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Temperature distribution in karst systems: the role of air and water fluxes

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Abstract

A better understanding of heat fluxes and temperature distribution in continental rocks is of great importance for many engineering aspects (tunnelling, mining, geothermal research,…). This paper aims at providing a conceptual model of temperature distribution in karst environments which display thermal "anomalies" when compared to other rocks.

In temperate regions, water circulations are usually high enough to completely "drain out" the geothermal heat flux at the bottom of karst systems (phreatic zone). A theoretical approach based on temperature measurements carried out in deep caves and boreholes demonstrates however that air circulations can largely dominate water infiltrations in the karst vadose zone, which can be as thick as 2000 m. Consequently, temperature gradients within this zone are similar to the lapse rate of humid air (~0.5°C/100 m). Yet, this value depends on the regional climatic context and might present some significant variations.

Keywords: Karst; temperature; geothermic; energy exchanges.

Introduction

The temperature distribution in the subsurface is, beside its scientific interest, of great importance for various fields of practical applications such as for the construction of underground facilities, the use of groundwater resources or the development and exploitation of geothermal energy (Medici and Rybach 1995). Due to technical limitations, working conditions or sanitary aspects, elevated temperatures might frequently represent a source of troubles for numerous applications. Karst systems display "anomalous" temperature distributions (Fig.1) which are frequently ignored or imperfectly understood. Hence, hundreds of caves explored by speleologists to more than 500 m below surface show temperatures close to those of the outside atmosphere (e.g. Choppy 1984, Badino 1992, Bitterli 1996, Audra 2001). As more than ten percent of the Earth outcropping continental rocks are subject to intense karstic processes, interactions with human activities are frequent (Ford and Williams 1989). A better understanding of heat fluxes in karst environments seems therefore necessary. This paper aims at providing a new light on this question.

For the last fifteen years, several authors focused their research interest on a better understanding of heat flow processes within the saturated zone of karst systems (phreatic zone) (e.g. Benderitter et al. 1993, Renner 1996, Liedl et al. 1997).

Due to the high permeability of karst massifs, hydraulic gradients remain close to zero and water tables are almost at the level of their outlets during low water episodes. The unsaturated (vadose) zone can therefore reach a thickness up to 2000 m. Only few authors have studied thermal processes in these thick vadose zones. Early attempts were made to predict cave

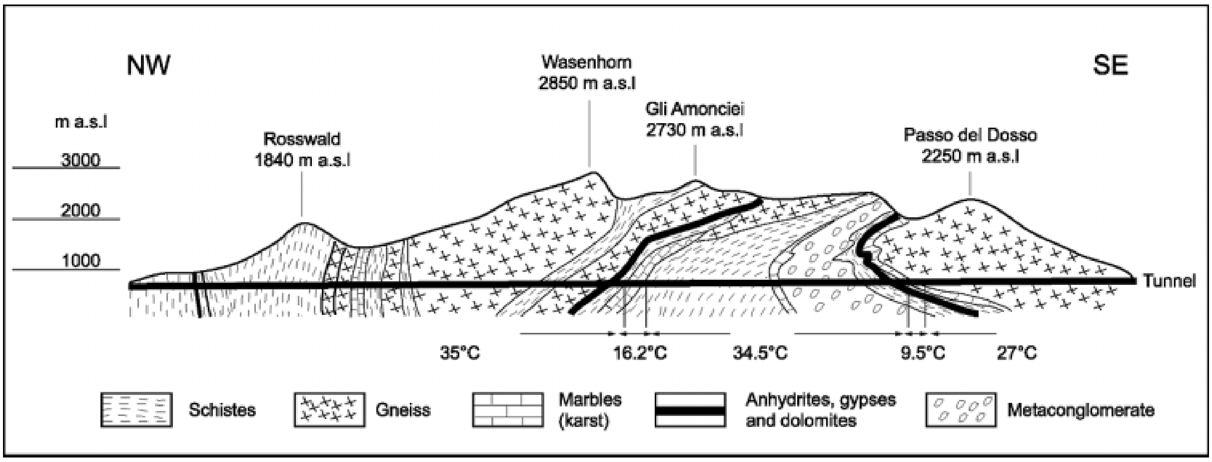

Fig. 1. Temperature profile in the Simplon tunnel (Switzerland). As in many other tunnels, thermal anomalies have been recognized in carbonate environments (figure adapted from Bianchetti et al. 1993).

