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Integrative Geothermal Resource Assessment of the Swiss Molasse Basin

T. Kohl[1], E.Schill[2], and C. Baujard[1]

[1] GEOWATT AG, Dohlenweg 28, CH-8050 Zurich, Switzerland

[2] Laboratoire de Géothermie, Université de Neuchâtel, Rue Emile Argand 11, CH-2009 Neuchâtel, Switzerland

info@geowatt.ch

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ABSTRACT

Quantification of technically usable geothermal resources of a nation has got a main factor for the planning of future energy scenarios. In the past, the resource analyses were merely based on measured and forecasted temperature distribution in subsurface. Currently, advances in computing and modeling allows the regional consideration of thermal effects (i.e. topography, 3D geology, transient effects, .) in the calculation of the subsurface temperature fields. In the assessment of the Swiss geothermal resources, the hydrogeological conditions were additionally included into the evaluation scheme. This resulted in a dynamic approach to forecast the possible geothermal productivity over a 30-year life span of a geothermal utilization scenario. Purely on the basis of measured data and numerical interpretation, the temperature field and the hydraulic transmissivity of the most important hydrogeological structures have been regionally assessed. Using these two key parameters the possible geothermal productivities were predicted for the Swiss Plateau, which represents the major populated area in Switzerland. Herein, the following aquifer systems of the Swiss Molasse Basin were considered: Upper Marin Molasse, Upper Malm, Upper Muschelkalk and fractured top crystalline basement. In each of these systems, the fault and fractured zones got special attention.

The results from the geothermal resource assessment, elaborated between in the period 2000 and 2006, were now compiled in a uniform procedure to evaluate the possible areal suitability for a geothermal production. The interest of this study was to define areas for possible waste scenarios that will not conflict with future geothermal production. In this integrative approach the economic analysis for geothermal production is only of little interest since the investments required in future production is presently unknown. However, geothermal production will continuously focus on reservoirs that are accessed easier and cheaper than others. To determine possible geothermal utilization at arbitrary locations of the Swiss Molasse Basin for future production a cost model was taken that considers linearly increasing drilling costs with depth. Necessary investments for infrastructure, buildings or heat exchangers were taken to be identical. The results of this investigation are expressed by an areal distribution of a normalized productivity. Especially the areas of Northern Switzerland like the Cantons of Thurgau, Zurich and Aargau seem to be well suited for future production. In the western part of Switzerland elevated values are reached in the Canton of Vaud.

1. INTRODUCTION

The basic factor of a geothermal resource analysis is the quantification of the available heat in a defined volume, the so-called heat in place (Muffler and Cataldi, 1978). Since this value depends mainly on temperature, the heat in place generally increases linearly with greater depth. Analyses for a geothermal resource result in huge theoretical values that can however not be taken as representative value on possible production of heat and power since technical and economic viability are not considered. Taking into account the limitations on drilling, stimulation capacities or geological conditions to extract fluid from deep subsurface, the so-called technical potential is derived. It includes only a part of the total resource and is often described by a recovery factor, R, (Nathenson, 1975). It accounts for the technical production possibilities that depend on the reservoir type, the state of development of exploitation methods. R can be described as the ration between technical usable and theoretically available energy. Most natural geothermal resources have rather small recovery factors. The analysis of operation data yields values between 8% and 21% in highly convective areas in the Western states of USA (Williams, 2004). For resources in Germany values between 5.6% and 7.3% have been forecasted under conductive dominated conditions (Jung *et al.*, 2002). However, the technical potential itself does still not include economic viability of a system. Real systems are strongly based on the character of a geothermal resource such as on transmissivity of fracture zones, mineralization of pore fluids and production technologies. The remaining part is then characterized as the economic potential of a geothermal resource. It should however also include long-term effects on sustainable production.

