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The present therrnal state of the Alpine region: Influence of fluid circulation

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ABSTRACT

There is a good correlation between the Swiss heat flow density (HFD) map (Medici & Rybach, 1995) with the uplift map, the topographic map and the high-grade metamorphic rocks distribution (Wenk & Wenk, 1984; Steck & Hunziker, 1994). It suggests that there are relationships between the geology, the tectonics and the presence of geothermal resources (anomalies). Areas with the lowest heat flow values correspond to the Alps, where the higher uplift values are found. 1D thermal simulations demonstrate that the exhumation of metamorphic rocks, and consequently the **HFD** values, should be higher than those observed, as already proposed by Oxburgh and England (1980). Therefore, low **HFD** values in the alpine region might reflect large amounts of cold groundwaters circulating **into** the massifs that decrease the internal temperatures. On the other hand, ascending warm waters with relatively high flowrates can heat the surrounding rocks and consequently induce local positive geothermal anomalies (≈ 50°C/km, e.g. Gotthard highway tunnel).

KEYWORDS

Alpine chain, exhumation, heat flow density, groundwater circulation, geothermal resources.

Introduction

The Alpine chain consists of pre-Triassic basement sheets, Mesozoic cover lithologies and flysh sequences that underwent different grades of metamorphism during the Cretaceous and Tertiary orogenies (ESCHER & BEAUMONT 1997). The units currently outcropping in the Ossola-Ticino region reached the amphibolitic facies approximately 30Ma ago (STECK & HSJNZIKER, 1994). This fact implied important and variable exhumation rates which influenced the temperature vs. depth profile of this region.

Now the geothermal resources in the Western Alps are represented both by springs (figure 1) and inflows in deep Alpine tunnels (WATAZ 1982, 1997; BIANCHETTI et al. 1993; RYBACH 1995). The circulation of these thermal waters is generally related to the presence of high permeable zones which allow rapid upflow where morphological and structures are adequate (MARTINOTTI et al. 1999). However, large descending flows determine a substantial cooling of the interacting rocks, as observed in the Simplon tunnel (HUNZIKER et al. 1990), Mont-Blanc Tunnel (MARÉCHAL, 1998) and Piora zone (BUSSLINGER, 1998). OXBURGH & ENGLAND (1980) estimated that the "cooling effect" of groundwater circulation could affect the internal temperature values for 30% of the total Heat Flow Density (HFD).

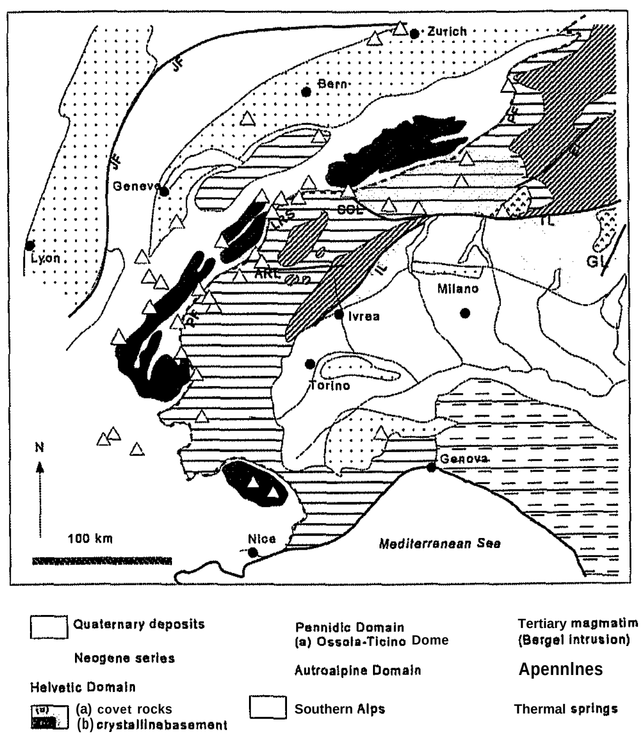

Figure 1: Geological sketch map of the Western and Central Alps with the location of the main thermal discharges.

