic unit*

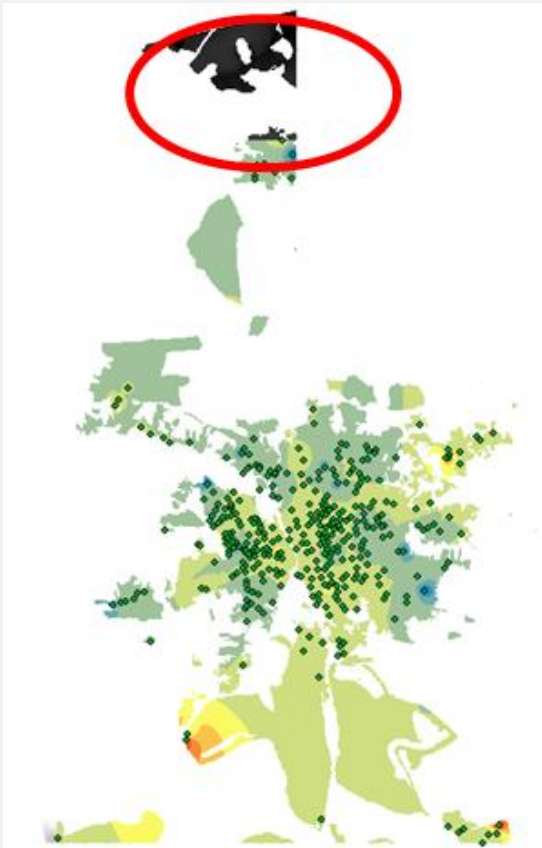
*Processing extent → snap raster → select the geometry raster of the geologic unit*

**Since the mask has to be different for each geologic unit, you can only interpolate the wet and dry thermal conductivity for one unit in one step!**



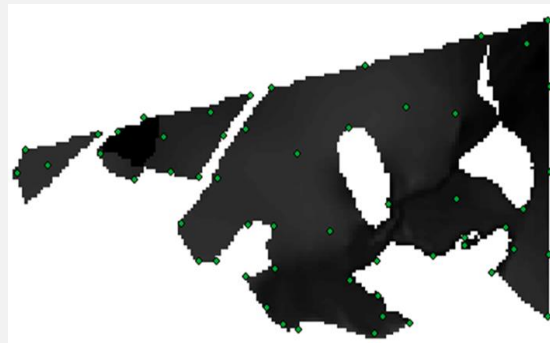
### F.3.1.10. Quality check and correct interpolation result

#### Description of workflow steps



**Figure 43: Check of the interpolation result: Regions with no data were not interpolated properly.**

**Figure 43** shows the interpolation result. Some bodies of the geologic unit, where no drilling data are available, were not included in the interpolation (red ellipse). In order to obtain an interpolation result for the full extent of the geologic unit, artificial points have to be added (**Figure 44**). The artificial points have to be placed in the centre of each body and in all corners. Since only one input data set can be specified for the interpolation, the artificial data have to be added to the original point feature by digitizing.



**Figure 44: Erroneous region with artificial data points.**

*Right-click the feature class in the TOC → start editing → select the tool “create feature”*



*→ go to the window “create feature” and select “unit1” → select “points” → go to the editor tool bar and digitize the points*



*Save the edits and exit the editor mode*

*Right-click the feature class in the TOC → open attribute table → click into the header of the conductivity field → sort the data in ascending order*

*click into the header of both conductivity fields → statistics → read the mean value*

*select all fields with no data for the wet conductivity → click to the left of the first column in the first line with no data → press the shift-key → click to the left of the first column in*



*the last line with no data*

*click into the header of the wet conductivity field → field calculator → type the mean value of the wet conductivity*

*click into the header of the dry conductivity field → field calculator → type the mean value of the dry conductivity*

*click into the header of the borehole name field → field calculator → type 'virtual point'*

**Don't forget to reactivate the full data set!**

*Main menu → selection → clear selected features*

Repeat the interpolation and check the result.

## Thermal conductivity and heat extraction capacity - calculations

### F.3.1.11. Calculate thermal conductivity and heat extraction capacity for various depth levels

#### General remarks

In this work step, the data sets for the wet and dry specific thermal conductivity of several geological units are combined in order to calculate the average thermal conductivity for a defined depth interval below the ground surface. In the same step, the heat extraction capacity can be calculated for the same depth levels.

**Note: The calculation of the 10 m intervals is necessary for the location query of the conductivities and heat extraction capacities!**

For a map visualization of these parameters, few representative levels may be selected, not all 10 m intervals have to be shown.

#### Description of workflow steps

##### Start the extension

Precondition: The license for the spatial analyst tool must be available and activated.

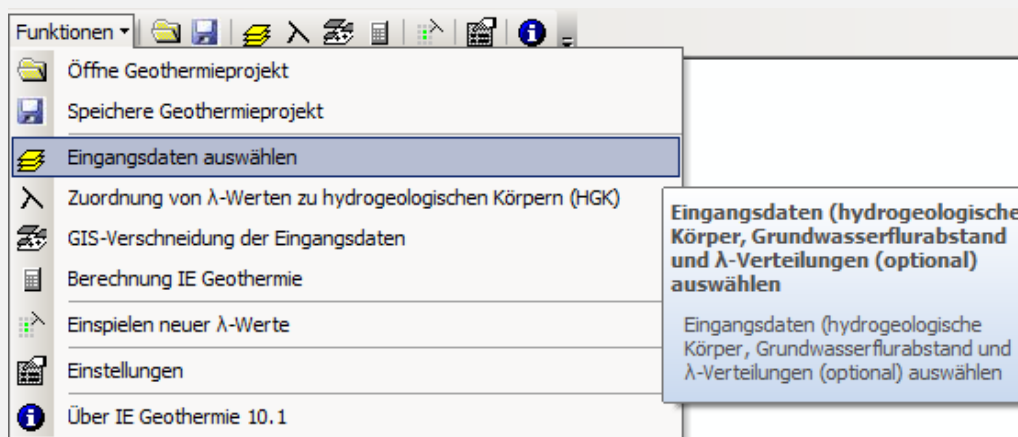
*Main Menu → Customize → Extensions → tick IE Geothermie*

*Main Menu → Customize → Toolbars → tick IE Geothermie*

The IE Geothermie toolbar appears in the head of your ArcGIS viewer (**Figure 45**)



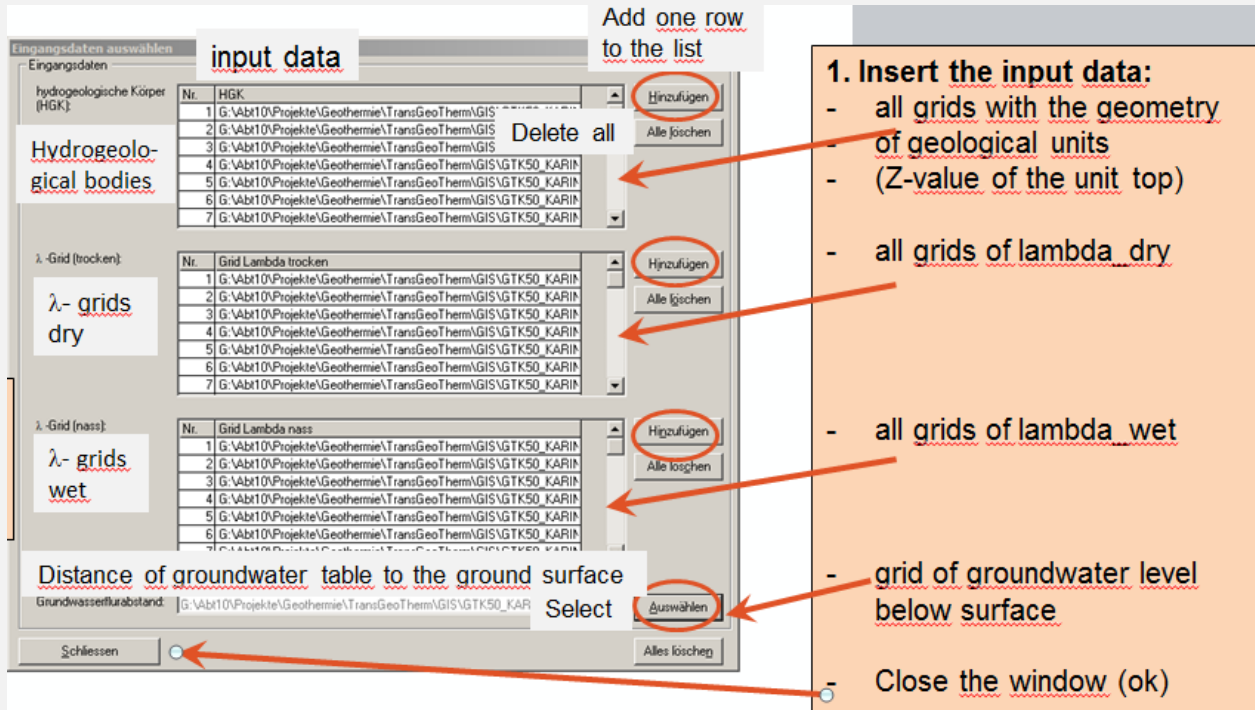
The function (“Funktionen”) menu contains all available tools. The same tools are also provided as icons next to the drop down menu. Lambda stands for the thermal conductivity in  $W/(m \cdot K)$ . The first step is to select the input data (Eingangsdaten auswählen).



