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Generalized Pan-European Geological Database for Shallow Geothermal Installations

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Received: 18 December 2017; Accepted: 17 January 2018; Published: 22 January 2018

Abstract: The relatively high installation costs for different types of shallow geothermal energy systems are obstacles that have lowered the impact of geothermal solutions in the renewable energy market. In order to reduce planning costs and obtain a lithological overview of geothermal potentials and drilling conditions, a pan-European geological overview map was created using freely accessible JRC (Joint Research Centre) data and ArcGIS software. JRC data were interpreted and merged together in order to collect information about the expenditure of installing geothermal systems in specific geological set-ups, and thereby select the most economic drilling technique. Within the four-year project of the European Union's Horizon 2020 Research and Innovation Program, which is known as "Cheap-GSHPs" (the Cheap and efficient application of reliable Ground Source Heat exchangers and Pumps), the most diffused lithologies and corresponding drilling costs were analyzed to provide a 1 km × 1 km raster with the required underground information. The final outline map should be valid throughout Europe, and should respect the INSPIRE (INfrastructure for SPatial InfoRmation in Europe) guidelines.

Keywords: GSHP systems; ground heat exchanger; ArcGIS; drillability; thermal conductivity

1. Introduction

Nowadays, geothermal energy is one of the most seminal renewable energy sources, due to its high potential and multiple uses. With the aim of both reducing the overall costs of shallow geothermal systems and improving their installation safety, a European project is recently undertaken, under the Horizon 2020 EU framework program for Research and Innovation. The "Cheap-GSHPs" (the Cheap and efficient application of reliable Ground Source Heat exchangers and Pumps) project (http://cheap-gshp.eu/) involves 17 partners among nine European countries: Belgium, France, Germany, Greece, Ireland, Italy, Romania, Spain, and Switzerland. The project is financed for four years, for the period between June 2015 and May 2019. In order to achieve the planned targets, a holistic approach is adopted, where all of the involved elements in shallow geothermal activities are integrated. Since the technical feasibility, total performance, and installation costs are affected enormously by underground properties, it is indispensable to have detailed information about these parameters. Based on information provided by the partners, drilling costs differ from country to country as a function of the maturity of the market, the soils and near-surface geology, the hydrology, and the competitiveness of the drilling companies. The general aim of the project is to reduce the overall cost up to 20%. In order to reach that goal, installation techniques on the construction site are reviewed and rectified where applicable. Also, the probe and backfilling materials will be examined in terms of cost-saving adjustments, with at least the same or better performance than standard materials. In order to reduce the drilling costs, new helicoidal and coaxial GSHEs (ground source heat exchangers) are developed within the project. These types of GSHE are expected to reduce installation costs, since they can be installed at a much shallower depth than standard double-U probes. As for double-U probes, the drilling costs reach almost 40% of total installation costs of a new geoexchange system (Figure 1) [1].

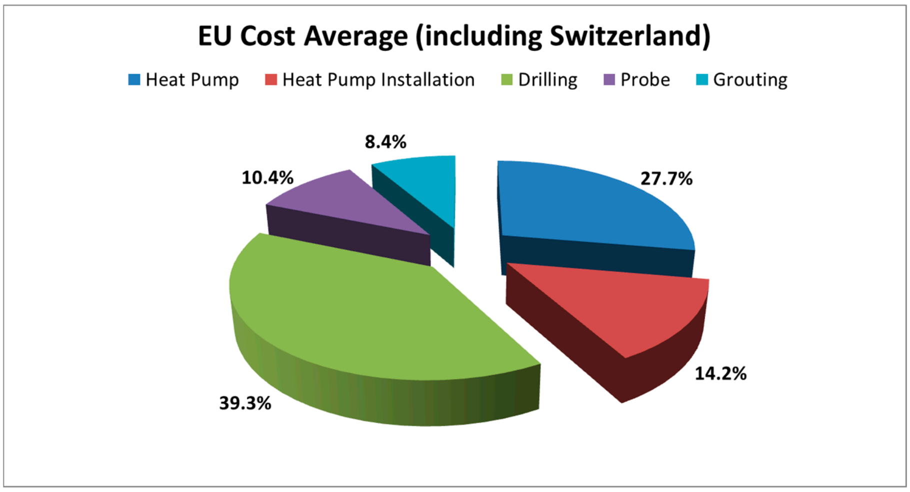


Figure 1. European average costs of a standard geothermal installation outside the house (+in-house located heat pump [1]).

Since it is very important to keep drilling costs low from an economic point of view, the drillers and planners need to have access to reliable data about the underground. This is an important challenge, as stratigraphy can be widely varied between different locations. Therefore, it is recommended to choose the drilling technique based on the physical properties of the underground to avoid extra financial burden.

To extrapolate these issues on a European scale, it is also important to provide a homogenous data set that is valid within all of the participating project partner countries to provide local predictions about expenditure. Additionally, the resolution of underground specific data sets has to be accurate. Soil and rock properties can change very rapidly within a small area. Within this project, newly developed heat basket-type GSHEs should reach around 15 m depth [2]. Hence, the challenge is to map small-scale, eventually vertical, underground variability versus a European-wide demand of data, in combination with relevant data for the improvements of the economic factors of the installation of shallow geothermal heating and cooling systems. At a later stage of the "Cheap-GSHPs" project, the final map will be implemented into the DSS (Decision Support System) of the project's homepage. Therefore, interested users can select their property's location, and the DSS will pick up the required information for its deciding algorithm. The system will recommend the best combination of GSHE, heat pump, and drilling technique, through also taking into account building-specific properties (size, insulation, materials) and the best cost–benefit ratio for stakeholders.

