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Synthetic Convection Log — Characterization of vertical transport processes in fluid-filled boreholes

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A B S T R A C T

Two main types of vertical convective flows play an important role in transport along the fluid column: forced convective and free convective flows. Forced vertical convection in fluid-filled boreholes (short-circuit flow) can be detected by means of borehole measurements, e.g. different types of flowmeters, temperature logs, and fluid-logging. For detecting free vertical convection (natural convection), so far, no special logging device or interpretation algorithm was available. This paper presents a new synthetic borehole log, the so-called Synthetic Convection Log (SYNCO-Log). It enables in-situ detection and identification of free convective, including double-diffusive, flows using state-of-the-art geophysical borehole measurements. Vertical convection in fluid-filled boreholes is known to lead to transport of heat and mass. Thus, understanding free convective flow is crucial for geothermics, borehole geophysics, hydrological investigations, and meaningful fluid sampling. The SYNCO-Log is divided into two closely linked parts: (1) the cause-oriented approach compares the situation along the fluid column with critical thresholds for the onset of free convection and (2) the effect-oriented approach separates the anomalies and patterns in fluid quality that are induced by free convection. Inputs for the interpretation algorithm are simultaneously acquired temperature and mudresistivity (or fluid conductivity) logs, hydraulic pressure, and borehole diameter. Output of the algorithm is a computer generated, descriptive illustration of the results including a classified plot for delineating the type of flow. The reliability of the SYNCO-Log is high, as causes and effects, i.e. driving forces and resulting heat and mass transport, are simultaneously identified. Its applicability and the relevance of the results are shown on the example of borehole measurements from the KTB-MH deep crustal borehole, located in the Bavarian region of Germany.

1. Introduction

Characterization of flow and transport is an important objective of borehole geophysics in fluid-filled boreholes and monitoring wells. Boreholes and wells locally distort the natural flow field and create a path that opens up an additional possibility of heat and mass transfer between rock formations (e.g. aquifers), surrounding, and atmosphere. Two main types of vertical convective flows play an important role in transport along the fluid column: forced convective and free convective flows (Fig. 1).

Forced vertical convection in fluid-filled boreholes (short-circuit flow) can be detected by means of borehole measurements, e.g. different types of flowmeters, temperature logs, and fluid-logging (Fricke and Schön, 1999).

For detecting free vertical convection (natural convection), so far, no special logging device or interpretation algorithm was available. This paper approaches the problem and describes an interpretation algorithm that allows for in-situ detection and even differentiation of various types of free convective flows.

As opposed to forced convection that is acting only in one direction, the density-driven free convective flow is simultaneously acting in all directions due to the circulation in convection cells (Fig. 1). Dissolved matters and heat can thus be transported upwards and downwards in the affected fluid column.

Free convective flows in boreholes or monitoring wells and their adulterating effects on in-situ measurements and groundwater samples were reported by Solodov et al. (2002) and systematically investigated by Berthold and Börner (2006, 2008). Strong convective flow within the fluid column may adversely affect fluid samples. Gases, as well as other substances, are possibly transported into new depths, where varying chemical processes may arise. So, knowing about the existence of vertical flows in fluid columns is important for hydrological investigations (e.g. determining points of in- and outflow) and for borehole geophysics (e.g. finding leakages in casings).

Furthermore, temperatures in fluid columns that are subject to vertical convection may depart significantly from the ones in the surrounding rock (Sammel, 1968). The developing convection cells can

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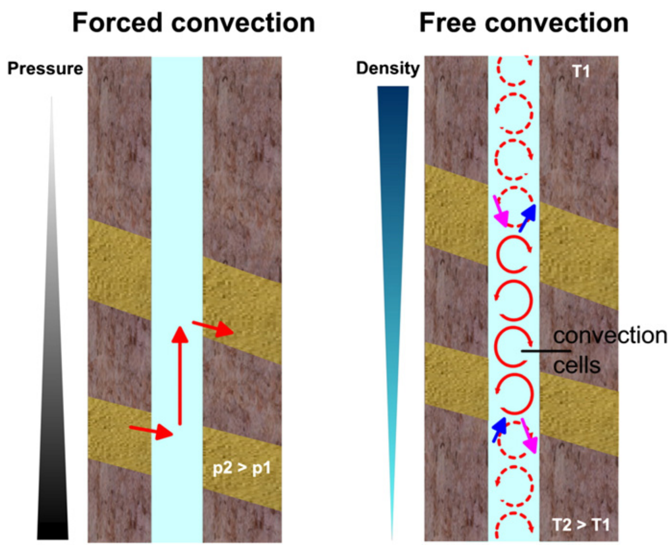

Fig. 1. Schematic illustration of forced and free convective flows in boreholes (p — pressure, T — temperature).

induce some sort of noise in temperature logs (Wisian et al., 1996). Noise is an accuracy limiting factor, e.g. for meaningful geothermal gradient determination (Pfister and Rybach, 1995). Thus, understanding convective flow within the borehole is also crucial for geothermics and subsurface water movement investigations.

