A novel approach in joint inversion of heat flow, elevation, geoid anomaly: Applications for determining deep thermal field and crustal structure in geothermal areas

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ABSTRACT

We present a novel approach for joint inversion of heat flow, elevation and geoid anomalies with the purpose of determining the deep thermal field and crustal structure in geothermal areas. The technique employed is based on computationally stable iteration schemes and provide simultaneous checks for compatibility of the inversion results with the observational data on surface heat flow, radiogenic heat production, elevation and geoid anomalies. The results are found to be far more robust and realistic than those obtained in conventional thermal models. Unlike the previous attempts, the new approach incorporates surface heat flow variation as an independent constraining parameter and at the same time allow for the non-linear effects of thermal conductivity variation with temperature in the crustal layers. The method was used in determining deep thermal structures of the crust in Southeast Brazil and North Africa. The model results point to substantial variations in Moho temperatures in both regions. There are indications that the deep thermal structure of crust in southeast Brazil are affected by residual thermal effects of mafic dykes and alkaline magma intrusions of Cenozoic age. In the Atlas Mountain area of North Africa there are significant variations in the crustal and lithospheric thicknesses but the heat flow anomaly seems to have a complex origin.

Key words: Joint inversion, Heat flow, Elevation, Geoid Anomaly, Southeast Brazil, North Africa

PRESENTER'S BIOGRAPHY

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Do all the wet geothermal systems represent natural EGS in India?

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All the geothermal provinces in India, located along major rift/collision tectonics do not support involvement of mantle processes. Although, earlier these geothermal manifestations, associated with anomalous geothermal gradients (57-90°C/km) and heat flow values (75-100 mW/m^2) have been related to different geological and tectonic events such as Deccan flood basalt volcanism, mid-continental rifting, subduction related tectonics, the isotopic signatures exhibited by the thermal fluids and thermal gases do not support any such relationship. For example, the oxygen and hydrogen isotopic composition of the thermal fluids strongly support meteoric origin. However, the feeding aquifers for the majority of the thermal systems, especially for those within the mid continental set-up, are not topographically driven unlike the several geothermal systems in Europe. High quantity of total helium content in the thermal gases suggests a large crustal component in these systems. The total helium, varying from 1 to 3 % (by volume) in these geothermal systems, and granite-water interaction experimental investigation suggest a deep "within crustal" circulating paths, with depths varying from 2 to 3 km. This pattern deviates slightly in the case of Himalayan geothermal system where a small mantle component, as expected, is present. This is true with regard to the entire geothermal manifestation along the Himalayan geothermal belt extending from Yangbajing (China) to Nangaparbat (Pakistan) as well. A close observation at the subsurface geology of these provinces shows that the entire SONATA (Tattapani, Salbadri and Tapi) and the Cambay geothermal systems derive their heat from the high heat generating granites, like the Bundelkhand and Baster granites (~ 3-5 $\mu W/m^3$). The high fluoride content (~3-20 ppm) in the thermal fluids further give evidence for intense water-granite interaction at temperatures, as indicated by the isotopic signatures, greater than 200 °C. This is true in the case of west coast geothermal province as well, as evident from the Rajapur thermal manifestation in southern part of the Deccan volcanic province, although the geochemical signatures of the thermal fluids is modified by saline component during the ascent of the thermal fluids. Recent report on the occurrence of 1450 Ma granite below the Deccan off the West coast give support to this inference. These investigations demonstrate that the geothermal systems in the mid Indian continent are driven by a high heat generating granites that are traversed by a system of interconnected fracture system.

On the morphology of the Curie surface in the Eastern Carpathians collisional setting (Romania), as defined by geothermal and geomagnetic studies

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ABSTRACT

The Curie temperature characteristic to minerals and crustal rocks controls the so-called magnetic thickness of the crust. A model of the Curie isothermal surface as defined by the temperature of 650 C is presented, based on geothermal modeling of tectonic processes that affected the lithosphere structure in the study area, namely a pre-Neogene oceanic subduction followed by a Neogene continental collision in the East Carpathians, the lithosphere extension in the Pannonian Depression, the intense Neogene sedimentation in the foreland (the Focsani Depression) and hinterland (the Pannonian and Transylvanian Depressions) of the Eastern Carpathians, the generation of magmas in the Neogene volcanic area. The magnetic thickness of the crust is compared with geomagnetic models derived from long-term variations of the geomagnetic field observed in a network of repeat stations.

Key words: Curie temperature, geothermal modeling, crust magnetic thickness

INFLUENCE OF SILICA PRECIPITATION AND RELATED CRACK SEALING ON THE EVOLUTION OF HEAT- AND MASS TRANSFER IN SEA-FLOOR HYDROTHERMAL SYSTEMS

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The sea-floor high-temperature hydrothermal systems are known as a phenomena of active segments of Mid-Ocean Ridges (usually fast or medium spreading). It is believed that the heat for the circulation of sulphide-bearing hot (350°C-450°C) water comes from the underlying magma chambers or hot intrusions.

The most critical factor for the evolution of the upflow zones, especially so-called “black smokers” is the precipitation of silica and some other minor species due to the cooling of hydrothermal fluid. The precipitation leads to the progressive crack sealing and reducing the permeability.

The full system of equations describing the processes of fluid heat- and mass transfer, kinetics of precipitation and related sealing of crack system is analyzed in this paper.. It is shown that under specific condition of a sufficiently high fluid flow rate, the rate of sealing can be prescribed on the base of obtained asymptotic solutions. Various regimes of flow are considered (the Poiseulle flow under relatively smooth variation in the crack profile and a given pressure drop, the case with a given temporal variation in the fluid flow flux, as well as the turbulent flow). The relevant scenarios of self-sealing processes and consequently diminishing of hydrothermal activity are studied. The existence of critical value for width of cracks is demonstrated. It is shown that the evolution of the hydrothermal system is highly dependent on whether the initial width of the cracks is larger or smaller than this critical value. In the last case the system of cracks can be uniformly sealed upon some time. The former case includes the second stage when sealing tends to move from the peripheral parts of the system to the central ones. The estimates of the critical crack width and life-time for hydrothermal systems has been obtained.

