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ATLAS OF GEOTHERMAL RESOURCES IN EUROPE: PLANNING EXPLORATION AND INVESTMENTS

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ABSTRACT

Geothermal resources for most European countries are assembled in the recently completed Atlas of Geothermal Resources in Europe. The participating countries are: Albania, Austria, Belgium, Bulgaria, Czech Republic, Denmark, Estonia, France, Germany, Greece, Hungary, Italy, Latvia, Lithuania, The Netherlands, Poland, Portugal, Romania, Russia, Slovakia, Slovenia, Spain, Sweden, Switzerland, and the United Kingdom. A volumetric heat content model for porous reservoirs assuming exploitation of geothermal energy by a doublet (production and injection wells) or a singlet (production well only) system is the basis of the resource calculation. Maps of depth, thickness, temperature and resources characterize the geothermal reservoir. The assessment methodology is simple and relies on a small number of parameters. In that way, assessments are also possible in regions of very limited data coverage. An illustrative example in the eastern North German Basin is discussed. This atlas does not replace the need for detailed local studiesof the geothermal reserves, the maps presented permit a first order evaluation in terms of technical and economic viability. This assessment procedure applied uniformly to all countries and regions permits comparisons and serves as a guide to setting priorities and planing geothermal development. This atlas also aids the search for appropriate objects for international cooperation in geothermal exploration.

1. INTRODUCTION

Heat in the upper crust of the Earth is stored in the rocks and the fluids that fill pores and fractures. Heat is transported by conductin across impermeable rocks or flows by convection with groundwater in the pores and fractures.

Geothermal energy can be extracted with a variety of technologies, although it generally involves drilling and pumping geothermal water from depth. This energy feed a great diversity of applications, alone or in combination with other sources of energy.

These two facts contribute to the difficulty in assessing and representing adequately geothermal resources. On the other hand, it is this heterogeniety which may be one of the strengths of geothermal energy application, providing various options tailored to supply specific needs and consumers.

Geothermal energy is stored in a certain concentration and fashion. This dictates the kind of possible application and extraction method. Rigorously, one would need a procedure to assess the geothermal reserves for each kind of application (doublet, heat pump, electric power generation, etc.) and each type of reservoir (e.g. porous or fractured, fluid or steam). However this approach is not very useful to gain an overview of geothermal resources at a large scale. The last decade has shown that many new, mostly low enthalpy, applications have been developed that can be installed in regions considered earlier not to have enough resource concentration to be of interest. One does not have to have a red hot anomaly on the map to be able to economically extract geothermal energy. Hotter is not (always) better!

Therefore, it is necessary to estimate the resources in such a way as not to constrain perspectives on new applications or technologies. It would be ideal to have a single procedure for assessing geothermal resources that would allow comparisons between regions and regional planning of investments in every kind of geothermal application. This has been attempted by a recently completed European project to assemble geothermal resources and present it in the form of an atlas to be released in the Fall 2000.

The representation of geothermal resources in order to allow comparisons across borders is the goal of the Atlas of Geothermal Resources in Europe, a companion volume to the Atlas of Geothermal Resources in the European Community, Austria and Switzerland published in 1988 (Haenel and Staroste, 1988). It contains updated information on geothermal resources from the participants of the first atlas and includes information of 14 new participating countries. Together these two atlases display information for 25 countries, pratically all of the European continent: Albania, Austria, Belgium, Bulgaria, Czech Republic, Denmark, Estonia, France, Germany, Greece, Hungary, Italy, Latvia, Lithuania, the Netherlands, Poland, Portugal, Romania, Russia, Slovakia, Slovenia, Spain, Sweden, Switzerland, and the United Kingdom.

Next we summarize the contents of the atlas and then define geothermal resources as applied to this atlas and describe the procedure used to represent these resources. An example from Germany is discussed and used to illustrate how this atlas might be used as a planing tool and to point out its limitarions.