Earlier studies have calculated the technical potential of direct use in Europe (Haenel and Staroste, 1988) and on electricity production in Germany (Jung *et al.*, 2002). Herein, classes of temperature distribution and a recovery factor have been used resulting in different determination of resources according to geometry, thickness and areal extension. It was thus estimated that crystalline rock includes 95%, fault zones 4% and deep aquifers approx. 1% of the technical potential (Paschen *et al.*, 2003). In contrast to this parameterization, the real producible energy assuming an operation with doublet systems have been estimated for the German Molasse Basin (Schulz and Jobmann, 1989) assuming a pre-defined grid of doublet systems. New geothermal resource assessment include hydrothermal and EGS (Enhanced Geothermal System) projects (Sanyal, 2005; Sanyal and Butler, 2004; Sanyal et al., 2004). Sanyal (2005) proposes a further classification of resources depending on temperature and operational type (heat or electricity production). Based on the inversion of thermal and hydraulic parameters from calibration wells with measured data on temperature and flow rate a geothermal raster analysis is developed to determine the potential for individual reservoir classes such as deep aquifers, deep fault zones and crystalline basement (Rath and Clauser, 2005). The resulting parameterization of subsurface has been included into large-scale coupled hydrothermal models to identify convective systems that are of major importance for geothermal utilization.

The analysis of the geothermal resource in the Swiss Molasse Basin has been carried out under the objective to describe as closely as possible the economic potential. Herein, the productivity of individual operation types are foreseen, the productivity of a plant depends on the operational parameters as temperature and flow rate and includes a 30 year life span of production (Gringarten, 1978). As expected, the two key parameters temperature and transmissivity of the aquifer types are most important for an economic viability. The studies were summarized in reports on the northern part of the Swiss Molasse Basin (Signorelli and Kohl, 2006) and on the Western Part (Baujard *et al.*, 2007). Both include the quantification of the productivity of individual plants and on the total energy extracted of the assumed 30-year life span on an economic system assuming maximum pumping pressures. In addition to other geothermal assessments, this dynamic assessment includes also the necessary operation conditions on sustainable production.

The goal of the present study is to integrate the earlier findings on individual aquifer types. The result of this investigation should identify zones for possible waste scenarios that will not conflict with future geothermal production in the same area. Therefore, the individual aquifers types were comprised by a geological and economical description.

2. GEOLOGY OF THE AREA OF INVESTIGATION

The area of investigation includes mainly the geological units from the Swiss Molasse Basin but also the neighbored areas from the Tabular- and Folded Jura Mountains, the pre-Alpine mountain range and the Rhinegraben. Underneath the molasse sediments different Permo-Carboniferous troughs were identified in seismic sections (Diebold, 1989, Signer and Gorin, 1995, Marillier *et al.*, 2006). These graben structures formed in an extensional regime during Variscian time bound by normal faults, which caused strong fracturation of the pre-Variscian basement. During Permian time, the troughs were filled with sediments. It is assumed that these trough structures extend to the southern folded Jura Mountains (Laubscher, 1985, Philippe, 1995, Philippe *et al.*, 1996). The overlying Mesozoic sediments include mainly carbonates and mudstones and they dip with a few degree towards the Alps (Müller *et al.*, 2001, Marillier *et al.*, 2006). During the upper Muschelkalk, well-layered dolomitic limestone was deposited (Müller *et al.*, 2001). Fracturation and karstification improved their hydraulic conductivity. The limestone of the middle and upper Dogger, which increase in thickness towards the west, is considered a regionally significant aquifer in the central and western Jura Mountains (Wilhelm *et al.*, 2003).

In the middle Oxfordian different facies are observed in the Malm Sea with shallow reefs in the North western part and clay and limestone in the southeast, i.e. in contrast to southern Germany, the middle Oxfordian of the “Plateau Suisse” is generally less relevant for geothermal utilisation. Here the permeable limestone is limited to the Upper Oxfordian, the Kimmeridgian and the Portlandian. A general karstification of the Mesozoic sediments down to the Oxfordian represents an erosion phase lasting form the upper Cretaceous to the Oligocene. The Mesozoic sediments to the south of the Black Forest are offset along NNE-SSW faults, which were formed during the subsidence of the Rhine graben from the Oligocene on. In the folded Jura Mountains fold axes strike E-W in the Eastern part to NE-SW in the Western part.

The sedimentation of the Molasse basin occurred in four major steps: 1) lower marine Molasse, 2) lower freshwater Molasse, 3) upper marine Molasse and 4) upper freshwater Molasse. The sedimentary layers generally dip to the SE and their thicknesses increase with proximity to the Alps as source area.

