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Geothermal potential of the Swiss Molasse Basin

By LADISLAUS RYBACH [1)]

ABSTRACT

The Swiss Molasse Basin (SMB) is characterized by a relatively smooth temperature field (average geothermal gradient 30 °C/km with a slight tendency for the gradient to decrease from north to south). In terms of geothermal energy potential (= "possibilities to use the heat content of the subsurface") several categories are addressed: a) thermal springs, b) stratiform aquifers, c) artificial systems (shallow geothermics: Vertical earth heat exchangers, VHE; deep geothermics: Hot Dry Rock, HDR).

The absence of thermal springs in the SMB is indicative of generally low vertical permeability of Molasse sediments. Several potential regional aquifers can be identified: Obere Meeresmolasse, top Mesozioc carbonates (?), Oberer Muschelkalk. Exploration and development risk increases with depth; a potential assessment with rather optimistic assumptions yields marginal figures. On the other hand, VHE potential is considerable (at least 5000 TJ/a); the SMB exhibits the highest VHE density in the world. The potential of HDR systems is difficult to assess; figures in the range 50000-500000 TJ/a might be conservative. This option still requires intensified research and development efforts.

ZUSAMMENFASSUNG

Das Schweizer Molassebecken (SMB) ist gekennzeichnet durch ein relativ ausgeglichenes geothermisches Feld (Gradient im Mittel um 30 °C/km mit der Tendenz zur Abnahme von Norden gegen Süden). Hinsichtlich des geothermischen Energie-Potentials (hier generell als die Nutzungsmöglichkeit der im Untergrund gespeicherten Wärme betrachtet) werden verschiedene Ressourcen-Kategorien behandelt: a) Thermalquellen, b) Schicht-Aquifere, c) künstliche Geothermie-Systeme (untiefe Geothermie: Erdwärmesonden, EWS; tiefe Geothermie: Hot Dry Rock, HDR).

Das Fehlen von Thermalquellen in der SMB spricht für eine generell niedrige vertikale Durchlässigkeit der Molasse-Sedimente. Verschiedene potentielle, regionale Aquifere wurden identifiziert: Obere Meeresmolasse, höchste Schichtglieder des Mesozoikums (?), Oberer Muschelkalk. Das Explorations- und Erschliessungsrisiko nimmt mit der Tiefe zu; eine Potential-Schätzung führt selbst mit eher optimistischen Annahmen zu marginalen Grössenordnungen im Vergleich zum Heizenergie-Bedarf der Schweiz. Hingegen ist das EWS-Potential beträchtlich (mindestens 5000 TJ/Jahr); das SMB weist schon heute die weltweit grösste EWS-Dichte auf. Das Potential von HRD-Anlagen ist schwer abzuschätzen; Zahlen im Bereich von 50000-500000 TJ/Jahr sind eher konservativ. Diese Option bedarf noch intensiver Forschungs- und Entwicklungs-Anstrengungen.

Introduction

The purpose of this paper is to address the geothermal potential of the Swiss Molasse Basin (SMB) using a pragmatic approach. The term "geothermal potential" is defined here in a broad sense to encompass all the possibilities to utilize the heat content of the earth's interior. Thus "geothermal potential" refers to the resource rather than the

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reserve (in the sense of the McKelvey diagram, see e.g. Haenel et al. 1988). Of particular interest is the "technically available potential", TAP (in TJ/a).

The following resource categories will be addressed: a) natural resources (thermal springs, stratiform aquifers), and b) resources for artificial heat extraction (vertical heat exchangers, Hot Dry Rock systems). The lateral boundaries of the study will be taken as the surface boundary of the SMB proper. However, resources lying below the base of the Tertiary Molasse sediments will also be considered (Mesozoic/Paleozoic formations, crystalline basement).

For stratiform aquifers the European Community (EC) guidelines provide a rigorous definition of the geothermal potential in terms of the heat content present below a surface area of 1 m^2 (Haenel 1988). Specifically, the resource (or heat in place, in J) is quantified by the parameter R which is defined in terms of aquifer properties as

$$R = hF(T_a - T_o)[\phi \rho_w c_w + (1 - \phi)\rho_m c_m]. \tag{1}$$

The exploitable heat is given by the "specific resource potential" (SRP, in J/m^2):

$$SRP = (R/F)f_r(T_a - T_r)/(T_a - T_o). \tag{2}$$

Here F (m^2) is the areal extent of the aquifer, h(m) its useful thickness, ϕ its porosity, T_a(°C) the temperature at the aquifer top, ρ_w(kg/m^3) the formation water density, c_w(J/kg, °C) the formation water heat capacity, ρ_m(kg/m^3) the rock matrix density, and c_m(J/kg, °C) the rock matrix heat capacity. Equation (2) involves the utilization parameters: the recovery factor f_r which depends on the system (i.e. whether reinjection is used; f_r is usually less than 0.25), the reinjection/disposal fluid temperature T_r(°C), and the local (mean annual) surface temperature T_o(°C).