**Figure 45: The menu bar of the IE Geothermie extension for ArcGIS.**

You have to insert triples of data sets (geometry,  $\lambda$  dry and  $\lambda$  wet) for each geologic unit in the model (Figure 46). Additionally, a data set specifying the depth of the groundwater table below surface is needed.

Finish the data input with close (“Schliessen”).




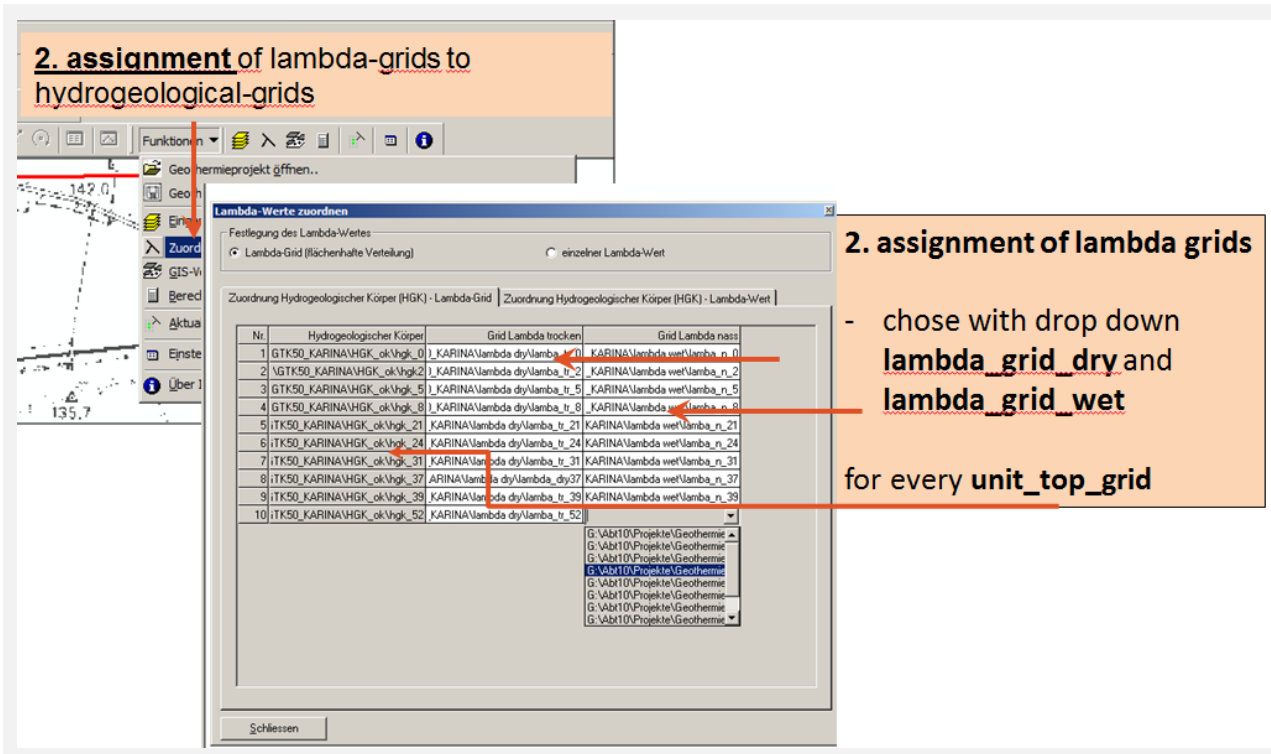
Add one row to the list

**1. Insert the input data:**

- all grids with the geometry of geological units (Z-value of the unit top)
- all grids of lambda\_dry
- all grids of lambda\_wet
- grid of groundwater level below surface
- Close the window (ok)

**Figure 46: The menu point “select input data”.**

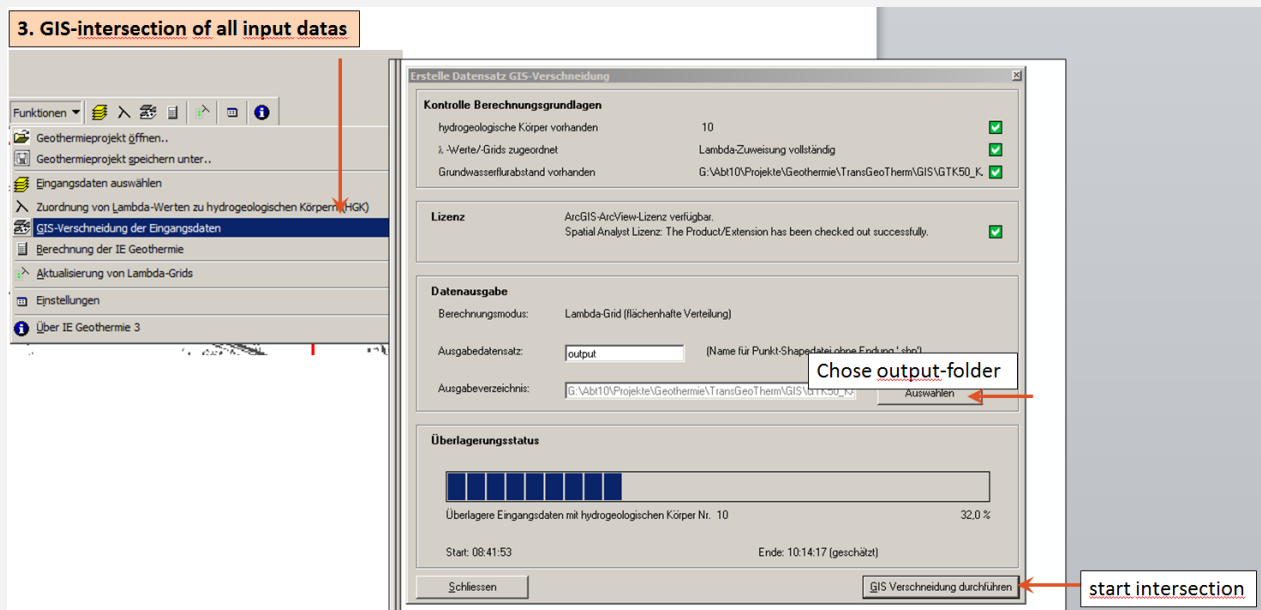
In the next step, you have to order the triples of the data sets for each unit (Figure 47). Start the tool  “assignment of  $\lambda$ -grids to geological grids” (“Zuordnung von  $\lambda$ -Werten zu hydrogeologischen Körpern”).



**Figure 47: Menu point “Assignment of λ -grids to geological grids”.**

Next, use the tool “GIS-intersection of the input data” (“GIS-Verschneidung der Eingangsdaten”)


This tool combines the data from the wet and dry λ-grids, depending on whether the geological units are located above or below the ground water table (**Figure 48**).



**Figure 48: Menu point „GIS intersection“.**

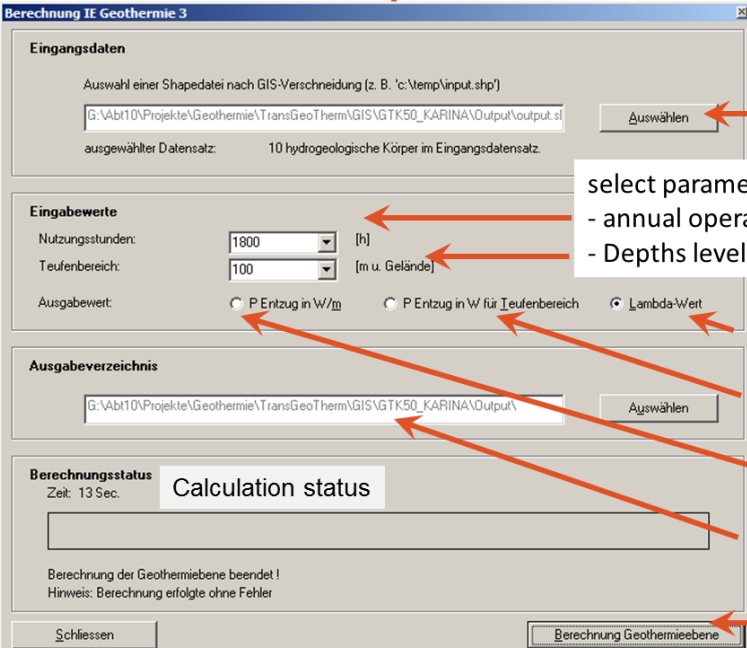
The first two boxes show whether all input data and licenses are available. If so, a green checkbox is shown. Select an output folder and click on “start intersection” (“GIS-Verschneidung durchführen”).

