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# Hydrothermal circulation systems of the Lavey-les-Bains, Saint-Gervais-les-Bains and Val d'Illiez areas associated with the Aiguilles Rouges Massif in Switzerland and France

R. Sonney[1], F.-D. Vuataz[2], E. Schill[2]

**Keywords:** Hydrothermal circulation systems, crystalline rocks, sedimentary cover, chemical-mineral processes, geothermal reservoir, Aiguilles Rouges Massif, Western Alps, Switzerland, France.

**Abstract**

The three studied hydrothermal systems are located around the Aiguilles Rouges Massif, one of the external crystalline massifs in the Western Alps. The general aim is to gather all the information in a paper and to provide a better description of these systems by comparison of their geological, hydrogeological, geochemical and isotopic properties. Lavey-les-Bains in Switzerland and Saint-Gervais-les-Bains in France represent the two low-elevation points of the Aiguilles Rouges basement, respectively on the north-eastern and south-western sides. The chemical and isotopic properties of these waters present similarities. The thermal component Na-$SO_4$ › Cl for both sites was infiltrated before nuclear weapons atmospheric tests (‹ 1953). In contrast, Val d'Illiez in Switzerland is located out of the Aiguilles Rouges basement in a sedimentary domain belonging to the autochthonous cover outcropping along the north-western edge of the basement. The Val d'Illiez deep flow system produces a Ca-$SO_4$-rich and low-Cl thermal water and its residence time is quite younger (about 5 years). For the studied thermal waters, the average elevation of the recharge zones seems to be similar, of around 1700–2100 metres, but the fluid temperatures at depth would be quite different. Indeed, the reservoir temperature would reach 100–110 °C for Lavey-les-Bains and 70–80 °C for Saint-Gervais-les-Bains, whereas it would be lower than 40 °C for Val d'Illiez.

**Résumé**

Trois systèmes hydrothermaux ont été étudiés et sont localisés en bordure du massif cristallin des Aiguilles Rouges, un des massifs cristallins externes des Alpes. L'objectif principal est de comparer les caractéristiques géologiques, hydrogéologiques, géochimiques et isotopiques de ces trois systèmes, et de regrouper les informations connues dans un unique document. Lavey-les-Bains en Suisse et Saint-Gervais-les-Bains en France représentent les deux points altitudinaux les plus bas du massif cristallin des Aiguilles Rouges, respectivement aux extrémités nord-est et sud-ouest. Les eaux de ces deux sites présentent des similarités chimiques et isotopiques. Le pôle thermal Na-$SO_4$ › Cl s'est infiltré les premiers essais nucléaires (‹ 1953) car il est dépourvu de tritium. En revanche, Val d'Illiez en Suisse est localisé à proximité de la couverture sédimentaire autochtone des Aiguilles Rouges d'âge Triasique à Tertiaire, qui affleure sur la bordure nord-ouest du massif cristallin. Le système hydrothermal de Val d'Illiez produit une eau thermale riche en Ca-$SO_4$ et pauvre en Cl. Son temps de transit souterrain est estimé à environ 5 ans, à partir des données en tritium. Pour les trois sites étudiés, l'attitude moyenne de la zone de recharge des eaux thermales est voisine, autour de 1700–2100 mètres d'après les valeurs des isotopes stables de l'eau. En revanche, la température du réservoir profond calculée pour chaque système à partir des géothermomètres montre des différences: 100–110 °C pour Lavey-les-Bains, 70–80 °C pour Saint-Gervais-les-Bains et inférieure à 40 °C pour Val d'Illiez.

[1] Bureau d'Etude Géologique SA, Rue de la Printse 2, 1994 Aproz

[2] The Centre for Hydrogeology and Geothermics (CHYN), University of Neuchâtel, Rue Emile Argand 11, 2000 Neuchâtel, Switzerland

## 1. Introduction

The Alps range is one of the areas in Europe where many low-enthalpy thermal springs can be witnesses of deep circulation systems of meteoric water origin. The occurrences of low-enthalpy geothermal systems in the Alps are determined by a series of specific conditions: infiltration area, active downflow, permeability at depth, concentrated and fast upflow, favourable geomorphological surface patterns, etc. These hydrogeological conditions often occur within crystalline basement, dipping sedimentary formations, fault intersections, thrust faults, etc., putting in contact various types of rocks.

In the Swiss, and French and Italian parts of the Alps massif, some of the discharging thermal systems are directly used from springs or pumped through boreholes at different depths. More or less complete investigations have been carried out for most of these thermal waters, such as geological, hydrogeological and geochemical studies. These studies bring scientific basis providing information for the management of a sustainable exploitation of the thermal water, qualitatively and quantitatively. They also bring the knowledge for successful geothermal exploration projects.