2. Materials and Methods

2.1. Standard Drilling Techniques and Developments

The most common drilling techniques are auger, rotary, and down-the-hole (DTH) hammer drilling. Auger is usually used for shallow drilling in clayey geological conditions with intercalations of sand and/or gravel layers. The spiral of the auger promotes the cuttings to the surface. The geological conditions define the drilling bit at the bottom of the auger. In primary clayey conditions, it is more feasible to use a drilling bit that executes sharping and cutting (e.g., drag bit, chevron bit). When using auger drilling in areas with more consolidated material, the drilling bit should be equipped with cutting teeth that have a more rupturing impact [3].

Another very common drilling technique is rotary drilling, which is based on a rotating drill stem and a drilling bit at the end of the drill rods. The drill rods are flushed with a drilling fluid, which can be water, water-based mud, air, or a mixture of air, water, and a foaming agent. The drilling fluid is ejected through nozzles at the drilling bit, and is recovered between the drill stem and borehole wall. The promoted cuttings have to settle out in a mud tank before the circulation system recirculates the fluid. The settled-out cuttings are declared hazardous waste, and have to be disposed of properly. However, rotary drilling also uses air as a drilling fluid if drilling in consolidated and/or rocky formations.

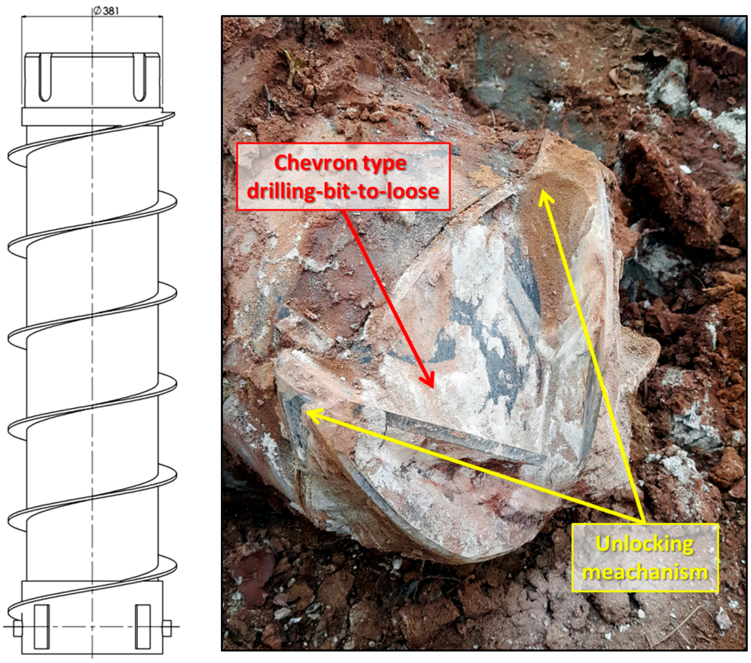
In general, there are several bits available for rotary drillings, whereas the most regular ones are tricone roller bits. Compared with other roller bits, they drill faster, with only small deviations along the vertical axis. Depending on a low, moderate, or high level of rock hardness, different designs are used for the cutting teeth, the angle of the cones compared with the vertical axis, the offset of the cones, and the dimensioning and robustness of the different bearings [3,4].

The DTH hammer system is used especially for hard, consolidated sediments and/or rocks, and provides a faster and more economical way to penetrate the underground compared with conventional drilling techniques. This technique combines hammering with the rotation of the bit. The pneumatic-driven hammer is located at the bottom of the drill stem. The efficiency of the DTH hammer depends on the air pressure that the above-ground compressor is able to supply. The compressed air is also used as drilling fluid, and promotes the drill cuttings to the surface. Small quantities of water and foaming agent can be added to the compressed air, using air water mist as drilling fluid. If dry compressed air is used as drilling fluid, a mud tank and waste disposal do not need to be provided on site [5].

Project participant HYDRA S.R.L. developed standard, easy drill technology that consists of high-tech drilling equipment with special drilling casings as drilling rods, coupled with a particular extractable drill bit that allows drilling boreholes with a diameter between 101–152 mm. The casing is designed to play a dual role: drilling tool, and casing to prevent the collapse of the borehole. This double function has been possible due to the special extractable drilling bit that can be removed at the end of the perforation, leaving the hollow passage for geothermal probes. To accomplish the bit extraction operation, a particular tool called a fishing tool is necessary. The fishing tool is connected to the winch of the machine, and is then dropped down into the hole. Then, it automatically connects to the drill bit, unlocking it from the casing. Rewinding the winch, the fishing tool will drag the drill bit out of the hole, leaving a hollow hole in the ground. Compared with other traditional drilling systems, a standard easy drill can lead to a cost reduction in terms of time, as fewer operations need to be completed.