temperature distribution theoretically (e.g. Eraso 1965, Cigna 1967, Andrieux 1969, Wigley and Brown 1971, Choppy 1984) but most authors were only concerned with the first hundred meters of karst systems, where the cave temperature is still influenced by seasonal variations. If recent publications agree to neglect the role of the geothermal heat flux in the energy balance of such systems (e.g. Badino 1995, Jeannin et al. 1997, Lismonde 2002,…), an active discussion is still open about the respective importance of heat fluxes transported by water and air. By the way, field data are often missing. Observations presented in this paper aim at providing a new synthetic conceptual model of temperature distribution in a karst massif, based on available (mostly unpublished) models and data.

Heat fluxes in a karst massif: a synthetic conceptual model

Basic assumptions

Karst systems under consideration are limited on their upper part by the outside atmosphere and on their lower part by a low permeability (marls or unkarstified limestones). These aquifers can be subdivided into two major hydrological subsystems: the vadose (unsaturated) and the phreatic (saturated) zone (e.g. Ford and Williams 1989). Both of them are subject to karstification processes leading to the genesis of new conduits. Air and/or water circulations will therefore be observed in the active and fossil part of a karst system (Fig. 2).

Heat transfer around the conduits, within the matrix, is supposed to be restricted to conductive exchanges (i.e. water flow velocity in the matrix is low enough to be neglected) and tectonic complications leading to deep warm water uplifts are not considered yet in this approach.

Thermal boundary conditions

Upper boundary: temperature at the surface

Air temperature at the surface of the karst massif is the result of a thermal balance taking into account heat fluxes due to radiation, water precipitation, evapo-condensation processes and thermal exchanges between the soil and the air. In the atmosphere, air temperature varies linearly with the altitude. Depending on the air humidity, the observed gradient will vary between about -0.4°C/100 m (saturated air) and -1°C/100 m (dry air) (e.g. Triplet & Roche 1986, p. 64).

Lower boundary: deep geothermal heat flux

In the continental lithosphere, the geothermal heat flux ranges between 40 and 140 mW/m^2 depending on the location on the Earth surface (e.g. Hurtig et al. 1995). As this flux mostly results from radioactive decay within the Earth, steady state conditions can be assumed.

It can easily be demonstrated that, due to the important specific discharge of karst springs in temperate regions (10-50 ls^{-1} km^{-2}), the energy due to the geothermal heat flux is mainly drained off and does not affect the temperature distribution in the unsaturated zone of a karst

