# European temperature models in the framework of GEOELEC : linking temperature and heat flow data sets to lithosphere models

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## ABSTRACT

The GEOELEC project is funded by Intelligent Energy Europe (IEE) and started in June 2011. GEOELEC aims at assessing the geothermal resources available for the production of electricity within European Union Member states and other peripheral countries. An important parameter for assessing geothermal resources at European scale is the temperature model up to 5 - 10 km depth. As part of GEOELEC, we compiled available data to construct a temperature model. At shallow depth up to 1 km, these data are relatively reliable in large parts of Europe, however the robustness of existing temperature estimation at larger depth is strongly limited, since temperature data from wells are sparse.

The temperature at depth is calculated using a forward modeling procedure that incorporates a priori temperature information available in the form of grid data. This routine is based on a preconditioned conjugate gradient method. Here the temperature is calculated using a thermal conductivity and radiogenic heat production structure in combination with boundary conditions including surface heat flow, surface temperature and Moho depth. It is shown that is possible to generate a conduction based, 3D temperature model for different boundary conditions. Fitting the radiogenic heat production to the depth of the Moho in such a way that A is equal to 40% of $Q_0$, yielded the best result in combination with the a priori temperature information.

In the this temperature model of Europe, temperatures at 5 km depth vary from 25°C in the areas of the Baltic shield and East European craton, to 340°C in Iceland, with a mean of 111°C. At 10 km depth temperatures vary from 41°C in the areas of the Baltic shield and East European craton to 686°C in Iceland, with a mean of 201°C.

The Trans-European Suture Zone (TESZ), separating Precambrian and Phanerozoic Europe, causes low temperatures to be mostly restricted to areas north east of the TESZ, while high temperatures occur mostly south west of the TESZ.