During his PhD thesis, Sonney (2010) studied three hydrothermal systems or low-enthalpy geothermal systems, Lavey-les-Bains and Val d'Illiez in Switzerland and Saint-Gervais-les-Bains in France, where the uprising thermal waters are continuously exploited for various uses such as spas, heating of buildings, medical care and cosmetics. Lavey-les-Bains and Saint-Gervais-les-Bains were selected on the following criteria: 1] deep flow systems in the crystalline basement, 2] similar chemical and isotopic characteristics, 3] presence of several end-members with mixing processes, 4] high inferred reservoir temperature, 5] a large database and 6] on-going or planned geothermal projects. On the contrary, Val d'Illiez was selected for other criteria: 1] deep flow system in the autochthonous sedimentary cover of the basement, 2] different chemical and isotopic characteristics of thermal waters from the cover compared with those flowing in the basement and 3] existence of the springs related to the Salanfe Lake.

Many data exist on geothermal fluids in Lavey-les-Bains, Saint-Gervais-les-Bains and Val d'Illiez. These data come from thermal springs and from shallow to deep boreholes drilled for geothermal exploitation. All these data are contained in many papers and reports, often unpublished and not very accessible to potential users of this information. The objective of this study is to gather the maximum amount of information on these systems in a same paper and to provide a synthesis of the results with additional comments than it was done in the past studies. This paper would be useful to all geothermal projects planning to prospect, to produce or to inject fluids at depth, in the external crystalline massifs of the Western Alps. A better description of these systems will be carried out with the comparison of their geological, hydrogeological, geochemical and isotopic properties, the construction of a table summarizing all the results allowed the comparison to be achieved. This method is essential for the understanding of the Saint-Gervais-les-Bains deep flow system that occurs in a high complicated hydrogeological domain. New chemical and isotopic data on thermal waters from springs and wells are used in the paper, fluids sampled in the period 2007-2009. New tritium data on Val d'Illiez thermal and cold springs are also presented in the paper and allow the groundwater residence time to be better discussed.

## 2. Geology

The three hydrothermal areas are associated with the Aiguilles Rouges Massif, one of the massifs of the Western Alps. Lavey-les-

Bains and Saint-Gervais-les-Bains are on the north-eastern and south-western sides, respectively, of the crystalline Aiguilles Rouges basement; Val d'Illiez is located within sedimentary autochthonous cover of the Aiguilles Rouges basement that outcrops north-west of the basement (Fig. 1).

### 2.1 Aiguilles Rouges Massif

The Hercynian basement of the Aiguilles Rouges Massif consists of various metamorphic rocks (mainly paragneiss, biotite or chlorite hornfels and orthogneiss), other tectonic units such as the Vallorcine Granite intruded along the Miéville shear zone, the Permo-Carboniferous Salvan-Dorénaz syncline and the Servoz-Les Houches Formation (von Raumer 1984, 1987; von Raumer et al. 2003; von Raumer & Bussy 2004). In Switzerland, these rocks outcrop from the Salanfe and Emosson areas to the Martigny sedimentary zone, and in France the basement forms mountains north-west of the Chamonix Valley that reach the Saint-Gervais-les-Bains region (Fig. 1).
The Aiguilles Rouges basement underwent the Variscan and Alpine tectonic events that are responsible for the visible NNE-to-NE trends by major faults, open fractures, lineations and fold axes (von Raumer & Bussy 2004). The NNE-to-NE trend of major faults was inferred by Sonney (2010) as the main direction of flow paths for deep infiltration, probably allowing the decompressed zone and the geothermal reservoir to be hydraulically connected. Faults tend north-to-south in the southern part of the Aiguilles Rouges Massif following the Contamines-Montjoie fault system where the Bon Nant Valley occurs. Moreover, subvertical strike-slip faults with a NW-SE trend occur in the basement which is characteristic of the movements of great rock masses during the Alpine tectonic events (Collet et al. 1952).

### 2.2 Autochthonous sedimentary cover

The Aiguilles Rouges crystalline Massif is unconformably overlain by its autochthonous sedimentary cover (von Raumer et al. 2003) that outcrops along the basement (Fig. 1). This cover is relatively thin (Steck et al. 2001) and consists of quartzite and dolomites (Permian to Trias), limestones (Dogger, Malm and lower Cretaceous), breccias and marls (upper Eocene) and marls and sandstones (Oligocenous flysch, Val d'Illiez Formation). The Triassic layers are an important unit in this context, because of their petrology (coarse sandstone, quartzite, argillite, dolomitic limestone and gypsiferous cellular dolomite) and their hydrogeological characteristics. For example, gypsum dissolution creates preferential pathways for surface water infiltration and deep groundwater circulation.
Alpine overfolds of north-east orientation occur in the autochthonous cover. Early geological investigations (Gagnebin 1934; Ducloz 1944; Lanterno 1954; Bianchetti et al. 1992) found that these folds consist of a succession of anticlines, probably wide, implying that the limbs have low dips. However, Pantet (2004) and Sonney (2010) found that autochthonous cover in the Vièze Valley ends in a great anticline with a basal thrust fault system plunging towards the south-east which is related to the thrust fault system of crystalline massifs (see cross section in Fig. 1).