**This operation can take more than 12 hours!**

This tool generates an intermediate point data set (shape) which will be loaded for the calculation of the conductivities and heat extraction capacities at specific depth level. For this calculation, start the tool “calculation of the geothermal information” (“Berechnung der IE Geothermie”) .

You have to load the shape calculated during the previous work step. Then you have to specify the annual operational hours. Select 2,400 h/a, as the GeoPLASMA-CE partners agreed during the technical workshop in Vienna 2017. Select all depth levels you want to output. Select the parameter you want to calculate. You can choose between the thermal conductivity and the heat extraction capacity. Select the output folder (**Figure 49**) and go to “start calculation” (“Berechnung Geothermieebene”).

#### 4. Calculate the geothermal grids



**Berechnung IE Geothermie 3**

**Eingangsdaten**  
 Auswahl einer Shapedatei nach GIS-Verschneidung (z. B. 'c:\temp\input.shp')  
 G:\Abt10\Projekte\Geothermie\TransGeoTherm\GIS\GTK50\_KARINA\Output\output.shp  
 ausgewählter Datensatz: 10 hydrogeologische Körper im Eingangsdatensatz. **Auswählen**

**Eingabewerte**  
 Nutzungsstunden: 1800 [h]  
 Teufenbereich: 100 [m u. Gelände]  
 Ausgabewert:  P Entzug in W/m  P Entzug in W für Teufenbereich  Lambda-Wert

**Ausgabeverzeichnis**  
 G:\Abt10\Projekte\Geothermie\TransGeoTherm\GIS\GTK50\_KARINA\Output\ **Auswählen**

**Berechnungsstatus**  
 Zeit: 13 Sec. **Calculation status**  
 Berechnung der Geothermieebene beendet!  
 Hinweis: Berechnung erfolgte ohne Fehler

**Schließen** **Berechnung Geothermieebene**

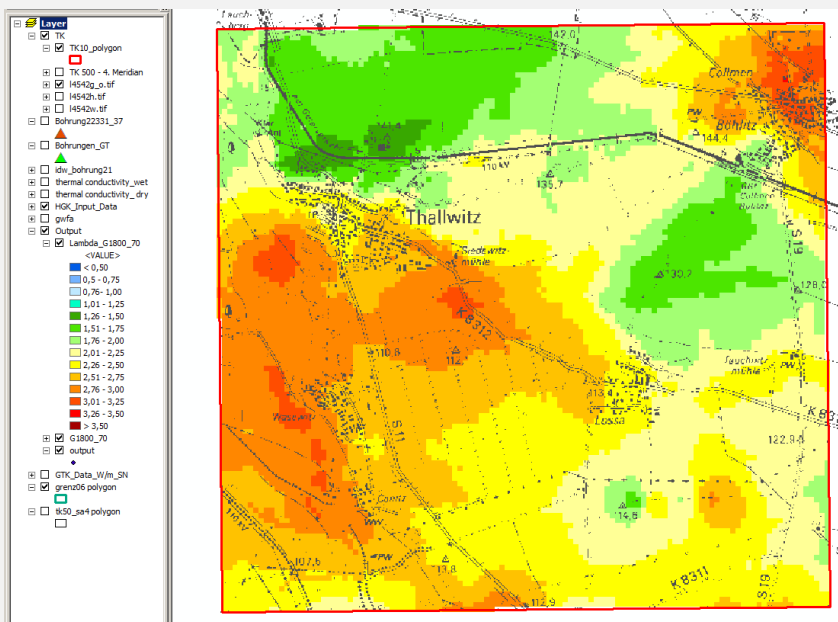
Annotations:

- select generated output\_shape
- select parameters:
  - annual operation hours of heat pump: 1800 h or 2400 h
  - Depths levels: select all levels you are interested in
- select outputs:
  - specific heat conductivity in W/(K\*m)
  - heat extraction capacity for one depth interval
  - heat extraction capacity in W/m
- Select the output path
- start calculation

**Figure 49:** Menu point „Calculate geothermal grids“.

Finally, you get a set of rasters where names are specified by the depth interval (**Figure 50**) and the operational hours.



The formula which was used for calculating the heat extraction capacity is valid for a double U probe!



**Figure 50: Calculation result: The thermal conductivity at a depth interval to 70 m below surface.**

Reclassify the conductivity maps for the harmonized GeoPALSMA-CE output (Table 16):

*Spatial analyst toolbox → reclassify → reclassify → classify → 10 or 11 classes → specify the break points as listed in the table*

Average thermal conductivity	continuous	-9999	No data available	200 200 200	
	1	1	<0.3	000 000 255	
	2	2	0.3-0.6	000 102 255	
	3	3	0.6-0.9	093 224 255	
	4	4	0.9-1.2	063 205 148	
	5	5	1.2-1.5	000 204 000	
	6	6	1.5-1.8	000 255 000	
	7	7	1.8-2.1	227 250 152	
	8	8	2.1-2.4	247 233 129	
	9	9	2.4-2.7	236 155 036	
	10	10	2.7-3.0	250 109 022	
11	11	>3.0	255 000 000		
Heat extraction capacity	continuous	-9999	No data available	200 200 200	
	1	1	<40	000 000 255	
	2	2	40.0-42.5	000 102 255	
	3	3	42.5-45.0	093 224 255	
	4	4	45.0-47.5	063 205 148	
	5	5	47.5-50.0	000 204 000	
	6	6	50.0-52.5	000 255 000	
	7	7	52.5-55.0	227 250 152	
	8	8	55.0-57.5	247 233 129	
	9	9	57.5-60.0	236 155 036	
	10	10	>60.0	255 000 000	

**Table 16: Standardized classification of the output.**

Thermal conductivity and heat extraction capacity - rock property map

**F.3.1.12. Classify a categorial map characterizing the rock properties**

**General remarks**

In order to give a brief overview on the geothermal rock properties for public users, a categorized version of the conductivity map in 200 m is provided. The map comprises four categories:

- Small thermal conductivity,
- Medium thermal conductivity,
- Large thermal conductivity,
- Very large thermal conductivity.

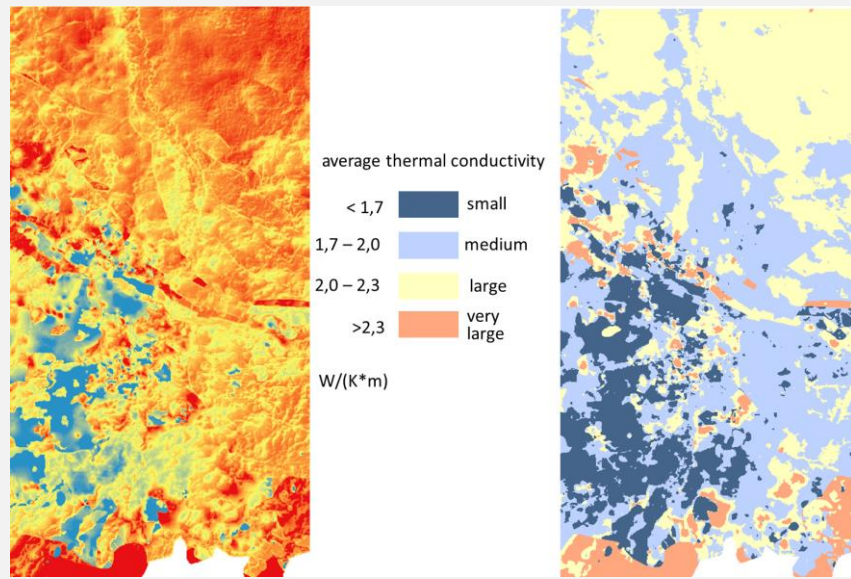
**Description of workflow steps**

*Reclassify the conductivity map in 200 m depth:*

*Spatial analyst toolbox → reclassify → reclassify → classify → 4 classes → specify the break points 1.7, 2.0, 2.3*

The RGB colour codes used for the visualization are:

-9999	No data available	200 200 200
1	0-1.7	068 101 137
2	1.7-2.0	190 210 255
3	2.0-2.3	255 255 190
4	>2.3	255 167 127



**Figure 51: The thermal conductivity map for the base of the modelling domain (200m depth, left) and the rock property map derived from it by reclassification (right).**





Thermal conductivity and heat extraction capacity - processing of input data

### F.3.1.13. Standardized output maps

#### General remarks

The standardized output of all maps is an **ESRI raster of the .adf file format**. The cell location and size has to be coincident with the master grid. The no-data value is specified with -9999.

An attribute table specifying the depth level for each map is necessary.

In addition, a metadata table has to be completed for each group of data (e.g. one for all thermal conductivity maps).