The aim of this paper is to compare available results concerning metamorphic evolution, thermal modelling and geothermal observations in order to evaluate the effect of water circulation on the thermal state of the Alpine chain.

HFD map compared to other data sets

The recent publication of a HFD map (corrected for topography effect) of Switzerland (MEDICI & RYBACH 1995) allows to compare the geographic distribution of the HFD values with the topographic relief and with the existent geological and sismotectonic data. The resulting observations are summarised in the following paragraphs:

- There is a good correlation between the HFD map and the topography over the 2500 m.a.s.l. (figure 2). Except for the Mont-Blanc region, HFD values do not exceed 80 mW/m^2 but are essentially lower than **70** mW/m^2. The higher values in the Mont-Blanc region are difficult to interpret due to the very small number of HFD data points in that area.
- The lower HFD values are mostly located in the Alpine region, in particular in the Ossola-Ticino region. This can be an artefact due to the number of available data which is too small to outline the geological structures.

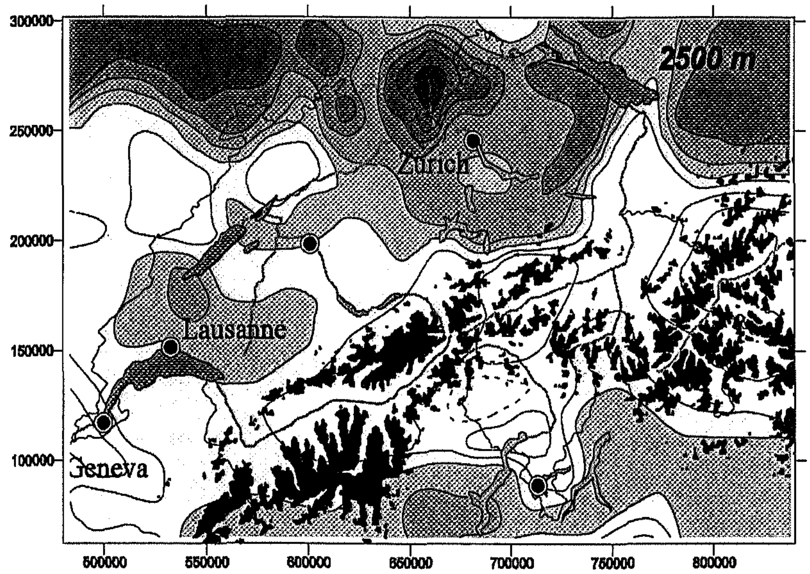

Figure 2: Comparison of the topographic high level (in black above 2500m) with the HFD map. Note that the higher metamorphic terrain of figure ***3*** *are mostly located below 2500m. For HFD legend see figure* ***3.***

- The metamorphic isogrades in the Ossola-Ticino region outline the rocks with higher metamorphic degree (figure 3) currently outcropping in the Alps (WENK & WENK, 1984; STECK & HUNZIKER 1994). During the past 30Ma years, this region underwent a rapid exhumation together with a cooling rate up to 30°C/Ma (STECK &

HUNZIKER 1994). On the contrary, the recent (<2Ma) tectono-thermal history seems to indicate a slower exhumation rate (GRASEMANN & MANCKTELOW 1993).

- The uplift rates (>0.8mm/y; KAHLE et al. 1997) are also correlated with the HFD low values and with the higher topographic levels (figure 3). The Ossola-Ticino region is an exception with a the rate of uplift around 0.9 mm/y.
- Most of the past and present recorded seismic activity (PAVONI 1977; DEICHMANN et al. 1998) is located along the Alpine chain, the Jura region and the Rhine graben (figure **4).** Again, the Ossola-Ticino Dome presents a noteworthy exception, excluding in the SW border where the Simplon-Centovalli Line outcrops. This may indicate a low superficial tectonic activity in this region (MAURER et al. 1997).