### 2.3 Deep structure

A seismic profile was carried out in the Western Alps going through Saint-Maurice and Martigny to evaluate deep structures (Pfiffner et al. 1997; Sartori et al. 2001). The interpretation of the seismic velocities highlighted an anomaly at about three kilometres below Lavey-les-Bains. This anomaly could be a synclinal structure formed by sedimentary rocks belonging to the autochthonous cover. In detail, geologists assume that there

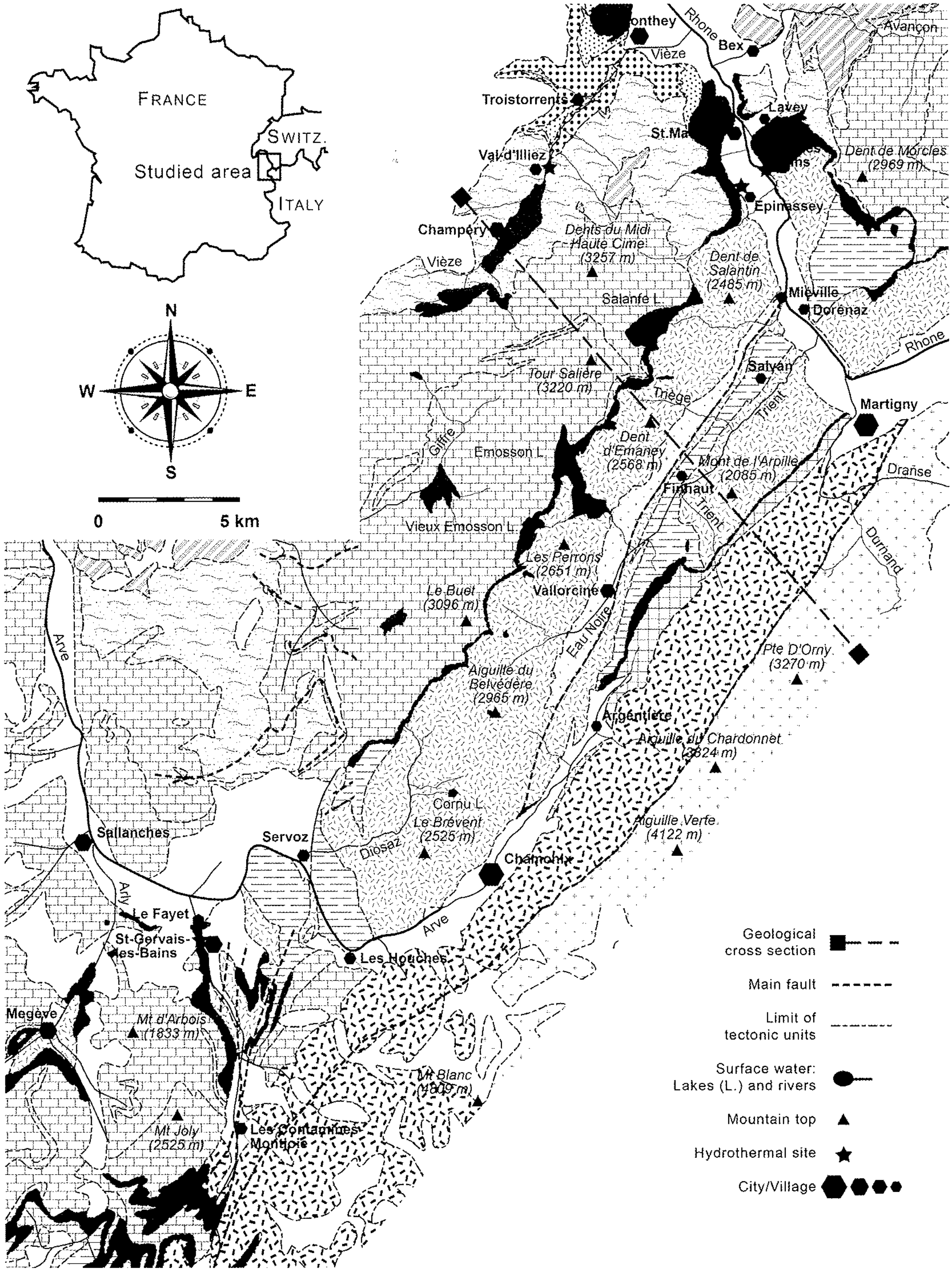



Fig. 1: Geological map and cross section of the Aiguilles Rouges regional area according to the tectonic map of the Western Switzerland Alps (modified after Steck et al. 2001).

LEGEND OF THE TECTONIC MAP

Quaternary

- Not differentiated quaternary formations

Subalpine molasse

- Lower Freshwater Molasse : Sandstone and conglomerate (red molasse, Mont Pelerin pudding stone, coal molasse): Chattien.
- Lower Marine Molasse : Marl and sandstone (Vaulruz sandstone): Lower Oligocene.

Aiguilles Rouges massif

- Marl and sandstone (parautochthonous Flysch): Lower Oligocene.
- Marl and sandstone (autochthonous Flysch): Lower Oligocene.
- Quartzite, dolomite, limestone and marl: Trias - Eocene.
- Conglomerate (Vallorcine pudding stone), sandstone, pelite and rhyolite: Carboniferous - Permian.
- Vallorcine granite: Upper Carboniferous (307 ± 2 Ma, Bussy and Hernandez 1997).
- Gneiss and migmatite: Proterozoic - Paleozoic.