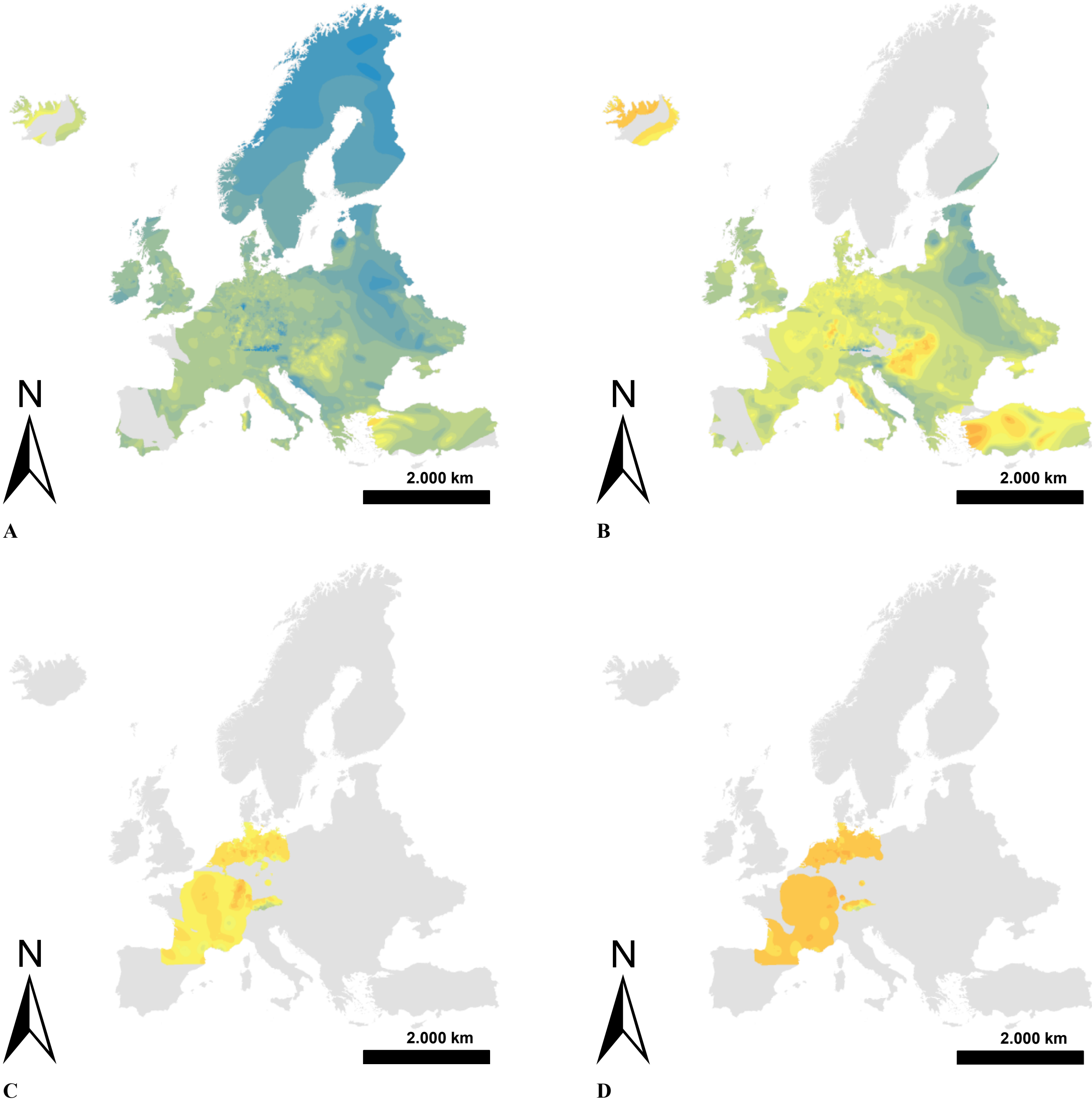
## 1. INTRODUCTION

In the last decades, breakthroughs in geothermal plant technology and innovations in the oil and gas industry have enabled the development of Enhanced Geothermal Systems (EGS). EGS can operate at lower temperatures, do not require steam and are less dependent on the natural permeability of reservoirs (Huenges (Ed.), 2010). Consequently, this development enhanced flexibility and tremendously increased the number of suitable locations for the development of geothermal systems. According to the International Geothermal Association (IGA), the global capacity of geothermal power is currently 10.7 GW and is still growing (Bertani, 2010).

As current drilling technologies improve and new drilling technologies emerge, higher temperatures at the depth interval between 5 to 10 km becomes increasingly important for EGS. For the successful development of future EGS in Europe, it is therefore crucial to better constrain these temperatures.

## 2. DATA AVAILABILITY

Since 1970, several assessments of the geothermal resources of Europe have been done. Several versions of the Atlases of Geothermal Resources in the European Community have been commissioned by the European Union. These atlases include heat flow maps, locations of temperature measurements and interpolated subsurface temperature maps of (parts of) Europe (Haenel (Ed.), 1979; Haenel and Staroste (Eds.), 1988). The most recent atlas commissioned by the EU was published in 2002 by Hurter and Haenel (Eds.) (2002) and used temperature data from Hurtig (Eds.) et al. (1992) but also included new temperature data. The temperature maps are based on Bottom Hole Temperature (BHT) and Drill Stem Test (DST) meas-