The simplest system to utilize the heat content of a geothermal aquifer consists of a single production drillhole (i.e. no reinjection but disposal to surface drainage, a so-called "singlet"). If reinjection is necessary, then there must be another drillhole for this purpose ("doublet"). Given a flow/pumping rate $\dot{m}$ (in m^3/sec) and a useful temperature drop ΔT [$= (T_a - T_o)$ or $(T_a - T_r)$], then the geothermal capacity, Q (in MW_{th}) can be calculated from the expression,

$$Q = c_w \rho_w \dot{m} \Delta T. \tag{3}$$

The *technically available potential* TAP (in TJ/a) of a given stratiform aquifer is given by,

$$TAP = NQ_s t_{an}, \tag{4}$$

where N is the (hypothetical) number of installed geothermal systems, Q_s is the geothermal capacity of a single system, and t_{an} is the average annual operation time (for Swiss conditions this is usually set at 8600 hr/year). The TAP thus represents the total heat production possible from a given aquifer per year, regardless of economic viability.

Geothermal characteristics of the SMB

The SMB is characterized by a smoothly regular, normal *temperature field*, devoid of significant geothermal anomalies. In general, the geothermal gradient decreases slightly with depth within the first 400–500 m (Rybach & Bodmer 1980).

Fig. 1 assembles the presently available information about the lateral variation of the geothermal gradient in Switzerland (Data from BEW 1981 and from Rybach et al. 1987). The data density for the SMB and the Jura is sufficiently high to justify the construction of isolines (accuracy: $\pm$ 5 °C/km). In the SMB the gradient is between 25 and 40 °C/km with the highest values in the north, and decreasing to the south across the basin.

The moderate vertical gradient and the north-south trend seem to have prevailed since the deposition of the Molasse sediments (Rybach & Bodmer 1980, Rybach 1984). Just north of the SMB there is a pronounced geothermal anomaly with its center located in the lower Aare valley coincident with the Permocarboniferous trough of northern Switzerland (Rybach et al. 1987, Griesser & Rybach 1989). The continuation of the well-known anomaly of the Upper Rhinegraben, a continental rift structure, towards the south (Rybach et al., 1987) is also clearly visible.

It is striking that there are no occurrences of *thermal springs* in the SMB (the 23 °C thermal water produced at Yverdon is pumped from Mesozoic (Malm) strata located below the Molasse sediments). The absence of thermal springs in the SMB indicates that vertical permeability (which is needed both for recharge and discharge in the deep-reaching circulation of thermal spring systems) of the Molasse sediments is generally low.

The general stratigraphic section of the SMB down to basement is shown in Fig. 2. Several stratiform aquifers of general interest for low-enthalpy geothermal energy development have been identified in the section (BEW 1981). From top to bottom these are as follows.

The Miocene *Obere Meeresmolasse (OMM)*, especially its basal part consisting of porous/permeable sandstones, is at depths suitable for geothermal development between the lakes of Zurich and Constance. The aquifer has been reasonably well characterized from hydrocarbon and geothermal exploration data, and much is known about depth, thickness, lithology, porosity, and permeability of the sediments as well as about the physical and chemical characteristics of the formation fluid (temperature, mineralisation). Several drillholes have established that the basal section of the OMM is a regional aquifer of geothermal interest: Brauerei Hürlimann/ZH, Tiefenbrunnen/ZH, Hohstrasse Kloten/ZH (where a complex of several multifamily houses is supplied by geothermal heat), Kreuzlingen/TG. A failure ("dry hole") must also be noted (Fehraltorf/ZH). The mineralisation of the geothermal fluid is rather low (usually well below 5 g/l) which permits surface disposal and thus enables the development of singlet systems.

The base of the Tertiary Molasse sediments can also be considered to have geothermal potential. The carbonatic *Cretaceous* or *Malm* formations can have significant permeability due to karstification: several hydrocarbon exploration holes indicate, by drilling fluid loss, locally high permeability (Rybach 1982). However, the karstic cavities can be filled and sealed by fine-grained Eocene clays which reduce the permeability. Exploration and development risk is thus high. Mineralisation is expected to be moderate ($<$ 10 g/l).

The deeper lying Triassic *Obere Muschelkalk* is known from several drillholes as an another regional aquifer with geothermal potential. The permeability is due to fracturing and/or karstification. The mineralisation is generally high (several tens of g/l) and thus "doublet" systems are required for geothermal energy utilization. Exploration risk, in absence of geophysical methods capable to give permeability information from surface measurements, is rather high.