Within the project, a new designed shallow heat exchanger (diameter 260–275 mm) was developed that allows lower drilling depths around 15 m, which reduces the time required for drilling and the amount of tools (casings, rods) used. At the same time, the helicoidal heat exchanger has a smaller diameter compared with the standard product (e.g., REHAU Helix diameter = 350 mm). This lowers the fuel consumption, as less material has to be removed.

To install the new designed GSHE, the cost-saving standard easy drill technology was modified to the enlarged easy drill technology (EEDT) within this project. The new design consists of 1500-mm long tubes (Figure 2a) with an external diameter of 356 mm. On the outer surface of the tube, a metal spiral with an external diameter of 450 mm has been welded. A drag/chevron-type drill-bit-to-loose has been designed with a low-cost manufacturing approach, and an unlocking system has been designed to unfasten the bit at the end of the drilling (Figure 2b) [6].



(**a**) (**b**)

Figure 2. Enlarged easy drill technology (EEDT) tools: (**a**) casing segment with external spiral; (**b**) drag bit-to-loose for soft, clayey geological conditions.

2.2. Data Acquisition

The main idea was to identify a European-wide valid data set with the best possible resolution. The data acquisition should provide freely available and digital data with an opportunity for modifications. The working base was selected from several data sources that are on the market with different data quality levels. The first data set was from the European 1G-E project OneGeology-Europe, which created a harmonized data model of geological maps with a scale of 1:1,000,000. The project followed the INSPIRE (INfrastructure for SPatial InfoRmation in Europe) guidelines, but a small amount of countries did not participate [7], which limited the level of accuracy and comprehensiveness. Another potential data set dealing with thermal conductivities of the underground would have been the outcomes of the European ThermoMap project [8]. Within this project, a pan-European outline map providing the very shallow geothermal potential (vSGP) was developed and expressed within *ThermoMap-MapViewer* [9]. The pedological data set for creating the pan-European outline map was provided by the ESDAC's (European Soil Data Centre) TXSRFDO (Dominant surface textural class) for STU (soil typological unit) or by national datasets for different test areas on a small-scale level. [10]

The last data sets in the collection were directly from the JRC (Joint Research Centre) of the ESDAC, which is organized under the umbrella of the European Commission. The ESDAC provides several thematic maps for soil-related data that cover Europe almost completely. There is the opportunity to access and download the European Soil Database (ESDB) v2.0 after registration. There are several groups within ESDB, which contain 73 soil-classifying attributes in total. Dominant value maps based on 1 km × 1 km raster data are selectable, as well as additionally corresponding purity and confidence level maps [10–12]. The data covers the EU28 states (excluding Iceland and Cyprus) plus

Switzerland, Norway, and the Balkans. As shallow geothermal systems could be installed within unconsolidated as well as consolidated material, the attribute group called 'parent material' was chosen. This attribute group provided information about the most common material in one spatial location. The attribute PAR-MAT-DOM1 is included in this group, which contains the SGDBE (Soil Geographical Database) codes and values for the "major group code for the dominant parent material of the STU (Soil Typological Units)". This major group code is called PARMADO1, and it is outlined in Table 1.

Table 1. Soil Geographical Database (SGDBE) values PARMADO1: Major group code for the dominant parent material.

Code	Value
0	No information
1	Consolidated clastic sedimentary rocks
2	Sedimentary rocks (chemically precipitated, evaporated, or organogenic or biogenic in origin)
3	Igneous rocks
4	Metamorphic rocks
5	Unconsolidated deposits (alluvium, weathering residuum, and slope deposits)
6	Unconsolidated glacial deposits/glacial drift
7	Eolian deposits
8	Organic materials
9	Anthropogenic deposits

The raster data were downloaded from the ESDB (https://esdac.jrc.ec.europa.eu/content/european-soil-database-v2-raster-library-1kmx1km) to set up a new geodatabase (*.gdb), and to build an ArcGIS project, focusing on geology, drillability, and shallow geothermal systems. Figure 3 shows an already existing working database for further creations of itemized maps covering almost completely the margins of the European Union. Some more peripheral areas, such as Iceland and Cyprus, are not covered within this database.