3. RESOURCE ASSESSMENT

The methodology of the resource assessments (Baujard et al., 2007; Signorelli and Kohl, 2006) is based on the volumetric heat in place, HIP evaluation (Muffler and Cataldi, 1978). The dynamic approach that derives the technically usable energy over a 30-year period is based on the calculation of the hydraulic yield from selected aquifer systems (Gringarten, 1978). Herein the transmissivity values are purely taken from measured borehole values. the derived Recovery Factor, R, thus corresponds to the ratio of the totally produced energy over the 30-yr life span to the stored HIP energy. Resource depletion was assumed to be due to today's technically realizable doublet plants that include stimulation measures. In contrast to other studies (Jung *et al.*, 2002) future concepts like Hot Dry Rock-plants will obtain rather low perspectives due to a low natural transmissivity. The calculation of productivity in individual approx. 30 x 30 km^2 areas is performed using the following steps:

Model of regional significant geologic units and assignment of the petrophysical parameters: Due to the regional scale the geologic concept has to be limited on large-scale geothermal relevant structures. They constitute the basis of the structural geological 3D model. It includes especially the limiting surfaces of each considered unit. The model is realized using the software package GOCAD that interpolates the geological structures with the Direct Smooth Interpolation (DSI) Algorithm (Mallet, 1992). It basically uses triangulated surfaces that account of predefined geological boundary conditions such as borehole data and interpreted seismic profiles. Individual weighting factors accounts for different data quality. The structural 3D model was discretized in a tetrahedron FE grid using the plug-in TGridlab (Lepage, 2003) and additional test software. The petrophysical parameters were like thermal conductivity, specific heat capacity and heat production were assigned according to the Swiss geothermal data base (Schärli and Kohl, 2002) and the data bank of the Swiss Molasse (Leu et al., 1999).

Determination of potential hydrogeological relevant aquifers: Only aquifers between 200 and 5000 m depth have been considered. They represent defined resource classes II (depth above 200 m and temperatures below 100°C) and III (temperatures above 100°C and depths < 5000 m). The measured data from various aquifer systems indicate mostly a strongly varying permeability even in the same geologic unit. In Northern Swiss Molasse Basin the following units are known for significant permeabilties: Upper Marin Molasse, Upper Malm, Upper Muschelkalk and fractured top crystalline basement (Müller et al., 2001; Rybach, 1992). In Western Switzerland the Upper Marin Molasse has only little coverage but the Dogger aquifer is more significant. Porosity and permeability within the same formation generally reduce with depth and towards the Alpine front (Keller, 1992). However, re-interpretation of crystalline data does show - if any- only weak correlations. Most of the hydrogeological data have been presented in various technical reports for the Swiss nuclear waste research

(Nagra, 1985; Nagra, 1989; Nagra, 1990; Nagra, 1991; Nagra, 1991; Nagra, 1992; Nagra, 1992).

Evaluation of measured temperature data: The temperature data have been analyzed in dependence of depth and quality by a numerical thermal simulation. In the calibration procedure only undisturbed measurements have been used (Schärli and Kohl, 2002). However, the quality of the partly quite old measurements depends on the method applying a ranking ranging from best quality for continuous HRT logs over HT measurements during hydraulic testing to BHT measurements. The calculation of the temperature field was strongly focused on aquifer and fault zones. Here, the numerical tetrahedral mesh was also most refined. The simulation was performed assuming a transient diffusive thermal regime:

$$\rho\, c_p \frac{\partial T}{\partial t} = \nabla \cdot \left(\lambda \cdot \nabla T\right) - A \qquad (1)$$

with temperature T [K], time t [s], density ρ [kg m^{-3}], specific heat capacity c_p [J kg^{-1} K^{-1}], thermal conductivity λ [W m^{-1} K^{-1}] and heat production A [W m^{-3}].

The effect of ice-age induced cooling was considered to reliably extrapolate temperatures to greater depth. Heat transport by advection has been only considered locally when measured temperatures cannot be explained by diffusion.

Evaluation of geothermal productivity of individual aquifers: The thermal productivity of the considered geothermal relevant structures are evaluated combining the hydraulic solution of Gringarten (1978) for a doublet system with the above described temperature assessment. Thereby the technically usable productivity can be calculated from:

$$P_{THERM} = \left[\rho c_P\right]_f \cdot Q \cdot \left(T_{PROD} - T_{REINJ}\right) \qquad (2)$$

with production temperature T_{PROD} [K], reinjection temperature T_{REINJ} [K], flowrate Q [m^{-3}/s] and heat capacity of produced fluid $[\rho\, c_P]_f$. Reinjection temperature depends on the considered utilization scenario (pure heat, combined heat/power production, .)