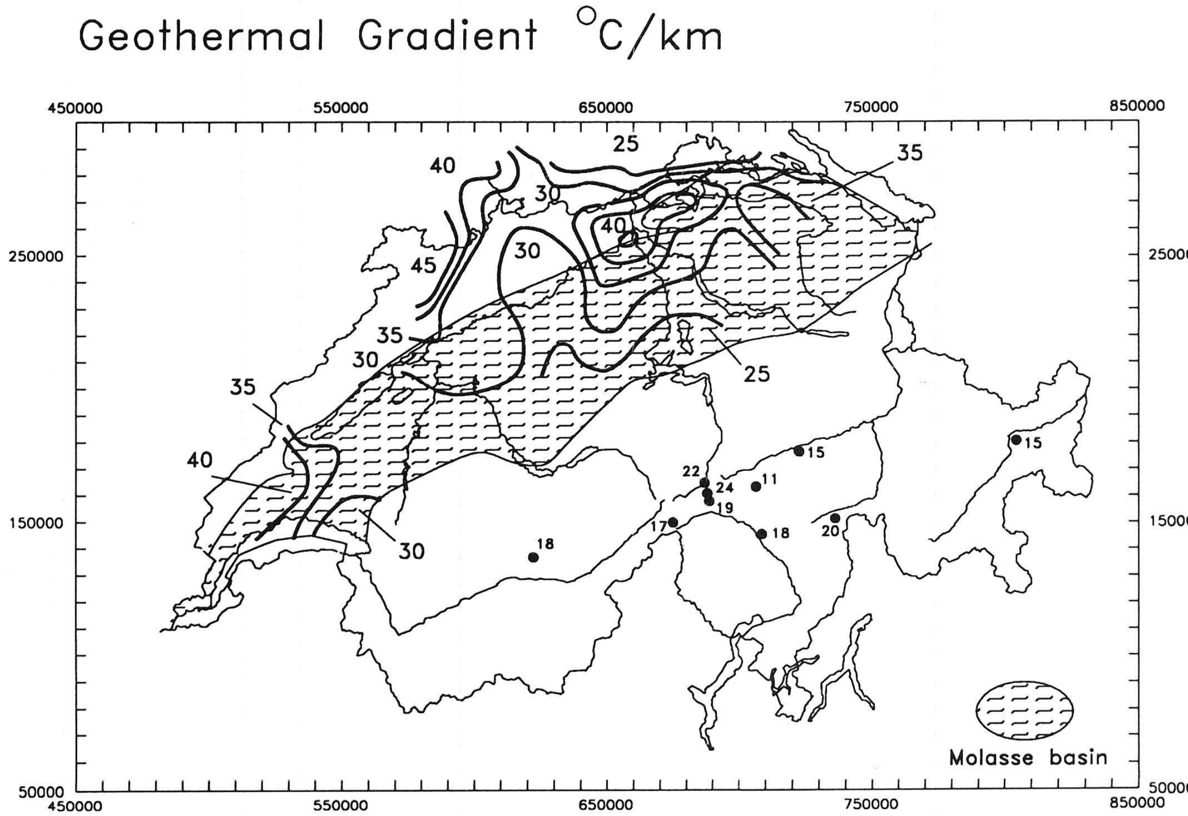

Fig. 1. Geothermal gradient data from Switzerland (in °C/km). The positive anomaly in the northeast coincides with the Permocarboniferous trough (cf. Rybach et al. 1987).