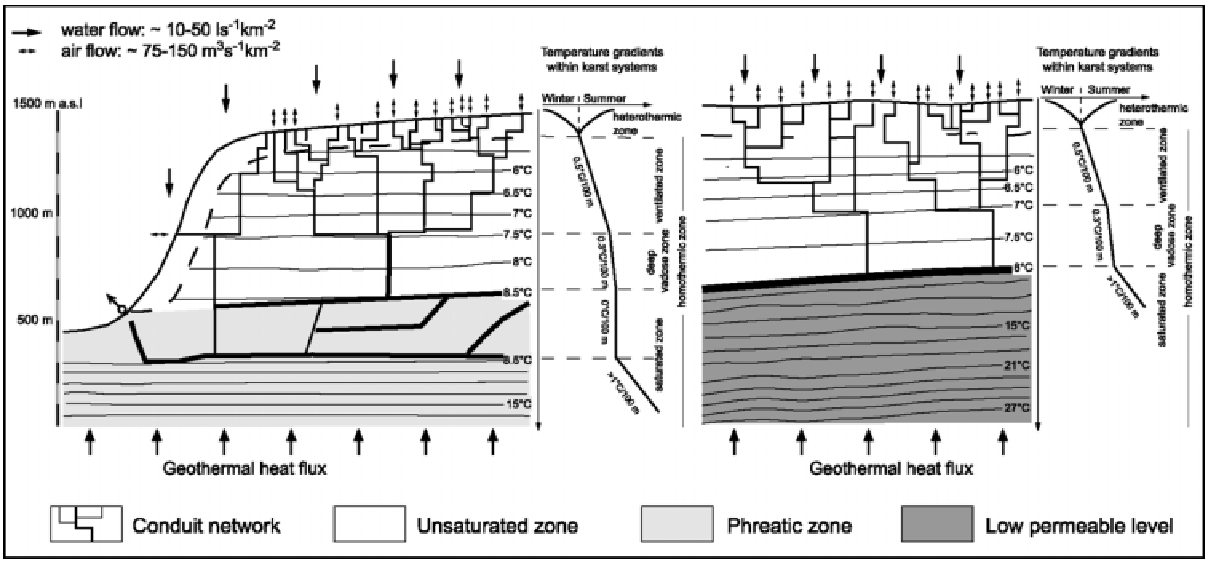

Fig. 2. Conceptual model of the temperature distribution in a karst aquifer. Close to the surface (i.e. for the first 50 m) seasonal variations are still observed. This is the heterothermic zone. Highly ventilated conduits located on the top of the unsaturated homothermic zone show steeper temperature gradients than the deep and poorly ventilated part of the vadose zone. Within the saturated zone, down to the bottom of the main conduit network, the gradient is close to zero. Below the main conduit system, temperature gradients are controlled by the geothermal heat flux.

system (Mathey 1974, Bögli 1980, Drogue 1985,…). The overall lower limit of the system can therefore be considered as a “constant heat flow boundary”, but this flux will hardly reach the unsaturated zone of the karst massif.

The heterothermic vadose zone

Thermal variations at the surface will affect the karst massif either by heat conduction through the matrix or heat advection by water and/or air circulations. The upper part of the massif will therefore show annual temperature variations.

Based on numerous field observations (Table), the depth of this heterothermic zone is estimated at about 50 m, while some particular cases show values of more than 100 m. Unlike water and air flows, the conductive heat flux due to outside annual thermal oscillations cannot induce significant temperature variations at depths greater than 5 m. It can therefore be assumed that temperatures in the heterothermic zone are controlled by heat fluxes related to water and/or air circulations. This assertion is supported by the high porosity and permeability of the epikarst.

The homothermic vadose zone

The homothermic vadose zone is characterized by a high temperature stability: inversion of temperature gradients are not observed. Badino (1995) demonstrated the major role played by the rock heat capacity in this remarkable stability. Measurements have shown that rock, air and water are almost in thermal equilibrium although water and rock temperatures are always slightly lower than air (~0.15°C, Jeannin 1991). Observed gradients usually vary between 0.4 and 0.6 °C/100 m[1] (Table). An estimation is carried out in order to assess the respective contribution of heat fluxes related to water and air circulation in the energy balance of the homothermic zone.

<u>Heat fluxes due to water infiltration</u>

Measured precipitations in temperate karst regions range between 500 and 2500 mm per year. Considering the evapotranspiration processes, it is possible to estimate a specific infiltration between 10 and 50 $ls^{-1}km^{-2}$ which is in good agreement with the discharge observed at most karst springs (e.g. Ford and Williams 1989, p. 155).

[1] where z is positive with depth

TABLE 1

Temperature measurements in various karst massifs.
Observations have shown that air, water and rock temperatures are always almost in equilibrium.
Most observed gradients vary between 0.4 and 0.6 °C/100 m (z is positive with depth, n.d.: no data);

A) Measurements carried out in caves show the role of air circulation in the temperature distribution of the vadose zone.