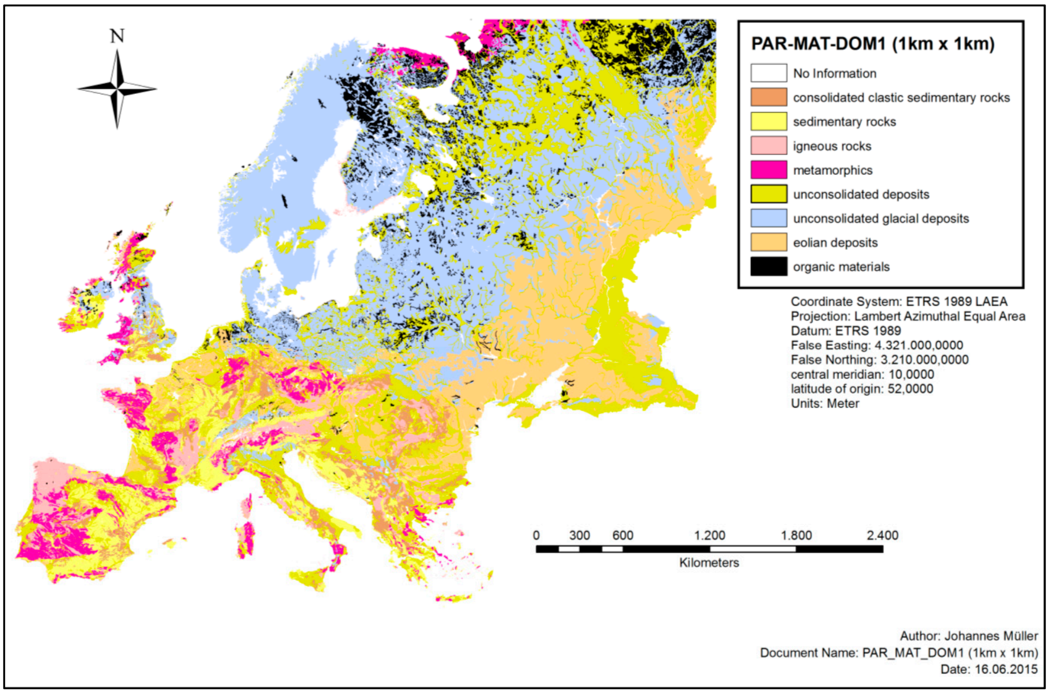


Figure 3. Major groups for dominant, parent material using attributes of PAR-MAT-DOM1, modified after van Liedekerke et al. [12].

For the ArcGIS project, there is a single shapefile provided by the ESDAC that contains all 73 soil-classifying attributes with their unique codes and values. The cell size of the grid is maintained constant, with 1 km × 1 km. For the purpose of the Cheap-GSHPs project, only two codes were extracted from the shapefile for further processing: PARMADO and PARMADO1.

2.3. Data Modification

Within a first modification, defined classes were qualified after the level of rock hardness. These descriptions were done in close collaboration with a drilling machine producer and an applied drilling specialist that were participating within the Cheap-GSHPs project. This evaluation is essentially to choose the most practical and economical drilling technique, and to avoid exorbitant costs. In order to unify the major groups of PAR-MAT-DOM1, the sediment classes were structured after their assumed degree of hardness, as shown in Table 2.

Table 2. Assumed hardness levels of PARMADO1 code.

PARMADO1 Code	Value	Level of Hardness
0	No information	No information
1	Consolidated clastic sedimentary rocks	Moderately consolidated
2	Sedimentary rocks (chemically precipitated, evaporated, or organogenic or biogenic in origin)	Moderately consolidated
3	Igneous rocks	Intensively consolidated
4	Metamorphic rocks	Intensively consolidated
5	Unconsolidated deposits (alluvium, weathering residuum and slope deposits)	Slightly consolidated
6	Unconsolidated glacial deposits/glacial drift	Slightly consolidated
7	Eolian deposits	Slightly consolidated
8	Organic materials	Slightly consolidated
9	Anthropogenic deposits	No information

Within a certain major group of PAR-MAT-DOM1, the drilling time per meter (using auger, tricone, DTH hammer, etc.) is a function of the level of rock hardness. By applying this classification, predictions are easier to perform when making simplified statements about underground properties. Finally, the end user of the DSS should receive a three-color code that depends on the underground conditions. As a result of this advantage of knowledge, they are able to receive a more detailed offer from a drilling company.

To be more precise, the data set was extended in a second step. The attribute group PAR-MAT-DOM1 was originally built up out of 212 attributes and their corresponding codes from the attribute code PAR-MAT-DOM (Appendix A), the dominant parent material. There, the corresponding PARMADO code consisted of four digits, where the first defined the associated PARMADO1 code. As an example, the transition from PAR-MAT-DOM to PAR-MAT-DOM1 is explained in Table 3.

As the stability, and consequently the drillability, of a borehole depends on the underground's hardness and grain size, the first approach—to define all unconsolidated materials as slightly consolidated—is not detailed enough to declare drillability classes. In order to provide more exact information, the major groups #5-unconsolidated deposits (alluvium, weathering residuum, and slope deposits), #6-unconsolidated glacial deposits/glacial drift, #7-eolian deposits, and #9-anthropogenic deposits of PAR-MAT-DOM1 were discarded. Furthermore, these attributes were reinterpreted within the PARMADO codes #6000 and #9300 in order to discriminate between codes that contain mostly sandy, clayey, or gravely material. The classification is now focused on the material's grain size (distribution). Also, additional properties for unconsolidated materials such as water content, bulk density, thermal conductivity, and field capacity could be assigned more specifically to a certain material class.

Table 3. Relationship between codes of PAR-MAT-DOM and PAR-MAT-DOM1.