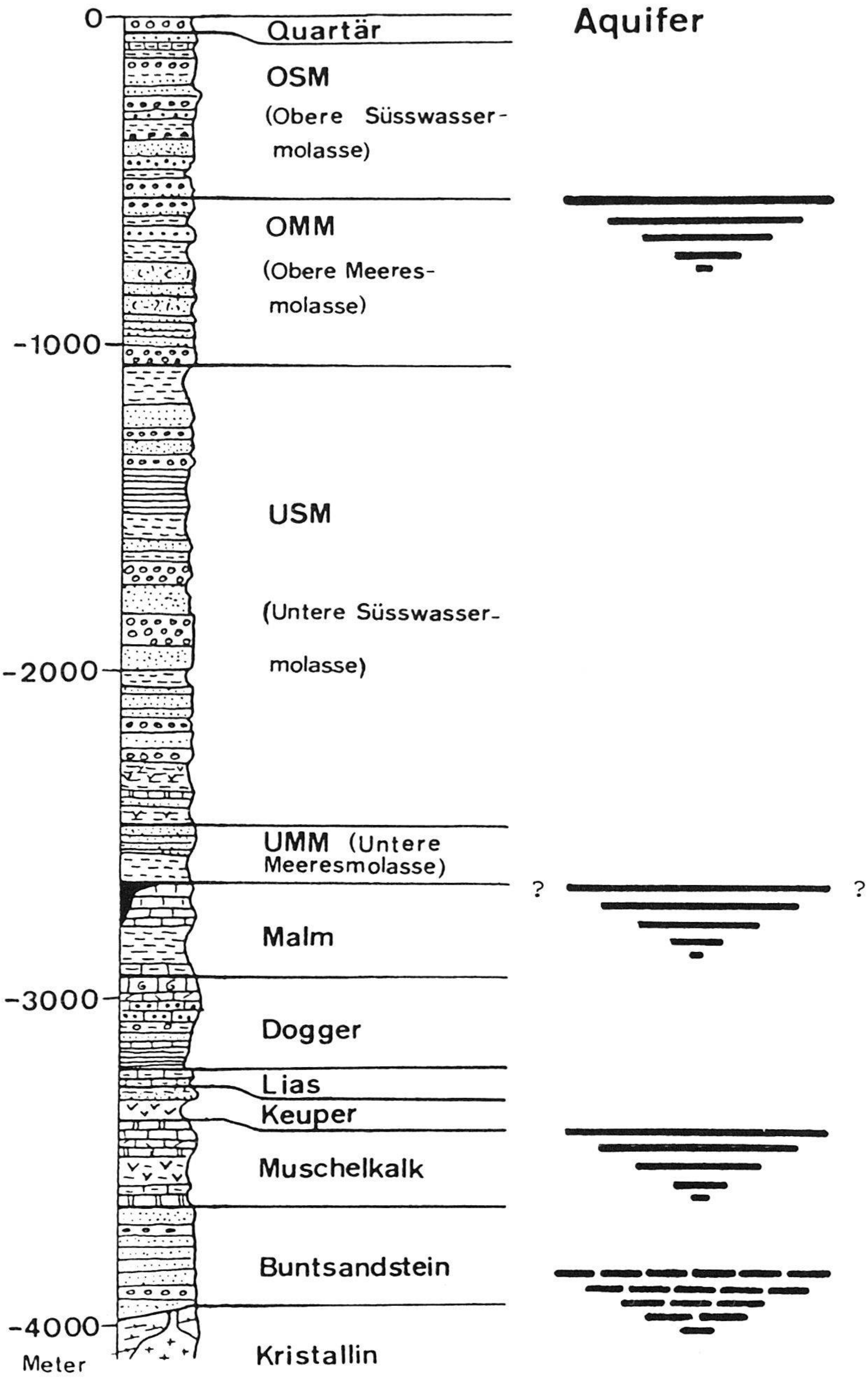

Fig. 2. Schematic geological column in the Swiss Molasse Basin. Formations which can be considered as aquifers of geothermal interest are indicated.

Finally it should be noted that the possibility of useful geothermal resources being present in the SMB at even greater depths cannot be excluded. Exploitable resources may exist in the Buntsandstein, in locally permeable Upper Paleozoic sediments, or in the weathered top parts of the crystalline basements. However, exploration risk is particularly high here.

Natural resources: Aquifer potential

For the regional aquifers OMM and Obere Muschelkalk, the areal distribution of the specific resource potential [SRP, in J/m^2] will be mapped by isolines. The total technically available potential [TAP, in TJ/a] will also be estimated.

The point values of the SRP (input for the isoline mapping) are calculated in the following way. The relevant surface area is subdivided into a quadratic mesh with elements of size 10×10 km. For each element the SRP value is calculated from formulas (1) and (2) by taking into account the local aquifer properties (data from BEW 1981). For the OMM the following values have been used: $T_a > 20$ °C, $T_r = 15$ °C, $f_r = 0.1$ ("singlet"). For the Obere Muschelkalk the corresponding values are: $T_a > 20$ °C, $T_r = 20$ °C, $f_r = 0.25$ ("doublet"). The numerical values of the individual elements have been contoured by isolines in GJ/m^2. Further details can be found in EGES (1988). Fig. 3 shows the SRP isolines for the OMM, with maximum values around 2.5 GJ/m^2. The numerical values found are in the same order of magnitude as values of comparable aquifers in Germany (Haenel & Staroste 1988). Fig. 4 shows the SRP isolines of the Obere Muschelkalk; the increase of the SRP values towards the Alps is due to the successively greater depth (and thus higher T_a) of this aquifer. The southern boundary of the isoline pattern is given by the practical consideration that drilling to depths greater than 3 km is not viable for low-enthalpy geothermal development. The lower SRP figures (relative to the OMM) are due to the lower porosity assumed for the Obere Muschelkalk (on the average 2%).