Free convection is already induced by slight density differences along the fluid column and is thus often called natural convection. In boreholes, density influencing components are typically vertical temperature and/or salt concentration gradients and their temporal changes. Temperature and concentration gradients often vary with depths, resulting in different types of density-driven transport processes (Fig. 2). As there exist vertical density-driven transport processes that enhance gradients (double-diffusion) and processes that flatten gradients (e.g. thermal or solutal convection), it is important to distinguish between the diverse types.

This paper presents a new synthetic borehole log, the so-called Synthetic Convection Log (SYNCO-Log). It enables in-situ detection and identification of free convective, including double-diffusive, flows using state-of-the-art geophysical borehole measurements (temperature and mudresistivity or fluid conductivity logs). In the sense of a "quick look" interpretation, the SYNCO-Log visually divides the fluid column into sections that are characterized by a density-driven flow and sections that are characterized by no density-driven convective flow. Additionally, it classifies the areas with density-driven flow according to its flow type.

The applicability of the SYNCO-Log and relevance of the results are shown on the example of borehole measurements from the KTB deep crustal borehole, located in the Bavarian region of Germany.

2. Background on free convective flow types

According to the prevailing temperature and salinity gradients one differentiates between thermal convection, solutal convection, thermosolutal convection, saltfingering, and diffusive convection (Fig. 2).

Thermal, solutal, and thermosolutal convections (classified according to the destabilizing gradients) are overturning convections. They compensate a vertical density contrast by mixing.

In double-diffusion, density-driven flows arise in fluid columns with a theoretically stable vertical density gradient, as heat conduction in fluids is a much more effective transport process than molecular mass diffusion (Stommel et al., 1956). Two types of double-diffusion exist: saltfingering and diffusive convection (Ruddick and Gargett, 2003). When temperature and salinity decrease with depth, saltfingering may arise (Stern, 1960). When temperature and salinity increase with depth, diffusive convection may arise. Theory and experimental investigations suggest that double-diffusive convection with diffusive layering is most intense when temperature and salinity gradient are neutralizing themselves in their effect (Kelley et al., 2003). Both flow types enhance a vertical density contrast.

3. Synthetic Convection Log (SYNCO-Log)

3.1. General description of the algorithm

The SYNCO-Log for detection and differentiation of vertical density-driven transport processes is divided into two parts or algorithms that are closely linked: (1) the cause-oriented algorithm that compares the situation along the fluid column with the critical thresholds for the onset of free convection and (2) the effect-oriented

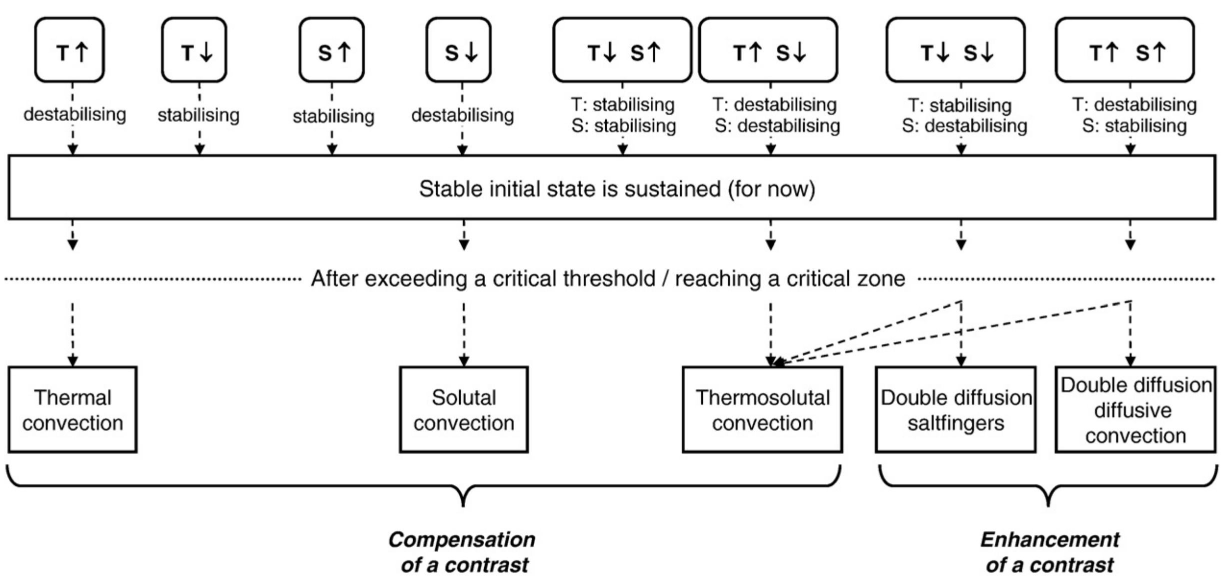

Fig. 2. Classification of density-driven vertical transport processes induced by gradients in temperature (*T*) and salinity (*S*) (arrow upwards: increasing with depth, arrow downwards: decreasing with depth).

algorithm that separates the anomalies and patterns in fluid quality that are induced by free convection.