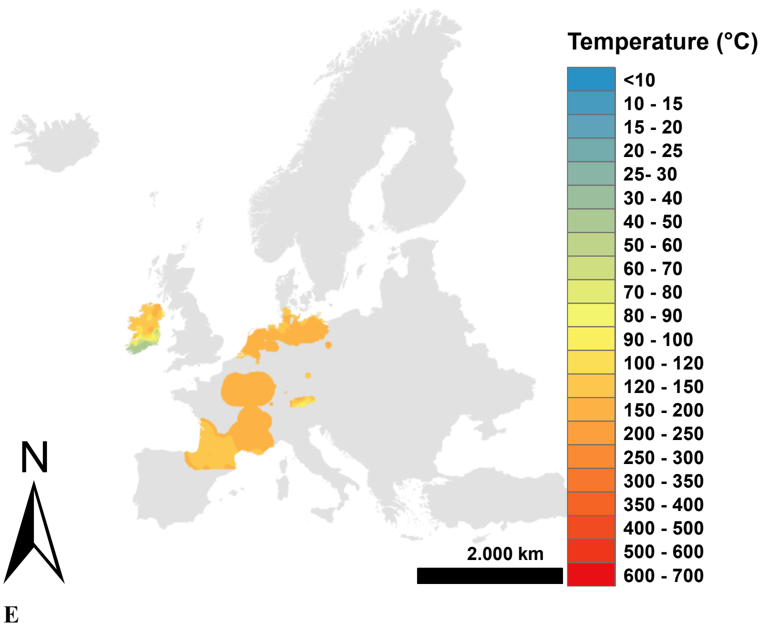




**Figure 1: A compilation of all the available subsurface temperature grids at various depths below ground level that were used as input for the modeling routine. (A) 1 km depth, (B) 2 km, (C) 3 km, (D) 4 km and (E) 5 km. Based on data from Hurter and Haenel (Eds.) (2002); Bouchot et al., 2008; Bonté et al., 2010; Agemar et al., 2012; Goodman et al., 2004; Busby et al., 2011; Bonté et al., 2012. For the Netherlands there is also a temperature grid available at 6 km depth from Bonté et al., 2012, which is not depicted here.**

urements, but the actual values are not given and only the location and depth of these measurements are included. All the geothermal atlases use ground level (GL) as datum for the depths. The depth notation used in this paper is also relative to GL unless specified differently.

Lacking the original temperature grids from the European geothermal atlases, an attempt has been made to digitize several temperature maps from the geothermal atlases for the GEOELEC project. For this purpose, hard copies of the temperature maps of 1 km and 2 km depth from Hurter Hurter and Haenel (Eds.) (2002) and 5 km depth from Hurtig (Eds.) et al. (1992) were scanned to TIF format and the temperature contours were converted to vectors. Using ArcGIS the contours were georeferenced to a WSG84 coordinate system and reprojected to a Web Mercator (Auxiliary Sphere) projection. Using the Topo to Raster function from the Spatial Analyst Tool in ArcGIS, the temperature contours were interpolated to a temperature grid with a resolution of 10 by 10 km.

From several national and regional geologic surveys TNO received temperature models, including France, Germany, Ireland, the United Kingdom and the Netherlands. Apart from the UK, which only provided a map of 1 km depth, the temperature models are relatively well constrained up to a depth of 5 km (see Figure 1). All of these models are in essence based on BHT data, but the model approaches differ.

The temperature models of France, Germany, Ireland and the UK are based on a simple interpolation and extrapolation methodology. The French and German models are based on 3D Kriging geostatistical estimation (Bouchot et al., 2008; Bonté et al., 2010; Agemar et al., 2012). The Irish model is based on natural neighbor interpolation and the deeper temperature intervals have been generated by simple extrapolation of the average geothermal gradients observed in the boreholes (Goodman et al., 2004). The UK model is based on interpolation of BHT data using a minimum curvature algorithm (Busby et al., 2011).

The Dutch temperature model uses a more advanced approach that does not rely on simple interpolation, but uses a 3-step Runge-Kutta finite difference approach with a finite volume approximation. This model approach incorporates the effects of petrophysical parameters, including thermal conductivity and radiogenic heat production, and transient effects that affect temperature such as sediment accumulation or erosion and crustal deformation (Bonté et al., 2012).

Since there are less to no data available for the depth interval between 5 to 10 km, the uncertainties in the modeled temperature at these depths are significantly higher than for the depths up to 5 km.

## 3. METHODOLOGY

For generating temperature models, a single method is used with different model assumptions and boundary conditions. The model mainly relies on temperature and heat flow values measured at the Earth's surface and on a simple distribution of thermal properties in the upper crust. The modeling routine is designed in a way that it can easily be extended with additional information like BHT measurements and existing local temperature models.

### 3.1 Modeling Approach

A forward modeling approach is used to calculate a steady state solution for the temperature. This forward model is a finite difference approximation based on a Preconditioned Conjugate Gradient method (PCG) that is used here to solve the heat equation but is more often used to solve the pressure equation for groundwater related problems (Guo and Langevin, 2002).

The discretization of the problem into a large set of linear equations allows for a computational efficient calculation of a model solution. The PCG-method is an indirect method to solve linear equations iteratively and is a good choice for large problems. The method works by the principle of convergence by solving each equation until the solution approaches a certain limit. The method uses preconditioning which constrains the problem before the equations are being solved to improve the rate of convergence.

The PCG method is used in combination with a predefined set of boundary conditions. As boundary condition for the top of the model, fixed values for the temperature are imposed, which is known as a Dirichlet boundary condition. Obviously, these fixed temperatures should be the average surface temperatures.