The assessment of the technically available potential (TAP) requires additional consideration of the the possible number of geothermal installations. This is dependent upon the lateral radius of influence of geothermal heat extraction, which in turn depends both on the aquifer properties and the expected duration of heat production. For the OMM, one extraction unit per 25 km^2 was assumed, whereas for the Obere Muschelkalk one installation per 100 km^2 was adopted (for further details see EGES 1988). The results are assembled in Table 1. Even though the numbers given in Table 1 have been calculated on the basis of rather favourable assumptions they would represent only a very modest

Table 1. Estimated TAP (= *T*echnically *A*vailable *P*otential) for regional aquifers in the Swiss Molasse Basin (from EGES 1988)

Aquifer*	number of units	Average geothermal power per unit	Total heat production (TAP)
OMM	100	0.8 MW_{th}	≈ 2500 TJ/a
Cretaceous/Malm	?	?	?
Ob. Muschelkalk	55	2.1 MW_{th}	≈ 3600 TJ/a

*) Exploration risk increases with depth due to lack of data/experience

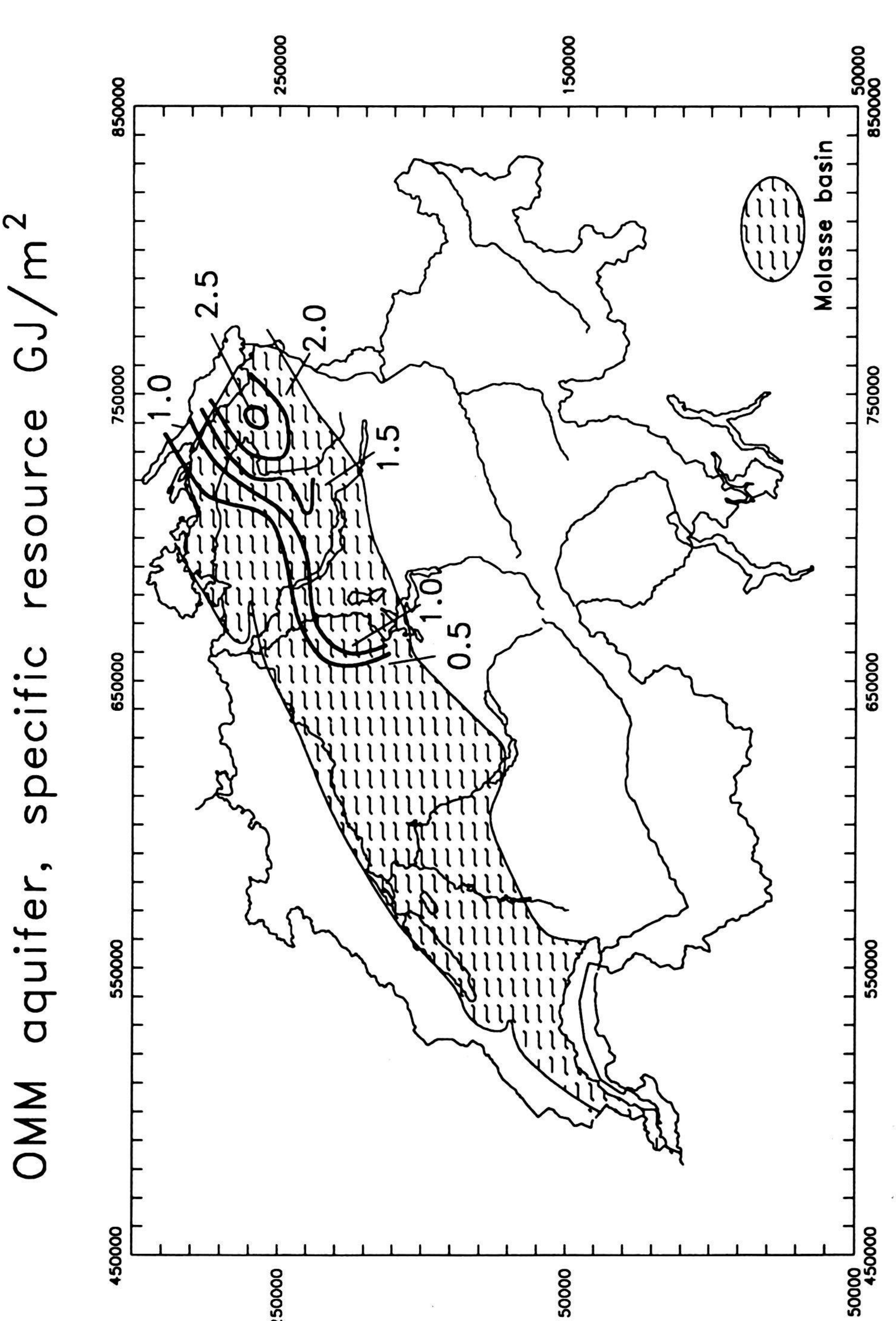

Fig. 3. Distribution of the specific resource potential (SRP) within the Obere Meeresmolasse (OMM) aquifer (after EGES 1988). For details see text.