Morcles nappe

- Limestone, marl and sandstone (including flysch): Cretaceous - Lower Oligocene.
- Limestone and marl: Dogger - Malm.

Chamonix zone (root of reversed limb of the Morcles nappe)

- Limestone, dolomite, marl and sandstone: Trias - Eocene.

Mont Blanc external crystalline massif

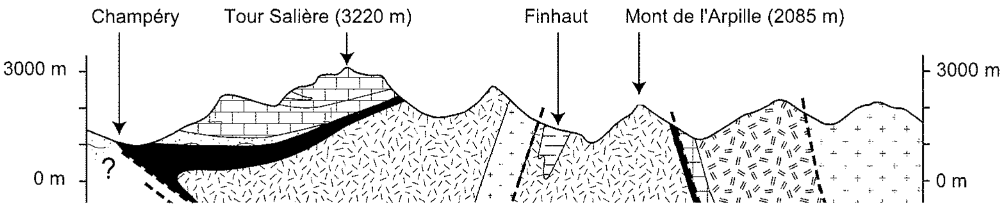
- Montenvers granitic gneiss: Carboniferous (307 ± 3 Ma, Bussy and Von Raumer 1993).
- Gneiss: Proterozoic - Paleozoic, lenticular banded gneiss (453 ± 3 Ma, Bussy and Von Raumer 1993).

Mont Blanc internal crystalline massif

- Leucogranite: Carboniferous - Permian.
- Mont Blanc granite: Upper Carboniferous (304 ± 3 Ma, Bussy and Von Raumer 1993).
- Rhyolite: Upper Carboniferous (307 ± 2 Ma, Bussy and Von Raumer 1993).
- Gneiss: Proterozoic - Paleozoic.

Ultrahelvetic and Penninic nappes

- Sandstone: Eocene (Dent de Valère Flysch).
- Limestone and marl: Malm - Cretaceous (Anzeinde nappe).
- Wildflysch: Oligocene (Plaine Morte nappe).
- Submedian zone : Dolomite, evaporite, limestone, marl and sandstone (including flysch): Trias - Eocene.



is a syncline pinched inside the thrust fault between the Aiguilles Rouges basement and the Infra-Aiguilles Rouges Massif. The thrust fault deepens towards the south-east below another thrust fault in the Mont Blanc Massif. One should be cautious when assuming the presence of a complex sedimentary syncline below Lavey-les-Bains, as there is no direct geological proof given by outcrop or deep wells. This structure may drain deep fluid towards highly fractured areas in the Aiguilles Rouges Massif, assuming the structure is present and has a favourable hydraulic conductivity. However, the structure could represent an impermeable barrier for groundwater circulating in the Aiguilles Rouges Massif if the syncline has a low hydraulic conductivity. In this case the pressure of trapped waters could cause natural hydraulic fracturing in the basement just above the thrust fault that would increase the hydraulic conductivity in the Aiguilles Rouges Massif allowing upwelling of deep fluids.

### 2.4 Local geology in the thermal areas

The Lavey-les-Bains thermal area is located close to the boundary of the Aiguilles Rouges Massif and its autochthonous cover (Fig. 2). Fractured basement outcrops a few hundreds metres upstream from the spa. Close to Lavey-les-Bains, Aiguilles Rouges Massif fractures were characterised as three main families of fractures with high hydraulic conductivities which probably drain deep geothermal fluid to the surface: a NNW-SSE family of extension cracks, subvertical and parallel to the Rhone Valley, a NE-SW family of fault breccias and a family of micro-thrust and brecciated faults with low dip (Flamm 1993). Mesozoic dolomitic limestones of the autochthonous sedimentary cover outcrop near the spa. Quaternary sediments 0–600 metres thick, as measured in drill holes, fill the valley from the mountain slope to the Rhone River in the Lavey-les-Bains thermal area. The top section of the valley fill is made up of coarse gravels and river sands tens of meters thick which host an upper aquifer. The middle section of the valley fill includes several hundred metres of laminated glaciolacustrine silts that are assumed to be an aquiclude. The bottom of the Quaternary fill is probably composed of glacial coarse deposits which could contain large amounts of water (Besson et al. 1992, 1993).

The Saint-Gervais-les-Bains thermal area is located in the south-west of the Aiguilles Rouges Massif (Fig. 1). The Aiguilles Rouges basement does not directly outcrop in the thermal area but is probably present at roughly at 300–500 metres below the autochthonous sedimentary cover. Close to the spa, the autochthonous sedimentary cover is overlapped by the Morcles nappe formations, which form the Mont d'Arbois and Mont Joly Massifs. Geological investigations and drilling near the Saint-Gervais-les-Bains thermal area identified a thrust fault system in the autochthonous sedimentary cover. This thrust fault puts in contact a normal series of upper-middle Trias (including dolomites, limestones, gypsum, cellular dolomites, schists, quartzite and sandstones) with black and green schists at the bottom of the series over the lower Triassic-Permian quartzite. Movements of the thrust fault near the contact generated a complex zone of imbricated structures where a large amount of thermal water rises. In the spa area, a N-S fault called «Springs Fault» which is a dextral strike-slip and reverse fault shifts the thrust fault system (Fig. 2). The «Springs Fault» which has a great dip towards the east crosses the autochthonous cover as well as the basement and goes on towards the Contamines-Montjoie fault system.