Inputs for both algorithms are simultaneously acquired temperature and mudresistivity (or fluid conductivity) logs, hydraulic pressure which is either measured directly or calculated from depth, and the borehole diameter which is either derived from a caliper log or the known casing diameter. Recording these logs within the scope of borehole geophysical measurements is state of the art.

Measurements have to be taken during downward movement of the probe and it is crucial that the fluid column is undisturbed. Measurements always reflect the current state of the fluid column. So depending on the aim of the investigation it might be necessary that the fluid column has achieved thermal equilibrium with the surrounding rock and, if so, the casing. Thermal equilibrium is severely disturbed by the drilling process or cementation, requiring several months to several years for stabilization of temperatures (e.g. Bullard, 1947). Minor disturbances are caused by pumping or other mixing of the water column e.g. by moving geophysical probes, requiring only few hours to days for temperature stabilization.

Output of the algorithm is a computer generated, descriptive illustration of the results in form of the SYNCO-Log including a classified plot for delineating the type of flow.

3.2. Cause-oriented part

In the *cause-oriented part* the fluid column is sectionwise evaluated according to its stability or instability, including the type of flow (Fig. 3). The determining parameters are the temperature and salinity gradients calculated along with specific stability measures from the borehole logs. For the following calculations, a pressure log is required. If not obtained in the field, a hydrostatic pressure log can be derived from depth of measurement considering the water level.

In the first algorithm step, a low-pass filter is applied to the input logs temperature and mudresistivity or fluid conductivity to eliminate sensor induced noise and little oscillations superimposed on the local gradient (which are key for the effect-oriented part of the SYNCO-Log). From the filtered temperature and mudresistivity or fluid conductivity logs and the pressure log, salinity is computed based on the Practical Salinity Scale (Perkin and Lewis, 1980).

In the second step, the decisive parameters: temperature gradient, salinity gradient, and the instability measures described below, are calculated sectionwise.

3.3. Instability measures

Relevant instability measures for free convection analysis are: thermal Rayleigh number (Ra_T), solutal Rayleigh number (Ra_S), local stability (R_ρ) and global stability (N^2).

The thermal Rayleigh number Ra_T is defined as (Rayleigh, 1916):

$$Ra_T = \frac{\alpha g}{D_T \nu} \frac{\Delta T}{\Delta z} r^4$$

with gravity acceleration g, thermal expansion coefficient α, temperature gradient $\Delta T/\Delta z$, thermal diffusivity D_T, kinematic viscosity ν, and a characteristic length r that is the radius for fluid columns.