Transthermal – geothermal potential study at the trans-border region of Austria and Slovenia regarding thermal and hydrological conditions

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ABSTRACT

The border region between Austria, Slovenia and Hungary represents one of the most important balneological areas in Central Europe. The substantial use of thermal water in south-eastern Styria, southern Burgenland, north-eastern Slovenia and south-western Hungary has become an essential driving force of the economic development within the last decades. Moreover, since the public awareness of environment-neutral alternative energy sources constantly increases, the geothermal energy utilization for heating and electricity production is of growing interest within this region and first demonstration plants already operate in south-eastern Styria (Blumau, Waltersdorf & Fuerstenfeld) covering almost 40 percent of all Austrian geothermal energy production. According to the hydrogeological and morphological premises in the western part of the project area the existing geothermal reservoirs comprise of near surface, partly naturally discharging subthermal and moderate temperature thermal springs (i.e. Bad Kleinkirchheim, Zgornja Besnica). The eastern and south-eastern part of the project area is affected by the basin scenery of the prevalent Pannonian basin. Thermal water is produced by deep wells and the temperatures of the basin waters range from moderate to highly elevated (i.e. Bad Blumau, Lendava).

In order to allow sustainable and cost effective future geothermal exploration within border region of Austria and Slovenia the project TRANSTHERMAL was aimed to analyze and represent geothermal capacities with a focus on hydrothermal systems. Based on a transnational representation of basic geological, hydrological and thermal parameters and unified processing of geological data analyzes of the geothermal potential were carried out focusing on delineation of sedimentary and bedrock reservoirs. This resulted in elaboration of different thematic maps showing sedimentary thickness and bedrock lithologies, which exhibit the basic hydrogeological potential. To improve the knowledge of reservoir geometries several geological trans-border cross sections has been composed. Specification of prospective utilization possibilities covers the aquifer data (capacity, water temperature, chemistry) and current uses (yield). Based on calculated chemical signatures and available hydraulic parameters known aquifer systems have been compared and classified. These parameters led to different thematic maps showing the actual exploitation potentials. Finally the combination of hydrogeological potential and actual exploitation potential maps allowed elaborating maps exhibiting hydrothermal utilization potential. Furthermore, strong focus was set on the regional geothermal regime (heat flow density, rock temperatures at different depths), all the more so since the geothermal gradient represents an important factor for economic efficiency of the project (exploitation depths).

The achieved results implicit the existence of confined trans-border aquifer systems at the eastern part of the project area within the Pannonian Basin. Despite of this hydrological conditions generally vary strongly within low spatial distances as a consequence of facies change-over within the eastern part (Pannonian Basin) and strong fault system connection at the western part (South Alpine Orogeny) of the project area. The complex tectonic situation at the transition zone between Southern Alpine & Dinaride orogenies and the Pannonian Basin lead to strongly varying thermal conditions within the project area showing surface heat flow densities between 30 mW/m² and 150 mW/m² within distances of less than 200 km.

Key words: Pannonian Basin, Southern Alpine Orogeny, Geothermal Utilization Potential, Surface Heat Flow Density**.**

PRESENTER'S BIOGRAPHY

Gregor Goetzl has a several year experience on geothermal science and is responsible for geothermal studies at the geological survey of Austria. His scientific activities cover the elaboration of heat flow maps, the correction of borehole temperature datasets as well as the execution of 2D and 3D thermal modelling of pure conductive and joint conductive and convective heat transport. He is involved in several studies concerning surface near geothermal utilization (environmental impact of shallow heat exchangers) and deep geothermal systems (geothermal regime of the Eastern Alps and its adjacent basins).

The Astrakhan Arch of the Pricaspian Basin (Russia): Geothermal Analysis and Modeling

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ABSTRACT

The Astrakhan Arch (ASAR) region contains one of the largest sub-salt carbonate structures of the Pricaspian salt basin (located to the northwest of the Caspian Sea), where perspectives for hydrocarbon generation and accumulation in the Devonian to Carboniferous deposits are considered to be high. In this paper we analyse measured temperatures in the boreholes drilled in the region and present a generalized column for the vertical temperature gradient within stratigraphic units. The gradient varies between 25 and 41 °C km^{-1} in the sub-salt sediments and is about 20 °C km^{-1} in the Lower Permian halite deposits. The relatively high temperature gradient in salt can be associated with its impurities. We develop a three-dimensional geothermal model of the ASAR region constrained by temperature measurements in deep boreholes, seismic-stratigraphic and lithological data. The temperatures of the sub-salt sediments predicted by the geothermal model range from about 100 to 200 °C and are consistent with the temperatures obtained from the analysis of vitrinite reflectivity and from previous two-dimensional geothermal models. The surface heat flux in the model varies laterally from about 40 to 55 mW m^{-2}. These variations in the heat flux are likely to be associated with structural heterogeneities of the sedimentary rocks and with the presence of salt diapirs. The results of our modelling support the hypothesis of oil and gas-condensate generation in the Upper Carboniferous to Middle Devonian sediments of the ASAR region.

Key words: Pricaspian Basin, borehole temperature, heat flux, numerical modelling

PRESENTER'S BIOGRAPHY

Alik Ismail-Zadeh received his B.Sc. (1982) in mathematics from Baku State University, M.Sc. (1983) in mathematical physics from M. Lomonossov Moscow State University, Ph.D. (1989) and Sc.D. (1997), both in geophysics, from the Russian Academy of Sciences (RAS). He has been a research professor at RAS, Moscow (since 1998); senior research fellow at University of Karlsruhe (since 2001), and professor of IPG Paris (since 2005). His research experience covers numerical and analytical modeling and data interpretation in studies of dynamics and structure of sedimentary basins, the lithosphere, and the mantle.

Study of the variation of thermal conductivity with water saturation of different German sandstones

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ABSTRACT

The measurements of thermal conductivity are usually made on saturated or dry rocks. But these measurements cannot be accomplished easily in unconsolidated sediments or rocks which are very rich in clay minerals. The water saturation is difficult and sometimes impossible for unconsolidated sediments or clay without changing the microstructure. Apart from this, there is little information in the literature on the correlation between thermal conductivity and water saturation level of sedimentary rocks and sediments. Therefore we study the variation of thermal conductivity with the water saturation and search for models which fit our data. As a new aspect, we consider in our model the water bound in clayey sandstones. The bound water content was determined by NMR measurements.