This concept for resource assessment allows for a representation of the productivity and the energy produced from a hypothetical plant on a graphical map scale. Herein, a typical geothermal utilization with an equilibrated balance between injection and production along a 30-year production perios is assumed. The lateral extension of the involved subsurface flow pattern determines the possible number of plants. The distance between the boreholes, d, is optimized from the hydraulic solution (Gringarten, 1978). Within the assessment scheme, an economic utilization requires a minimum distance of d = 200 m. The maximum possible distribution of the plants could rise as much as 25% of the theoretically possible distribution.

4. RESULTS

4.1 Depth and Hydrogeological Properties of Geothermal Relevant Aquifers

The assessment assumes a possible 500 m vertical extension of the fractured crystalline rock. The top crystalline dips towards the Alpine front and varies in the Swiss Molasse Basin from 0 m (at the Black Forest) don to approx. 6000 m at the Alpine Front. At the center of the Permocarboniferous trough a depth of 4000 m was taken. On the basis of mostly Nagra investigations the hydraulic conductivity of the rock was determined be K=5·10^{-8} m s^{-1} (characteristic median value). It needs to be noted, that the available investigations focus on Northern Switzerland. The Alpine reactivated faults zones can extend to surface through the thick molasse overburden. Their hydraulic conductivity was limited to K = 10^{-7} m s^{-1} in agreement with Nagra investigations (Thury et al., 1994). The strongly fractured crystalline units in Northwestern Switzerland got attributed a mean value of K=8·10^{-8} m s^{-1}. For the geothermal exploration of a reservoir a possible increase of ambient hydraulic conductivity by a factor of "10" was assumed in the crystalline. A lower stimulation factor of "2.5" was attributed to the sedimentary units.

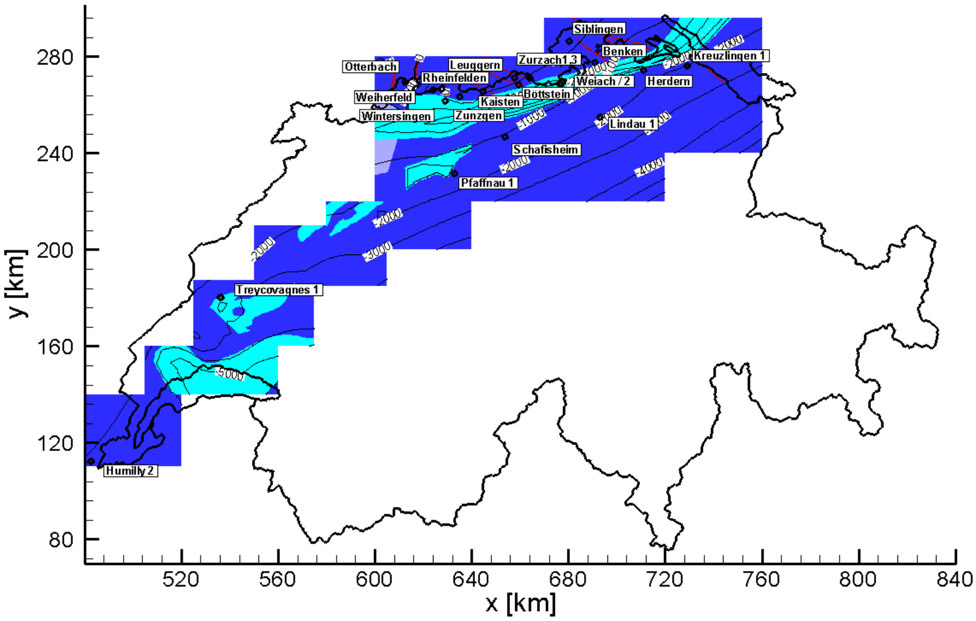

Figure 1: Area distribution of top crystalline in the Swiss Molasse Basin. The overburden constitutes mostly of Mesozoic units and Tertiary Molasse layers. Crystalline with blue color represents this "normal" situation. Crystalline in cyan color indicates possible Permocarboniferous troughs. Towards the North red lines identify large fault zones with increase conductivity.