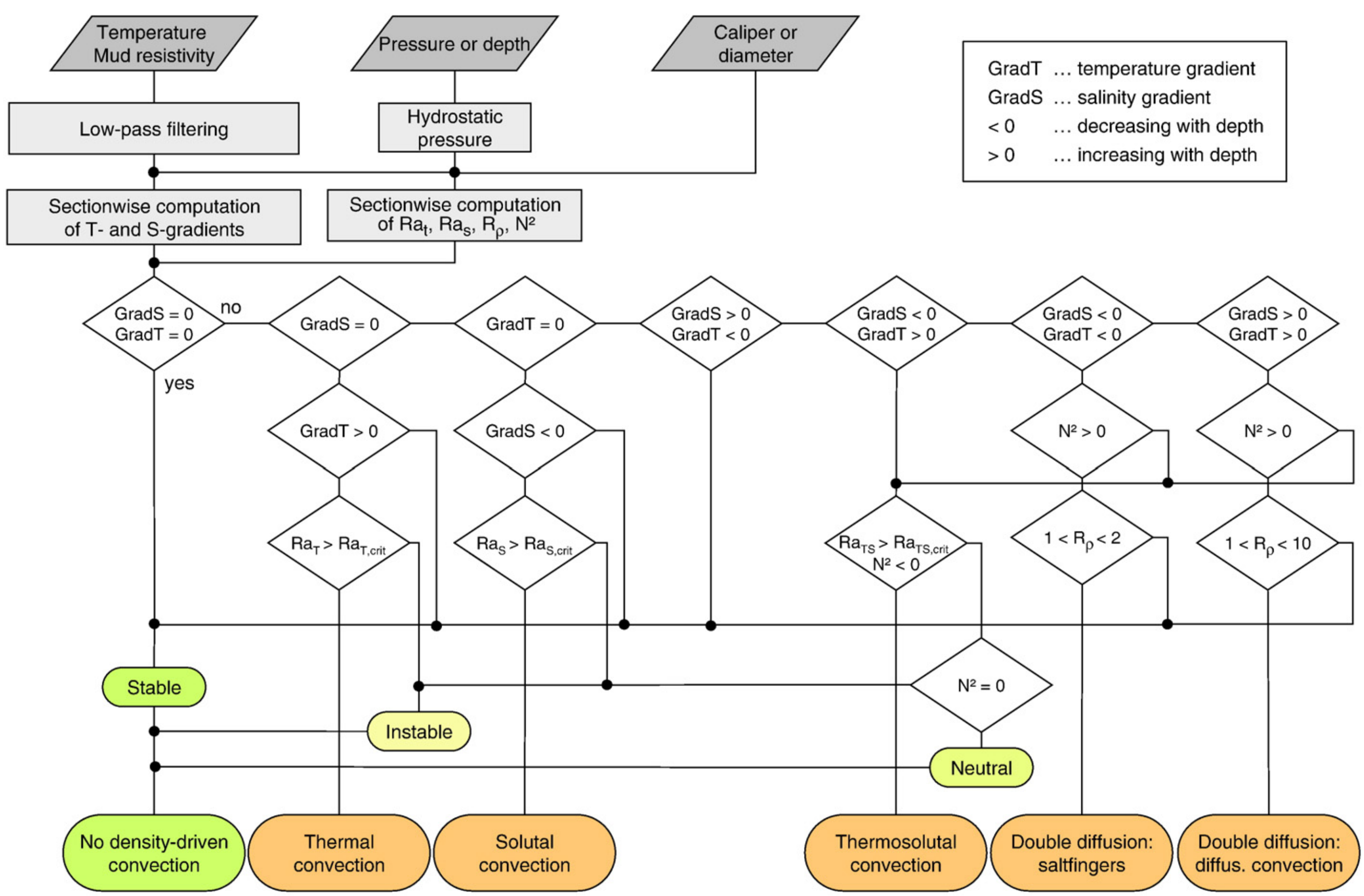

Fig. 3. Flow chart of the cause-oriented part of the Synthetic Convection Log: comparison of the situation along the fluid column with the critical thresholds for the onset of free convection and classification according to the density-driven vertical transport processes — black points symbolize a linking operation.

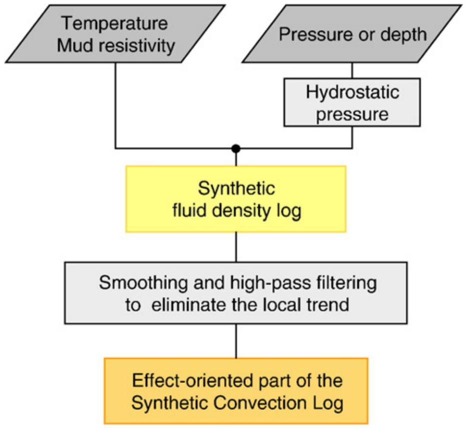

Fig. 4. Flow chart of the effect-oriented part of the Synthetic Convection Log: determination of a synthetic fluid density log and separation of the anomalies and patterns that are induced by free convection.

The solutal Rayleigh number Ra_S is defined as (Gershuni and Zhukhovitskii, 1976):

$$Ra_S = -\frac{\beta g}{D_S \nu}\frac{\Delta S}{\Delta z} r^4$$

with haline contraction coefficient β, solutal gradient $\Delta S/\Delta z$, and solutal diffusivity D_S. The equation carries a negative sign as the solutal gradient has an inverse effect on density compared to the temperature gradient.

The thermosolutal Rayleigh number Ra_{TS} is defined as (Veronis, 1968):

$$Ra_{TS} = Ra_T + Ra_S.$$

The so-called local stability R_ρ describes the ratio of the stabilizing to the destabilizing component and is defined as (Turner, 1973):

$$R_\rho = \left(\frac{\alpha \partial T/\partial z}{\beta \partial S/\partial z}\right)^{\pm 1}.$$

The exponent +1 is applied if temperature decreases with depth and the exponent -1 is applied otherwise.

For deep boreholes, where compressibility of water becomes significant, the adiabatic lapse rate Γ needs to be included:

$$R_\rho = \left(\frac{\alpha(\partial T/\partial z - \Gamma)}{\beta \partial S/\partial z}\right)^{\pm 1}.$$

The adiabatic lapse rate describes the ratio of the in-situ temperature increase with depth due to the isentropic compressibility of water (Wüest et al., 1996) and is defined as:

$$\Gamma = -\frac{g\alpha T_\theta}{c_p}$$

with absolute temperature T_θ and specific heat capacity c_p.