We chose five German sandstones of different mineralogical composition because we could saturate them several times without changing their microstructures. First, the mineralogy was characterised by XRD and then the porosity was determined by NMR. Measurements by mercury porosimetry were also made yielding information on the pore radius distribution.

Porosity of these samples varies between 6 % and 24 %, and they contain mainly quartz, feldspar, and clay minerals. We measured thermal conductivity with an optical scanner. After complete water saturation of the samples, thermal conductivity and the loss of water saturation were recorded as water evaporated under laboratory condition until the samples obtained an equilibrium weight. We noticed three different types of sandstones with different behaviours of the variation of thermal conductivity with water saturation. This seems to be connected to the mineralogical composition of the samples: (1) samples with porosity less than 15 %, containing quartz (≈ 67%), clay (≈ 16%) and feldspar (17 %); (2) samples with a high porosity (24 %), rich in quartz; (3) a sample with high feldspar content (32 %) and a porosity of 21 %.

Finally, we searched for appropriate models to describe these different behaviours, trying to use a minimum of parameters. We used a modified arithmetic model introducing three phases (air, water and matrix) and two types porosity, i.e. volume fraction of the free water and the volume fraction of the bound water. We also used the series model to calculate the average thermal conductivity of the free water and the air phases.

The modified arithmetic model fits very well the decrease of thermal conductivity with dehydration of the samples of type 1 as well as that of sandstones of type 2, but only for low water saturation. The sample rich in feldspar (type 3) shows a different behaviour. We found the modified geometrical model fits best the measurements for low water saturation but not for high saturation.

PRESENTER'S BIOGRAPHY

Rachel Jorand studied geophysics at “Institut de Physique du Globe de Paris”. She received her PhD in 2006. During her doctoral studies, she performed an experimental study on the thermal conductivity of core samples from EST205 at the site of Meuse / Haute Marne (France). She characterised the thermal properties of the ANDRA underground laboratory to validate the reliability of a possible burying of radioactive waste. Since 2006 she has been working at RWTH Aachen University within the framework of a research project financed by the German Federal Environment Ministry. This project aims to study the thermal and hydraulic properties of the subsurface of Germany in order to optimise the design of geothermal installations. Her research interests cover all the physical properties of rocks and in particular thermal conductivity. Her work focuses on laboratory work on sedimentary rocks. Furthermore she is interested in extrapolating her measurements to other scales (drilling and subsurface).

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AN OVERVIEW ON THE GEOTHERMAL RESOURCES OF ALGERIA

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Abstract

Algeria has a large potential for exploitation of low enthalpy geothermal resources. Two hundred hot springs have been recorded in the north part of the country with discharge temperature between 22 and 98°C. While toward the south, many wells reached the geothermal reservoir the hottest temperature is about 70°C. Calcareous rocks, sandy limestone and sandstones of Mesozoic age constitute the main geothermal reservoirs.
Heat flow in 230 oil wells was evaluated using bottom hole temperatures *T*BHT and temperature of the fluids in the drill stem test *T*DST and various rock-porosity data.
Presently, the principal utilization of hot water is the balneology and in a more small scale, space and greenhouses heating. Eight hot springs are used as public thermal resorts for medical purposes.

Key words: Thermal springs ; Wells ; Heat flow; Geothermal resources; Algeria

Development of geothermal information system for South Korea

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ABSTRACT

The GIS based geothermal information system was developed to efficiently manage the geothermal resource information for South Korea, and to provide it quickly to the concerned person. The spatial database of the system is consisted of 4 group, basic information, reference information, analysis information and additional information, assigned as a role with 39 spatial data. The measured data from rock samples or boreholes such as thermal properties (rock density, specific heat, thermal diffusivity, thermal conductivity, etc), geothermal gradient, heat production and heat flow are assigned to Group-1 basic information. The data of geological map, fault, tectonic boundary map, depth map of Mohorovicic Discontinuity and county map are assigned to Group-2 reference information. The distribution maps of geothermal gradient, heat flow, heat production and heat content are assigned to Group-3 analysis information. The data of road map, river map, DEM and satellite image are assigned to Group-4 additional information. Geothermal Information System was developed as stand-alone system on desktop computer using ArcGIS engine software. The functions of the system are consisted of 3 main menu, ‘edit’, ‘query’ and ‘analysis’. Edit menu is used to add new data and to edit the measured data (Group-1). Query menu is performed by selecting the geographical designation, coordinates and rectangular area. The result of query is able to save as a figure or spreadsheet data. Analysis menu has 4 submenu, ‘statistical analysis’, ‘profile analysis’, ‘relationship analysis’ and ‘area analysis’. Statistical analysis submenu is used to get statistical information of the selected data such as average, maximum, minimum, variance and histogram. Profile analysis submenu shows the graph of relationship between the distance and the value on distribution maps along the specified line by user. Relationship analysis submenu shows the relationship graph of heat properties between two specified data. Area analysis submenu is used to make the interpolated map for the selected point data, such as thermal properties, geothermal gradient and heat flow, within the specified subarea or the lithology. This Geothermal Information System is improving to Web-GIS supported system, and then the concerned person will be able to get easily more specialized information on geothermal resources by internet.