The Val d'Illiez Valley is located at the limit between the Helvetic domain in the south-east and the Prealps in the north-west. In the spa area at Buchelieule, the parautochthonous flysch with sandstone layers overlaps the Tertiary autochthonous cover in its lowest elevation (at about 790 m a. s. l.). The autochthonous cover is folded and consists of marly and micaceous schist, the Carrières sandstone and the red molasse. Thrust faults are present in these formations. In detail, Schroeder & Ducloz (1955) specified that these thrust faults are in reality faulted anticlines with axial planes plunging towards the south-east. Quaternary formations overlie the Tertiary bedrock and consist of moraine and alluvial deposits. Lateral mountain streams of ESE-WNW direction follow fractures and form alluvial fans along the Vièze valley. Sometimes, the moraine directly overlies the recent alluvial deposits as in Buche-

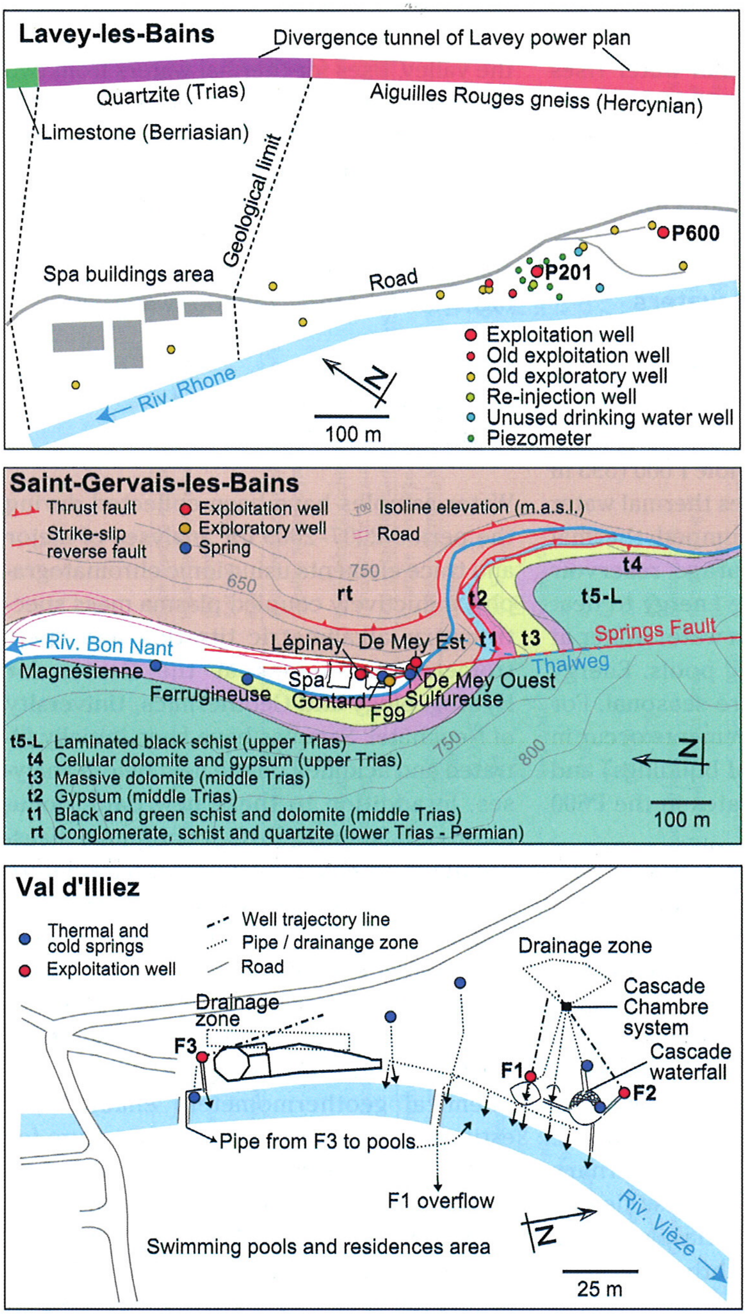



Fig. 2: Geology and location of wells and springs for the three studied low-enthalpy geothermal systems.

lieule where boreholes crossed the Vièze deposits below the moraine. The thermal springs at Buchelieule emerge on the left bank of the valley from seepages in the moraine, 10 metres above the level of the river. The bedrock composed of sandstones and argillite, with a strong dip and with locally crushed zones, was drilled by several wells and by the subhorizontal drainages. According to Bianchetti et al. (1992), the crossed sandstones where the thermal water rises would correspond to the so-called Carrières sandstone (upper Rupelian), which should not be confused with the sandstone of the Val d'Illiez quarry (parautochthonous flysch).