Cave name	**Climate**	**Hetero-thermic zone**	**Ventilated system**		**Deep vadose zone**		**Reference**
		Depth [m]	**Depth** [m]	**T°air gradient** [°C/100m]	**Depth** [m]	**T°air gradient** [°C/100m]	
Cathy (Switzerland)	Temperate	0-70	70-290	0,61	n.d.	n.d.	(this study)
Pleine Lune (Switzerland)	Temperate	0-180	180-230	0,59	-	-	(this study)
Bärenschacht (Switzerland)	Temperate	0-20	-	-	20-600	0,33	(this study)
Longirod (Switzerland)	Temperate	0-100	40-100	n.d.	180-450	0,38	(this study)
Mutsee (Switzerland)	Temperate	0-140	-	-	140-755	0,32	Weidmann (pers. comm)
Hölloch (Switzerland)	Temperate	n.d.	>900	~0.5	-	-	Bögli (1980)
Rasse (France)	Temperate	0-100	100-470	0,43	n.d.	n.d.	Valton (pers. comm.)
Spluga della Preta (Italy)	Temperate	0-130	130-245	0,52	245-878	0,21	Bertolani (1975)
Tatras region (Poland)	Temperate	0-300	>300	~0.5	-	-	Pulinowa & Pulina (1972)
Lechugilla (USA)	Semi-arid	-	0-300	0,55	-	-	(this study)
Kievskaya (Ouzbekistan)	Semi-arid	0-100	100-300	0,78	300-420	0,33	(this study)
KT16 (Ouzbekistan)	Semi-arid	0-25	25-150	0,1	150-200	0,18	(this study)
Gor Ulugh Beg (Ouzbekistan)	Semi-arid	0-150	n.d.	n.d.	>150	~0.35	Badino (1992)
Kijahe Xontjoa (Mexico)	Tropical	-	0-320	0,57	320-900	0,33	(this study)
Muruk (Papouasie Nouvelle Guinée)	Equatorial	0-75	-	-	75-780	0,25	Audra (2001)

B) Data from boreholes show the influence of the geothermal heat flux below the main karst conduit network base level and of air circulation in the vadose zone.

Borehole	**Climate**	**Hetero-thermic zone**	**Ventilated system**		**Phreatic zone**		**Deep phreatic zone**		**Reference**
		Depth [m]	**Depth** [m]	**T°air gradient** [°C/100m]	**Depth** [m]	**T°water gradient** [°C/100m]	**Depth** [m]	**T°water gradient** [°C/100m]	
FM1 (Switzerland)	Temperate	0-60	60-440	0,61	n.d.	n.d.	n.d.	n.d.	(this study)
FM2 (Switzerland)	Temperate	0-80	80-200	0,55	-	-	200-635	~1.5	(this study)
Cachot (Switzerland)	Temperate	0-50	-	-	50-130	0.5 to 0.8	130-170	1,8	Matthey (1974)
Basse Fin (Switzerland)	Temperate	0-50	-	-	-	-	50-370	3,5	MFR (2002)
St-Aubin 2 (Switzerland)	Temperate	n.d.	n.d.	n.d.	140-320	0,002	320-360	0,42	CHYN (pers. comm.)

The loss of potential energy of water during its vertical transit represents 9.81 $Jkg^{-1}m^{-1}$. If this energy is fully transformed into heat by friction it leads to a temperature increase of 0.234°C/100 m (Lismonde 2002). Considering the mean specific recharge (10-50 $ls^{-1}km^{-2}$), the heat supplied annually by the work of gravity to the homothermic zone of a 1000 m thick karst massif ranges between $3\cdot10^9$ and $1.5\cdot10^{10}$ kJ km^{-3}. Since in the homothermic zone the thermal equilibrium is maintained, the sensible heat advected by the water does not influence the vertical temperature distribution.

Heat fluxes due to air circulations

Considering the heat capacity and density of air and water respectively, the volumetric air flow should be more than 4000 times higher than that of water in order to play a dominant role in heat exchanges. Mangin & Andrieux (1988) considered this unlikely and attributed the major heat transfers to drip water. The following section attempts to assess the order of magnitude of heat fluxes related to air circulation.