Key words: geothermal information system, heat property, geothermal gradient, heat flow, heat production

PRESENTER’S BIOGRAPHY

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Thermal and hydraulic rock properties of the Paleozoic subsurface of western North Rhine-Westphalia (Germany)

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ABSTRACT

The high risk of failure due to the unknown properties of the target rocks at depth is a major obstacle for the exploration of geothermal energy. In general, the ranges of thermal and hydraulic properties given in compilations of rock properties are too large to be useful to constrain properties at a specific site. To overcome this problem, we study the thermal and hydraulic rock properties of the main rock types in Germany in a statistical approach. An important aspect is the use of data from exploration wells that are largely untapped for the purpose of geothermal exploration. In the current project stage, we have been analyzing mostly Devonian and Carboniferous drill cores from 20 deep boreholes in the region of the Lower Rhine Embayment and the Ruhr area (western North Rhine Westphalia). In total, we selected 230 core samples with a length of up to 30 cm from the core archive of the State Geological Survey.
The use of core scanning technology allowed the rapid measurement of thermal conductivity, sonic velocity, and neutron density under dry and water saturated conditions with high resolution for a large number of samples. In addition, we measured porosity, bulk density, and matrix density based on Archimedes' principle and pycnometer analysis.
As first results we present arithmetic means, medians and standard deviations characterizing the petrophysical properties and their variability for specific lithostratigraphic units. Bi- and multimodal frequency distributions correspond to the occurrence of different lithologies such as shale, limestone, dolomite, sandstone, siltstone, marlstone, and quartz-schist. In a next step, the data set will be combined with logging data and complementary mineralogical analyses to derive the variation of thermal conductivity with depth. As a final result, this may be used to infer thermal conductivity for boreholes without appropriate core data which were drilled in similar geological settings.

Key words: thermal conductivity, petrophysical properties, core scanner, logs, statistical analysis.

PRESENTER'S BIOGRAPHY

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Geothermal Resources of Korea

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ABSTRACT

In Korea, geothermal energy has been used for hot spring and balneology for thousands of years up until modern times, and for space cooling/heating recently. However, in general geothermal resources are vastly underexploited in Korea. It is mainly due to the fact that there is no quantitative information about geothermal resource potential of Korea. Therefore, in this work, we made a first geothermal resource assessment in Korea.

To estimate available geothermal energy and to construct temperature at depth maps in Korea, various geothermal data have been used. Those include 1560 thermal property data (conductivity, specific heat, and density), 353 heat flow data, 54 surface temperature data, and 180 heat production data.

In Korea, subsurface temperature ranges from 23.9°C to 47.9°C at a depth of 1 km, from 34.2°C to 79.7°C at a depth of 2 km, from 44.2°C to 110.9°C at a depth of 3 km, from 53.8°C to 141.5°C at a depth of 4 km, and from 63.1°C to 171.6°C at a depth of 5 km. The total available subsurface geothermal energy in Korea is 4.25×10^{21} J from surface to a depth of 1 km, 1.67×10^{22} J to a depth of 2 km, 3.72×10^{22} J to a depth of 3 km, 6.52×10^{22} J to a depth of 4 km, and 1.01×10^{23} J to a depth of 5 km. In particular, the southeastern part of Korea shows high temperatures at depths and so does high geothermal energy. If only 2% of geothermal resource from surface to a depth of 5 km is developed in Korea, energy from geothermal resources would be equivalent to about 200 times annual consumption of primary energy ($\sim 2.33 \times 10^{8}$ TOE) in Korea in 2006.

Key words: geothermal energy, geothermal resources, geothermal resource assessment

PRESENTER'S BIOGRAPHY

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Coupled heat and mass transfer from the interior: geothermal and isotopic constraints

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ABSTRACT

Distribution of conductive heat flow density, q, in continents revealed its regional tectonic-related variations (heat flow–age dependence). Dispersion of the "synchronous" q-values masks these lateral variations, but cannot conceal them completely. Correlation of q and tectonic age, τ, indicates local and temporary *unknown* heat sources in the interior. The sources assumed to be mantle-derived diapirs, but this assumption requires material evidences.

Such evidences appeared due to studying helium isotope composition, $^3He/^4He=R$. This ratio in geological objects is determined by proportion between two genetically different components of He: 1) primordial helium with $R \sim 10^{-4}$ captured by the Earth during its accretion, and 2) radiogenic helium generated within the planet due to U and Th decay.

In MOR basalts and smokers the composition of He is very uniform: according to (Marty and Tolstikhin, 1998), the $R_{av} = (1.15\pm0.1)\times10^{-5}$ that indicates a presence of 10% of primordial He in the present-day upper mantle. On the contrary, the continental crust with the clarke contents of the mother elements should produce the "canonic radiogenic" He with $R\approx2.10^{-8}$, although in rocks and minerals distinguished by composition, structure and origin varies this ratio in a wide range.

But volatile He is eventually released from rocks into free-circulating fluids (Gerling, 1957). There He isotopic composition is naturally averaged. The resulting R-value represents a background quasi-stationary characteristic of the given tectonic unit. These R-values in subsurface fluids indicate tectonic ordering similar to that observed in the distribution of background conductive heat flow (Polyak and Tolstikhin, 1985).

The positive correlation between the background q- and R-values provides evidence of coupled output heat and helium enriched with ^3He from the interior. Common carrier of the abyssal heat and He cannot be autonomous flux of volatile components only, since such an assumption is in conflict with independent estimations of terrestrial heat and He losses. The $^3He/^4He$–$^{87}Sr/^{86}Sr$ correlation revealed in products of volcanic and hydrothermal activity (Polyak et al., 1979; etc.) indicates the coupled transfer of these volatile and lithophile elements by silicate matter.

The triple q-R-τ relationship observed in the areas subjected to folding and magmatic activation during Phanerozoic gives the impression that all of these tectonic units were created by ascending mantle-derived flux in a course of different tectonic cycles. This concept, however, is totally irreconcilable with the data of isotope geochemistry showing that the continental crust was formed mostly in pre-Riphean time (McCulloch & Wasserburg, 1978; etc.). A paradox can be eliminated when taken into account exothermic character of material transformation of the continental crust in a case of its repeated folding. This supposition is supported by the signs of collision-related intracrustal thermal activation (Leonov, 1991, 1993; Yakovlev, 2003; etc.).

Key words: heat flow, helium isotopes

Experimental geothermal data from the Yen-Yakhinskaya and Tyumen super-deep wells (West Siberia, Russia)

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ABSTRACT

The Tyumen and Yen-Yakhinskaya super-deep wells SG-6 and SG-7 (7501 and 8250 m in depth correspondingly) were drilled in West Siberia, Russia, near to the Urengoy oil-gas field.