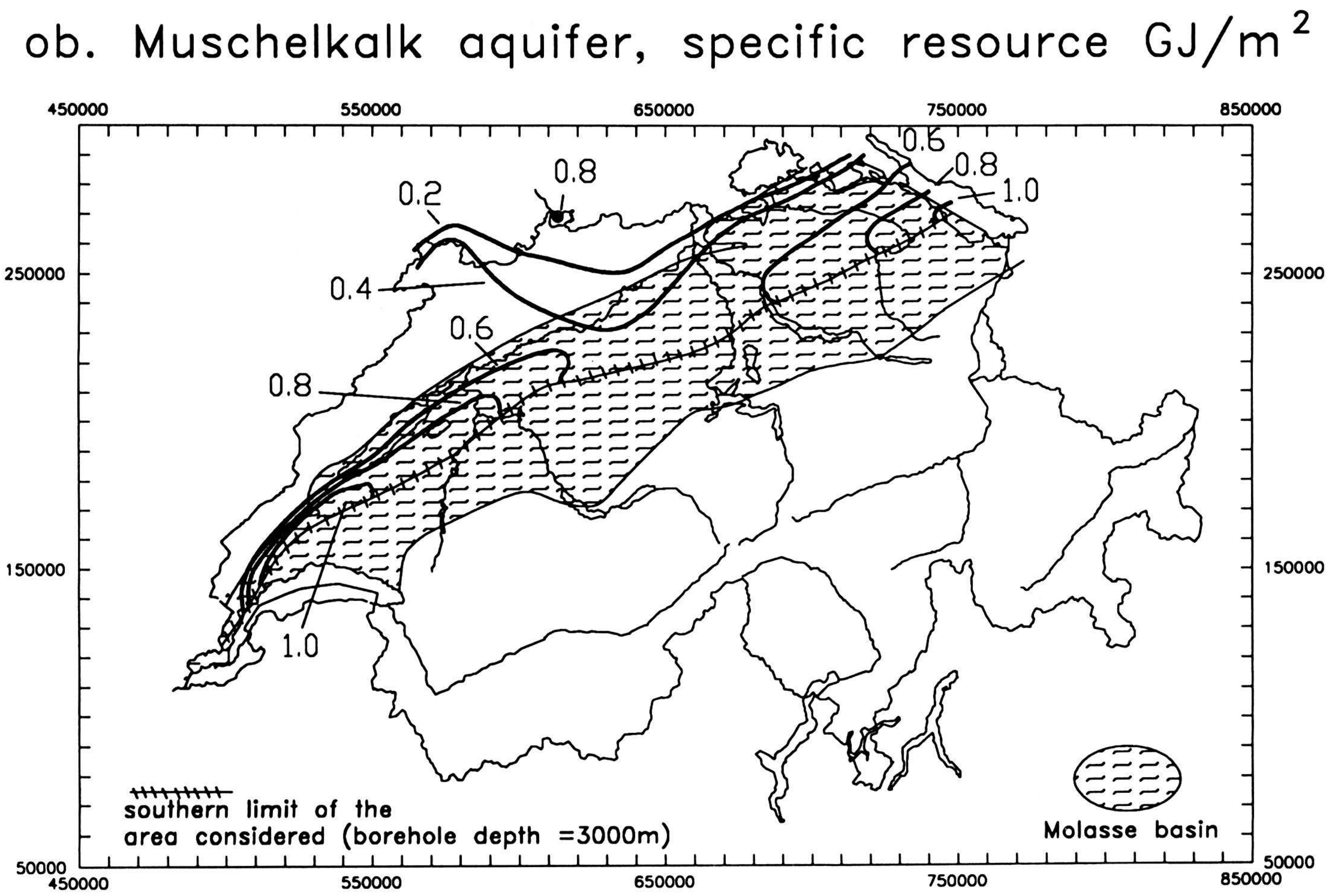

Fig. 4. Distribution of the specific resource potential (SRP) within the Obere Muschelkalk aquifer (after EGES 1988). For details see text.

contribution (roughly 1%) to the heating demand of Switzerland (440000 TJ/a in 1990; BEW 1991).

Artificial systems

The geothermal utilization potential of the aquifers discussed above depends primarily on the yield of the production wells. Limited experience has shown that productivity is by no means high and laterally uniform in aquifers of the SMB, and thus the exploration risk is considerable, particularly at greater depth. On the other hand the heat content of the subsurface is certain, and this focuses attention on artificially-engineered systems for extracting this heat. The two principal classes of artificial heat exchange systems are vertical earth heat exchangers (VHE) which operate in the shallow depth range (several tens to a few hundred meters) and Hot Dry Rock systems (HDR) which are much larger facilities aimed at recovery of heat from depths of several kilometers.