2. CONTENTS OF THE ATLAS

This atlas follows closely the structure of the previous one. Overview maps at an European scale offer a context against which individual countries and regions can be set. The general information supplied by the project partners was supplemented by partial contributions of Belarus, Croatia and the Ukraine that were incorporated into these European overviews. Heat-flow density and temperature at depths of 1000 and 2000 m provide a large scale view of the thermal field, while maps depicting the locations of presently operating geothermal installations and the areas for which more detailed resources assessment can be found complete this general section.

The general section is followed by more than 500 maps at a national or regional scale. Contributions for individual countries include: Albania, Belgium, Bulgaria, Czech Republic, Denmark, Estonia, France, Germany, Greece, Hungary, Italy, Latvia, Lithuania, the Netherlands, Poland, Portugal, Romania, Russia, Slovakia, Slovenia, Spain, Sweden, Switzerland, and the United Kingdom. Geothermal springs and installations currently operating or under construction are presented on the geothermal thematic map containing the major geological and tectonic features in the background. Geological cross-sections supplement this information. A map of temperature at a depth of 500 m reveals the shallow thermal regime. Maps characterizing the geothermal potential and resources of selected aquifers form the body of this atlas. These maps include depth, thickness, temperature and geothermal resouce of the aquifer. Where available, transmissivity, piezometric head and salinity are also shown on the maps. The explanatory text and tables include information that cannot be adequately displayed on maps.

3. GEOTHERMAL RESOURCES: DEFINITION, ASSESSMENT AND REPRESENTATION

Geothermal resources are that part of the geothermal energy which might be extracted economically and legally in the near future (Muffler and Cataldi, 1978). Geothermal reserves can be exploited at present and are also part of the resources. Potential geothermal areas are regions for which the available data do not allow an assessment of resources yet.

In order to quantify the resources, the amount of heat available in the rock (geothermal reservoir) and the characteristics of the reservoir with respect to the extraction method need to be determined. There are numerous methods and models for the quantification of these resources, however, they will not be discussed here. The work of Muffler and Cataldi (1976) is a useful starting point.

The resource H_1 (in joules, J), is given by

$$H_1 = H_0 \cdot R_0 \tag{1}$$

H_0 represents the heat in place (in J) assuming a volume model of heat extraction (Muffler and Cataldi, 1978). It takes into account the heat stored in the rock matrix (m) and in the water occupying the pores (w):

$$H_0 = \left[(1-P)\cdot \rho_m \cdot c_m + P \cdot \rho_w \cdot c_w\right]\cdot\left[T_t - T_0\right]\cdot A \cdot \Delta z \tag{2}$$

where:

ρ_m, ρ_w density of the rock matrix and water, respectively, kg/m^3,
c_m, c_w specific heat capacity of the rock matrix and water, respectively, J/(kg K),
P effective porosity, unitless,
T_t temperature at the top of the aquifer, ºC,
T_0 temperature at the surface, ºC,
A surface area under consideration, m^2,
Δz net aquifer thickness, m.

The fraction of this heat capable of being extracted is R_0, a recovery factor that depends on the extraction technology used. If exploitation is made with a doublet system, i.e. with a production borehole and a injection borehole used to re-inject the fluid after use, it can be shown that (Lavigne, 1978):

$$R_0 = 0.33 \frac{(T_t - T_r)}{(T_t - T_0)} \tag{3a}$$

where T_r is the re-injection temperature. Re-injection avoids a pressure decline in the aquifer during exploitation or prevents environmental degradation of surficial water and soil due to the disposal of highly saline geothermal water. The expert group of the European Commission (EC) recomends a value of T_r = 25 ºC. This restriction cannot be applied to countries in which the mean annual temperature is low (e.g. Sweden). The same temperature difference (T_t-T_r), albeit with much lower reservoir and re-injection temperature may produce the comparable resource and exploitation possibilities as in countries of warmer climate and higher reservoir temperatures.