For the surface temperature ($T_0$), data from the WorldClim-Global Climate Database based on Hijmans et al. (2005), are used. This dataset contains mean temperatures from 24542 locations that represent the 1950-2000 time period. To correct for the topography the ETOPO1 1 Arc-Minute Global Relief Model of Amante and Eakins (2009) is used.

As boundary condition for the base of the model, fixed heat flow values are used, which is known as a Neumann boundary condition. These heat flow values are obtained by subtracting the sum of the heat production in a grid cell from the surface heat flow.

For the surface heat flow ($Q_0$), where possible, the heat flow model of Artemieva (2006) is used. The map is based on the global heat flow data base of Pollack et al. (1993), but has been updated with new borehole measurements.

To minimize edge effects along the sides of the model, values of zero heat flow are imposed, which can be considered as a special case of a Neumann boundary condition. This model calculates values for the temperature, given an initial 3D thermal conductivity and radiogenic heat production structure. The forward modeling routine is executed for different sets of boundary conditions and assumptions to generate a 3D temperature model.

### 3.2 Assumptions and Boundary Conditions

The model assumptions of the temperature model are similar as in the protocol proposed by Beardsmore et al. (2011). The methodology of the protocol was based on earlier work of Tester (2006) and Blackwell et al. (2007) and it has been used to assess the geothermal potential of the USA. When data are scarcely available it is a fast way to generate an adequate initial temperature model for a large area like Europe or the USA. It makes optimal use of data that are relatively easy to acquire and the variability of the model parameters can be easily adjusted for whenever more data are available. For this method it is assumed that heat is only transported via thermal conduction.

The model uses cells, which for the European assessment were chosen to be 10 by 10 km. Each cell consists of two layers, one that represents sedimentary cover and one that represents the crustal basement. Both layers have two thermal properties, thermal conductivity (k) and radiogenic heat production (A). Values for k and A are assigned according to the vertical position relative to the boundary between the sedimentary cover and the crustal basement. This boundary represents the depth of the sediment-basement interface (S) that divides the two layers.

The sediment thickness or the depth of the sediment-basement interface S, is created by using the sediment thickness map from the high resolution (0.25' by 0.25') EuCRUST-07 model from Tesauro et al. (2008). This model is a compilation of existing sediment thickness maps that, where possible, have been improved by using seismic profiles. Because the EuCRUST-07 model does not fully cover the area of interest, the older model of Laske and Masters (1997) is used to fill the gaps. This model is largely based on the sediment thickness from the Tectonic Map of the World, created by Exxon Production Research Company (1985).

**Table 1: Boundary conditions and assumptions used in the temperature modeling routine.**

| | Constraints | Layer | A (μW/m$^3$) | k (W/mK) |
|---|---|---|---|---|
| **A** | $T_0$ and $Q_0$ | Sediment | 1.0 | 2.5 |
| | | Basement | 2.65 | 2.14 |
| **B** | $T_0$, $Q_0$, T-models | Sediment | 1.0 | 2.0 |
| | | Basement | 2.0 | 2.6 |
| **C** | $T_0$, $Q_0$, T-models, $z_M$ | Sediment | fitted | 2.0 |
| | | Basement | fitted | 2.6 |

Three different sets of boundary conditions have been used to construct three temperature models (see Table 1). The first set of boundary conditions (model A) are equivalent to the model assumptions of the model of Beardsmore et al. (2011). A simple two layer model is defined with a sediment layer and basement layer for which average values for k and A are assigned. The geometry is based on the depth of the sediment-basement interface which is a combination of the crustal model of Laske and Masters (1997) and Tesauro et al. (2008).

The routine for the second set of boundary conditions (model B) is the same as the model A but the existing temperature models are added as hard constraints and different values for k are used. These values are believed to better reflect the geology of Europe than the values used by Beardsmore et al. (2011) for the United States. For the sediments we adopted an average value for k of 2.0. W/mK instead of the 2.5 W/mK. This slightly lower value is based on basin modeling predictions for lithologies which have not been subject to metamorphism (e.g. Van Wees et al., 2009). The value of 2.14 used by Beardsmore et al. (2011) for the basement is also changed to a higher value of 2.6, W/mK. This value is in agreement with values adopted in many tectonic studies for the European basement rocks dominated by plutonic and metamorphic rock (e.g. Van Wees et al., 2009; Cloetingh et al., 2010). A is set to a value of 2.0 μW/m$^3$ for the basement.