1D thermal model

During exhumation processes, the terrestrial HFD varies with time and the highest values correspond to the highest exhumation rates. HFD is also controlled by the thermal conductivity **of** the superficial rocks. The 1D finite difference model proposed here begins with an instantaneous thrusting of 25km thick granitic unit over 9 km of sedimentary rocks (3 **km** carbonates series and **6** km of flysch) lying above a granitic basement. The exhumation process is assumed to be due to erosion (figure 5).

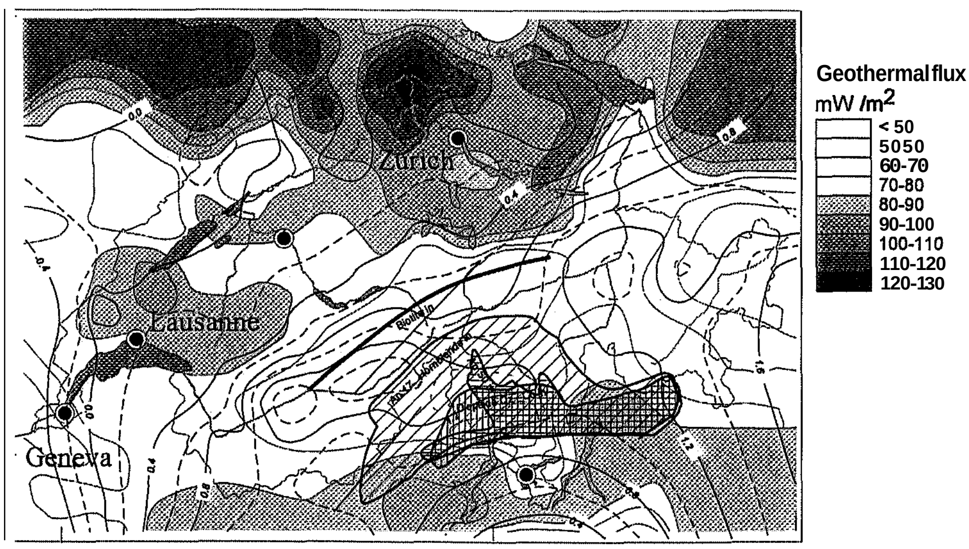

Figure 3: Comparison of the HFD map corrected for topographic effect and present uplift rate map in mm/years (after KAHLE et al. 1997; MEDICI & RYBACH 1995). Metamorphic isogrades delimiting the highest grade rocks are also reported (WENK & WENK, 1984; STECK & HUNZIKER 1994).

50 Ma metamorphic history have been modelled fiom the thrusting time until present. In order to show the decrease in HFD values when exhumation stops, 30 Ma are added to the simulation duration. Before the thrusting, the HFD value is approximately 65 mW/m^2. The cooling effect of the thrusting leads to a minimal value of 50 mW/m^2. An exhumation rate of 1mm/year induces an increase of the HFD to around 80 mW/m^2. If the exhumation rate is higher, a further increase is observed. The end of this process leads to HFD values below 80 mW/m^2 after 6 Ma and the original state is reached after 30 Ma.

Clearly, this model shows that for exhumation rate higher than 1 mm/year the terrestrial HFD value are above 100 mW/m^2. The order of magnitude obtained can be compared to the those of GRASEMANN & MANCKTELOW (1993), which was calculated with a model of exhumation by normal faulting and erosion.

Rock-water heat transfer: results of water inflow in alpine tunnels

All available δD and $\delta^{18}O$ data on springs and tunnel inflows indicate that waters circulating in the Alps have a meteoric origin. These meteoric waters infiltrate at different elevations on both sides of the Alpine orographic barrier and percolate with different velocities through the massifs.