#### Description of workflow steps

Ensure that the layers in the master grid coordinates, resolution and extent are specified when you calculate a raster data model for the first time in the workflow. This is done by setting the environment resolution, coordinates and extent to the master grid!

Use the standardized classification specified in the workflow!

Mean annual surface temperature

## F.3.2. Mean annual temperature

### F.3.2.1. Input data - mean annual surface temperature

#### General remarks

Ground Surface Temperature (GST) is defined as the surface or near-surface temperature of the ground (bedrock or surficial deposit), measured in the uppermost centimetres of the ground.

The surface air temperature (SAT) is measured 1 m above the surface, in shade, not affected by artificial influences.

The land surface temperature (LST) can be measured by satellites like the Moderate Resolution Imaging Spectroradiometer (MODIS) on NASA's Terra satellite. The thermal infrared signature received by satellite sensors is determined by surface temperature, surface emissivity/reflectivity, and atmospheric emission, absorption and scattering actions upon thermal radiation from the surface, and the solar radiation in daytime.

#### Description of workflow steps

For the design and calculation of geothermal closed loop systems, the information on the annual average ground surface temperature is necessary. Therefore, the temperature map provides important information for experts.

There are many climate web portals where data for the mean annual temperature might be available. Check these sources first!

This portal provides data for the whole of Europe: <http://www.geodati.fmach.it/eurolst.html>

It is derived from daily MODIS LST data for the period 2000 - 2013. The spatial resolution is 250 m, temperature resolution is 0.1 °C. There are annual mean temperatures as well as mean winter and summer temperatures (BIO1, BIO10 and BIO11). The data are free as long as the products derived also remain free (Open Database License).

Local data sources are:

Austria: Surface temperature map of Vienna

Czech Republic: <http://portal.chmi.cz/historicka-data/pocasi/mapy-charakteristik-klimatu?l=en>

Germany: [https://www.dwd.de/EN/climate\\_environment/climateatlas/climateatlas\\_node.html](https://www.dwd.de/EN/climate_environment/climateatlas/climateatlas_node.html)

Poland: [http://klimat.pogodynka.pl/en/climate-maps/#Mean\\_Temperature/Monthly/2010/1/Winter](http://klimat.pogodynka.pl/en/climate-maps/#Mean_Temperature/Monthly/2010/1/Winter)  
[http://www.eumetsat.int/website/home/News/DAT\\_3312875.html](http://www.eumetsat.int/website/home/News/DAT_3312875.html)

Slovakia: <http://klimat.shmu.sk/kas/>

Slovenia: [http://gis.arso.gov.si/atlasokolja/profile.aspx?culture=en-US&id=Atlas\\_Okolja\\_AXL@ARSO](http://gis.arso.gov.si/atlasokolja/profile.aspx?culture=en-US&id=Atlas_Okolja_AXL@ARSO)

Land Surface Temperature: [https://neo.sci.gsfc.nasa.gov/view.php?datasetId=MOD\\_LSTD\\_CLIM\\_M](https://neo.sci.gsfc.nasa.gov/view.php?datasetId=MOD_LSTD_CLIM_M)



**Make sure that you get a permit to present the temperature data on the web!**

If you get map data produce a standardized output.

If you get temperature point data go to the interpolation step. Select and if necessary correct the data.

- If point GST data are available and representative for the pilot area, use this data and make spatial distribution of GST by interpolation.
- If point GST data are available but sparse, define a relation between GST and SAT. Since SAT (and GST) is usually dependent on altitude, use temperature correction for spatial distribution of SAT/GST values.
- If no GST measurements are available, use SAT (mean annual) values.

### F.3.2.2. Interpolation by Kriging

#### General remarks

The surface temperature is a spatially continuous variable. Therefore, you can use interpolation methods to estimate the temperature in places where no measurement was performed. If a spatial covariance and continuity of the property is assumed,  $T(x)$  has values similar to the ones found in the neighbourhood. The spatial distribution of the temperature data may be characterized by anisotropies and trends. Therefore, geostatistical prediction methods are suitable, because they include all knowledge about the spatial distribution of the data.

#### Description of workflow steps

##### Spatial data analysis

###### *Tools for spatial analysis*

If we want to include much knowledge in the prediction model, we have to analyse the data set very carefully prior to performing an interpolation. Spatial data analysis comprises all techniques analysing the distribution of a property in space. Spatial data analysis is the fundamental step in geostatistical property interpolation since it provides the parameters that are used for the specification of the prediction model. In ArcGIS, spatial analysis can be performed with the Geostatistical analyst.

*Start the geostatistical analyst with*

*Main menu → customize → Toolbars → select Geostatistical analyst*

*Geostatistical analyst toolbar → explore data*

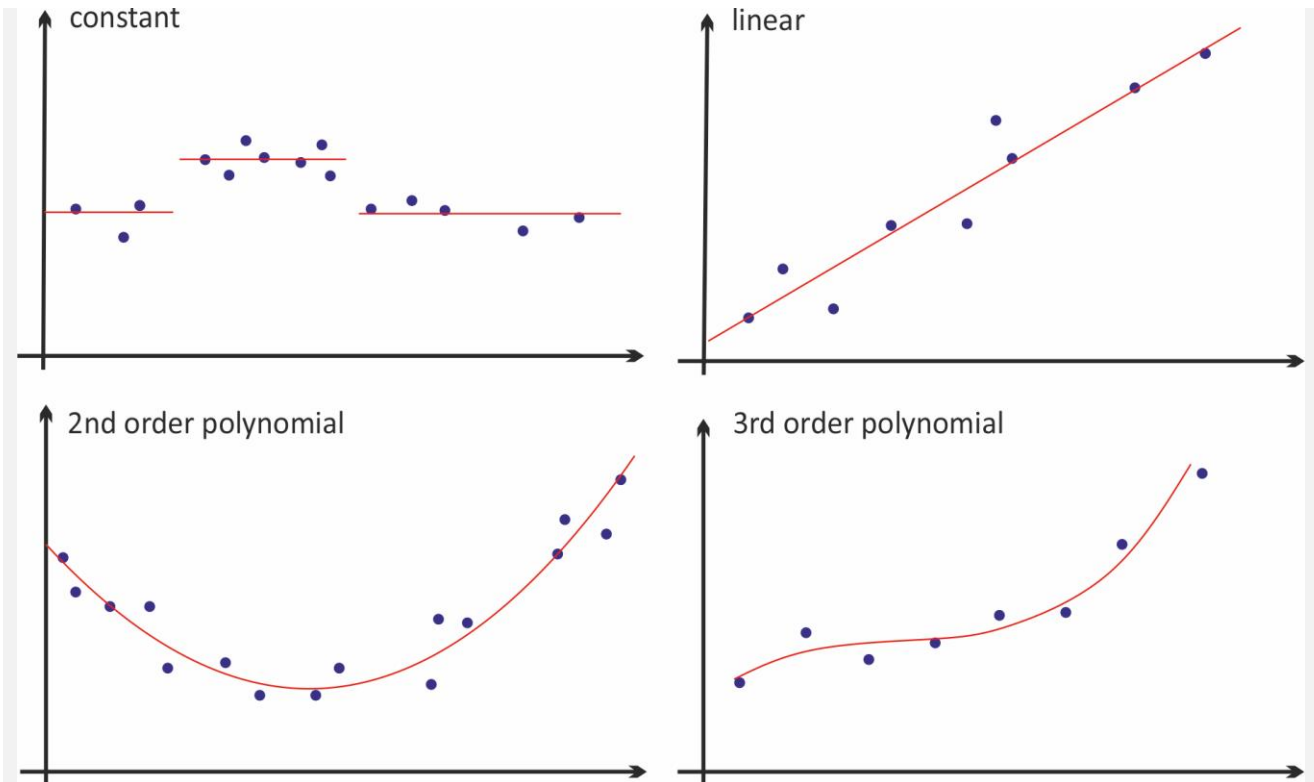
###### *Aim of spatial analysis*

Each data set has to fulfil modelling assumptions of the Kriging method applied for prediction. This means that, according to the results of the data analysis, you have to select the proper interpolation method:

- the mean is constant and known → simple Kriging,
- the mean is unknown and locally constant, the variability is constant → ordinary Kriging,
- an unknown trend exists → universal Kriging with a Trend model.

###### *Trend analysis*

A trend is a systematic change in the mean value (**Figure 52**). It can be described by a deterministic mathematical function. This means, the trend is fixed, and if you simulate data again and again, then the trend never changes. You do see fluctuations in the simulated surfaces due to the autocorrelated random errors. If a trend is present in the data set, you have to use universal Kriging; ordinary Kriging is not suitable.