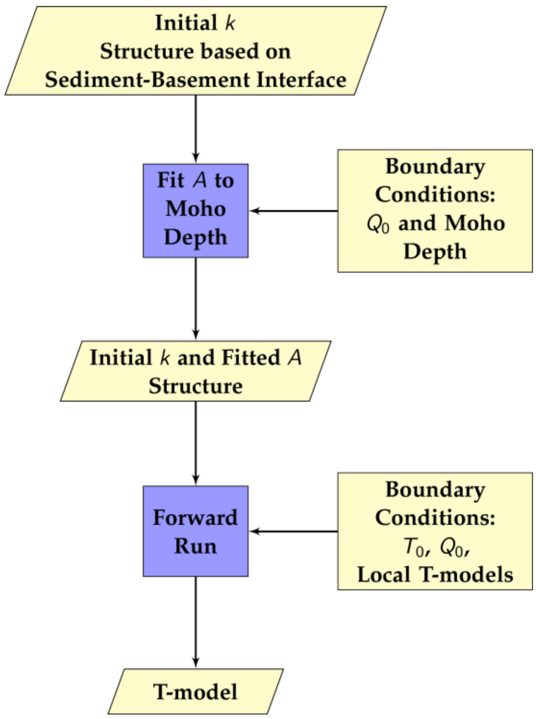



**Figure 2: Schematic workflow diagram depicting the workflow for the construction of temperature model C.**

Figure 2 describes the routine of the third model (model C), which is based on the assumption that roughly 40% of the $Q_0$ is derived from heat production in the upper crust (Pollack and Chapman, 1977; Van Wees et al., 2009; Cloetingh et al., 2010). A is fitted in such a way that the total radiogenic heat production in each column corresponds to 40% of $Q_0$ and the depth of the Moho. The Moho depth ($z_M$) in Europe varies from 15 km to 63 km and is derived from the EuCRUST-07 model from Tesauro et al. (2008). The values of k are determined in the same way as in model B. All these methods have been implemented into a Java routine that can handle the complexity involved with performing operations on large amounts of cells. This program is able to read input maps in ascii format and perform operations on these maps. The program creates voxets for k and A which are used in combination with the above mentioned boundary conditions to create a temperature voxet. A voxet is a 3D spatial distribution of the model parameters and is basically a collection of stacked grids from every depth level. Depth slices can be cut from the voxet and be converted to a grid in ascii format which can be opened in any GIS software package.

### 4. MODELING RESULTS

The outcome of the temperature modeling routine is a 3D temperature voxet which contains values for every 10 by 10 by 0.25 km cell. Depth slices of model C have been taken at depth levels of 1, 2, 3, 4, 5, 7 and 10 km (Figure 3).

In essence, all three models capture the general concept of the temperature distribution in the European subsurface. All three models show high geothermal gradients (50°C - 70°C) in volcanically active regions as Iceland, parts of Italy, Greece and Turkey. Especially in Iceland and around volcanic regions in Italy, temperatures can reach more than 300°C at a depth of 5 km and up to 700°C at a depth of 10 km. What really stands out, apart from the hot regions, is the profound division between relatively high temperatures in the southwestern part of Europe and low temperatures in the northeastern part. These colder zones are mostly constrained to the Eastern European craton and to the Fennoscandian or Baltic shield. This dichotomy fits with the Trans-European Suture Zone (TESZ), which marks a clear division between the stable Precambrian Europe and the dynamic Phanerozoic Europe (Pharaoh, 1999; Jones et al., 2010). The Precambrian zone has large lithosphere thicknesses and the Moho lies deep, while in the Phanerozoic part of Europe the lithosphere is thinner and the Moho lies more shallow.