The depth extension of the sedimentary aquifers is limited of course by the crystalline. As such Upper Muschelkalk reaches maximum depths of 4500m b.s.l., the Upper Malm depths of 4000m b.s.l. and the Top Upper Marin Molasse reaches depths of 350 m b.s.l. In each sedimentary aquifer, the hydraulic parameters vary from pure matrix properties to values in fault zones. The Upper Muschelkalk can be characterized by values between $K = 7{\cdot}10^{-7}$ m s^{-1} to $K = 3{\cdot}10^{-6}$ m s^{-1}. The Upper Malm can be characterized by values between $K = 7{\cdot}10^{-8}$ m s^{-1} to $K = 3{\cdot}10^{-7}$ m s^{-1}. In Western Switzerland a strongly increased value was established. Here, values between $K = 3{\cdot}10^{-7}$ m s^{-1} and $K = 7{\cdot}10^{-6}$ m s^{-1} were identified. In the further interpretation, special attention is paid to this value. In contrast, little importance of fracture zones is found for the Upper Marin Molasse. A typical median value of $K = 2{\cdot}10^{-7}$ m s^{-1} best describes this layer.

4.2 Temperature Distribution and Thermal Productivity of Considered Aquifers

The temperatures of the individual aquifers depend strongly on a conductive heat transport. Generally, temperature increases towards the Alpine front due to increasing depth. According to the thermally calibrated mdels, temperature can reach 240°C in the topmost 500 m crystalline units. Similar conditions are expected at the center of the Permocarboniferous trough. In the Upper Muschelkalk and Upper Malm Temperatures of >100°C in depths >1600m (relevant for resource class III) is anticipated. Maximum temperatures of 60°C (relevant for resource class II) are expected for the Upper Marin Molasse.

By combining the areal distribution of hydraulic and thermal values the possible thermal productivity was calculated. In crystalline rock, maximum values of above 150 MWth were calculated especially below the maximum overburden of the Permocarboniferous troughs. The maximum productivities for a plant exploiting the Upper Muschelkalk are far below and can result in 35 MWth near the Alpine front. In the Upper Malm the same tendency can be established. However in individual regions of Western Switzerland very high productivity values are estimated, based on extremely high individual hydraulic conductivities. As such, anomalies up to 240 MWth at depths of Top Upper Malm of < 2500m. near Fribourg and Nyon were identified. (Figure 2). These values are clearly related to the high transmissivity values assumed for these areas. In Northern Switzerland, the productivities in the Upper Malm reduce at typical conductivities up to only 4MWth. The productivities in the Upper Marin Molasse can increase up to 20 MWth at major aquifer depths of few 100 m b.s.l. next to the Alpine front (Figure 2).

Due to the higher hydraulic conductivities, fault zones are of major geothermal relevance. The expected productivity of a plant are also linked to the surrounding matrix properties. For example in the northern Upper Muschelkalk values of 30 MWth are estimated.

The assessment of the technical geothermal potential is based on the identification of individual aquifer systems. The calculated values however do not represent a local estimate since they are based on mean parameter values for a larger unit. Therefore such regional assessment does not replace a local feasibility study. The analysis could be easily extended towards treatment of economic profitability accounting for today's best available technology including especially the necessary drilling costs. In that way, the present study can be easily used for cost scenarios of individual aquifer applying plant investment, drilling cost and conversion efficiencies. However, an cost assessment of future conflict potential the cost schemes is not necessarily based on the current stage of technology. Therefore, only cost schemes for drilling and plant investments can be applied that concentrate mostly on reservoir productivity. Future geothermal application will certainly focus on the most advantageous and prosperous locations adapted to the infrastructure demand in Northern and Western Switzerland.