**Figure 52: Examples for trend models.**

Trend models

*Geostatistical analyst* → *Explore data* → *Trend*

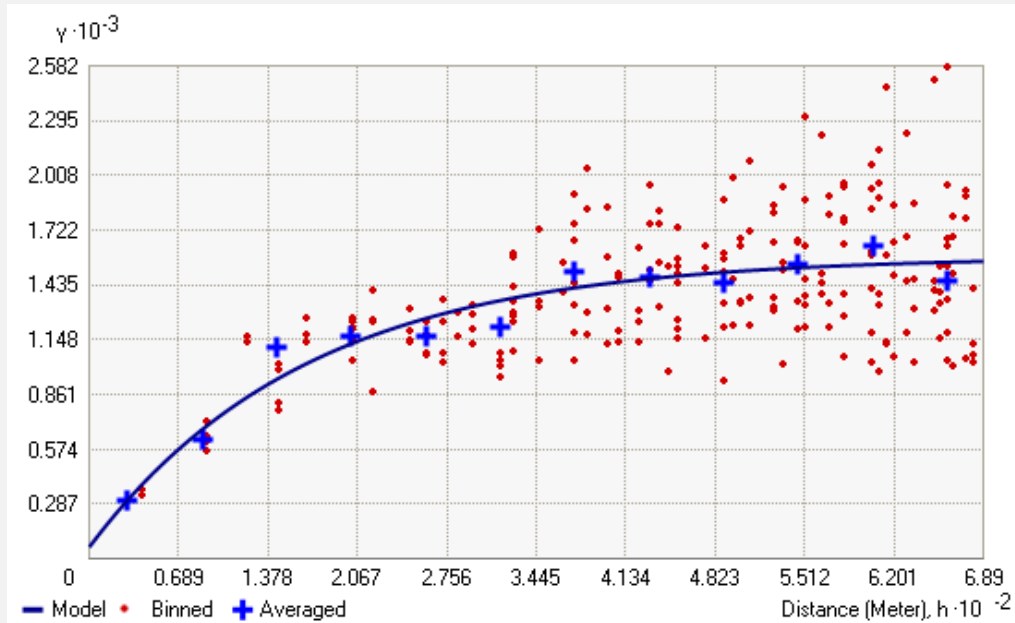
**Empirical variogram**

The main instrument used for exploring spatial relationships between the data is the (semi)variogram.

*Geostatistical analyst toolbar* → *Geostatistical wizard* → *Kriging/CoKriging*

The variogram describes the degree of spatial dependence in a data set. It relates the variance of the difference in a property at pairs of sample points to the directed separation distance  $h$  between those pairs. This means, you take all pairs of data that have a similar distance and direction from each other. For most natural phenomena it is generally expected that the spatial variability increases as the length of  $h$  increases. The mean of all variabilities for one length of  $h$  gives one point in the empirical variogram.

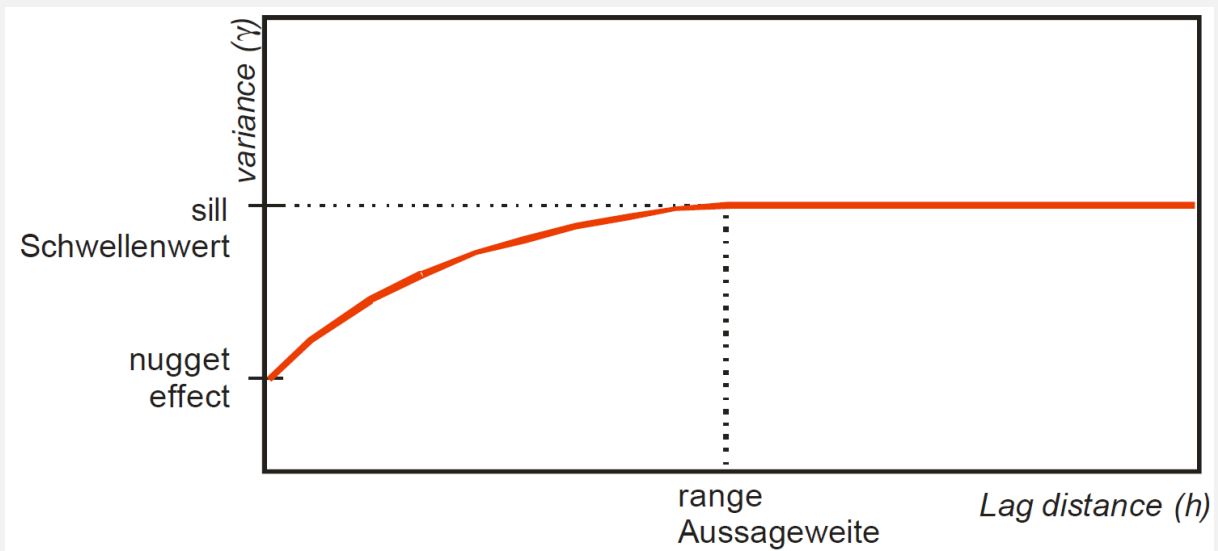
The ArcGIS variogram (**Figure 53**) shows the variability of the data pairs (red). Due to computing limitations, if the input dataset has more than 5000 observations, Geostatistical Analyst will randomly select 5000 observations for the structural analysis and variogram model fitting (this provides about 12 million pairs of points). The resulting interpolated surface is usually not affected by the random sampling since all the data are used to generate the predicted values. The blue crosses show the mean variability for each  $h$ .



**Figure 53: ArcGIS variogram.**

The empirical variogram is used to read the parameters of the theoretical variogram. The parameters specifying an theoretical variogram function are:

- NUGGET EFFECT: Microvariability, the intercept in the theoretical variogram,
- RANGE: The distance to which spatial dependence can be determined,
- SILL: The variance of the data set outside of the range.



**Figure 54: Parameters of a theoretical variogram.**



### Theoretical variogram

The theoretical variogram (**Figure 54**) allows calculating a variogram value for any distance  $h$ . The theoretical variogram contains all knowledge derived from the data and is the basis for the Kriging interpolation. Since every value in the variogram is a variance, it can never be negative. This is guaranteed by using a set of mathematically proven positive definite functions. Variogram modelling involves user decisions and is to some extent subjective. Parameters that are important for generating the theoretical variogram are:

- **LAG SIZE:** The lag distance defines the incremental distance at which the variogram is calculated. The lag size should be at least equal to the minimum sample spacing. On the other hand, it has to be several times smaller than the range, if this is to be displayed properly. Since the range is not known when starting a spatial data analysis, the lag size has to be changed and played with. As a rule of thumb, use a lag distance of half the diagonal of the data extent divided by 20.
- **LAG NUMBER:** Specifies the maximum number of length-steps; usually, a number  $>20$  should be chosen in order to get enough data points for modelling the theoretical variogram.
- **NUGGET EFFECT:** Think whether there might be a nugget effect for the interpolated property. If so, read it from the empirical variogram.
- **MODEL TYPE:** The variogram model fitted to the empirical data should pass through the center of the cloud of binned values and pass as closely as possible to the averaged values (blue crosses).

The variogram model is displayed by a blue solid line. The model parameters are written at the bottom of the variogram.

*Fit a variogram model by changing lag size and number!*

*Display the corresponding covariance model: General  $\rightarrow$  Variable  $\rightarrow$  Covariance*

### Anisotropy

Anisotropy is a directional dependency of a property. The range and sill can vary depending upon the direction, e.g. the direction of a valley or the aspect of a hill slope. This effect can be quantified by directional variograms. The anisotropic model reaches the sill more rapidly in some directions than others. The length of the longer axis to reach the sill is called the major range, the length of the shorter axis to reach the sill is called the minor range, and you also have the angle of rotation of the line that forms the major range.

The variogram map (**Figure 55**~~Fehler! Verweisquelle konnte nicht gefunden werden.~~) displays the variogram values as a surface. The color scale represents the calculated variogram value with lower values shown in blue and green and higher values shown in orange and red. The x-axis on the variogram graph is the distance from the center of the cell to the center of the variogram surface.

Explore the dissimilarity in data points for a certain direction with the Search Direction tool. This allows you to examine directional influences on the variogram chart. It does not affect the output surface:

*Type a new Lag size value of 15000 reducing the lag size  $\rightarrow$  change the Show search direction  $\rightarrow$  true.*

Note the reduction in the number of variogram values. Only those points in the direction of the search are shown in the graph.

*View setting  $\rightarrow$  search direction  $\rightarrow$  true  $\rightarrow$  drag the search direction tool (red pentangle)*

As you change the direction of the search, note how the variogram graph changes. Only the variogram surface values within the direction of the search are plotted on the variogram graph above.