Attribute Group *PAR-MAT-DOM* **(Group Code for Dominant Parent Material)**		**Attribute Group** *PAR-MAT-DOM1* **(Major Group Code for Dominant Parent Material)**	
Code *PARMADO*	**Value** *PARMADO*	**Code** *PARMADO1*	**Value** *PARMADO1*
6000	unconsolidated glacial deposits/glacial drift		
6100	morainic deposits		
6110	glacial till		
6111	boulder clay		
6120	glacial debris	6	unconsolidated glacial deposits/glacial drift
6200	glaciofluvial deposits		
6210	outwash sand, glacial sand		
6220	outwash gravels glacial gravels		
6300	glaciolacustrine deposits		
6310	varves		

3. Results

Hardness Map

With the focus on the state of hardness, Table 2 was integrated into ArcGIS 10.3 software. The attribute tables of the corresponding shapefile were modified to receive a three-colored map, where red stands for intensively consolidated, orange stands for moderately consolidated and green stands for slightly consolidated lithology conditions. This provides a first hint about the drillability of the material, and which drilling technique will be the most suitable for a given area. A first stage drillability map is displayed in Figure 4.

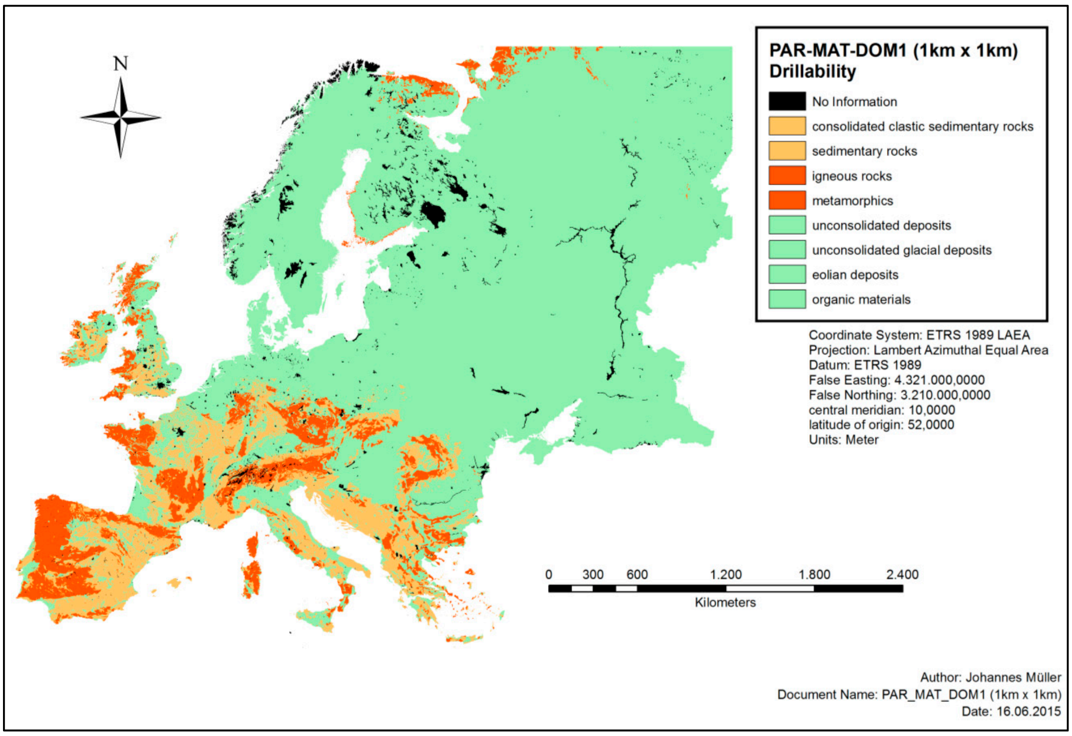


Figure 4. Drillability map using major groups for dominant parent material and using attributes of PAR-MAT-DOM1 (modified after [10–12]). Three classes of hardness: Green = slightly consolidated; orange = moderately consolidated; red = intensively consolidated.

Within the final map, which was used as a working base for the DSS of the Cheap-GSHPs project, unconsolidated sediments were distinguished between primarily gravely, sandy, or clayey material. The choice of the drilling equipment differs most from the lithology and its geotechnical properties, which are very disparate between the above-mentioned unconsolidated sediments. Further, according to VDI 4640 [13], the thermal conductivity values are different, and this crucially affects the heat extraction. Also, the type of GSHE is specified by the underground's parameter. For example, areal collector systems are usually not installed in an underground of igneous rock or metamorphic rock. However, probes or heat baskets can be installed through drillings. Therefore, the PAR-MAT-DOM attributes table was re-organized (Table 4) to provide a solution to discriminate these materials from each other, and further predict intending drilling activities at the best possible rate. The result is the attribute group FAU_PAR-MAT-CON, with its codes and values called PARMAFAU.

Table 4. Relationship between codes of FAU_PAR-MAT-CON and PAR-MAT-DOM.