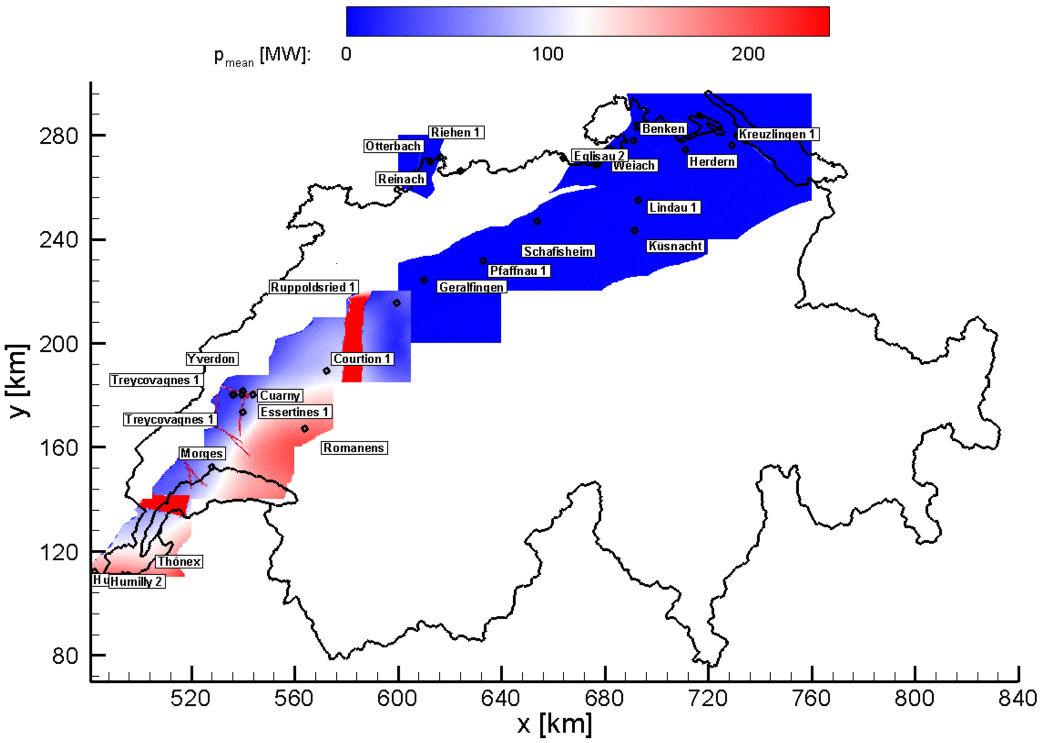

Figure 2: Calculated mean geothermal productivity of the Upper Malm. Boreholes are marked by dots. For better overview, boreholes with temperature data are additionally labeled.

5. NORMALISED GEOTHERMAL PRODUCTIVITY

The interest of this study was to define areas for possible waste scenarios that will not conflict with future geothermal production. In this integrative approach the economic analysis for geothermal production is only of little interest since the investments required in future production is presently unknown. In the framework of the present study the results of the individual aquifer systems of the 3D thermo-hydraulic model had to be comprised for a single 2D representation. Clearly, the realization of a geothermal project depends significantly on reservoir depth (temperature, drilling costs, .). A resource conflict in future can however not include the perspectives of today's economic conditions but will certainly based on the hypothesis that geothermal production will continuously focus on reservoirs that are more profitable than others. To determine possible geothermal utilization at arbitrary locations of the Swiss Molasse Basin for future production a cost model was taken that considers linearly increasing drilling costs with depth. Necessary investments for infrastructure, buildings or heat exchangers were taken to be identical. The results of this investigation are expressed by an areal distribution of a normalized productivity. Especially the areas of Northern Switzerland like the Cantons of Thurgau, Zurich and Aargau seem to be well suited for future production. In the western part of Switzerland elevated values are reached in the Canton of Vaud.

To derive 2D maps for future geothermal exploration a normalization of the thermal productivity needs to be performed. Thereby the minimum necessary drilling depth to reach the top of an aquifer is taken as basis for drilling depth. The costs associated with these drilling depth are assumed to increase linearly with depth and represent the economic basis of the assessment. I.e. for a utilization of an aquifer with productivity P_i in a depth z_i can be as interesting as if the aquifer has a productivity 2 x P_i and is situated in a depth of 2 x z_i. For a comparative assessment of future production the established data were used and integrated into a normalized geothermal productivity, P_n,. This includes the consideration of all aquifers at every location. The normalized productivity corresponds to the ratio of power, P, and drilling depth, z, in the unit W m^{-1}. At every point considered the productivity P_n was thus calculated as:

$$P_n = \frac{\sum_{1}^{n_A} P_i / z_i}{n_A} \qquad (3)$$

with n_A the number of aquifers at a point, P_i the productivity of the aquifer and z_i the minimum drilling depth of the aquifer.