The potential for vertical earth heat exchangers

The VHE is a closed-circuit device for a fluid to take heat from the first tens/hundreds of meters of the ground and to feed the cold side (evaporator) of a heat pump. The heat exchanger is formed from coaxial or U-shaped tubes, installed in backfilled drillholes. They can be installed in nearly all kinds of geologic media (except in materials like dry gravel with low thermal conductivity). The design and performance of VHE systems have been well studied and the key parameters identified (e.g. tube lenght, diameter; ground thermal conductivity, fluid circulation velocity) (Burkart et al. 1989). A zone of thermal drawdown develops along the entire drillhole due to heat extraction which can extend radially up to 10 meters from the heat exchanger axis (Eugster et al. 1991). Therefore, only a limited number of VHE systems can be installed within a given surface area.

Up to now, over 8000 VHE systems have been installed in Switzerland. Fig. 5 shows the locations of VHE's installed by a single commercial company and illustrates the high concentration of installations in the SMB. Indeed here the VHE density (number of installations per unit area) is the highest in the world. Nevertheless, many more systems could be installed without any environmental or legal problems (i.e. respecting the minimum distance between installations and neighbour rights).

The technically available potential (TAP) of VHE systems has been estimated in EGES (1988). For this assessment the area of construction zones in the individual communities (= "Bauzonen") was taken into account. The study concluded that as much as 100000 VHE's could easily be operated in the SMB, corresponding to about 5000 TJ/a net energy production. However it should be born in mind that the operation of VHE's requires electricity for the heat pumps. For the 100000 VHE units a total of 100 MW_e installed capacity must be available.

The potential for Hot Dry Rock systems

By virtue of its comparatively unrestrictive requirement of hot, low-porosity rocks at drillable depths, Hot Dry Rock (HDR) systems represent the most promising option for geothermal energy utilization; one which offers CO_2-free heat-electric power coupling.