If the extraction of geothermal energy is planned with one production borehole only, a singlet, then the recovery factor reduces to (Gringarten, 1979):

$$R_0 \approx 0.1 \tag{3b}$$

In order to display the geothermal resources of a region a set of four maps is recommended:

1. The map of the depth to the top of the aquifer shows the range of depth variation of the reservoir. Depth is a critical parameter for evaluating the order of magnitude of the investment needed to develop the available geothermal potential, as drilling costs still make up the major part of this investment.
2. The map of the aquifer thickness indicates the size of the resource. Experience in geothermal energy applications in northern Germany indicate that aquifers of net thickness less than 20 m rarely are capable of supporting the required production rates.
3. The temperature at the top of the aquifer provides a lower bound on the range of temperatures in the aquifer, indicating what type of application may be installed.
4. The distribution of the resources over a region is shown with a map of isolines representing the resources per unit area (H_1/A, in GJ/m^2). Here the effects of all parameters in equations 2 and 3 are lumped together. It is possible to display resource information that includes confidencial data (e.g. porosity of certain aquifers) without explicitly revealing this data.

The data needed for this assessment consist of borehole information (stratigraphy, porosity from cores or geophysical logging, temperature measurements) and geophysical and geological surveys to determine structures (faults) and the spacial distribution of reservoir formations. In the procedure presented above, the resources are based on the effective porosity of the aquifer. Generally, fluid extraction is governed by hydraulic conductivity or transmissivity. However, the knowledge of these parameters requires expensive pumping tests, an investment more often undertaken in local studies for a specific location rather than for the overall characterisation of an aquifer. Information on the chemistry (salinity) of the geothermal fluid is important for evaluating the extraction technology. The need to re-inject the spent fluid can be evaluated and measures planned for preventing scaling or corrosion can be taken. Wherever available, these data have been included in the set of four maps in the atlas. Although these additional data are essential, they are frequently not available. On the other hand, porosity determinations (on cores in the laboratory or during geophysical logging) seem to be easier to secure.

4. AN EXAMPLE FOR THE BUNTSANDSTEIN IN NORTHERN GERMANY

A resource assessment for the Middle Bunsandstein formation in the eastern section of the North German Basin is presented as an illustration.

The Buntsandstein was deposited under calm tectonic conditions and represents the main subsidence episode of the North German Basin. Therefore deposits exhibit uniform lithologies and thickness over large distances. Uplifted regions to the north and to the south were the source areas of the clastic material. Coarser sandstones were deposited along the margins and finer grained sediments in the central part. Halokinetic movements of the Zechstein layers are responsible for the intense and complex deformation of Mesozoic and Cenozoic formations (DEKORP-BASIN Research Group, 1998). This tectonic disturbance strongly affects the local conditions of the geothermal reservoirs. Because of the salt tectonics, great variations of depth and thickness (locally > 1000 m) occur along short distances.

The deepest aquifer complex formed by the Middle Buntsandstein comprises four clastic units, each representing a cycle of fining upward and composed of a coarse sandstone at the base overlain by alternating sandy-silty strata.

Formation depth and thickness was obtained from borehole data. The reservoir thickness was obtained by adding up all sandstone intervals in the formation. Temperature measurements (logs and Bottom-Hole-Temperatures) where corrected for drilling disturbances whenever possible. Porosities obtained from geophysical logs were averaged and weighted according to the depth interval of measurement. Porosities from borehole cores were simply averaged. Mean porosities from geophysical logs and laboratory measurements were combined to a mean aquifer value for each borehole. Overall the mean porosity is 22 % with a range of 10 - 35 % over the region of interest. A value of heat in place per unit area (H_0/A) was computed for each borehole from equation 2.

Highly concentrated Na-Cl-brines of 150 - 280 g/l and greater can be found in the E North German sandstone aquifers. Corrosion is potentially more important than precipitation, as these waters are rich in chloride. Re-injection is compulsory for any geothermal application in this area. Therefore we assumed geothermal exploitation by a doublet and applied the corresponding recovery factor given in equation 3a, so that. a value of H_1/A was obtained for each borehole.

Gridding and contouring was accomplished with an algorithm that puts a continuous curvature surface in tension through the data (Wessel and Smith, 1995) resulting in the maps of depth to the top of the reservoir (Fig. 1), cumulative sandstone thickness, i.e reservoir thickness (Fig. 2), temperature at the top of the reservoir (Fig. 3) and resources (Fig. 4). The data was not extrapolated to depths greater than borehole depth. The local discontinuities due to faults are not considered explicitly for isoline tracing. Therefore, the isolines on the maps are a smooth version of reality based on borehole data. Especially in this region, local studies are necessary in order to better constrain the geometry and dimensions of the aquifer and characterise its engineering characteristics.