Attribute Group *FAU_PAR-MAT-CON*		**Attribute Group** *PAR-MAT-DOM*
Code *PARMAFAU*	**Value** *PARMAFAU*	**Code** *PARMADO*
0	No information	0 8320 9000 9210 9220 9230 9240 9300
1	consolidated sedimentary rocks	1000 1100 1110 1111 1120 1200 1210 1211 1212 1213 1214 1215 1220 1230 1231 1300 1310 1311 1312 1320 1400 1410 1411 1412 1413, 1420 2100 2110 2111 2112 2113 2114 2115 2116 2117 2118 2119 2120 2121 2122 2130 2140 2141 2142 2150 2200 2210 2220 2230 2300 2310 2320
2	igneous & metamorphic rocks	3000 3100 3100 3120 3130 3131 3132 3140 3200 3210 3300 3310 3320 3400 3410 3411 3412 3420 3430 3431 3440 3441 3450 3500 3510 3520 3530 3600 3610 3620 3630 3700 3710 3711 3712 3713 3720 3721 3722 3723 3730 3740 4000 4100 4110 4120 4121 4200 4210 4211 4220 4230 4240 4250 4260 4300 4310 4311 4312 4313 4320 4330 4400 4410 4411 4500 4510 4520 4600 4610 4611 4620 4630 4700 4710 4720 4730
3	sand (unconsolidated)	5100 5110 5111 5120 5121 5122 5311 5321 5430 5510 5830 5831 6120 6210 7120 7200 7210 7220
4	clay (unconsolidated)	5200 5210 5211 5212 5220 5221 5222 5400 5410 5411 5412 5420 5421 5431 5432 5500 5520 5530 5610 5611 5612 5620 5621 5710 5711 5712 5713 5714 5715 5720 5721 5820 6111 6300 6310 7110 9120
5	gravel (unconsolidated)	5312 5322 5810 6110 6220 9110
6	organic material	8000 8100 8110 8111 8112 8113 8120 8200 8210 8300 8310 8330
9	unconsolidated material (undefined)	5000 6000

The final attributes group FAU_PAR-MAT-CON contains eight classes: The PARMAFAU value "no information" represents mainly lakes and rivers, metropolises, and peripheral areas such as orogens and fjords. However, undefined anthropogenic material and waste is also added to this attribute. The values "igneous & metamorphic rocks" and "consolidated sedimentary rocks" remain unchanged, and keep their PARMADO codes. "Unconsolidated material (undefined)" represents soft material, and does not differentiate between sand, clay, or gravel as the main component. All of the remaining codes and values of PARMADO were analyzed and redefined according to their grain size and expected occurrence, and were described best with a value of PARMAFAU. Finally the numerous code of PARMAFAU was transferred to the base raster grid with corresponding cell locations, and imported to ArcGIS to generate a new shapefile and produce the final version of the outline map. The final map for the dataset FAU_PAR-MAT-CON is displayed in Figure 5.

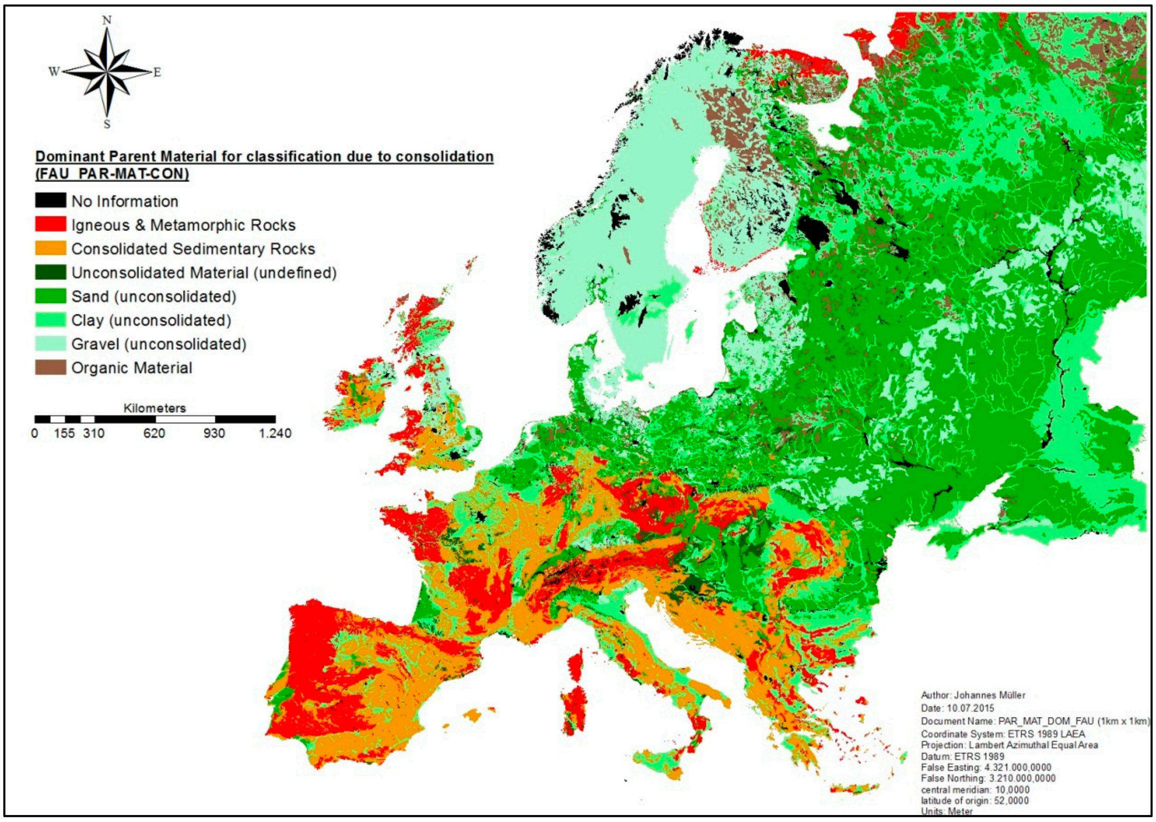


Figure 5. Map for the dominant parent material for a classification due to hardness. The map allows assertions about the level of hardness and drillability.