The global stability or Brunt–Väisälä frequency N^2 is the frequency of a displaced particle oscillating back and forth according to its equilibrium position and is defined as (e.g. Tritton, 1998) (including the optional adiabatic lapse rate Γ):

$$N^2 = g\left(-\alpha\left(\frac{\partial T}{\partial z} - \Gamma\right) + \beta\frac{\partial S}{\partial z}\right).$$

The instability measures are crucial, as even if a section of a fluid column is not stably stratified, it is not necessarily subject to free convection. The fluid column can absorb a certain level of instability without leaving its initial stable state. Only if the impelling forces (density-driven buoyancy) are exceeding the retarding forces (viscosity and diffusion) to a certain critical value, free convection can start (Rayleigh, 1916).

3.4. Critical thresholds

The corresponding critical thresholds are depending on the type of free convective flow (e.g. thermal or solutal convection). The type of density-driven flow is determined based on the temperature and salinity gradient and the global stability N^2 in this section of the fluid column (see Fig. 3).

For thermal, solutal, and thermosolutal convections, the important instability measure is the corresponding Rayleigh number, which describes the ratio of the impelling to the retarding forces. Convection starts when the Rayleigh number exceeds the critical Rayleigh number.

The thermal critical Rayleigh number for fluid columns can be obtained from an equation of Gershuni and Zhukhovitskii (1976):

$$Ra_{T,crit} = \frac{96}{5(1+7\lambda)}\left[3(33+103\lambda) - \sqrt{3(2567+14794\lambda+26927\lambda^2)}\right]$$

which is based on λ, the ratio of the thermal conductivities of fluid and surrounding material.

For the solutal critical Rayleigh number the value $Pi^4 \approx 97.4$ is used (Gershuni and Zhukhovitskii, 1976):

$$Ra_{S,crit} = \pi^4.$$

The thermosolutal critical Rayleigh number is identical to the thermal critical Rayleigh number under the assumption of a linear superposition of the thermal and solutal destabilizing forces (Love et al., 2007):

$$Ra_{TS,crit} = Ra_{T,crit}.$$

For double-diffusion the important instability measures are the global and local stability. First of all, the global stability N^2 has to be positive. If so, the critical zone based on the local stability R_ρ is $1<R_\rho<2$ (Saiki et al., 2000) for saltfingering and $1<R_\rho<10$ for diffusive convection (Kelley et al., 2003).

3.5. Convection analysis and typing

Using these critical thresholds or zones, each section of the fluid column can be evaluated according to its stability or instability and according to the type of free convective flow (Fig. 3).

Clearly stable sections can be already delineated from the calculated temperature and salinity gradients (GradT and GradS). The section of the fluid column is definitely stable when both gradients are zero (GradT = GradS = 0), only temperature varies with depth and decreases (GradS = 0, GradT < 0), only salinity varies with depth and increases (GradT = 0, GradS > 0), or temperature decreases and salinity increases with depth (GradT < 0, GradS > 0).

Thermal convection exists when only temperature varies with depth and increases (GradS = 0, GradT > 0) and the thermal Rayleigh number exceeds the critical thermal Rayleigh number ($Ra_T > Ra_{T,crit}$).