**Table 2: Results of the temperature modeling routine for the three different sets of boundary conditions.**

| | z (km) | $T_{min}$ (°C) | $T_{mean}$ (°C) | $T_{max}$ (°C) | σ |
|---|---|---|---|---|---|
| **A** | 5 | 8 | 96 | 388 | 55 |
| | 10 | 17 | 178 | 772 | 103 |
| **B** | 5 | 16 | 105 | 388 | 56 |
| | 10 | 25 | 186 | 772 | 102 |
| **C** | 5 | 25 | 111 | 340 | 44 |
| | 10 | 41 | 201 | 686 | 75 |

From the three modeling routines, model A yields the most deviant results (see Table 2). This is in part caused by the difference in modeling routine, as model B and C use temperature grids from existing temperature models as temperature constraint. These differences are most apparent in the 1 - 5 km depth interval, since this is the interval where most temperature data are available.

The differences between the three models that can be observed in the maps are also clearly reflected in the statistics. At 5 km depth model A has a mean temperature of 96°C, with a total range that varies between 8°C - 388°C and a standard deviation σ of 55. Model B has a mean temperature of 105°C, a variation between 16°C - 388°C and σ = 56. At 5 km depth model C has a mean temperature of 111°C, a total range varying between 25°C - 340°C and σ = 44.

At 10 km depth model A has a mean temperature of 178°C, with a total range varying between 17°C - 772°C and a standard deviation σ = 103. Model B has a mean temperature of 186°C, a total range between 25°C - 772°C and σ = 102. At 10 km depth model C has a mean temperature of 201°C, a total range between 41°C - 686°C and σ = 75.

On average, model A has the lowest temperatures and the highest variability. Mean temperatures for model B are higher than model A although the variability is similar.

With 201°C, model C shows the highest mean temperatures and also has the lowest variability. The temperatures north east of the TESZ are extremely low for both model A and B. Temperatures in and around the cold spot located in Finland at 10 km depth can be as low as 8°C for model A and as low as 15°C for model B. For model C, the lowest temperatures at 10 km depth are around 40°C, which is more in line with geothermal gradients of 5°C - 10°C per km that are observed in cratons.

### 4.2 Preferred Model

From the three modeling routines model C is selected as the preferred model that will be used as input for performance assessment in the GEOELEC project. This selection is based on a number of criteria.

- The values for k used in model C (and in model B) better reflect the geology of Europe than the values used by Beardsmore et al. (2011) for the United States.

- The values for radiogenic heat production A have been fitted to the surface heat flow using the depth of the Moho. Although this yields fixed values for A for each xy-column in the voxet, it does conform to the widely used hypothesis that 40% of the surface heat flow $Q_0$ is generated by radioactive decay in the crust (Pollack and Chapman, 1977; Van Wees et al., 2009; Cloetingh et al., 2010).

- Model C uses the best and newest national temperature models available.

- The modeled minimum temperatures of model C are more in agreement with the gradients of 5°C - 10°C per km that are commonly observed in stable cratons (Neubauer., 2003).