Air circulations in major karst systems are mostly driven by pressure differences between upper and lower entrances. In simple cases, this pressure difference can be approximated by (e.g. Trombe 1952, Lismonde 1981):

$$\Delta P_m \approx \frac{\rho_0 g h}{T_0}\left(T_i - \frac{T_A + T_B}{2}\right) \qquad (1)$$

where: ΔP_m: driving pressure [Pa]; ρ_0: mean density of air [kg/m³]; g: acceleration due to gravity [m/s²]; T_0: 273 [K°]; T_i: mean air temperature of the system [K°]; T_A: outside temperature at the top of the system [K°]; T_B: outside temperature at the bottom of the system [K°]; h: altitude difference of the system [m].

with an air flow given by the turbulent flow equation (Darcy-Weisbach):

$$q_m = \sqrt{\frac{|\Delta P_m|}{R}} \qquad (2)$$

where: q_m: air flow through the system [kg/s]; ΔP_m: driving pressure [Pa]; R: aeraulic resistance of the conduit [$kg^{-1}m^{-1}$].

The aeraulic resistance (R) reflects the headlosses occurring in a natural conduit. Jeannin (2001) demonstrated that in karst conduits, regular headlosses dominate on singular ones. This author proposed measured values leading to an aeraulic resistance for conduits of 1 m diameter varying between 0.01 and 0.5 kg^{-1} m^{-1}, in agreement with estimations provided by Lismonde (2002).

Mean annual driving pressures of about ±300 Pa are frequent in alpine karst systems. In such cases, a conduit with a simple geometry and a diameter of 1 m leads to an equivalent air flow of about 4.5 m^3s^{-1}. Yet, our measurements confirm that air fluxes might be several times higher than that (e.g. Hölloch/CH $Q_{03.01.04}$: 15 m^3/s^{-1}; La Diau/F $Q_{20.02.04}$: 11 m^3/s^{-1}).

Worthington (1991) and Badino (1995) evaluated empirically the conduit density of a mature karst system to about 100 $kmkm^{-3}$, which is consistent with observations in well explored karst areas. Hence, an estimated air flow of 150 $m^3s^{-1}km^{-2}$ can probably be considered as a lower limit for a 1000 m thick karst system. Given the temperature gradients of water and humid air (0.234°C/100 m and 0.5°C/100 m respectively), the heat flux associated with air circulation is assessed to be between 2-20 times larger than that of water, depending on recharge rates.

In many caves of the World (Table), the observed temperature gradient is close to that of humid air (0.5°C/100 m). Therefore, it can be assumed that air circulation plays a dominant role on the temperature distribution in karst systems.

As observed in deep vadose zones (>~500 m), or depending on local geological conditions, part of the unsaturated zone may be less connected to the landsurface. Furthermore, the hierarchical structure of karst networks will concentrate into less numerous conduits at higher depth. As a consequence, air circulation due to forced convection will be progressively reduced. However, as water circulation is still present in the same amount, its relative effect on heat transfers might be highly increased and temperature gradients will be much closer to 0.3°C/100 m.

Discussion

The suggested conceptual model is based on the assumption that "chimney effect" is at the origin of most air circulation observed in alpine karst systems. It must be emphasized that further processes, like barometric fluctuations, might lead to significant air flows in larger systems (e.g. Conn 1966; Massen et al. 1998). Those will however increase the influence of air flow, as suggested by our model.

Nevertheless, several aspects were not included yet in this approach, which might be particular cases disproving the present conclusions. We try in the following section to summarize the main controversial aspects and to suggest a theoretical explanation for them.

Geometrical factors

If the unsaturated zone is thinner than 100 m, air flow can be strongly reduced compared with the estimations provided by relations (1) and (2). Therefore, temperature gradients lower than 0.5°C/100m could be observed. This situation is supposed to occur in lowland plateau karst systems. However, this type of systems usually receives little rain and the energy flux related to water is therefore also reduced. Then, temperature gradients close to 0.5°C/100m are still possible.