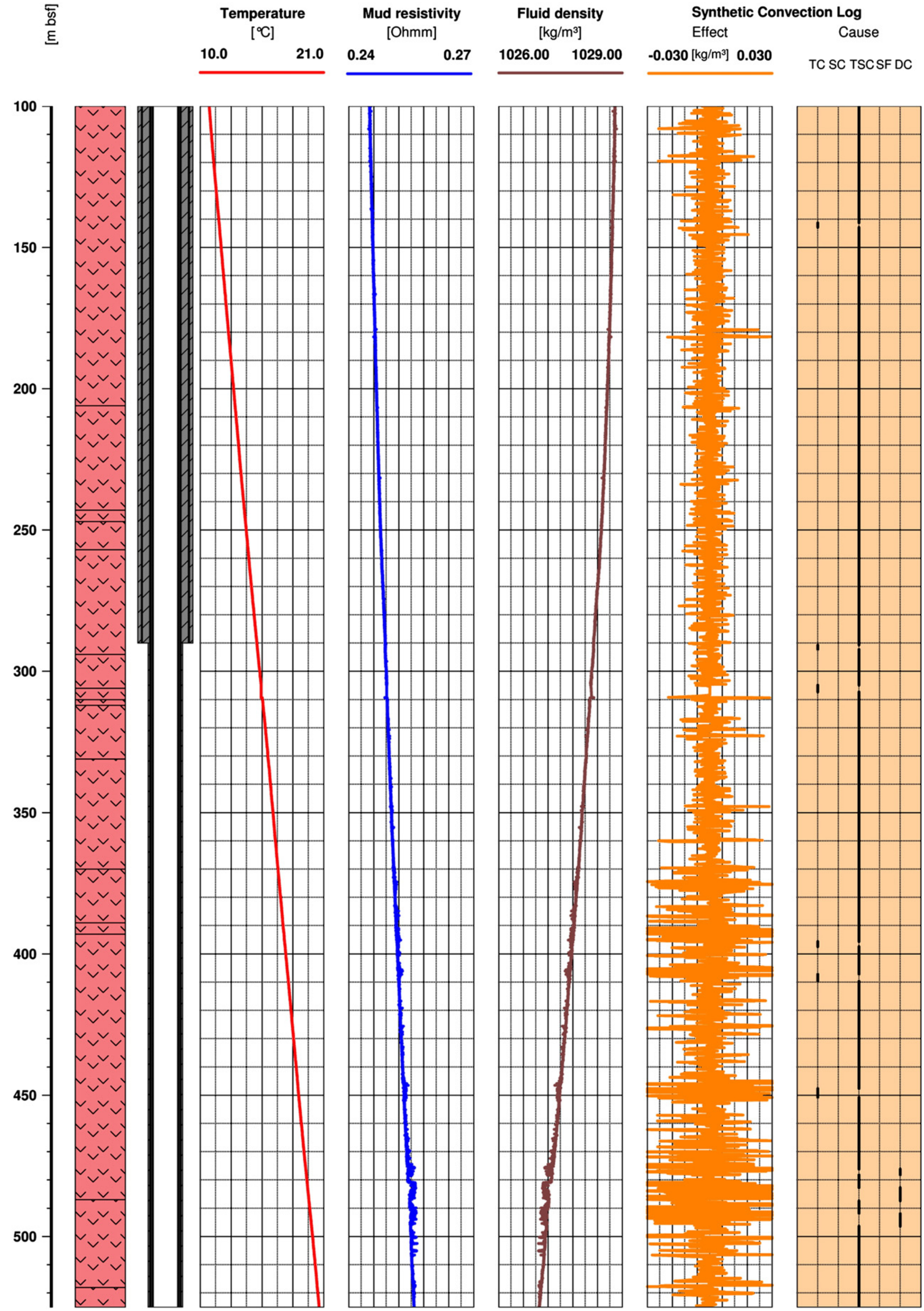

Fig. 5. Temperature and mudresistivity measurement results from the KTB main hole along with the calculated fluid density and Synthetic Convection Log showing causes (TC, SC, TSC — thermal, solutal, thermosolutal convection; SF — saltfingers; DC — diffusive convection) and effects (anomalies and patterns induced) of free convection.

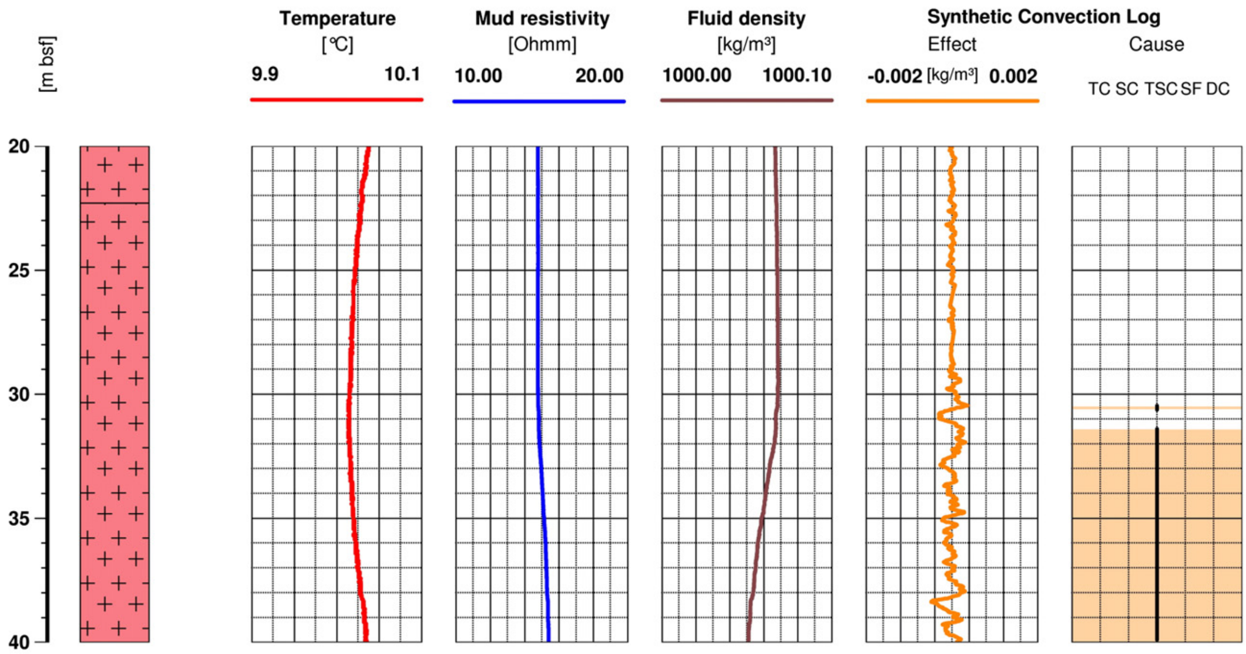

Fig. 6. Temperature and mudresistivity measurement results from a shallow uncased borehole along with the calculated fluid density and Synthetic Convection Log showing causes (TC, SC, TSC — thermal, solutal, thermosolutal convection; SF — salt fingers; DC — diffusive convection) and effects (anomalies and patterns induced) of free convection.