Thermal properties and porosity were determined correspondingly on 1,219 and 449 cores in dry and water-saturated states. The optical scanning technology was used for the thermal property measurements at normal conditions to enable the study of the thermal anisotropy and inhomogeneity of the rock. Rock porosity ranges from 0.2 to 18% and from 0.1 to 17% correspondingly. Thermal conductivity was determined as 1.13…5.10 $W \cdot m^{-1} \cdot K^{-1}$ for dry samples and 1.14…5.45 $W \cdot m^{-1} \cdot K^{-1}$ for water-saturated samples from the Tyumen well (within a depth interval of 3,700…7,501 m). For the Yen-Yakhinskaya well thermal conductivity and diffusivity were determined correspondingly as 0.91…5.32 $W \cdot m^{-1} \cdot K^{-1}$ and (0.53…3.12)$\cdot 10^{-6}$ $m^2 \cdot s^{-1}$ for dry samples, and 1.90…5.43 $W \cdot m^{-1} \cdot K^{-1}$ and (0.71…3.50)$\cdot 10^{-6}$ $m^2 \cdot s^{-1}$ for water-saturated samples (within a depth interval of 3627…8247 m). Thermal anisotropy coefficient was found to be 1…2.61 for dry cores and 1…2.10 for water-saturated cores from the Tyumen well, and correspondingly 1…1.36 and 1…1.49 for cores from the Yen-Yakhinskaya well.

The measurements of the thermal properties at formation temperature and pressure with differentiation of porous, axial, and confining overburden pressure were performed on selected cores. Our new instrument has been applied to measure rock thermal conductivity (TC) *in situ* conditions at simultaneous influence of elevated temperature and pressure, on 18 cores uniformly selected from a depth interval study. The average correction for the rock's thermal conductivity for the formation conditions was established to be -19.7%.

Thermal conductivity values established from the measurements significantly exceed the data predicted by A. Kurchikov (1992) for deep formations (2.10 $W \cdot m^{-1} \cdot K^{-1}$ for argillites and 2.40 $W \cdot m^{-1} \cdot K^{-1}$ for sandstones).

Formation zones with significant rock fracturing were found from the thermal property and porosity measurements. A special technique has been developed to estimate rock fracturing and microcracks orientation from the thermal property measurements on dry and water-saturated cores.

Possible influence of artificial fracturing of cores (due to decompressional effect), was taken into account to estimate conductive heat flow density values.

The temperature gradient values were estimated from temperature logging performed in both super-deep wells, which allowed us to calculate a conductive component of the heat flow density.

Heat flow density values were estimated as 75–86 mW/m^2 for the drilling site of the Tyumen super-deep well SG-6, and 78–96 mW/m^2 for the Yen-Yakhinskaya super-deep well SG-7. These estimates essentially exceed the previous estimates for these areas (52–60 mW/m^2 - Duchkov et al., 1987; Kurchikov, 1992) taken from the measurements in shallow wells.

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Key words: thermal properties, heat flow.

PRESENTER'S BIOGRAPHY

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Research Laboratory of Geothermic Problems at the Russian State Geological Prospecting University Professional experience concerns development of experimental methods and equipment in geothermics and petrophysics, geothermical and petrophysical research of oil-gas fields and the Earth's crust within programs of scientific deep drilling. Vice president of International Commission on Heat Flow of IASPEI (2007), a full member of the Russian Academy of Earth Sciences, Council of Russian Foundation of Basic Research.

What can be learnt from inverse simulations about the hydraulic and thermal regime at the European EGS demonstration site Soultz-sous-Forêts?

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ABSTRACT

The Enhanced Geothermal System (EGS) research project is located at Soultz-sous-Forêts at the western border of the Rhine rift valley. Three wells were drilled into the deep reservoir (4000 m – 5000 m) within the granitic basement. Subsequent hydraulic stimulations loosened the rock in the vicinity of the wells. In July 2005, a tracer with a concentration of 0.389 mol m^{-3} was injected into the well GPK3 for 19 hours at 15 L s^{-1}. Tracer concentration was monitored in the production wells during the following 5 months, and the produced water was reinjected into GPK3. This experiment demonstrated a good hydraulic connection between GPK3 and one of the production wells, GPK2, but only a poor one with the other one, GPK4. In the following we concentrate on the high productivity connection between GPK3 and GPK2. A conceptual model proposed by Sanjuan et al. (2006) suggests a second flow path between the two wells with longer residence times, additional to the direct connection through the main fracture zone.

Based on general geological information we constructed simplified three-dimensional heterogeneous models in order to explain the tracer concentration observed in GPK2 during the tracer test. To quantify porosity, permeability, and dispersivity of predefined property zones, we applied a full-physics Bayesian inversion (Tarantola, 2004). Numerical experiments with different models show that an excellent fit can be obtained with several models of different complexities and parameterizations. Rough estimates indicate that less than 4 parameters may be estimated from tracer data alone. As expected, a high-permeability, low-porosity zone (main fracture) is required in all models, although the numerical values depends on the extent of the zone and the properties of its immediate surrounding. Most of the tracer is transported near the main flow zone. An second, longer circulation path is not required. Each of these models explain the tracer concentrations equally well but correspond to different bottom-hole pressures and temperatures (which had not been available for inversion). Additionally, there is considerable uncertainty in the details of the experiments. In order to reduce this ambiguity and to procede from conceptual studies to model identification and calibration, independent constraints on model geometry are required, as well as additional types of data.

Sanjuan B., Pinault J., Rose P., Gérard A., Brach M., Braibant G., Crouzet C., Foucher J.,Gautier A., und Touzelet S. (2006): Tracer testing of the geothermal heat exchanger at Soultz-sous-Forêts (France) between 2000 and 2005, Geothermics, 35, 622–653.

Tarantola, A. (2004): Inverse problem theory. Methods for model parameter estimation, SIAM, Philadelphia Pa.

Key words: geothermics, EGS, Soultz-sous-Forêts, tracer test; simulation.