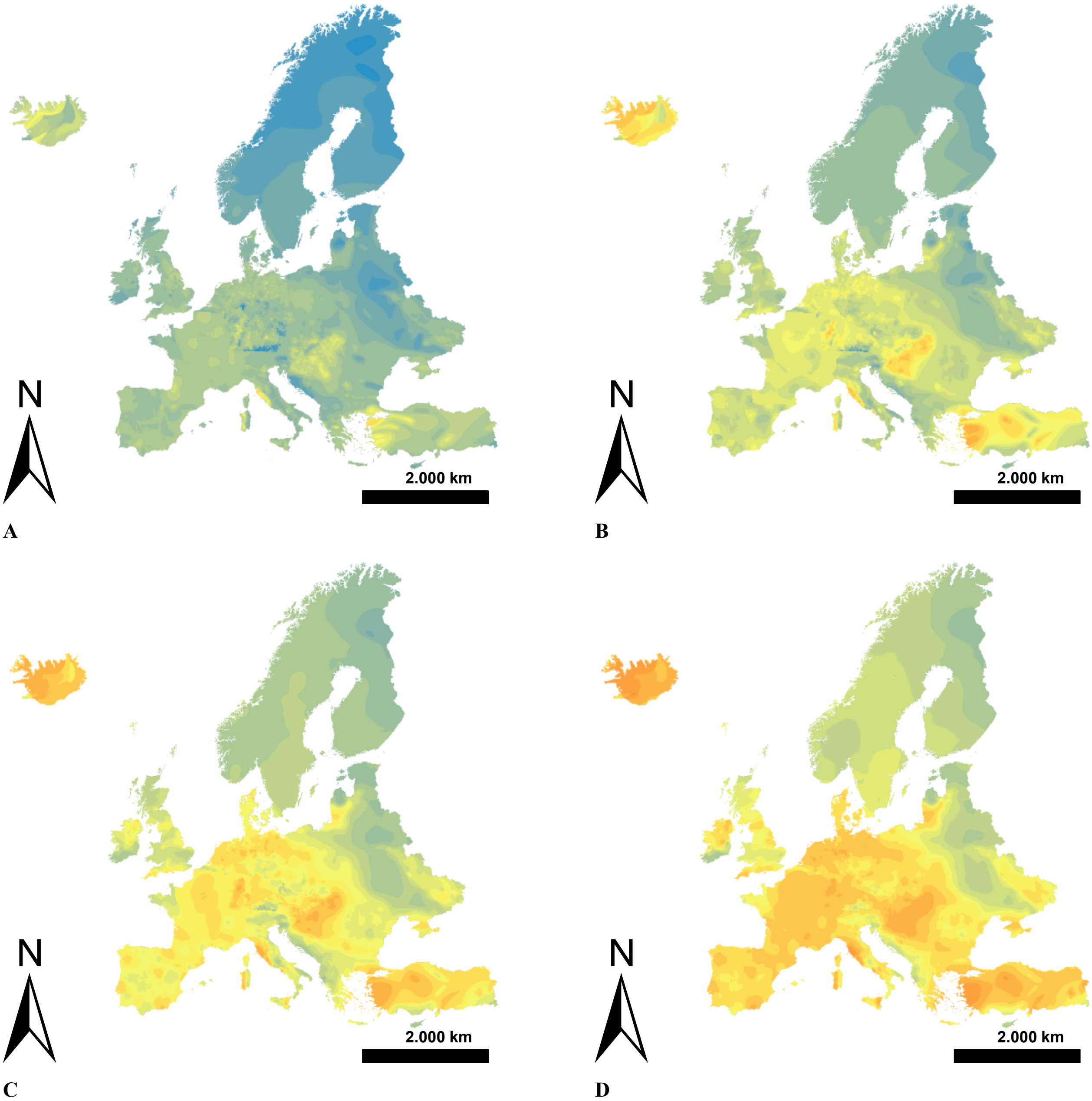



**Figure 3: Depth slices from the temperature voxet of model C taken at various depths below ground level. (A) 1 km, (B), 2 km, (C) 3 km and (D) 4 km.**