Likewise, solutal convection exists when only salinity varies with depth and decreases (GradT = 0, GradS < 0) and the solutal Rayleigh number exceeds the critical solutal Rayleigh number ($Ra_S > Ra_{S,crit}$).

Saltfingering can exist when temperature and salinity decrease with depth (GradT < 0, GradS < 0), global stability is positive ($N^2 > 0$) and local stability is between 1 and 2 ($1 < R_\rho < 2$). Whereas diffusive convection can exist when temperature and salinity increase with depth (GradT > 0, GradS > 0), global stability is positive ($N^2 > 0$) and local stability is between 1 and 10 ($1 < R_\rho < 10$).

Thermosolutal convection can exist under varying circumstances. Common to all three conditions is that global stability has to be negative ($N^2 < 0$) and that the thermosolutal Rayleigh number has to exceed the critical thermosolutal Rayleigh number ($Ra_{TS} > Ra_{TS,crit}$). In this case, thermosolutal convection can either exist when temperature increases and salinity decreases with depth (GradT < 0, GradS > 0) or temperature and salinity decrease with depth (GradT < 0, GradS < 0), or temperature and salinity increase with depth (GradT > 0, GradS > 0).

The essential cases and conditions considered in the algorithm are summarized in an easily interpreted flow chart in Fig. 3.

3.6. Effect-oriented part

The *effect-oriented part* is based on the fact that convection induced mixing within convection cells creates small oscillations in the otherwise even gradient of fluid quality parameters (e.g. temperature and mud resistivity). This was observed in many high-resolved logs and ascertained by numerical modeling (Berthold and Börner, 2008).

Due to their small amplitude, the effect of convection cells on the prevailing temperature gradient is partly hard to identify in the primary parameter logs or is otherwise often considered as noise and disregarded (Wisian et al., 1996).

The effect-oriented algorithm visualizes the small oscillations independently from the local trend or gradient (Fig. 4). As both fluid quality parameters (temperature and mud resistivity) influence density, the combined effect is considered for convection cell detection, i.e. the density profile in the fluid column.

For that purpose, in a first step, a synthetic fluid density log is determined from temperature, mud resistivity, and hydraulic pressure. Depending on the salinity of the fluid, either the Equation of State for Freshwater (Chen and Millero, 1986) or the International Equation of State of Seawater 1980 (UNESCO, 1981) is used. The Equation of State for Freshwater is valid for salinities up to 0.6 (psu or g/l). Further density formulas, considering further dissolved ions or a considerably amount of density affecting dissolved gases, can be easily implemented into the algorithm. The resulting synthetic fluid density log already shows sections with an unstable state according to density.

In a second step, the convection revealing oscillations are separated from the synthetic fluid density log by slight smoothing (considering sensor resolution) and high-pass filtering (Fig. 4).

In the resulting effect-oriented part of the SYNCO-Log, the existence of convection cells is indicated by strong oscillations. The absence of convection cells is indicated by small or no oscillations. Based on these information, the fluid column can be divided into sections with and without detectable vertical free convective flow.

3.6.1. Results from the KTB-MH

In this section, the applicability of the SYNCO-Log is shown on the example of field data, i.e. borehole measurements from the KTB main hole (KTB-MH). The KTB-MH is a deep crustal borehole, located in the Bavarian region of Germany. It was drilled from 1990 to 1994 through a solid rock formation from crystalline, metamorphous rocks of a continental collision zone and reached a total depth of 9101 m.

Presented here are the measurement and interpretation results from a section of the borehole between 100 and 525 m below surface (Fig. 5). The measurements in the cased borehole were conducted in October 2008 with a combined temperature–mudresistivity probe. In the considered section of the borehole, the inner diameter of the steel casing is 312 mm (Baum et al., 1995). The probe was centered in the fluid column and lowered with a velocity of 2 m/min using a sampling interval of 1 cm. As regards the KTB main hole, such high-resolved temperature and electrical conductivity measurements were conducted for the first time.

The high-resolved temperature log shows a continuous temperature increase with depth. Temperatures in this section of the fluid column ranged from about 10.8 °C up to about 20.6 °C (Fig. 5). The temperature gradient was about constant and amounted to 2.3 K/100 m. This relates well with the older value of 2.1 K/100 m, which was derived for the upper 1000 m of the KTB pilot hole that is about 200 m away (Wöhrl, 2003).