Because of the salt structures, depth to the top of this aquifer varies laterally from about 60 m to more than 3500 m (Fig. 1). The thickness of the aquifer (i.e. of the sandstones within the formation) is also highly variable (from 0 to 500 m), about from 100 to 360 m in the area depicted in Fig. 2. As shown in Fig. 3, temperature ranges from 20 ºC to almost 140 ºC.

5. HOW CAN THE INFORMATION IN THE ATLAS BE USED ?

Now we will take the example described above to discuss how we can interprete and use this information. The atlas is not a tool to determine drilling sites for geothermal installations. Rather, it should be employed in activities preceeding the targeting of drilling for geothermal purposes. It serves as a guide to set priorities for future investements in local studies and in delineating target areas for these investments.

As a first step we look at the map of resources (Fig. 4) against the distribution of potential consumers, here represented by the cities included in the map background. The best distribution of resources (> 2.5 GJ/m^2) is found in the south-west of the map, close to the ficticious cities A and B, indicated by letters in the red squares. The temperature map indicates that values of about 115 ºC and 120 ºC can be expected for A and B, respectively. The temperature at both sites is sufficient for a centralized hydrothermal space heating unit. The aquifer is 360 m thick at A, while B overlies more than 420 m of it. This indicates that the reservoir is large enough to support a major geothermal application similar to already operating ones in the region (Clauser, 1997), if the hydraulic properties are found favorable in some future local study. The map of depth to the top indicates investment in A (2200 m deep) would be more expensive than in B (1600 m deep), because one needs to drill deeper to reach the aquifer. B becomes our preferred site for a more detailed local study.

The information in this atlas is displayed in such a form, that decision makers at all levels can understand and use the information therein. The mayor of city B, together with local companies may then search for a partner from another European country with similiar geological setting to pool resources for a joint venture. Government authorities may use the atlas as an aid to ranking different regions for planing geothermal development. We stress again, that no decision on building a geothermal installation can be made on the basis of this atlas without a thorough local study.

6. DISCUSSION

The resource evaluation procedure used for compiling the present atlas is simple and requires generally available information. It does, however, not consider the critical conditions needed for sucessful extraction of the resources. Exploitation of geothermal resources is pratically determined by the permeability of the aquifer, which constrains production rates. Permeability data and pumping test results are only available for specific areas. It would not be possible to obtain assessements for most of Europe based only on such data. Furthermore, permeability may vary over several orders of magnitude within short distances with almost unpredictable consequences for the exploitation. Even if our resource assessment were to include permeability and more sophisticated models, it would still not allow predictions about the system. The atlas does not explicitly account for the availability of consumers for the resources presented. However, background information on the maps, such as cities, provides an indication of potential consumers.

Both atlases contain a selection of material. Format constraints of the hardware (paper with a determined page size) and financial limitations mandated a certain choice, which is, in some cases, not the choice of preference of the the editors nor participating countries. The material included there does not exhaust all knowledge on geothermal areas. The electronic media of representing such endevours in the future will do much to lift some of these limitations.

The geothermal resource assessment procedure adopted for the Atlas of Geothermal Resources in Europe does not invalidate other methods of resource evaluation and may even be considered inferior to other methods. However, at present, it is still the only manner to display resources from Portugal across to Russia on a comparable basis.

7. OUTLOOK

Exploitation technology will develop and hopefully be capable of overcoming some of the geological constraints to the use of geothermal energy, so that applications may be placed closer to the consumer. The first glimpse of such a development is seen in the present Hot-Dry-Rock technology of enhancing permeability with hydraulic stimulation. Where previously there was only a marginal possibility to install a geothermal application because of low hydraulic conductivity, hydraulic stimulation (hydrofracs) may open needed pathways.