This schematic calculation was performed for all locations in the Swiss Molasse Basin. For a practical classification of future resource utilization four categories have been defined:

- Not identified resource ($P_n < 0.004$ MW m^{-1})
- Possible resource ($0.004 < P_n < 0.007$ MW m^{-1})
- Increased resource ($0.007 < P_n < 0.010$ MW m^{-1})
- High resource potential ($P_n > 0.010$ MW m^{-1}).

If the calculated value would be due to a single aquifer, its productivity is easily obtained from the normalized geothermal productivity, P_n, to be:

$$P_{aquif} = P_i \cdot z_i \cdot n_A \qquad (4)$$

For the hypothetic example of an Upper Muschelkalk aquifer in 2 km depth as single dominating geothermal structure, its productivity would be P_{aquif} = 80 MWth for P_n = 0.010 MW m^{-1} and n_A = 4.

The areal representation is however easily dominated from individual aquifers areas. In the case of the Upper Malm in Western Switzerland the influence of hydraulic transmissivities from a small number of boreholes will even overshadow any other results. A first comparative calculation results in P_n of up to 1.2 MW m^{-1}. The corresponding high transmissivities (>10^{-6} m^2 s^{-1}) of the Upper Malm have been encountered at the fractured domains near Yverdon and are possibly not representative due to an insufficient data density in Western Switzerland. Until additional confirmation of the regional viability of this aquifer through additional drilling and testing activities the upper Malm is ignored for the analysis of future geothermal conflict potential.

The resulting representation of P_n in major areas of northern and western Switzerland is shown in **Error! Reference source not found.**. Increased resource potential can be established for the Cantons of Thurgau, Zurich and Aargau. In Western Switzerland this category is reached in the canton Vaud. Within these areas a high potential is identified especially for fault zones. In addition the areas around Zug and Lucerne with larger Molasse thickness would fall in this highest category. However, the interpretation is unconfirmed from local borehole measurements.

A further problematic geothermal relevant zone concerns the crystalline layer. In agreement with the existing data a rather arbitrary limit between intact and fractured crystalline is considered at 500 m depth (Signorelli and Kohl, 2006). This is due to the fact that data density from greater depths is rather sparse and does not allow an extrapolation to depth. This is shown in **Error! Reference source not found.** where areas next to the Northern border are identified only by moderate values. However, the large heat flow anomaly in northern Switzerland allows the hypothesis that crystalline rock is more deeply fractured than this rather conservative assumption suggests. Also a re-evaluation of the crystalline transmissivity values does not show a strong decreasing trend (Signorelli and Kohl, 2006). Therefore, deep circulating fluids seem to be well possible in this area. As result much-elevated P_n values would emerge due to higher temperatures and transmissivities in crystalline.