PRESENTER'S BIOGRAPHY

Christoph Clauser graduated in geophysics in 1981 and received his doctoral degree in 1988 at Berlin's Technical University. His obtained his qualification as a professor ("Habilitation") in 1995 and, in 2000, accepted the professorship for Applied Geophysics at RWTH Aachen University where, and in 2007 for Applied Geophysics and Geothermal Energy. His main fields of research are geothermal energy and the geological storage of carbon dioxide. He is chairman of the International Heat Flow Commission (IHFC) of IASPEI, speaker of the working group on Geothermics of the German Geophysical Society (DGG), member of the scientific advisory panel of the EU's "Hot Dry Rock"-Program. He served on the editorial board of several scientific journals and has been coordinating several international projects as well as convening various national and international conferences and symposia. For various international scientific funding agencies he served as a referee. He published two monographs, more than 40 reviewed technical papers, and holds two patents.

MeProRisk – a tool box for evaluating and reducing risks in exploration, development, and operation of geothermal reservoirs

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ABSTRACT

In developing geothermal resources there is a high risk of failure compared to hydrocarbon exploration. The MeProRisk projects aims at improving the strategies at all phases of the reservoir life cycle. It is a joint enterprise of three German universities and two companies: RWTH Aachen University; Berlin's Free University; CA University Kiel; Geophysica Beratungsgesellschaft mbH, Aachen; and RWE Dea AG, Hamburg. It is funded for three years by the German Ministry of Education and Science (BMBF).

The key idea of this project is to view the development of the understanding of a given reservoir as an iterative process. Starting from existing geological information and geophysical data, one or more conceptual models will emerge which will be used for first numerical simulation, forward and inverse. The use of inverse techniques in a broad sense will not only finally yield an optimal model but provides estimates of uncertainty and resolution for the model. This information is useful for further optimizations of experiments, not the least important of which comprises of choosing the locations of new exploration wells. At a later stage of reservoir development the numerical models will be updated continuously as new information becomes available from surface or borehole experiments. Once all wells have been drilled, the character of experiment shifts from static exploration to dynamic interaction with the reservoir, e. g. by injection experiments and their monitoring. The use of all of this information by one simulation tool poses a great challenge. Inverse problems require orders of magnitude more computing resources, and the development of appropriate theoretical and numerical methods for their use is one of this project's primary aims. Due to the often subtle signatures of geothermally relevant exploration targets, it is also necessary to improve the experimental base for setting up and updating the model by developing new and improved methods. This comprises, e. g., developing methods for estimating hydraulic and thermal parameters from geophysical (e. g. electric, seismic, and micro-seismological) observations and for characterizing natural or engineered fracture zones. This poster presents first achievements with respect to all of these fields.

Key words: geothermal energy, exploration, development, risk reduction

PRESENTER'S BIOGRAPHY

Christoph Clauser graduated in geophysics in 1981 and received his doctoral degree in 1988 at Berlin's Technical University. His obtained his qualification as a professor ("Habilitation") in 1995 and, in 2000, accepted the professorship for Applied Geophysics at RWTH Aachen University where, and in 2007 for Applied Geophysics and Geothermal Energy. His main fields of research are geothermal energy and the geological storage of carbon dioxide. He is chairman of the International Heat Flow Commission (IHFC) of IASPEI, speaker of the working group on Geothermics of the German Geophysical Society (DGG), member of the scientific advisory panel of the EU's "Hot Dry Rock"-Program. He served on the editorial board of several scientific journals and has been coordinating several international projects as well as convening various national and international conferences and symposia. For various international scientific funding agencies he served as a referee. He published two monographs, more than 40 reviewed technical papers, and holds two patents.

High geothermal anomaly in north-eastern Morocco

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ABSTRACT

According to the extent of the superficial thermal shows (hot springs, recent volcanic, tectonic activities, geophysical and heat flow anomalies), north-eastern Morocco has been a prospect geothermal domain. The sedimentary formations in this part of Morocco, especially Liasic carbonates which may reach a thickness of 500 m, constitute the most significant aquifer in the area.

In 2007 new temperature logging in a hydrogeological borehole (1100 m deep) near the Mediterranean coast has revealed temperatures higher than 50 ºC and an average geothermal gradient of about 126 ºC/km at depths greater than 300 m. This result confirms the average geothermal gradient estimated in a mining borehole located about 30 km west of the new borehole, in which water with temperatures about 96 ºC was reached at a depth of about 700 m and the estimated HFD exceeding 200 $mW.m^{-2}$. The estimated heat in place per square metre is about 9.5 G J/m^2.

The new geothermal gradient, exceeding by far the ones already determined for this Moroccan area leads the way of a good assessment of this geothermal resource and programs for using high temperature waters in north-eastern Morocco.

Key words: high geothermal gradient, geothermal prospect, north-eastern Morocco.

PRESENTER'S BIOGRAPHY

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Specialization

(i) Main field and Current research interest

- General and applied Geothermics
- Assessment of potential Moroccan geothermal energy areas.
- Thermal structure of the Moroccan lithosphere
- Thermal history of Moroccan sedimentary basins and implications in oil research
- Geomagnetism survey

(ii) Other fields

-Geophysics (seismology, gravity, magnetism, Palaeomagnetism)

-**Fellowship** of Japanese Society of Promotion of Science (JSPS) for three months of the year 2001

Some selected geothermal publications

* Rimi, A., Chalouan,A. & Bahi, L., 1998. Heat flow in the southernmost part of the Mediterranean alpine system, the External Rif in Morocco. *Tectonophysics* , n°285, pp. 135-136.

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* Rimi A., Zeyen H., Zarhloule Y., Correia A., Carneiro J. & Cherkaoui T. 2008. Structure de la lithosphère à travers la limite des plaques Ibérie - Afrique par modélisation intégrée de température et de densité, submitted to Bulletin Institut Scientifique Rabat.

New evaluation of heat flow in Moroccan Atlantic margin

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ABSTRACT

The thermal field in sedimentary basins of continental margins is disturbed by subsurface water circulations in onshore area while classical oceanic measurements in offshore area are disturbed by seasonal fluctuations induced by surface marine currents.