Another important consideration is the optimization of exploitation. Careful monitoring and research to gain detailed understanding of the geothermal reservoir in the Paris Basin (Demange, et al., 1995) has led to more geothermal energy being exploited from the same resource, although the number of wells tapping the system has slightly decreased.

The current trend to a global economic system will reinforce the need to carry out further comparative resource assessments.

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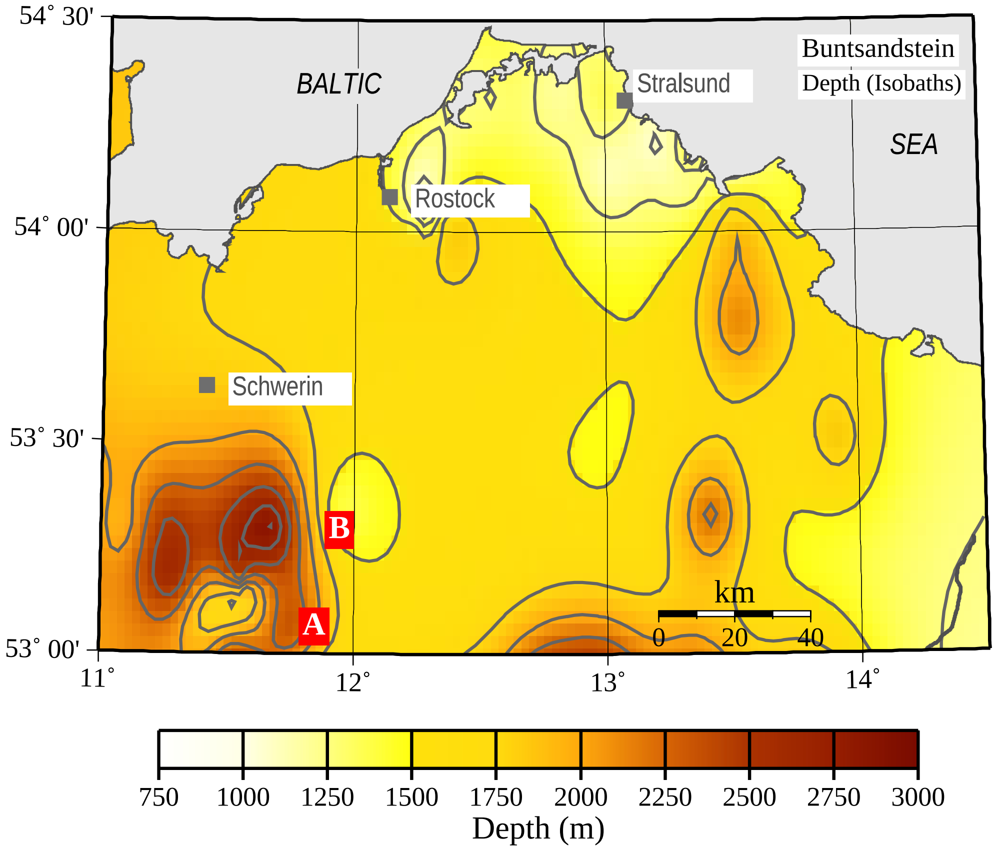

Fig 1. Map of depth to the top of the Middle Buntsandstein aquifer. Isoline interval is 400 m. Black dots represent the borehole sites from which data was obtained. A and B are ficticious cities for which resources are compared in the text.