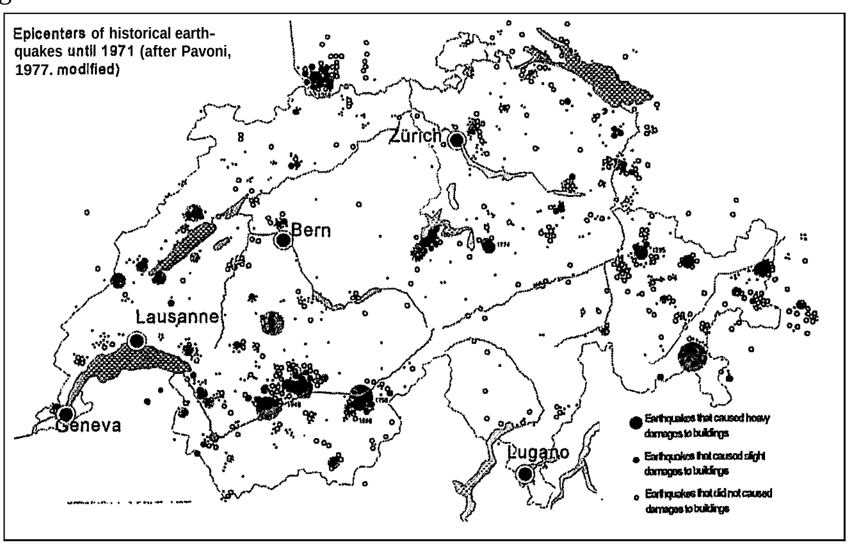

Figure 4: Recent seismic activity (modified after PAVONI 1977)

Most of the water inflows in the alpine tunnels are related to descending circuits in low permeable systems. Because of low permeabilities, waters descend slowly and extract heat fiom the rocks. The geochemical temperatures of these waters are close to their emergence temperatures and to the rock temperatures at the sampling site, suggesting that they approached the thermal equilibrium with the rocks. Large inflows of cold meteoric waters descending through high permeability channels cause more spectacular cooling effects on the surrounding rocks than the percolating systems (fig 6). The similarity between the rock-temperature and the water-temperature profiles suggest that an ubiquitous water-rock thermal equilibrium is attained. These kinds of circuits are present in the Simplon tunnel (1000 kg/s) and in the Gotthard exploration tunnel (Piora Zone) and are related to Mesozoic cover layers where permeability is mainly controlled by dissolution. Large flowrates related to cataclastic zones in gneissic rocks are present in the Mont-Blanc tunnel (800 kg/s). In these cases the regional geothermal gradient is strongly disturbed and low temperatures are measured in both, rocks and waters inflows.

On the opposite, thermal springs and warm inflows in deep tunnels ascend from relatively deep aquifers, which represent potential "geothermal reservoirs". Calculated equilibrium temperatures of these waters range from 30 to 125°C suggesting that they reached depths of several lun. Discharge temperatures depend on the flowrates and on the velocities of the uprising waters. Uprising warm waters with relatively high flowrates can heat the surrounding rocks and consequently induce unusual high geothermal gradients.

In figure 6 water and rock temperatures are reported for the Gotthard Massif. Based on rock-temperatures measured in the Gotthard railway tunnel, a regional geothermal gradient of 22°C/km was estimated by CLARK & NIBBLET (1956). A similar value, 19°C/km, was obtained by RYBACH et al. (1982) elaborating the temperature data of the GHT. Two vertical boreholes in the Hospental (300 m) and in the Guspisbach (500 m) show that temperature increases quite regularly with depth, indicating geothermal gradients **of** ~30°C/km and ~50°C/km, respectively which are considerably higher than the regional geothermal gradient.