## 3. Direct use of thermal waters

Two deep wells provide thermal water to Lavey-les-Bains spa. Borehole P201 (201 m deep), drilled in 1972-1973, provides thermal water at 55 °C and borehole P600 (595 m deep) drilled in 1997 provides thermal water at 65 °C (Table 1). The pumped thermal water flows to a large storage reservoir where heat exchangers take energy to heat buildings and produce warm water. Water at 37 °C is used for swimming pools. Energy requirements for the spa are seasonal. For example, high energy requirements occur in winter, largely for heating of buildings) and the maximum production rates in the P600 well occur at this time.

At Saint-Gervais-les-Bains, four vertical boreholes between 99 and 207 m deep, and a shallow well 7.45 m deep, reach thermal waters (Fig. 2). Three wells are pumped to produce thermal water (Table 1). For example, the 101.5 m deep Lépinay well drilled in 1999 produces water at 39 °C. Direct use of the thermal water includes swimming pools, heating of buildings and cosmetics (Table 1). All of the wells crossed the Quaternary deposits and reached more or less deeply the fractured Permian and Triassic formations belonging to the autochthonous sedimentary cover.

Three inclined boreholes drilled in 1996 and several thermal and subthermal springs from horizontal drainage are present in the Val d'Illiez thermal area also relies on wells to provide thermal water (Fig. 2). However wells are not equipped with pumps because artesian flows occur from three inclined boreholes drilled in 1996. The deepest well (F3, Table 1) produces water at 30 °C that is used for swimming pools on the two sides of the valley. Uses for thermal waters from two other wells (F1 and F2, both at 28 °C) include heating of outside pathways, bottled drinking water and medical care. Downstream from F3 well, subhorizontal drainage pipes into the slope collect thermal waters into a small catchment named «Chambre de Captage» and feed three outdoor waterfalls.

## 4. Chemical, isotopic and temperature tracers

Water samples have been collected during the period 2007-2009 for analyses of major and trace elements using ionic chromatography, inductively coupled plasma mass spectrometry, alkalimetric titration and spectrometry techniques at the Center for Hydrogeology and Geothermics, University of Neuchâtel. Samples have been initially filtrated and acidified on the field before analyses. In addition to these new data, documented in Sonney (2010), continuous measurements of physico-chemical parameters before 2007 in waters from wells and springs and discrete measurements on several sampling points were also used and made possible to highlight mixing processes and water-rock interactions occurring in the three studied geothermal systems (Figs. 3, 4). Chemical geothermometers enabled the estimation of the reservoir temperature for each studied geothermal systems, using the chemical composition of the thermal end-members. The chalcedony geothermometers from relations of Fournier (1977) and Arnórsson et al. (1983) are strongly affected

| | Lavey-les-Bains | | Saint-Gervais-les-Bains | | | Val d'Illiez | | |
|---|---|---|---|---|---|---|---|---|
| Canton or Department / Country | Vaud / Switzerland | | Haute-Savoie / France | | | Wallis / Switzerland | | |
| River linked to the system | Rhone | | Bon Nant | | | Vièze | | |
| Swiss kilometric coordinates (CH1903) | 568'000 / 116'600 | | 544'000 / 80'050 | | | 558'400 / 117'500 | | |
| Elevation of the thermal area (m.a.s.l.) | 425 | | 620 | | | 791 | | |
| Regional geology | North-eastern low elevation point of the Aiguilles Rouges crystalline Massif | | South-western low elevation point of the Aiguilles Rouges crystalline Massif | | | Sedimentary autochthonous cover of the Aiguilles Rouges crystalline Massif Triassic to Tertiary formations | | |
| Local geology | Aiguilles Rouges gneiss | | Sedimentary autochthonous cover | | | Tertiary parautochthonous flysch | | |
| Local tectonic conditions | NE and NNW fracturing | | Thrust fault in the autochthonous cover Springs fault (Contamine-Montjoie fault system) | | | Thrust fault between the autochthonous and parautochthonous flysch | | |
| Rocks outcropping in the thermal area | Gneiss (Hercynian) | | Quartzite - Evaporite (Permian - Trias) | | | Flysch (Tertiary) | | |
| Reservoir rocks at depth | Crystalline rocks (Hercynian) | | Gneiss (Hercynian), sedimentary formations ? | | | Carbonates with evaporites (Trias) | | |
| Production well | **P600** | **P201** | **Lépinay** | **De Mey Est** | **De Mey Ouest** | **F1** | **F2** | **F3** |
| Year of drilling | 1997 | 1972-1973 | 1999 | 1988-1989 | 1989 | 1996 | 1996 | 1996 |
| Length of the production well (m) | 595 | 201 | 101.5 | 196 | 207 | 37 | 60 | 120 |
| Depth of the production well (m) | 517 | 201 | 101.5 | 196 | 207 | 26 | 42.5 | 113 |
| Geochemical water type | $Na-SO_4>Cl$ | $Na-SO_4>Cl$ | $Na-SO_4>Cl$ | $Na-SO_4>Cl$ | $Na-SO_4>Cl$ | $Ca-SO_4$ | $Ca-SO_4$ | $Ca-SO_4$ |
| Average well head temperature (°C) | 65 | 57 | 39 | 36 | 27 | 28 | 28 | 30 |
| Total Dissolved Solids (mg/L) | 1450 | 1215 | 4245 | 4820 | 3100 | 1715 | 1700 | 1805 |
| pH | 7.7 | 7.4 | 6.9 | 6.9 | 7.1 | 7.3 | 7.3 | 7.2 |
| Current production rate (L/min) | 300-1200 | 50-450 | 225 | 92 | 58 | >10 | 200 | 1170 |
| Geothermal potential (KWth) - 10°C* | 1150-4600 | 165-1475 | 455 | 165 | 70 | >15 | 250 | 1470 |
| Current use of thermal water | Swimming pools, full heating of the thermal spa, sanitary hot water | | Medical care Partial heating of thermal spa | Cosmetics | Protection of De Mey Est production | Heating of an outside pathway | Unused | Swimming pool |
| Observed mixing processes | Weak mixing with a cold $Ca-HCO_3$ water flowing in the gneissic slope (decompressed zone) | | Weak to medium mixing with two cold waters: a $Ca-SO_4$ water from the Triassic autochthonous cover and a $Ca-HCO_3$ water from the Quaternary filling | | | Weak mixing with a cold $Ca-HCO_3$ water flowing in the Tertiary and Quaternary formations | | |
| Elevation of the recharge area (m.a.s.l.) | 1700-2100 | | 1700-2100 | | | 1700-2100 | | |
| Recharge area of the thermal end-member | North-eastern part of the Aiguilles Rouges basement | | South-western part of the Aiguilles Rouges basement | | | Autochthonous cover outcropping along the Aiguilles Rouges basement | | |
| Reservoir temperature (°C) | 100-110 | | 70-80 | | | 35-40 | | |
| Reservoir depth (m.a.s.l.) | About - 3000 | | About -2500 | | | About -500 | | |