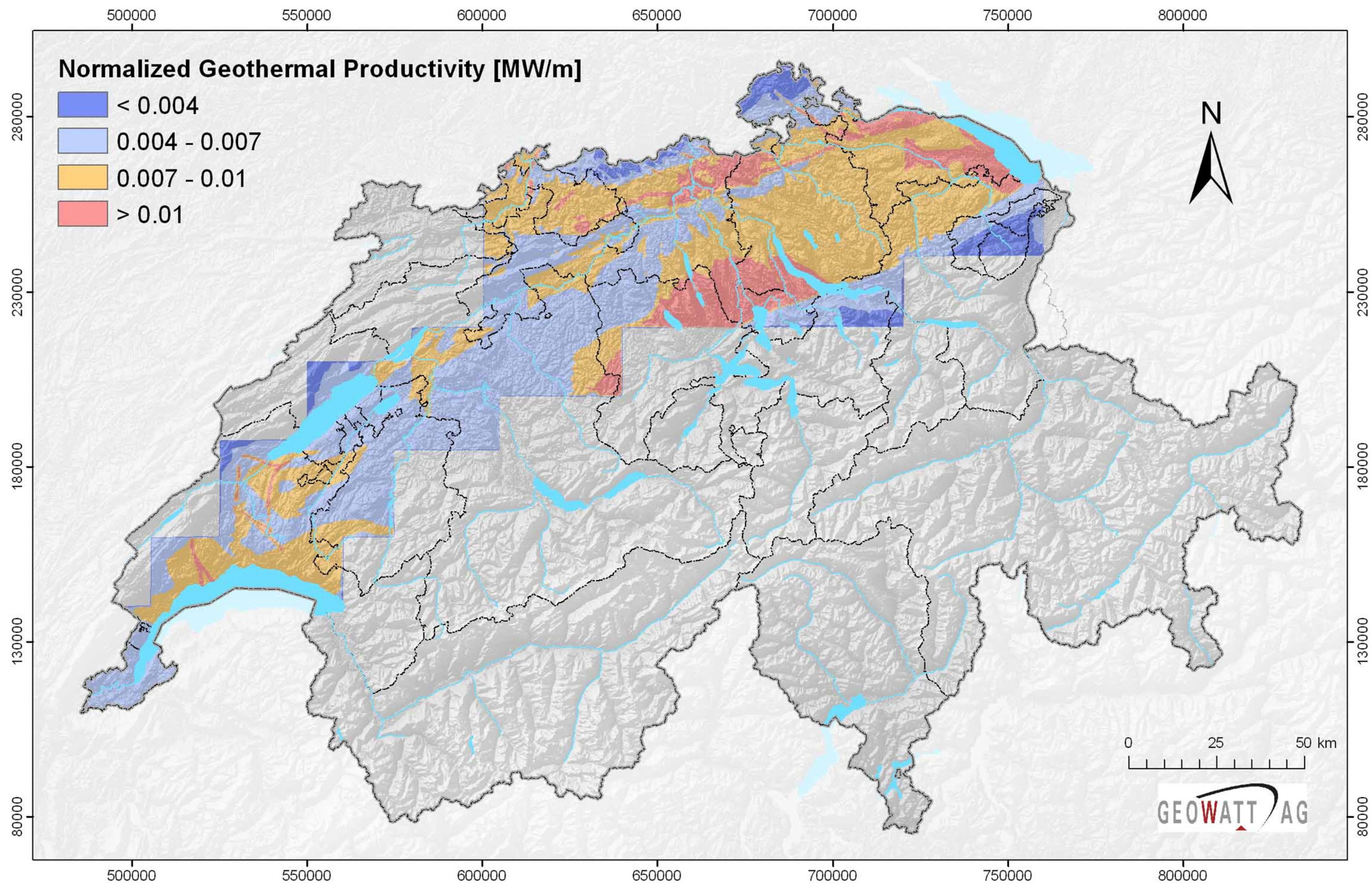

Figure 3: Depth corrected representation of the normalized geothermal productivity for major parts in Northern and Western Switzerland (see text).

6. CONCLUSIONS

The conflict between geothermal resources utilization has been discussed frequently. For example in low enthalpy systems the minimum distance between ground-coupled heat pump systems is of major importance for a sustainable long-lasting use. Herein, an approach for a future conflict with other utilization is presented. In Europe, a conflict of geothermal utilization with CO_2 sequestration has already been discussed intensively, in future also conflict with waste deposit or hydrocarbon mining can be also anticipated. Such conflict will certainly always be driven by current economic interests that lead necessarily to the exclusion of a single utilization in a defined area. Given the time frame and validity of a legislation process especially long-term running waste deposit scenarios can only be established for areas with minor possibilities for future use. Under this perspective the herein presented application of a regional geothermal assessment is relevant for a society.

The elaborated geothermal resources models present the basis of the assessment of future potential for conflict with other utilization of subsurface. The evaluation of geothermal resources has to be based on thermal and hydraulic conditions. If the available database is sufficient both key parameters allow for a calculation of geothermal productivity from different depth ranges. Clearly the approach shown here is only valid for a regional assessment and does not substitute a local feasibility study that can use more sophisticated information from a confined area. The presented results from Northern and Western Switzerland are due to a large database of seismic profiles, of geological interpretation or of borehole measurements that has been established some 20 years ago for nuclear waste research. The productivities have been calculated for the four well-known geothermal relevant aquifers: Upper Marin Molasse, Upper Malm, Upper Muschelkalk and fractured top crystalline basement. In each unit the matrix and fault properties could be considered from measurements and calibrated models. Beside subsurface parameters also economic factors from surface infrastructure, utilization system and investment costs are relevant for an economic resource assessment.

Already now, the existing geothermal resource assessment will be used within regional hydrogeological estimations. As such, the quantification of the potential for conflicts is only another example of the variety of applications that can be derived from the results of geothermal resource assessments.

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