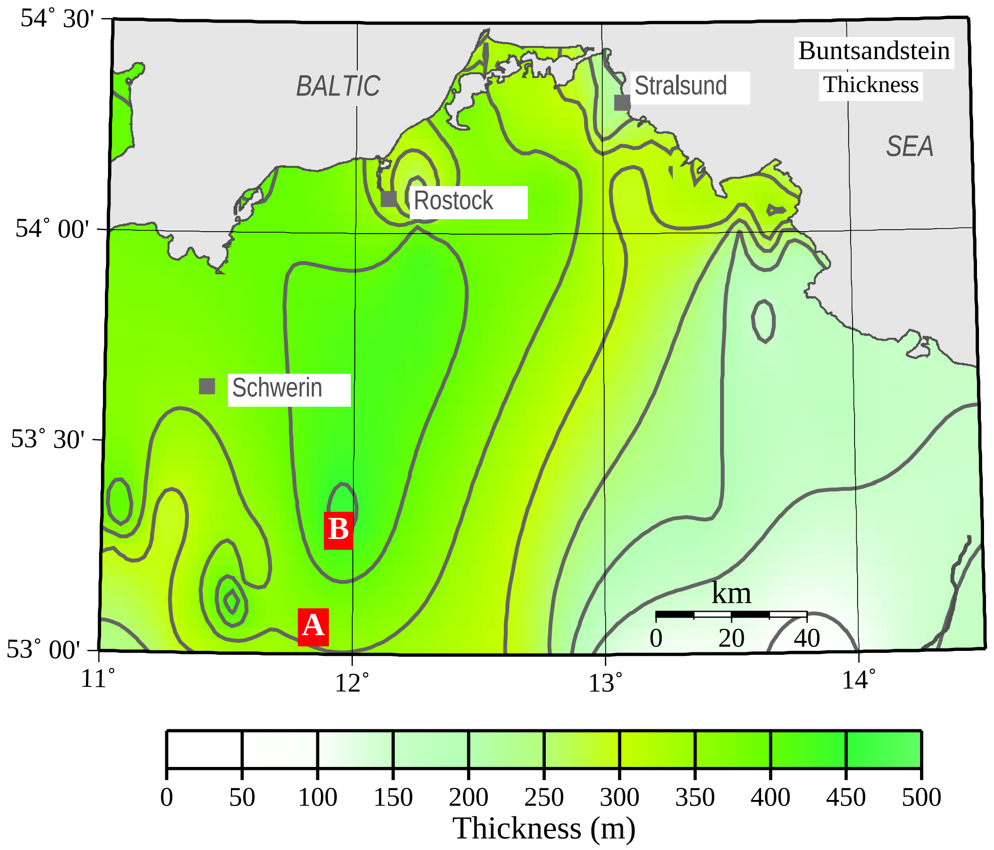

Fig 2. Map of accumulated sandstone thickness for the Middle Buntsandstein aquifer. Isoline interval is 40 m, other symbols like in Fig1.