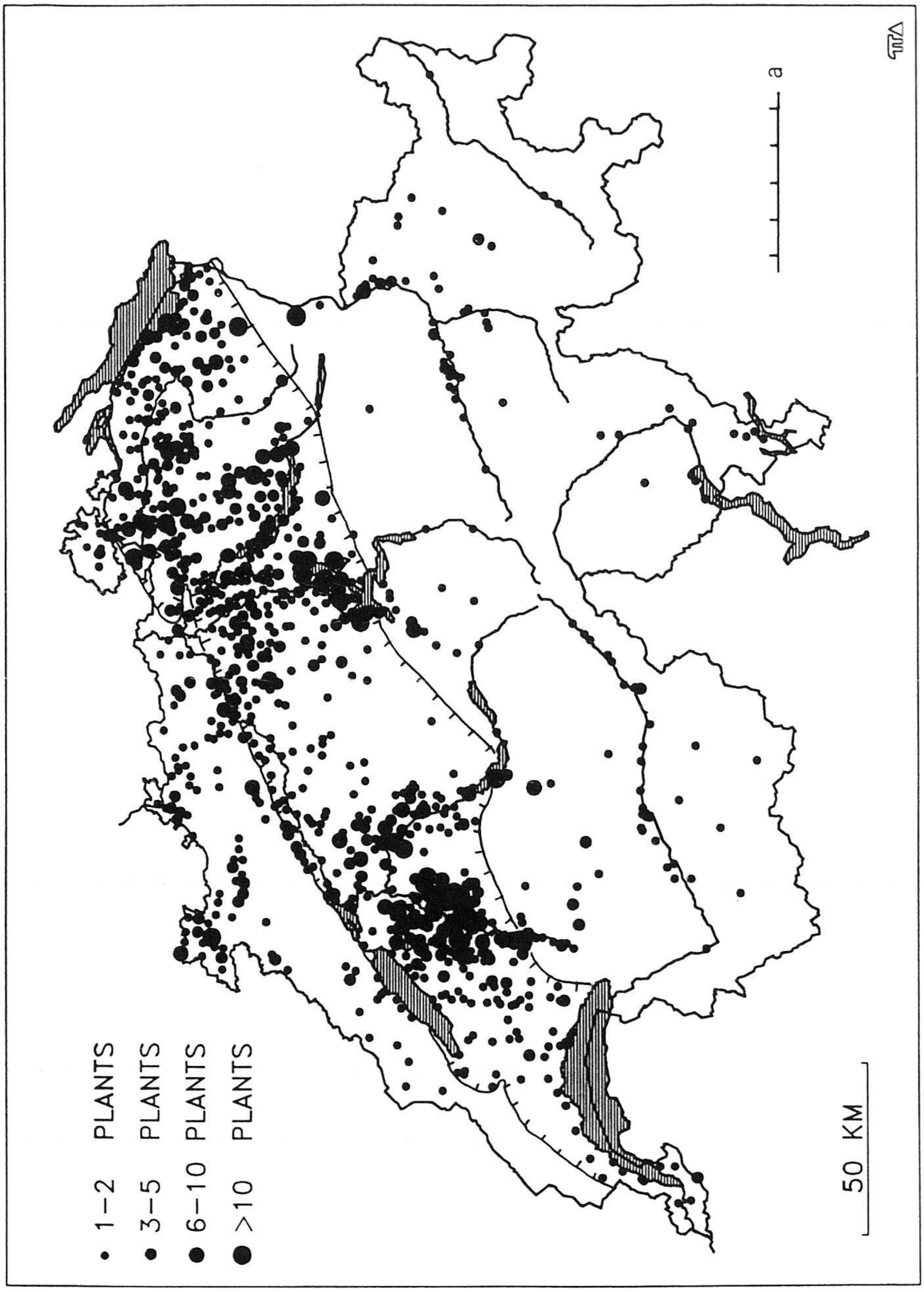

Fig. 5. Sites of installed vertical heat exchanger (VHE) systems. Installations of one commercial company only. Note the high VHE density in the Swiss Molasse Basin (highest worldwide). a: limit of the SMB.

A simple calculation suffices to illustrate the attraction: if a rock volume of only 1 km^3 is cooled down by 10 °C, then a thermal power output of 25 MW could be sustained over 30 years. The key component of a HDR system is the heat exchanger at depth and this must be formed either by hydraulic fracturing or by enhancing the permeability of flow conduits within the natural fracture system. In both cases it is local conditions that largely dictate the geometry and orientation of the flow system and thus site characterization plays a crucial role in system development. A practical strategy that is currently favored for system development is to drill a single hole to the depth range of interest (in-situ temperatures 150–200 °C) and then inject water at a high rate to both promote the enhancement of fracture conductivity and stimulate microseismic events. The latter can be located by conventional microseismic methods and the resulting distribution of the events taken to indicate the naturally-favored direction of fluid flow within the reservoir. A second hole can then be drilled to intersect the "microseismic cloud" at a suitable distance from the first hole, thereby maximising the likelihood of establishing low impedance hydraulic communication. Once this has been achieved, cold water can be injected into one borehole, pass through the heat exchanger at depth and be recovered as steam and/or steam/hot water mixture from the other drillhole. Several experimental HDR facilities are in operation woldwide (e.g. in USA, UK, Japan, France) and others are currently being developed. However, there remain many, fundamental problems to overcome in developing the heat exchanger in diverse geological environments, and a large research and development effort is needed to exploit the immense potential of this option. International cooperation of research groups from several European Community (EC) countries and from Switzerland and Sweden has been recently initiated within the framework of the EC Research and Development (R & D) program JOULE II (*J*oint *O*pportunity of *U*nconventional or *L*ongterm *E*nergy and Deep Geology).

The geothermal potential of HDR systems within the SMB can be assessed only in very rough terms. The heat content of the crystalline rocks below the SMB is enormous; it has been estimated for the top 10 km to be on the order of 10^{10} TJ (BEW 1981). A realistic figure for the TAP of HDR systems cannot be given at this time although it is most likely to be at least an order of magnitude larger than the TAP of VHE systems (i.e. 50 000–500 000 TJ/a). The northern border of the SMB appears to be particularly suitable for siting HDR installations (Rybach 1992).

Conclusions

There is an interesting geothermal energy potential in the Swiss Molasse Basin (SMB). The geothermal characteristics and the energy potential can be summarized as follows:

- the temperature field is generally smooth with a decrease in gradient from north to south
- there are no thermal spring occurrences within the SMB; this indicates generally low vertical permeability in the Molasse sediments
- several stratiform aquifers can be considered to be prospective from a geothermal point of view:
  a) The Upper Marine Molasse (OMM) shows specific resource (SRP) values of up to 2.5 GJ/m^2 and a technically available potential (TAP) of about 2500 TJ/a, and is a target with moderate risk;
  b) the top Mesozoic (e.g. Malm) is highly questionable (sealed karst?);
  c) the Obere Muschelkalk has SRP values up to 1.0 GJ/m^2 and a TAP of about

3600 TJ/a but represents substantial risk. Aside from the risk (which increases with depth) the economic impact of these aquifers is marginal.

– Artificial heat extraction systems offer much more promise for geothermal energy production in the SMB:

a) several thousand vertical heat exchangers have already been installed in the SMB area which represents the highest VHE density in the world. A realistic TAP figure for VHE energy production is 5000 TJ/a.

b) The most promising "engineered" geothermal energy however, is the Hot Dry Rock system which enables CO_2-free heat-electric power coupling. It is difficult to assess the TAP of the SMB for HDR systems; a figure of some 50000–500000 TJ/a is a rather conservative estimate. However, this option still needs intensive R & D efforts.

Acknowledgment

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