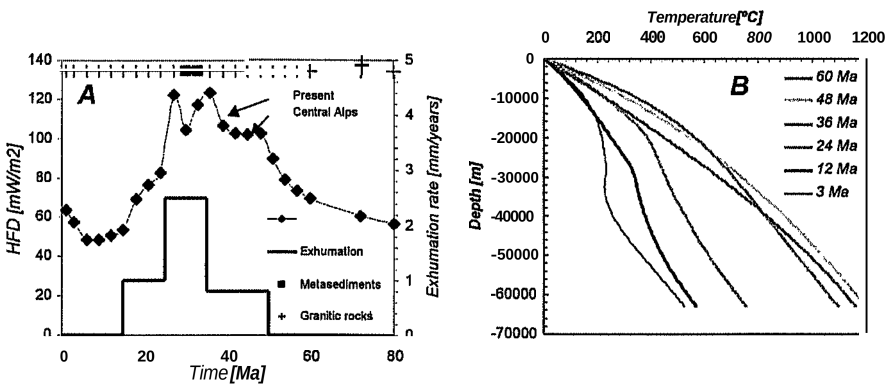

Figure 5: Exhumation ID thermal modelling byfinite difference method. A granitic slab of 25 km thrusts 6 kmjlysch and a granitic basement is topped by 3 km carbonates series. The thermal conductivities and the diffusivities are 3 $Wm^{-1}K^{-1}$ and I mm^2s^{-1} respectivelyfor granite. The conductivities is 2 $Wm^{-1}K^{-1}$ for sedimentary rocks and the diffusivity is I mm^2s^{-1} forjlysch and 0.6 I mm^2s^{-1} for carbonates. A) Evolution of HFD values with time and associate exhumation rate. B) Change of the depth- temperatureprofile with time. Note the increase of the HFD and gradient values with increasing exhumation rate, and their decrease with the stop of exhumation. Present situation is located 40-50Ma.

The temperatures of most waters are close to the expected values for a regional geothermal gradient of 22°C/km (figure 7). These meteoric waters, either descending or ascending towards the tunnel, approach thermal equilibrium with rocks. However, the relatively large descending flow waters near the Gotthard exploration tunnel termination (Piora Zone) and in the Gotthard highway tunnel (4.0-4.28 km from the southern portal) determine a substantial cooling of the interacting rocks, whereas the ascending warm waters of the Guspisbach zone in the Gotthard Highway Tunnel (6.2-9.0 km from the southern portal) heat the rocks.

Therefore, fluid circulation in a mountainous region can strongly disturb the internal distribution of rock temperatures. The thermal equilibrium reached by groundwater with the surrounding rocks demonstrates that heat transfer processes, from the rocks to the meteoric waters, induce a general cooling of the massif. Therefore, relatively low geothermal gradients are related to large flows of cold meteoric waters through highly permeable levels. Conversely, flows of ascending warm waters can induce locally higher geothermal gradients than those of the entire massif.