The study aims to propose a new analysis of terrestrial heat flow along the Moroccan continental margin, based on rocks thermal conductivity estimate from the oil wells geophysical logs. This method uses the neurons networks technique which has been tested successfully worldwide in the ODP wells. Bottom Hole Temperatures are corrected by using the cylindrical source models. The geophysical logs data are reduced in order to estimate the heat flow, as well as the in-depth temperatures distribution. In the second time, the study will also examine the possible presence of the Bottom Simulating Reflectors characterizing a thermodynamic interface between methane hydrates and free gases. These BSR can be interpreted in term of temperature and integrated in a total analysis of the present day thermal transfers.

Examples of the Moroccan Atlantic margin thermal regimes are presented.

Key words: heat flow, thermal conductivity, neural network, geophysical logging, Morocco.

PRESENTER'S BIOGRAPHY

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Perspectives for development of geothermal energy resources in India

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ABSTRACT

In contrast to active tectonic zones with widespread recent magmatism and abundance of surface manifestations (geysers, fumaroles and steam fields), such as the regions within the "Pacific Ring of Fire", the conventional geothermal resources in Precambrian terrains such as the Indian shield are represented primarily by the low enthalpy hot springs systems. In India, some of the major groups of hot springs occur in the west coast region, the Son-Narmada-Tapti lineament zone in central India, Rajgir-Monghyr, Surajkund and Bakreshwar in eastern India, Manikaran and Puga-Chhumathang valley springs in northern India. Of these, the Tattapani hot springs located in the central parts of Indian shield and the Puga-Chhumathang valley springs located in the Ladakh Himalaya hold promise for development as geothermal fields for power production using the binary-cycle method. In the case of the former, the temperature of the issuing waters is ~110 ^{o}C at a depth of <1 km, the highest recorded so far in the shield. Lack of evidence for Quaternary magmatism as well as the meteoric nature of the hot spring waters indicate that the hot springs are controlled by forced convection facilitated by peizometric gradient existing between the recharge area and the hot springs, and that the hot springs could be simply mining the normal heat flow. However, no heat flow measurements outside the localized hot springs zone have been made. There is therefore a clear need to establish the regional thermal conditions by systematic geothermal measurements because they would contain additional information about subsurface flow and location of recharge area. In the case of Puga valley springs, geothermal evidence gathered so far and the occurrence of cesium deposits around the springs have indicated the possibility of high temperature hydrothermal circulation in the subsurface. Further exploration efforts are necessary to verify the hypothesis regarding the existence of subsurface magma chambers or young intrusive granites in the region. Such heat sources alone can sustain power generation on a reasonable scale. The heat extracted from warm-to-hot waters emerging from other hot spring systems can be gainfully employed for a number of direct uses such as development of tourist spas for bathing, swimming and balneology, greenhouse heating in cold climates, and agricultural product processing. The significant economic and environmental benefits of using moderate-to-low enthalpy geothermal waters to replace even small quantities of conventional fuels for direct uses cannot be ignored today in view of the steep increase in costs of fossil fuels and associated greenhouse gas emissions.

A second category of geothermal resource traditionally referred to as "hot dry rock" and more recently as "enhanced geothermal systems", has not yet been explored in India. In such resources, heat is stored in hot and poorly permeable rocks at shallow depths within the Earth's crust without any fluid availability to store or transport the heat. The primary requirement for such a resource is the occurrence of high temperatures (typically upwards of 125 ^{o}C) in the top 1-4 km. Areas of anomalous high heat flow, and localized zones of highly radiogenic heat sources of Tertiary-Quaternary age, high heat producing granites and other silicic igneous intrusive rocks having a depth extent of a few kilometers, could be possible targets of future exploration efforts in the country. These considerations reinforce the need for carrying out systematic heat flow as well as radiogenic heat production investigations on a country-wide scale.

Key words: India, Precambrian terrain, geothermal energy resources, heat flow, radiogenic heat production

PRESENTER'S BIOGRAPHY

Sukanta Roy is leading the Geothermal Studies program at the National Geophysical Research Institute, Hyderabad, India. Dr. Roy's research interests include continental thermal structure, exploration and assessment of geothermal energy potential, and geothermics of climate change. Among his most significant contributions have been the generation of extensive datasets on heat flow, thermal properties of rocks and radiogenic heat production characteristics of continental crust. He has published his work in peer-reviewed national and international journals. He has co-authored a book on Geothermal Energy, which was published by Elsevier in 2006. Dr. Roy is a Fellow of the Geological Society of India and member of several other professional bodies. He has been a Visiting Scholar at the University of Utah, Salt Lake City, USA during 2000-01 and again during 2006-07. He is currently serving as a Bureau Member of the International Heat Flow Commission of the IASPEI and a lead author of the ICSU-ROAP Science Planning Document on Sustainable Energy for the Asia-Pacific region. Dr Roy received his Ph.D. in Geophysics (Geothermics) from Banaras Hindu University, India and the country's "Best Ph.D. Thesis in Geophysics" award for the year 1998.

Status, development, and prospects of geothermal energy

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ABSTRACT

Geothermal energy is available round around the clock all year. There are two main lines of geothermal energy utilization: power generation and direct use. Base-load electricity is currently produced from geothermal resources in 24 countries, with a total capacity of 10 GWe; the power production is about 60 TWh/yr. The worldwide direct use of geothermal heat is currently about 300 PJ/yr; the highest growth rate is with geothermal heat pumps (GHP), one of the fastest growing renewable energy technologies. World-wide production by GHPs (in PJ/yr) increases rapidly: 14.6 in 1995, 23.3 in 2000, 87.5 in 2005. GHPs provide space heating, cooling and also domestic hot water.
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Geothermal resources can be harnessed in a sustainable manner; geothermal technologies operate with little or no greenhouse gas emissions since no burning processes are involved. Power generation and direct use contribute already and with further deployment they will – depending on future growth rates – significantly reduce CO_2 emissions. Estimated geothermal electricity production of about 1000 TWh/yr in 2050 will mitigate hundreds of million tons CO_2/yr (depending on what is substituted), with Enhanced Geothermal Systems (EGS), which are still at the experimental level, even more. Production from direct use in 2050 has been estimated at 5.1 EJ/yr, with the GHP portion at 4.2 EJ/yr. The total CO_2 emission reduction potential of geothermal heat pumps has been estimated to be 1.2 billion tonnes per year or about 6% of the global emission.