### Include anisotropy in the variogram model

To actually account for the directional influences on the variogram model for the surface calculations, you must calculate the anisotropic variogram

*Model#1 → anisotropy → change the anisotropy → true*

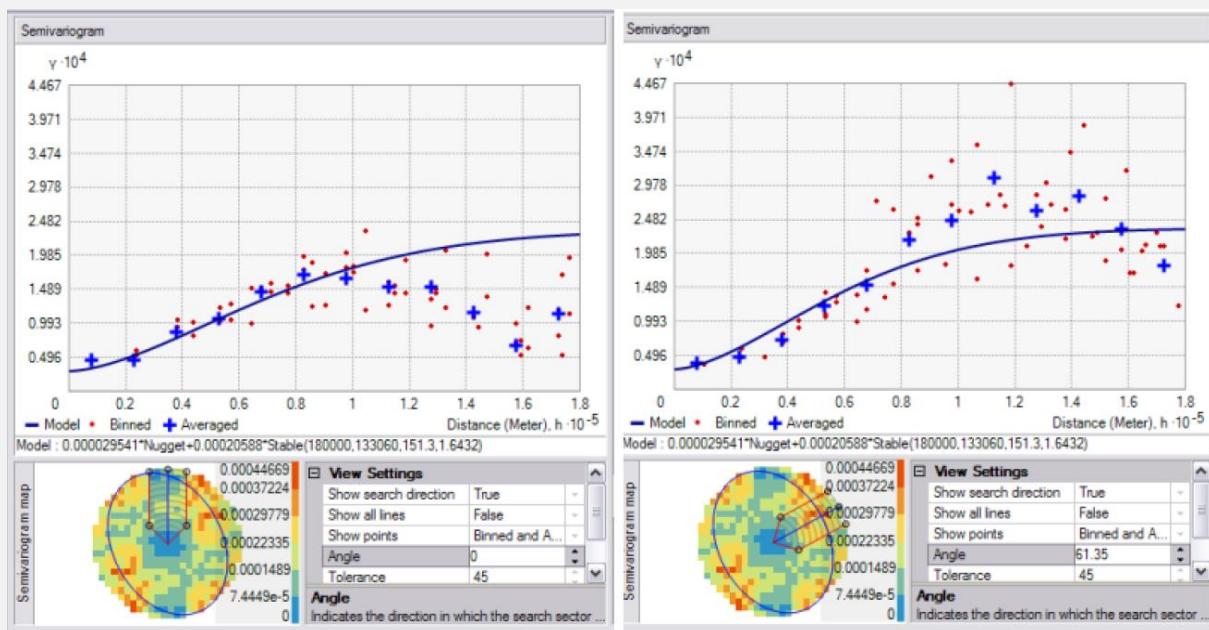
The blue ellipse on the variogram surface indicates the range of the variogram in different directions. In this case, the major axis lies approximately in the NNW-SSE direction. Anisotropy will now be incorporated into the model to adjust for the directional influence of autocorrelation in the output surface.

*View Settings → change the search direction angle from 0 to 61.35 to make the directional pointer coincide with the minor axis of the anisotropic ellipse*

Note that the shape of the variogram curve increases more rapidly to its sill value.

*View Settings → change the search direction angle under from 61.35 to 151.35 to make the directional pointer coincide with the major axis of the anisotropic ellipse*

*Click **next** to apply the variogram model*



**Figure 55: Variogram and variogram map.**





### *Specify the search neighborhood*

To predict a value, you can use the values at the measured locations. You know that the values of the closest measured locations are most alike to the value of the unmeasured location that you are trying to predict. It is common practice to limit the data included in the estimation by defining a circle (or ellipse) to enclose the points that predict a value at an unmeasured location. Additionally, to avoid bias in a particular direction, the circle can be divided into sectors from each of which an equal number of points is selected.

*Click on the surface preview → select a prediction location → note the change in the selection of data locations*

*Weights → display the weights of the data → select a prediction location*

*Searching Neighborhood dialog box → specify the number of points (a maximum of 200) → specify the radius (or major/minor axis) → specify the number of sectors of the circle.*

*Use the default!*

The points selected in the data view window indicate the weights that will be associated with each measured value to predict a value for the location marked by the crosshair. The larger the weight, the more impact that value will have on the prediction for the location at the crosshair.



Mean annual ground surface temperature - standardized output

### F.3.2.3. Standardized output maps

#### General remarks

The standardized output of all maps is an **ESRI raster of the .adf file format**. The cell location and size has to be coincident with the master grid. The no-data value is specified with -9999.

In addition, a metadata table has to be completed.

#### Description of workflow steps

Take care to specify the layers in the master grid coordinates, resolution and extent when you calculate a raster data model in the workflow for the first time. This is done by setting the environment resolution, coordinates and extent to the master grid!

Reclassify the raster for the harmonized GeoPALSMA-CE output as specified in **Table 17**:

*Spatial analyst toolbox → reclassify → reclassify → classify → 13 classes → specify the break points as listed in the table*

-9999	No data available	200 200 200	
1	<3	000 000 255	
2	3-4	000 102 255	
3	4-5	093 224 255	
4	5-6	068 234 179	
5	6-7	102 255 102	
6	7-8	204 255 153	
7	8-9	255 255 083	
8	9-10	255 255 153	
9	10-11	253 204 107	
10	11-12	252 174 057	
11	12-13	255 153 000	
12	13-14	253 098 049	
13	14-15	255 000 000	

**Table 17: Standardized classification of the output.**



## Geothermal gradient - input data

### F.3.3. Geothermal gradient

#### F.3.3.1. Temperature data

##### General remarks

Temperature data over depth can be directly measured by temperature logging in boreholes. The geothermal gradient is simple to calculate from this data:

$$g_{th} = \frac{\delta T}{\delta z} = \frac{T_{bot} - T_{top}}{z_{bot} - z_{top}} = \frac{T_{bot} - T_{top}}{\Delta z_i} \quad (6)$$

where:  $g_{th}$  - geothermal gradient,  $T$  - temperature ( $^{\circ}\text{C}$ , K),  $z$  - depth (m), indexes *bot* and *top* indicate bottom (base) and top of the respective borehole section. As far as base temperatures (vertical boundary temperatures) are known, the geothermal gradient can easily be calculated by (6) for particular horizons or a complete model.

##### Description of workflow steps

Several rules of thumb can apply for data collection:

- for surface temperature → use mean active soil profile temperature or mean air temperature
- specify the thickness of the neutral zone and discard the temperature data for this interval
- remember that a first approximation considers a steady-state model, equalling a temperature of the soil / bedrock to the temperature of water; correction for cold front inflow is not considered.

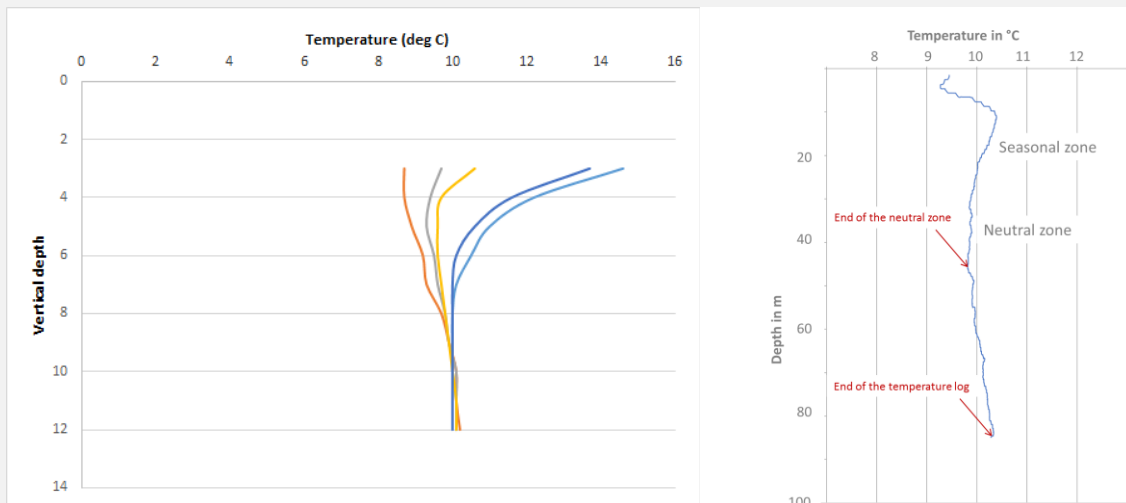
## Geothermal gradient - input data

### F.3.3.2. Temperature Logs

#### General remarks

The seasonal zone represents a zone where the heat transfer from the earth's crust is significantly influenced by solar radiation (**Figure 56**). The thickness of the seasonal zone varies in the range of 15-30 m. Within the seasonal zone, the temperature varies greatly throughout the year's seasons, depending on solar radiation. This is why, usually, the temperature of the seasonal zone is represented by the mean annual soil temperature.