** Discharge temperature after cooling is arbitrarily fixed at 10°C*

Tab. 1: Summary table of the main characteristics for the three studied hydrothermal systems.

by mixing processes with cold waters containing low silica concentrations. Consequently, the calculation using the thermal end-members is more appropriate than using directly the values of the sampled waters. Moreover, some silica precipitation may occur during the rise of the deep fluid and thus the calculation can be also underestimated. Cationic geothermometers using ratios between sodium, potassium, lithium and magnesium were tested for the three sites and give results largely above the calculated chalcedony temperature.

The average elevation of the infiltration area was estimated with the new data of water stable isotopes and the relation for the Bernese Alps from Kullin & Schmassmann (1991). The location of Lavey-les-Bains, Saint-Gervais-les-Bains and Val d'Illiez in the Western Alps implies that this relation is more appropriate than those given in Blavoux (1978), Bortolami et al. (1979) and Vuataz (1982). Water stable isotopes were analysed at the Center for Hydrogeology and Geothermics, University of Neuchâtel, with the high-precision laser spectrometry device. Oxygen-18 and deuterium isotope values for Lavey-les-Bains, Saint-Gervais-les-Bains and Val d'Illiez thermal waters were plotted in a graph including the World Meteoric Water Line of Craig (1961) and other Alpine thermal waters documented in Vuataz (1982) and Bianchetti (1993) (Fig. 5). No enrichment in oxygen-18 can be noted, as it sometimes happens in high-enthalpy geothermal systems. This doesn't happen in any of the low-enthalpy deep flow systems in the Alps. The information which enables the study of the groundwater residence time for the studied geothermal systems are the tritium values in waters. For Val d'Illiez, a new sampling campaign was made in 2009 on