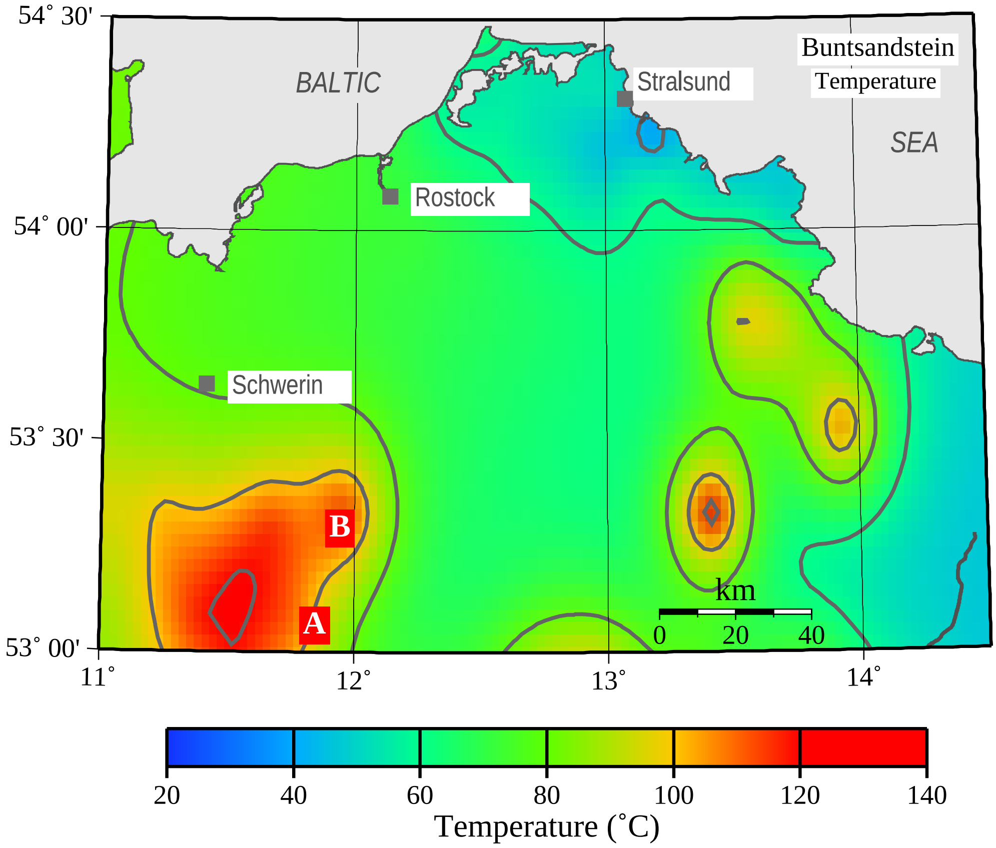

Fig 3. Temperature at the top of the Middle Buntsanstein aquifer. Isoline interval is 5 °C, other symbols like in Fig 1.

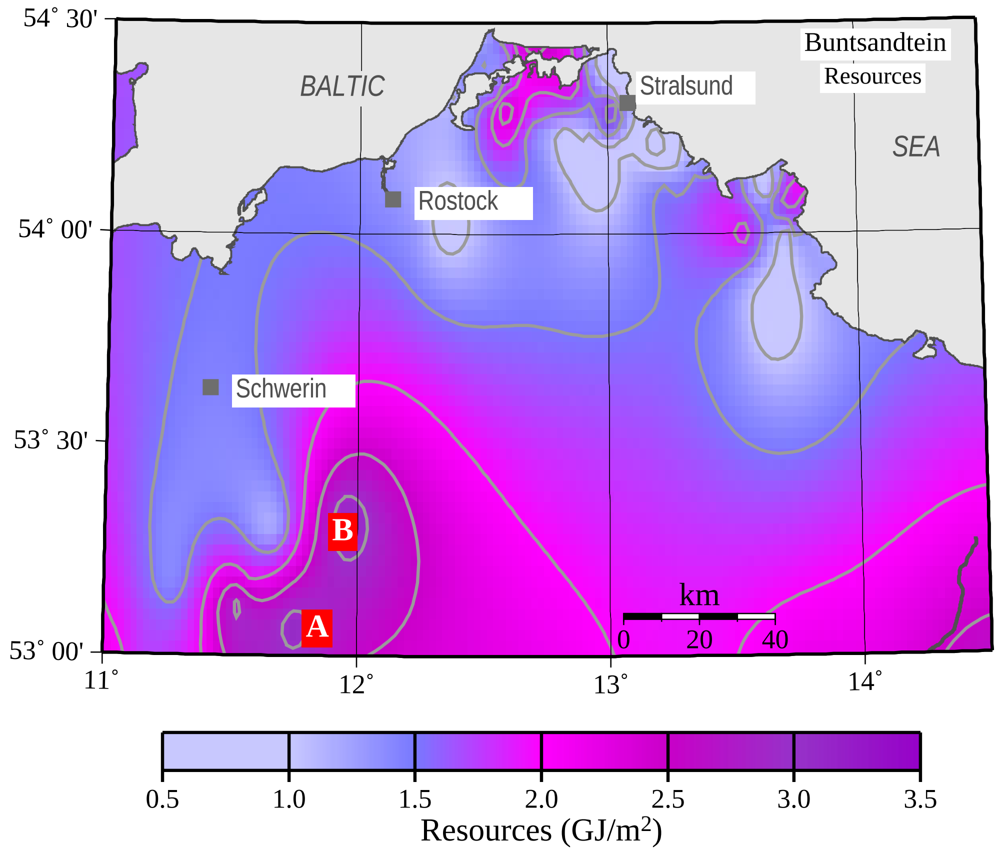

Fig 4.Map of geothermal resources for the Middle Buntsanstein aquifer. Isoline interval is 0.5 GJ/m^2. Other symbols like in Fig 1.