If the system is thinner than ~50 m, it belongs to the heterothermic zone and gradients mainly depend on the outside temperature.

Climatic factors

If temperature variations at the surface are small (for instance coastal or equatorial regions), temperature contrasts between cave air and outside air will be negligible. Thus, air flow due to forced convection will be reduced and temperature gradients approach values dominated by water circulation (e.g. Muruk cave, New Guinea, Fig. 3.).

Conversely, if the water recharge is low, temperature gradients might be much closer to those of dry air (i.e. > 0.5°C/100 m). Unfortunately field data supporting this idea are lacking.

Hydrological factors

Due to the reduced water circulation within confined aquifers, temperatures will be affected by the geothermal heat flux. Temperature gradients are therefore much higher than those observed in free drained aquifers. This case is illustrated by temperature measurements in various boreholes (Fig. 4).

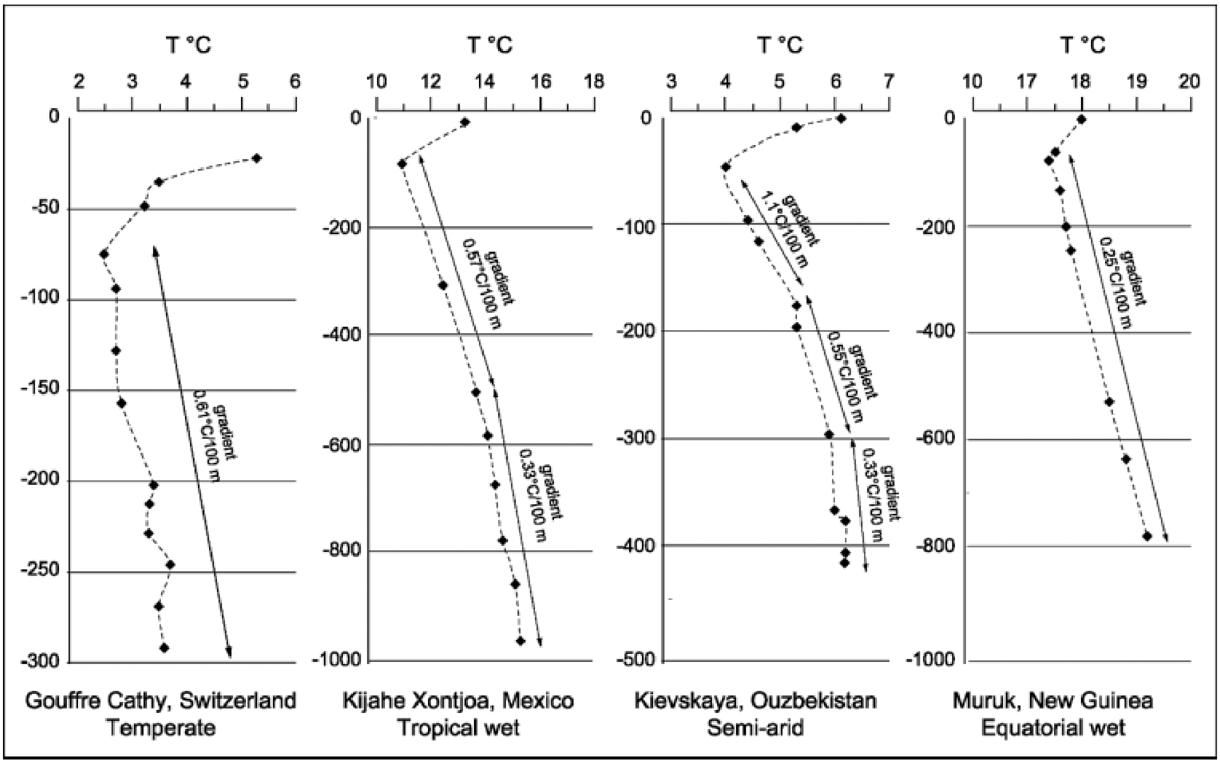

Fig. 3. Temperature measurements carried out in four caves under different climatic contexts (temperate, tropical, semi-arid and equatorial). Gradients in highly ventilated conduits are close to the humid air atmospheric gradient. In less ventilated zones, lower gradients are observed due to the relatively increased importance of water circulation. Data from Kievskaya show a temperature anomaly due to cold winter air circulation down to 160 deep. Data from Muruk cave are taken from Audra (2001).