Key words: power generation, direct use, CO_2 emission avoidance

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He is President of the International Geothermal Association (IGA) and Vice-Chairman, IEA Geothermal Implementing Agreement Executive Committee. He was the Organizing Committee Chairman, WORLD GEOTHERMAL CONGRESS 2000 in Japan and Honorary Chairman, EUROPEAN GEOTHERMAL CONFERENCE 2003 in Szeged/Hungary. He is also member of the IAH Commission on Mineral and Thermal Waters.

His research activities cover a wide range, from heat flow studies and lithospheric geothermics over low-enthalpy utilization (geothermal heat pumps) to Hot Dry Rock modelling.

He published >400 papers and several textbooks on general and applied geothermics and has been teaching at the International Geothermal Schools in Pisa/Italy and Reykjavik/Iceland, at the Geothermal Institute, University of Auckland/New Zealand, and works world-wide as an expert.

A Graphical user interface for computing and plotting the subsurface temperature and heat flow along with their error bounds

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The stochastic heat conduction equation has been solved for different sets of boundary conditions, an exponentially decreasing radiogenic heat generation and randomness in thermal conductivity. Closed form analytical expressions for mean and variance in the temperature depth distribution have been obtained and used for an automatic formulation for computing and plotting the thermal structure along with its error bounds. Also the expressions for heat flow and error bounds have been obtained and a Graphical user interface for computing and plotting the values has been developed. These GUI toolboxes allow us in giving the controlling thermal parameters on the screen and it instantaneously displays the graphs and results. The analytical results and the software developed have been used to quantify the thermal structure for a geothermal province of India. Hence estimation of accurate subsurface thermal field is of vital importance for the better understanding of crustal/lithospheric evolution and temperature controlled geological processes.

Seismically constrained geotherms for the Carpathian area (Romania). Consequences for the lithosphere rheology and crustal magnetic field

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ABSTRACT

The complex structure of the lithosphere beneath the Romanian territory is the result of the compressive tectonic interaction of three major tectonic compartments (East European Platform, Moesian Platform, Intra-Carpathian terranes) during the Carpathians orogeny.

Temperature is a key physical parameter controlling the crustal and mantle dynamics. The evaluation of the thermal structure beneath continental zones requires realistic estimates on crustal structure and distribution of the thermal parameters within the lithosphere. For the stable parts of the lithospheric compartments, where the temperature of the upper mantle could be approximated by a steady-state solution of the 1-D and 2-D thermal conductive equation with boundary conditions, the average value of the surface heat flux is used in obtaining the characteristic geotherm (heat flow derived geotherm). For the tectonically active zones, acceptable temperature models are obtained by thermal simulation of the main tectonic processes affecting the lithospheric structure, such as oceanic subduction followed by continental collision in the East Carpathians, extension in the Pannonian Depression, sedimentation and erosion in the Transylvanian, Pannonian, and Focsani Depressions, generation of magmas in the Neogene volcanic area of the Eastern Carpathians.

This study proposes a re-evaluation of the thermal structure of the lithosphere, based on the minimization of the uncertainties in the spatial distribution of the parameters required in thermal modelling, by assimilation of the information supplied by tomographic seismic data, using a conversion procedure of seismic wave velocity to temperature. Consequences on the lithosphere rheology, on the seismic wave propagation process (quality factor of the medium Q) and on the crustal magnetic field are discussed.

Key words: temperature distribution, temperature-seismic velocity conversion, strength envelope, Carpathian area.

GROUNDWATER FLOW AND THERMAL REGIME IN THE MIDDLE ATLAS

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ABSTRACT

We present hydro-geothermal models of the deep regional aquifer of north-western Morocco, based on results of measurements of rock thermo-physical properties and analyses of temperature data available from water wells. The study area is part of the Middle Atlas, one of the two main branches of an intra-continental Mesozoic-Cainozoic belt extending parallel to the northern limit of Africa, between the Mediterranean Sea and the Saharan platform. In north-western Morocco, the Middle Atlas comes into contact with another Alpine belt, called the Rif-Tell Chain. Geothermal data, mainly from deep exploration oil wells, point to an increase of the regional surface heat flux from the Rif to the Middle Atlas zone, from about 60 to more than 80 mW/m^2, respectively. A possible explanations for the relatively high heat flux is extensional tectonics, testified by basaltic volcanic activity aged 2-3 My. The Middle Atlas is locally characterized by a horst and graben succession and form the main recharge zones of deep water reservoirs. A marly substratum separates minor shallow aquifers, occurring in Plio-Quaternary terrains, from the main, deeper, artesian groundwater, located in the high-permeability Liassic carbonatic sequences. The confined aquifer extends throughout the region and yields several thermal springs with flow rates up to 0.04 m^3/s. Its top ranges from 200 to 1300 m depth and shows water temperatures as higher as 50 °C at about 500 m depth. We analysed thermal log from boreholes characterized by upward flow of hot water fed by the carbonatic formation. Thermal loss from fluid upwelling within the borehole produces a temperature pattern that can be modeled to recover information on the formation thermal gradient and/or the velocity of the raising water. The inferred temperature gradient above the advectively perturbed carbonatic formation exceeds 50 mK/m, thus locally boosting the heat flux to values larger than 100 mW/m^2. A number of thermal conductivity measurements was carried out on a set of samples representative of the stratigraphic sequence of the Middle Atlas. The carbonatic lithotypes forming the deep aquifer show a relatively high thermal conductivity. Values range from 2.0-3.1 W/(m K) in limestones to 4.6-5.0 W/(m K) in dolomites. The results of the thermal log analysis and the measurements of thermo-physical properties were then used to constrain analytical modelling of the heat and water transfer involved in the deep circulation. Several hypotheses of basal heat flux, porosity, aquifer thickness and water velocity were tested along selected hydro-geological cross-sections.

Key words: Borehole temperatures, heat flux, groundwater flow, Middle Atlas.

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