With seasonal observations available, the thickness of the seasonal zone can be taken from vertical logs of temperature with depth, usually in shallow boreholes providing higher data resolution. An example is provided below:



**Figure 56: The temperature profile within the seasonal zone varies with the seasons of the year (left). The temperature profile is characterized by the seasonal and the neutral zone, before the monotonous increase of the temperature starts due to geothermal heat flux (right).**

In the plot, each curve represents a vertical log of the temperature below the reference point (wellhead), measured in a single well throughout the year (**Figure 56 left**). The tree-like structure is coalescing with depth. The seasonal zone terminates where the temperatures through the year are stable. At approx. 10 m depth, the difference in temperature is quite small, so that the depth of the seasonal zone here is approximately 10 m. As an aside, even below the seasonal zone the temperature may vary to some extent, depending, however, on factors other than the solar radiation.

The neutral zone is located below the seasonal zone (**Figure 56 right**). It is still influenced by solar radiation, however, due to inertia caused by the heat capacity of the rock formations, the influence of the seasons is levelled out and a temperature close to the mean annual soil temperature is observed. The neutral zone reaches down to approx. 30-50 m depth. Below this zone, the influence of solar radiation and surface temperatures is negligible. The temperature increases continuously due to the geothermal heat flux.



## Description of workflow steps

The geothermal gradient in the GeoPLASMA-CE project will be calculated for the region beneath the neutral and seasonal zones.

Read the depth of the neutral zone from your temperature logs and take the deepest depth value as representative value for further processing.

Check which temperature log is the shortest and use the end depth of this log as the second representative value.

In order to determine the geothermal gradient, read the temperature at the end of the neutral zone (representative value as determined above) and in the depth of the second representative value (end of the shortest temperature log).

From these two values, calculate the geothermal gradient for each borehole and generate a table containing the borehole ID, the X and Y coordinates and the geothermal gradient in K/m.

Borehole ID	X coordinate	Y coordinate	Geothermal gradient
-------------	--------------	--------------	---------------------

**It has to be mentioned that the geothermal gradient is not valid for the neutral and seasonal zones. This has to be taken into account when estimating the subsurface temperature from the ground surface temperature, since otherwise the subsurface temperature will be overestimated.**

Load the table to ArcGIS:

*Main Menu → data → add data → add XY data → specify the geothermal gradient*

*Right-click on the table → save as shape or feature class*

*Main Menu → Geoprocessing → environment → output coordinates → master grid → extent → master grid → resolution → type the resolution specified for the master grid → raster analysis → cell size → ok*

Geothermal gradient - processing of input data

**F.3.3.3. Thermal conductivity**

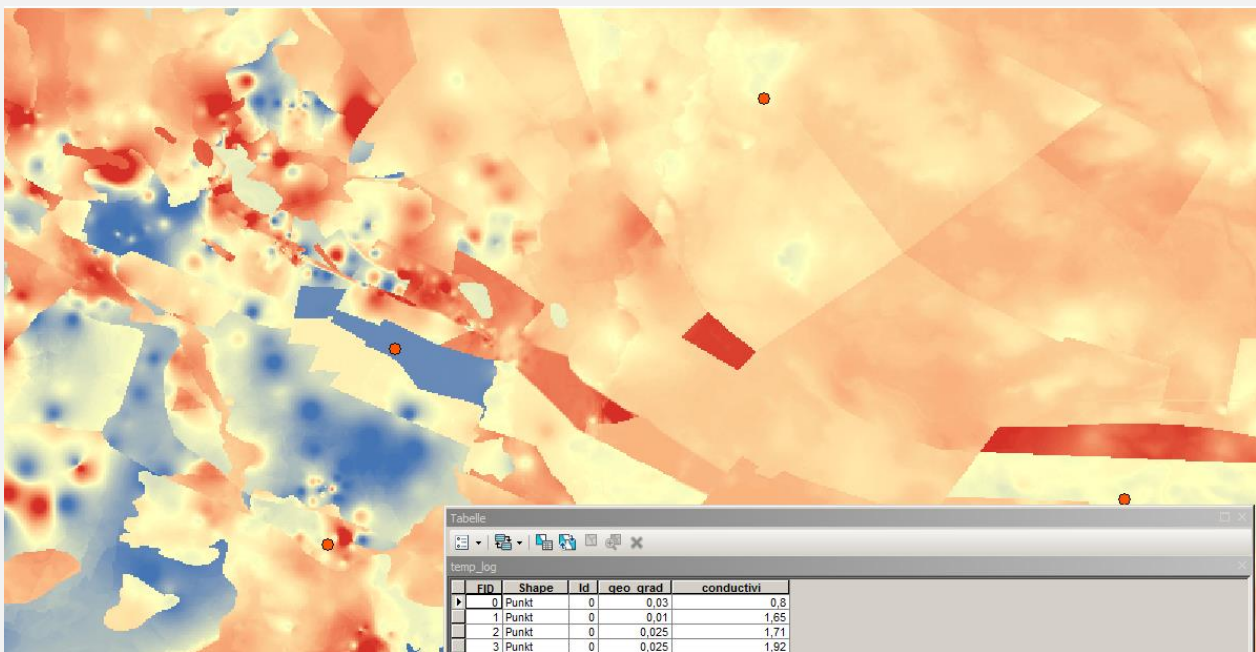
**General remarks**

The thermal conductivity at one borehole can be obtained by TRT measurements. The average thermal conductivity for the covered by the borehole beneath the neutral zone can be read from the raster calculated in the previous part of the workflow (**Figure 57**).

**Description of workflow steps**

Choose the conductivity raster which is closest to the second representative value (depth of the shortest temperature log).

*ArcToolboxes → Spatial Analyst → extraction → extract multivalues to point → select the point feature with the wells and the conductivity raster for 100m depth.*



**Figure 57:** The figure shows the raster with the average conductivity for the interval of 100m depth (background), the points where the temperature logs were recorded (orange), and the attribute table for the points after assignment of the thermal conductivity.

Geothermal gradient - processing of input data

**F.3.3.4. Calculating the heat flux at the location of the temperature logs**

**General remarks**

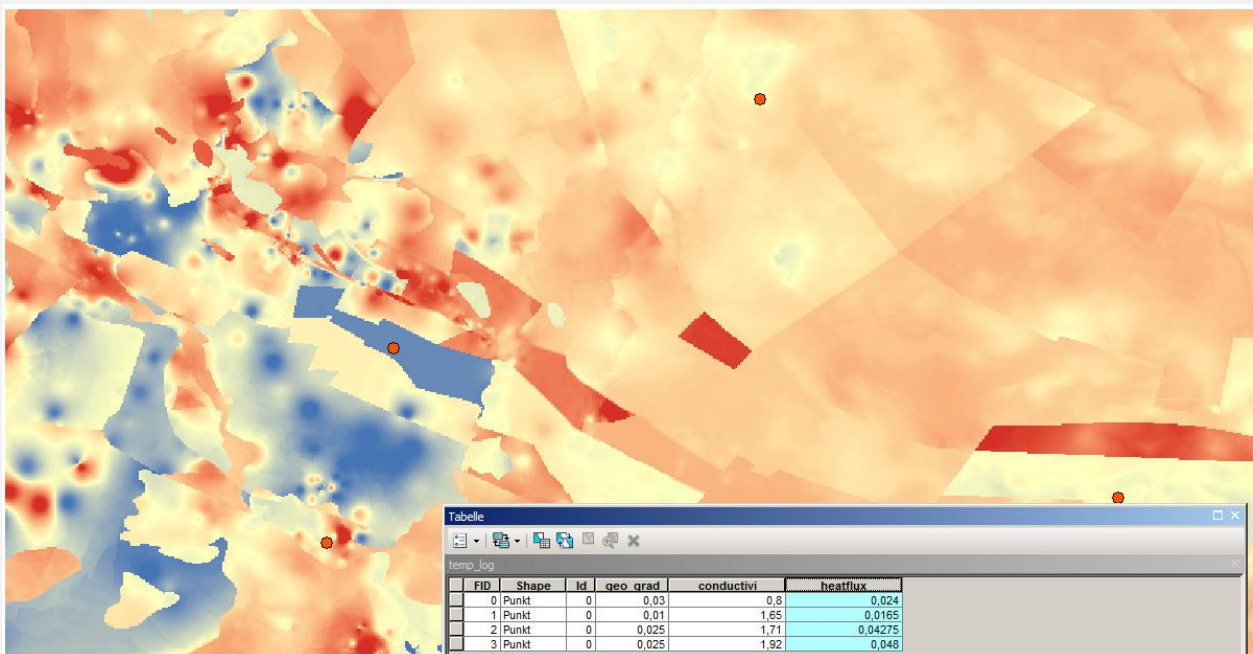
The surface and basal heat fluxes are boundary conditions of the heat equation. If no heat production occurs within the extent of the 3D model and other heat transfer processes can be neglected (e.g. thermal convection due to groundwater movement), a steady state can be assumed and the heat flux is constant. This assumption is made here since the modelling depth of GeoPLASMA-Ce is small and radiogenic heat production can be neglected. Similarly, lateral and vertical groundwater movements are disregarded.

**Description of workflow steps**

The heat flux for each borehole can be calculated with the field calculator in the attribute table (Figure 58).