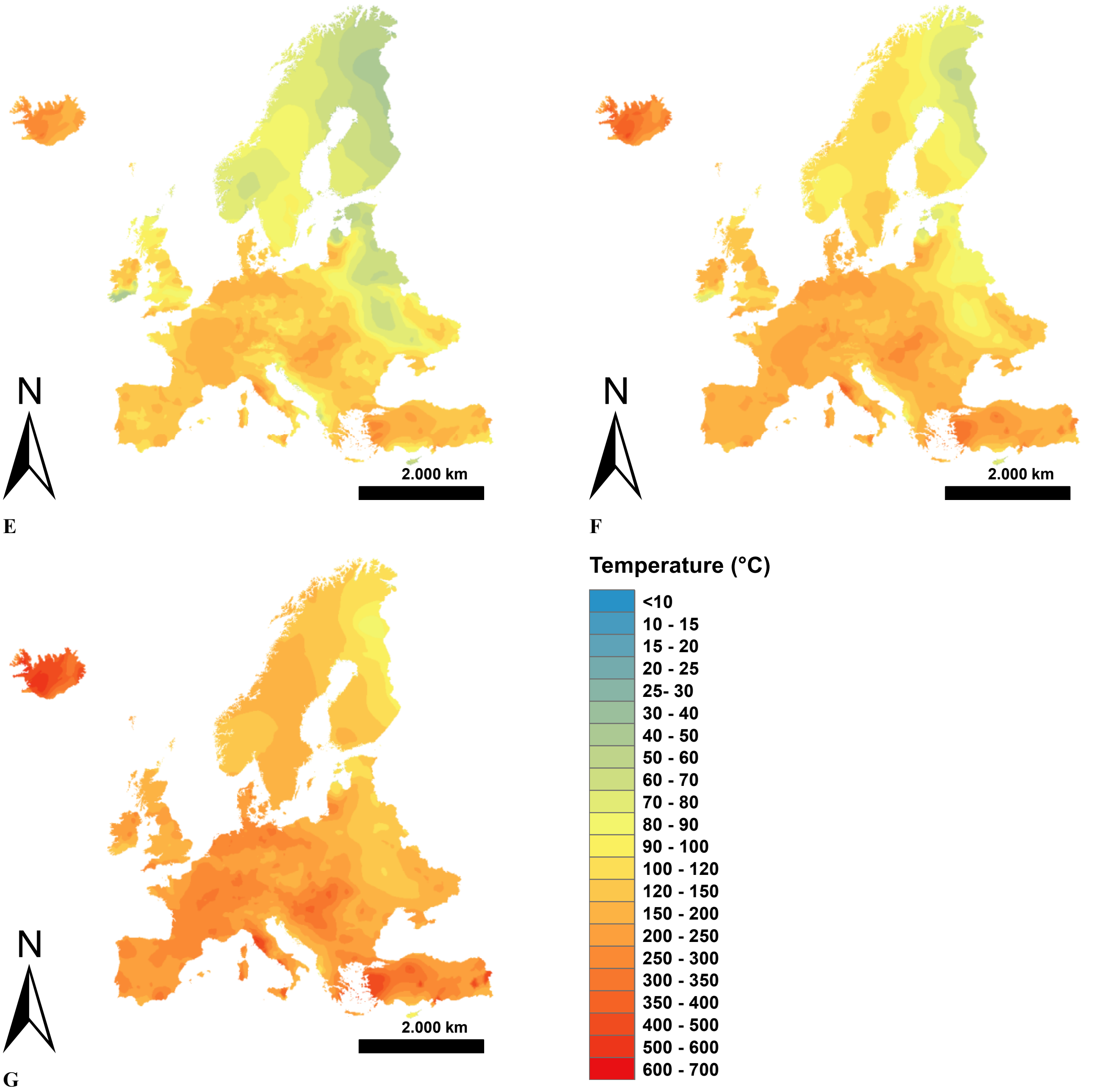



**Figure 3: Depth slices from the temperature voxet of model C taken at various depths below ground level. (E) 5 km, (F), 7 km and (G) 10 km.**

## 5. DISCUSSION

As described earlier, temperature and flow rate are the most important constraints for the development of an EGS project. These parameters are also the most uncertain since their exact values can only be determined by drilling a well.

To lower the uncertainty for the temperature, the temperature model should be improved. For this work, a simple two layer conductive model is used where values for k are distributed according to their location in respect to the sediment-basement interface for the basement. This could be improved by dividing the model into more geological layers with specific values for k and A. This has only been done for the Netherlands by Bonté et al. (2012). They constructed a temperature model to a depth of 6 km. This model has also been incorporated into the temperature modeling routine of model B and C.

Further improvements of the quality of the temperature model could be attained by building a routine that also uses the actual temperatures measured in boreholes. Our temperature model could serve as input for such an inversion routine. Brouwer et al. (2008) used a similar inversion approach to generate a 3D permeability model using actual pressure and porosity measurements from boreholes.

The successful implementation of the described improvements can only be achieved when the quality, quantity and accessibility of geological information in Europe improves drastically.

## 6. CONCLUSION

Only a few countries are able to provide temperature models to a depth of 6 km.

Fitting the radiogenic heat production to the depth of the Moho in such a way that A is equal to 40% of $Q_0$, yielded the best result in combination with existing temperature models.

In Europe, temperatures at 5 km depth vary from 25°C in the areas of the Baltic shield and East European craton to 340°C in Iceland, with a mean of 111°C. At 10 km depth temperatures vary from 41°C in the areas of the Baltic shield and East European craton to 686°C in Iceland, with a mean of 201°C.

The Trans-European Suture Zone (TESZ), separating Precambrian and Phanerozoic Europe, has an impact temperature model. In continental Europe, low temperatures are mostly restricted to areas north east of the TESZ, while high temperatures occur mostly south west of the TESZ.

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