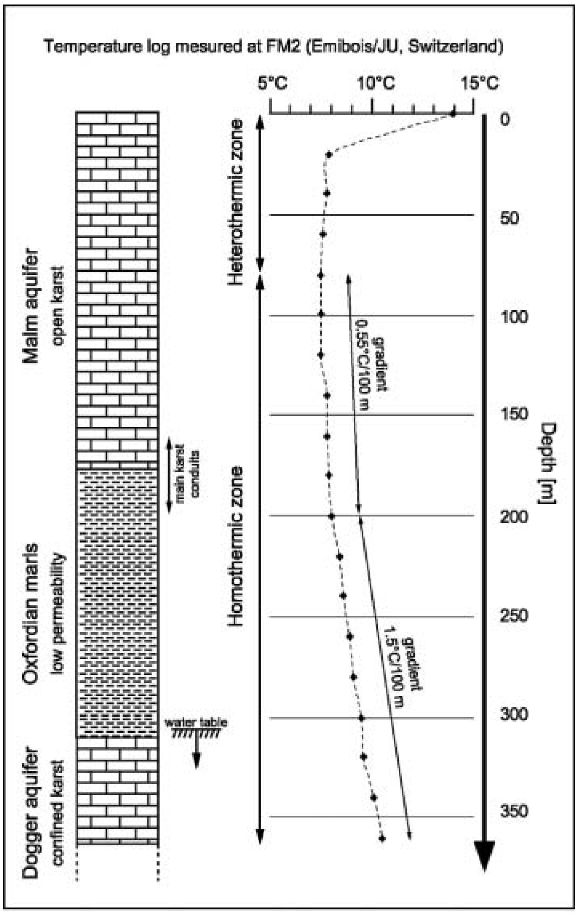

Fig. 4. Temperature measurements in a borehole of the swiss Jura Mountains. Down to 175 m, the observed gradient (0.55°C/100m) shows the influence of air circulation in boreholes, i.e. around the karst conduits. Below the main karst conduits (base of the Malm), a gradient of 1.4°C/100 m (instead of about 3.3°C/ 100 m) suggests that a slow water flow is present in the lower "confined" aquifer of the Dogger limestone.

Conclusions

Heat fluxes due to air circulations in karst massifs are frequently underestimated. Physical concepts and observations presented in this paper enable a better understanding of the temperature and heat flux distribution in karst environments. According to the proposed conceptual model, the following conclusions can be given:

1. Air circulations are defining temperature distribution in the homothermic unsaturated zone of karst aquifers in temperate climate;
2. Air temperature gradients approximately correspond to humid air atmospheric gradient: 0.5°C/100 m;
3. High water flows and/or low air circulation tends to reduce the temperature gradient to about 0.3°C/100 m;
4. Water and rock temperature are close but slightly lower than air temperature;
5. Temperature gradients between the main phreatic conduits and the top of the saturated zone are close to zero (Fig. 2);
6. Temperature gradients below the main phreatic system are close to the normal geothermal gradient;
7. Outside climatic conditions define the significance of air and water heat fluxes respectively.

The proposed conceptual model is built on numerous field observations. However, it has also been shown that heat fluxes might be significantly different depending on climate, geological context and maturity of a karst system. In order to validate the model, further temperature measurements in different karst regions are required. Also, temperature logs in boreholes including measurements in the unsaturated zone will provide the necessary data for an extrapolation of these conclusions to all types of karst massifs.

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