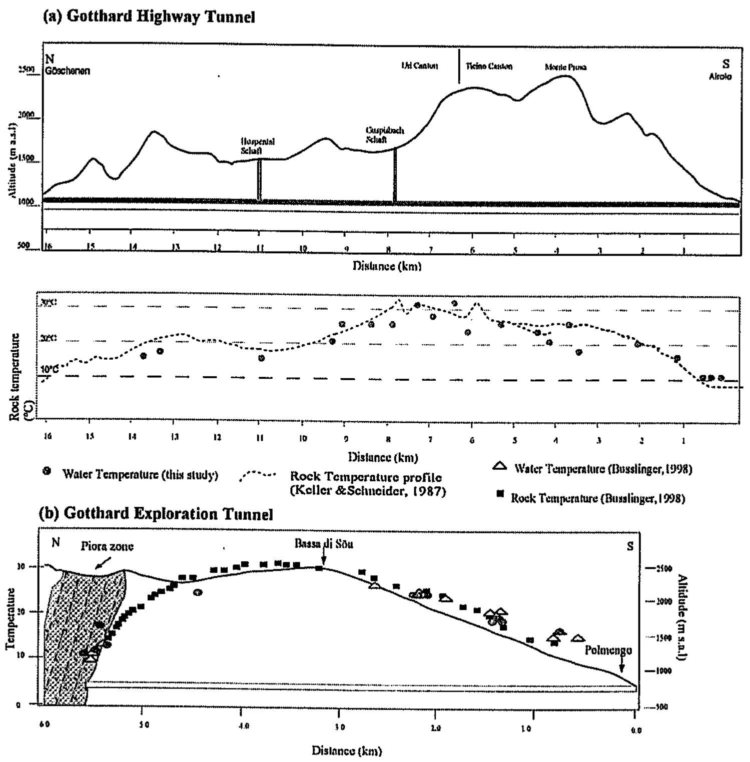

Figure 6: Geological cross-sections of the Gotthard tunnels (PASTORELLI et al.1999)

Discussion

All available geological, HFD and geochemical data and thermal modelling are in agreement with a cooling effect due to water circulation. The 1D thermal modelling described here indicates that the HFD values in the Alpine region should be higher than those observed, in the range of 100 mW/m^2, corresponding to a geothermal gradient of 33 °C/km (thermal conductivity = 3 $Wm^{-1}K^{-1}$). As demonstrated in previous paragraphs there is clear influence of groundwater circulation on the internal temperature of the massif. Evidence of deep circulation of these meteoric waters up to 4-5 km is provided by the equilibrium temperatures calculated for the thermal springs.

Permeability is related to the brittle tectonic structures which are located in the first –10-15 km of the crust (SIBSON 1977; MARTINOTTI et al. 1999). Efficient groundwater circuits are maintained by the fracturing resulting from tectonic movements. In the high topographic levels that **is** in the region with low HFD values, the tectonic activity is suggested by the high uplift rates and the seismic activity. Due to the elevated hydraulic head important water flows are generated producing relevant cooling of the massif. This process might be important due to the high exhumation rates which increase the HFD normal values.

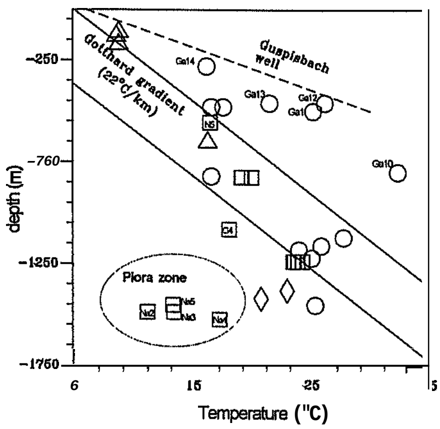

Figure 7: Plot of water temperatures measured in the Gotthard tunnels vs. depth. The regional geothermal gradient and the temperature vs. depth trend of the Guspisbach well are also shown (PASTORELLI et al. 1999).

The effect of groundwater circulation is limited where the topographic levels are lower and the exhumation rates and the seismic activity are reduced like the Ossola-Ticino region. But in these cases, HFD values remain low because the contribution by exhumation is weak.

Similar cooling effects affecting the upper crust have been identified in the first 2 km of the SG-3 well in Kola peninsula (POPOV et al. 1999; KUKKONEN & CLAUSER 1994): 20 mW/m^2 are extracted by the water circulation with a topographic slope of around 1%. Furthermore, SMITH & CHAPMAN (1983) have demonstrated by simulations that with a sufficient hydraulic head the advective process is the main effect. As a result the HFD values are perturbed.

The discharge of ascending warm water circuit in the bottom of the valleys may disturb the local HFD values. In addition topographic effect on the temperature field by conductive process must be taken into account (MANCKTELOW & GRAESEMAN 1997; RYBACH & PFISTER 1994).

Along normal fault zones the fast exhumation rates induce high HFD values by thermal conduction. The Simplon fault region is a good example (GRAESEMAN & MANCKTELOW 1993). The relatively high HFD value near the Mont-Blanc massif (SEWARD & MANCKTELOW 1994) might be explained by a similar situation along the Penninic frontal thrust.

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