The temperature corrected mudresistivity log shows a similar trend as the temperature log. That means that fluid resistivity also increased with depth. In a depth of 100 m below surface, fluid resistivity was about 0.245 Ohm m and increased continuously up to 0.256 Ohm m in a depth of 525 m below surface (Fig. 5). That corresponds to a decrease in salinity from 38.0 to 36.1 g/l NaCl equivalent and represents a regarding to the salinity gradient instable state of the fluid column.

Due to the high salt content, the synthetic density log was calculated using the International Equation of State of Seawater 1980 (UNESCO, 1981).

Analysis of the geophysical data concerning density-driven vertical flows revealed that at measurement time the entire considered fluid column of the KTB-MH was subject to free convective flow. The existence of revolving flows was confirmed by both interpretation algorithms: cause- and effect-oriented interpretation (Fig. 5).

According to the SYNCO-Log, the main part of the fluid column is influenced by thermosolutal convection (TSC). That means temperature as well as salinity gradients had a destabilizing effect. The high amplitudes of the density oscillations imply a very intense, strong convective flow. This becomes especially obvious, when comparing the results to results from a shallow uncased borehole with smaller diameter (190 mm) that was also drilled in a solid rock formation (Fig. 6).

Merely in small sections in the order of a few meters, the flow is identified as thermal convection (TC). In the section between 476.0 and 496.5 m below surface the cause-oriented part of the SYNCO-Log partly indicates diffusive convection.

Based on the analysis it can be assumed that a constant upward directed heat flow and a constant downward directed salt flow exist in the KTB-MH in the considered part of the fluid column. To what extent the heat flow induced in the borehole affects, for example, the determination of reliable heat flow densities of the surrounding rock formation remains to be clarified.

3.6.2. Discussion and conclusion

The Synthetic Convection Log (SYNCO-Log) enables in-situ detection and identification of free convective, including double-diffusive, flows using state-of-the-art geophysical borehole measurements. Using the SYNCO-Log it is possible, to differentiate between all forms of density-driven convections that can occur in boreholes: thermal, solutal, thermosolutal (overturning) convections, as well as salt fingers and diffusive convection.

The interpretation algorithm computes the essential parameters and instability measures from logs of temperature–mudresistivity probes and compares them to critical thresholds or zones for the onset of density-driven flows. Further required parameters are hydraulic pressure, which is either measured directly or calculated from depth, and the borehole diameter which is derived from either a caliper log or the known casing diameter.

The correctness of the basic concept of the interpretation algorithm has been proven by analytical approximations, numerical simulations, medium scale experiments, and numerous measurements in groundwater monitoring wells and shallow boreholes within the scope of previous investigations (Berthold and Börner, 2008).

With the novel SYNCO-Log, this paper presents a further development of the basic concept. The improved interpretation algorithm confirmed its applicability in deep boreholes (even with large diameter) as presented here on the example of measurements from the KTB main hole.

Output of the interpretation algorithm is a computer generated, descriptive illustration of the results. In the sense of a "quick look" interpretation, the novel SYNCO-Log visually divides the fluid column into sections that are characterized by a density-driven flow and sections that are characterized by no flow. Additionally, in a classified plot, areas with density-driven flow are delineated according to its flow type.

The advantage of the algorithm lies in the fact, that causes and effects are identified, i.e. driving forces and resulting heat and mass transport, are captured and evaluated. The cause-oriented part is based on the fact that density-driven vertical transport processes occur under different conditions, implying that identification and delineation of the diverse types are possible. The effect-oriented part is based on the idea that the phenomena resulting from free convection, like convection cells and layered structures can be identified in the primary logs.

Evaluation is conducted in both parts independently. A comparison proves, that the results of both approaches compare well in most cases. However, the reliable functioning of the effect-orientated approach depends on constraining factors like instrumental noise, sensor resolution, sampling interval, and sensor reaction time. To avoid these difficulties, it is recommended to utilize the Synthetic Convection Log as a whole. The combined analysis improves decisively the reliability of the interpretation.

Nomenclature

c_p	specific heat capacity
D_S	solutal (or mass) diffusivity
D_T	thermal diffusivity
g	gravitational acceleration
N^2	global stability or Brunt–Väisälä frequency
r	characteristic length that depends on geometry
Ra_T	thermal Rayleigh number
Ra_S	solutal Rayleigh number
Ra_{TS}	thermosolutal Rayleigh number
$\mathrm{Ra}_{T,crit}$	critical thermal Rayleigh number
$\mathrm{Ra}_{S,crit}$	critical solutal Rayleigh number
$\mathrm{Ra}_{TS,crit}$	critical thermosolutal Rayleigh number
R_ρ	local stability
S	salinity
T	temperature
T_θ	absolute temperature
z	depth
α	thermal expansion coefficient
β	haline contraction coefficient
Γ	adiabatic lapse rate
λ	ratio of the thermal conductivities of the fluid and the surrounding material
ν	kinematic viscosity

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