*Right-click on the point feature “temperature logs” → open the attribute table → add a field → heatflux → select float*

*Right-click in the header of the column “heatflux” → field calculator → heatflux= [geo\_grad]\*[conductivi]*



**Figure 58: Attribute table extended by a field for the heat flux.**

Geothermal gradient from temperature data - interpolation

### F.3.3.5. Interpolation of the heat flux with the Inverse Distance Method

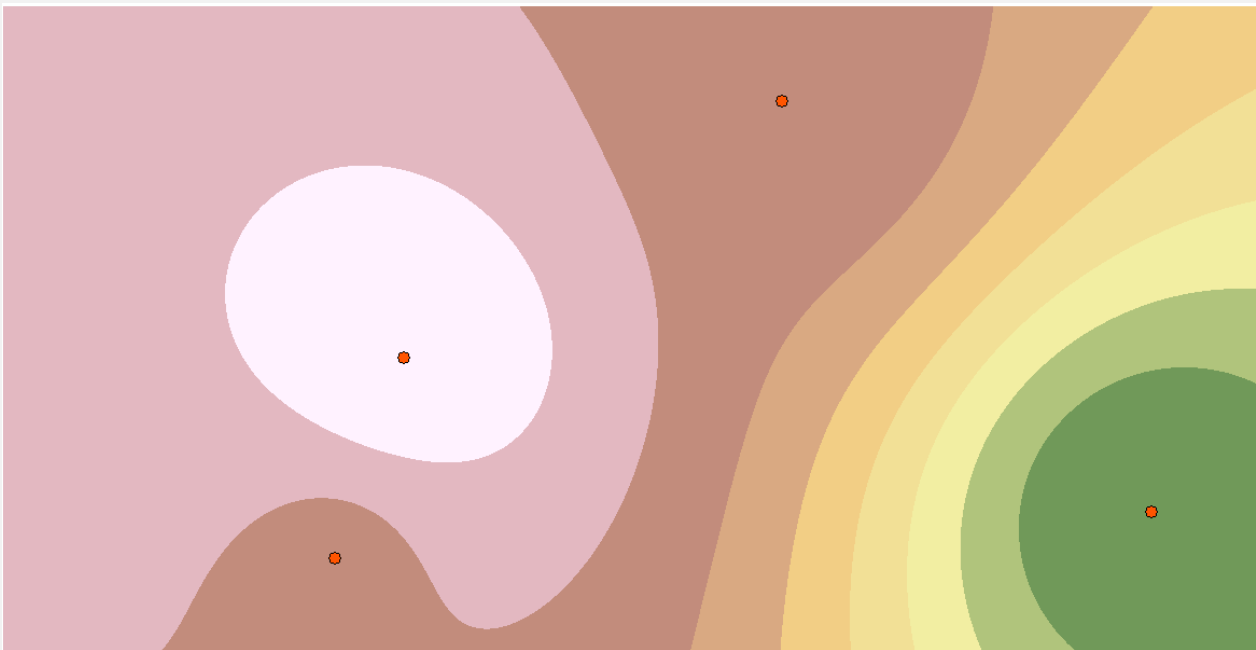
#### General remarks

Interpolate the heat flux between the boreholes using the Inverse Distance Method (**Figure 59**).

#### Description of workflow steps

See toolkits F.3.1.9 and F.3.1.10.

**Do not forget to use the conductivity map for specifying the extent and as snapping raster!**



**Figure 59: Interpolation result: Heat flux in the entire pilot area interpolated from borehole data.**



Geothermal gradient from temperature data - calculation for depth levels

### F.3.3.6. Calculate the geothermal gradient for the depth levels

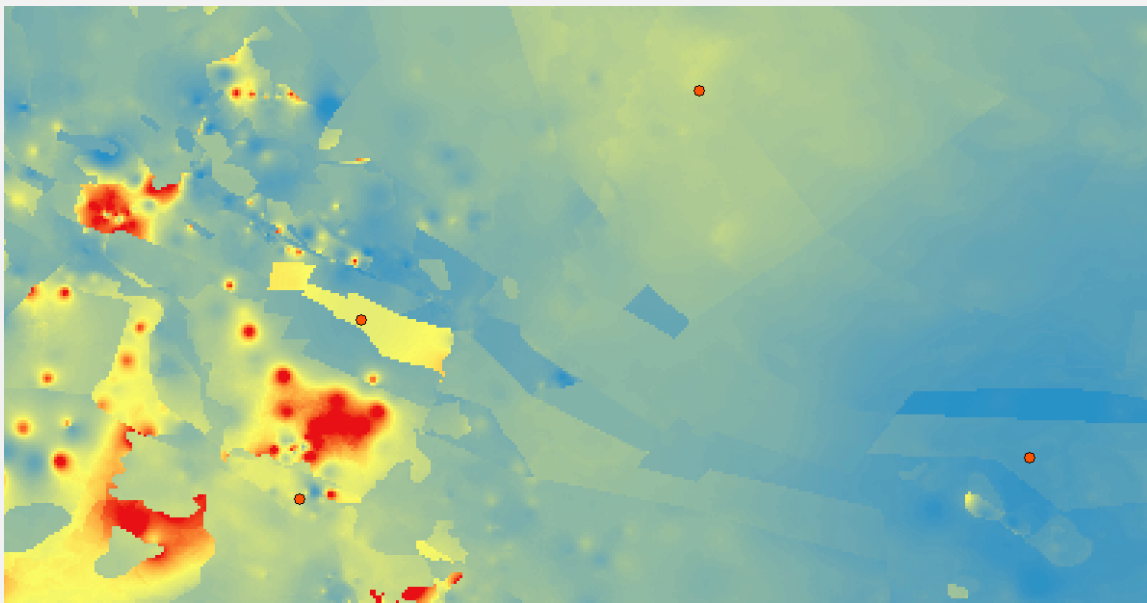
#### General remarks

Now, the data processed from the temperature logging and the thermal conductivity maps are combined. The result is a geothermal gradient in K/m, which has to be multiplied by 100 in order to obtain the standardized output in K/100m ( **Figure 60**).

**If a heat flow map is available for the pilot area, it can be used instead of the interpolation result from the last step.**

#### Description of workflow steps

*Spatial analyst toolbox → map algebra → raster calculator → "heatflux\_raster" / "conductivity\_raster" \* 100*

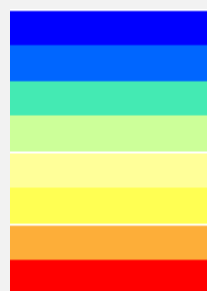


**Figure 60: Result: The geothermal gradient in the pilot area.**

Reclassify the raster for the harmonized GeoPALSMA-CE output:

*Spatial analyst toolbox → reclassify → reclassify → classify → 8 classes → specify the break points as listed in the table*

-9999	No data available	200 200 200
1	<0	000 000 255
2	0-1	000 102 255
3	1-2	068 234 179
4	2-3	204 255 153
5	3-4	255 255 153
6	4-5	255 255 083
7	5-6	253 174 057
8	>6	255 000 000





Geothermal gradient - standardized output

### F.3.3.7. Standardized output maps

#### General remarks

The standardized output of all maps is an **ESRI raster of the .adf file format**. The cell location and size has to be coincident with the master grid. The no-data value is specified as -9999.

The geothermal gradient should be calculated for the 100 and 200 m depth level.

In addition, a metadata table has to be completed.

#### Description of workflow steps

Ensure that the layers are specified in the master grid coordinates, resolution and extent when a raster data model is calculated for the first time in the workflow. This is done by setting the environment resolution, coordinates and extent to the master grid!

Use the standardized classification specified in the workflow!



## G. List of electronic appendixes

No	Script / template /software	Data type	Status	Responsible partner
	<b>General</b>			
1	Template documentation	EXCEL spreadsheet	available	PP04
2	Templates attribute data	ACCESS table	Has to be prepared	LP
3	Templates metadata	ACCESS table	Has to be prepared	LP
4	Glossary of terms		available	LP
5	Master grid	EXCEL macro ArcGIS workflow	available	PP04
6	Specification of the spatial reference system	Text	available	LP/PP04
	<b>3D modelling</b>			
7	Instruction for age and petrographic coding	Text	available	PP04
	<b>Closed loop workflow</b>			
8	Parameter list with specific thermal conductivities of rock samples	EXCEL spreadsheet	Has to be prepared	PP05
9	Assignment of conductivity-values wet /dry to the borehole data	EXCEL macro	Has to be prepared	PP04
11	Calculation of the thickness weighted mean of the conductivity-values for all geological units in the borehole data tables	EXCEL macro	Has to be prepared	PP04
12	Calculation of the thermal conductivity and heat extraction maps	ArcGIS extension IE Geothermie	Has to be prepared	PP04
	<b>Open loop systems</b>			
13	Template to calculate potentials	EXCEL spreadsheet	available	LP