4. Discussion

As with every map, Figure 5 has certain limitations in accuracy when making predictions about the lithology in deeper depth regions. In fact, it cannot be ruled out that technical parameter of the lithology might change with the depth. If there are no data from outcrops, the declining accuracy has to be noted. In general, maps try to reflect a three-dimensional system on a two-dimensional image. The map provides only information about the topmost material, and does not provide information about its vertical extent. If lithology changes with depth, the drilling equipment has to be modified, corresponding to a change in hardness. Another parameter that would be very helpful for predicting heat extraction rates and defining drilling requirements is the hydrogeological information. Groundwater presence has a positive effect on the heat extraction rate of many soils and rocks, as thermal conductivity values increase with higher water content [14,15]. Furthermore, drillers and planners have to be aware of the regional groundwater situation, as confined groundwater could lead to problems during the drilling process, which causes high costs for the client or drilling company. On the other side, several technical procedures have to be implemented when drilling in areas with groundwater present. During the approval process for geothermal applications, water protection areas have to be worked out to avoid grounds for rejection, as in many countries, drilling in such areas is forbidden by law. Another important geological aspect that is not covered by the FAU_PAR-MAT-CON data set is the appearance of swellable anhydrite. These sections can lead to extreme costly events of damage (e.g., Staufen im Breisgau, Germany), as anhydrite increases its volume by about 61% if it comes into contact with (ground) water [16]. With this data set, which was generated within the Cheap-GSHPs project, an allocation of thermal conductivities for each FAU_PAR-MAT-CON class could be made according to VDI 4640, part 1, Table 1. However, this is only a rough overview, as the rock-specific thermal conductivity values cover a wide range, and the water saturation also significantly affects the thermal conductivity values.

5. Conclusions

The freely available, INSPIRE conformal, data sets collected by the European Commission via the Joint Research Centre provide a powerful working base for different kind of underground-describing outline maps. The newly created dataset FAU_PAR-MAT-CON provides two major parameters. First, it provides the drillability and hardness of the ground, which are important for defining the major cost factor of the installation of shallow geothermal systems: the drilling costs. Second, in the next step, certain lithologies can be assigned to the literature values of thermal conductivities, which allows a classification in terms of the proposed heat extraction rate. The data sets of the JRC can also be very helpful in other areas of pan-European research as well; they are not only useful for shallow geothermal issues. All of the parameters are needed within the DSS tool of the Cheap-GSHPs project in order to provide the best results for the stakeholders' planning of a shallow geothermal system. Nevertheless, given that the data and maps described here are presented at a 1 km $\times$ 1 km scale, successfully planning and installing GSHE systems will require consultation with experts who are knowledgeable in the underground properties at the site being considered. Our data and maps are intended for use in the first stage in such planning. Notwithstanding the above, this work gives a first idea of what kind of natural circumstances could occur at a certain location, and whether these could cause any difficulties during the drilling process, which could affect the total cost of the installation. Additionally, local regulations and legislations should be considered before the planning phase.

Acknowledgments: This work has received funding from the European Union's Horizon 2020 research and innovation program under grant agreement No. 657982.

Author Contributions: Matteo Cultrera, Antonio Galgaro and Giorgia Dalla Santa researched into diverse possible data sets, and with Johannes Müller and David Bertermann developed the methodology. Further they created and analysed the results. Constantine Karytsas, Dimitrios Mendrinos, Sebastian Pera, Rodolfo Perego, Nick O'Neill, Riccardo Pasquali, Jacques Vercruysse, Leonardo Rossi and Adriana Bernardi provided technical and theoretical support of data handling. Johannes Müller and David Bertermann wrote the manuscript and all authors reviewed and approved the final version.

Conflicts of Interest: The authors declare no conflict of interest

Appendix A

Table A1. PAR-MAT-DOM: Code for dominant parent material of the STU.

0	No information
1000	consolidated-clastic-sedimentary rocks
1400	facies bound rock
1100	psephite or rudite
1410	flysch
1110	conglomerate
1411	sandy flysch
1111	pudding stone
1412	clayey and silty flysch
1120	breccia
1413	conglomeratic flysch
1200	psammite or arenite
1420	molasse
1210	sandstone
1211	calcareous sandstone
1212	ferruginous sandstone
1213	clayey sandstone
1214	quartzitic sandstone/orthoquartzite
1215	micaceous sandstone

1220	arkose
1230	graywacke
1231	feldspathic graywacke
1300	pelite, lutite or argilite
1310	claystone/mudstone
1311	kaolinite
1312	bentonite
1320	siltstone
2000	edimentary rocks (chemically pre-cipitated, evaporated, or organogenic or biogenic in origin)
2100	calcareous rocks
2110	limestone
2111	hard limestone
2112	soft limestone
2113	marly limestone
2114	chalky limestone
2115	detrital limestone
2116	carbonaceous limestone
2117	lacustrine or freshwater limestone
2118	travertine/calcareous sinter
2119	cavernous limestone
2120	dolomite
2121	cavernous dolomite
2122	calcareous dolomite
2130	marlstone
2140	marl
2141	chalk marl
2142	gypsiferous marl
2150	chalk
2200	evaporites
2210	gypsum
2220	anhydrite
2230	halite
2300	siliceous rocks
2310	chert, hornstone, flint
2320	diatomite/radiolarite
3000	igneous rocks
3100	acid to intermediate plutonic rocks
3110	granite
3120	granodiorite
3130	diorite
3131	quartz diorite
3132	gabbro diorite
3140	syenite
3200	basic plutonic rocks
3210	gabbro
3300	ultrabasic plutonic rocks
3310	peridotite
3320	pyroxenite
3400	acid to intermediate volcanic rocks
3410	rhyolite
3411	obsidian
3412	quartz porphyrite
3420	dacite
3430	andesite
3431	porphyrite (intermediary)
3440	phonolite
3441	tephritic phonolite
3450	trachyte
3500	basic to ultrabasic volcanic rocks

3510	basalt
3520	diabase
3530	pikrite
3600	dike rocks
3610	aplite
3620	pegmatite
3630	lamprophyre
3700	pyroclastic rocks (tephra)
3710	tuff/tuffstone
3711	agglomeratic tuff
3712	block tuff
3713	lapilli tuff
3720	tuffite
3721	sandy tuffite
3722	silty tuffite
3723	clayey tuffite
3730	volcanic scoria/volcanic breccia
3740	volcanic ash
3750	ignimbrite
3760	pumice
4000	metamorphic rocks
4100	weakly metamorphic rocks
4110	(meta-) shale/argillite
4120	slate
4121	graphitic slate
4200	acid regional metamorphic rocks
4210	(meta-) quartzite
4211	quartzite schist
4220	phyllite
4230	micaschist
4240	gneiss
4250	granulite (sensu stricto)
4260	migmatite
4300	basic regional metamorphic rocks
4310	greenschist
4311	prasinite
4312	chlorite
4313	talc schist
4320	amphibolite
4330	eclogite
4400	ultrabasic regional metamorphic rocks
4410	serpentinite
4411	greenstone
4500	calcareous regional metamorphic rocks
4510	marble
4520	calcschist, skam
4600	rocks formed by contact metamor-phism
4610	contact slate
4611	nodular slate
4620	hornfels
4630	calsilicate rocks
4700	tectogenetic metamorphism rocks or cataclasmic metamorphism
4710	tectonic breccia
4720	cataclasite
4730	mylonite
5000	unconsolidated deposits (alluvium, weathering residuum and slope deposits)
5100	marine and estuarine sands
5110	pre-quaternary sand

5111	tertiary sand
5120	quaternary sand
5121	holocene coastal sand with shells
5122	delta sand
5200	marine and estuarine clays and silts
5210	pre-quaternary clay and silt
5211	tertiary clay
5212	tertiary silt
5220	quaternary clay and silt
5221	holocene clay
5222	holocene silt
5300	fluvial sands and gravels
5310	river terrace sand or gravel
5311	river terrace sand
5312	river terrace gravel
5320	floodplain sand or gravel
5321	floodplain sand
5322	floodplain gravel
5400	fluvial clays, silts and loams
5410	river clay and silt
5411	terrace clay and silt
5412	floodplain clay and silt
5420	river loam
5421	terrace loam
5430	overbank deposit
5431	floodplain clay and silt
5432	floodplain loam
5500	lake deposits
5510	lake sand and delta sand
5520	lake marl, bog lime
5530	lake silt
5600	residual and redeposited loams from silicate rocks
5610	residual loam
5611	stony loam
5612	clayey loam
5620	redeposited loam
5621	running-ground
5700	residual and redeposited clays from calcareous rocks
5710	residual clay
5711	clay with flints
5712	ferruginous residual clay
5713	calcareous clay
5714	non-calcareous clay
5715	marly clay
5720	redeposited clay
5721	stony clay
5800	slope deposits
5810	slope-wash alluvium
5820	colluvial deposit
5830	talus scree
5831	stratified slope deposits
6000	unconsolidated glacial deposits/glacial drift
6100	morainic deposits
6110	glacial till
6111	boulder clay
6120	glacial debris
6200	glaciofluvial deposits
6210	outwash sand, glacial sand
6220	outwash gravels glacial gravels
6300	glaciolacustrine deposits

6310	varves
7000	eolian deposits
7100	loess
7110	loamy loess
7120	sandy loess
7200	aeolian sands
7210	dune sand
7220	cover sand
8000	organic materials
8100	peat (mires)
8110	rainwater fed moor peat (raised bog)
8111	folic peat
8112	fibric peat
8113	terric peat
8120	groundwater fed bog peat
8200	slime and ooze deposits
8210	gyttja, sapropel
8300	carbonaceaous rocks (caustobiolite)
8310	lignite (brown coal)
8320	hard coal
8330	anthracite
9000	anthropogenic deposits
9100	redeposited natural materials
9110	sand and gravel fill
9120	loamy fill
9200	dump deposits
9210	rubble/rubbish
9220	industrial ashes and slag
9230	industrial sludge
9240	industrial waste
9300	anthropogenic organic materials

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