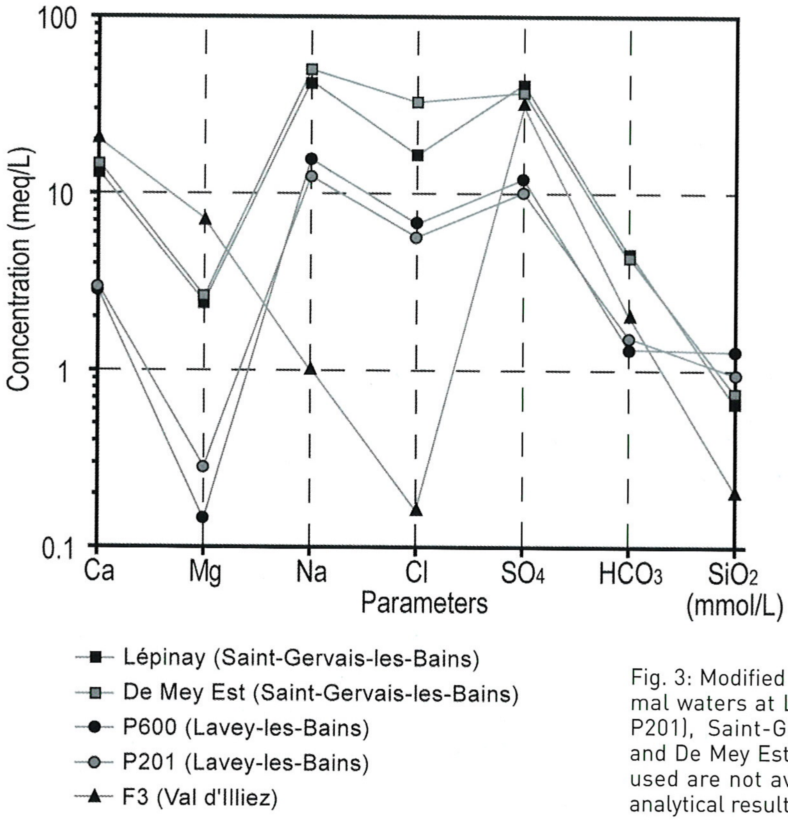



Fig. 3: Modified Schoeller diagram of thermal waters at Lavey-les-Bains (P600 and P201), Saint-Gervais-les-Bains (Lépinay and De Mey Est) and Val d'Illiez (F3). Data used are not average values but discrete analytical results found in Sonney (2010).

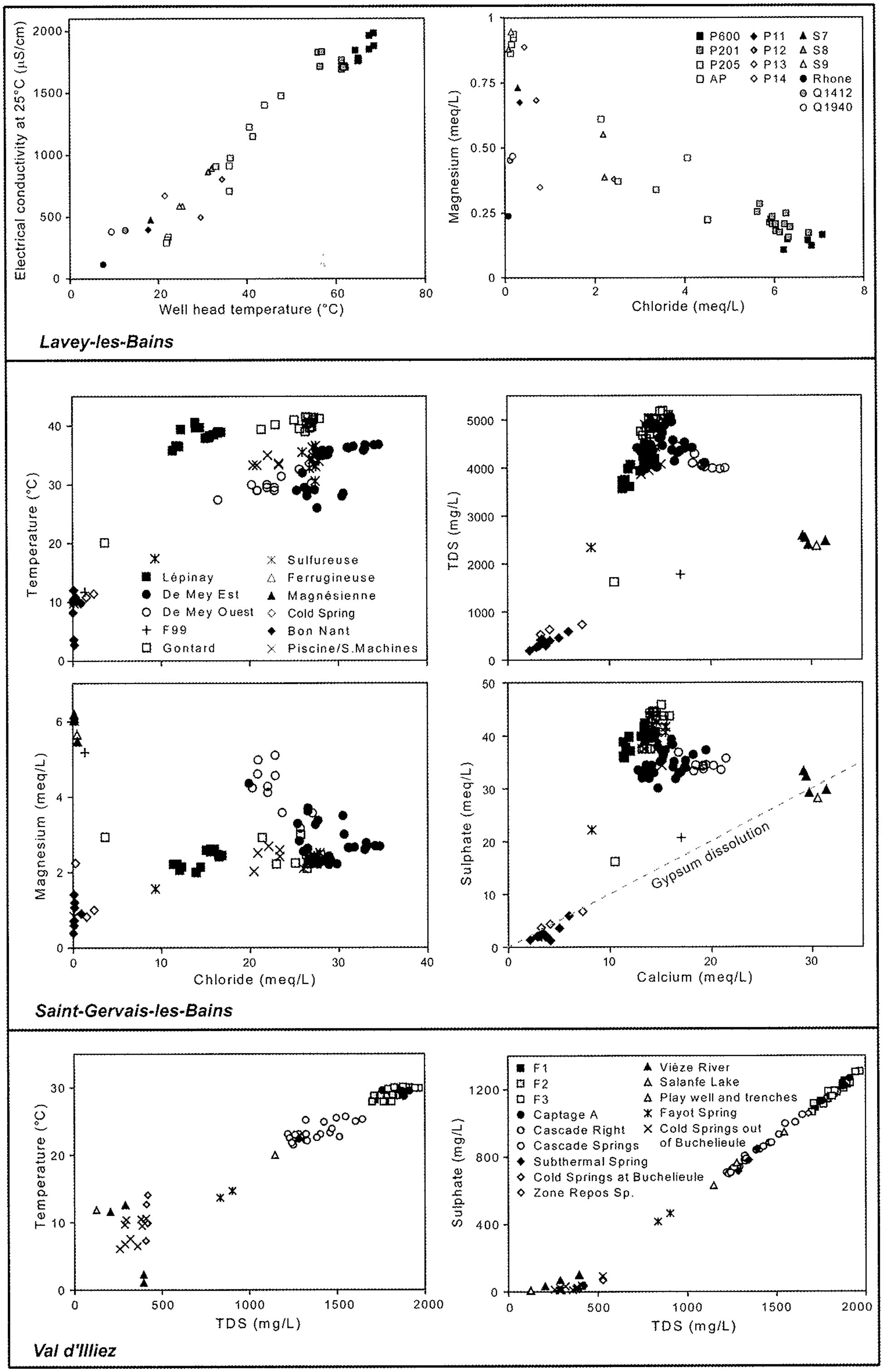



Fig. 4: Description of the mixing processes between thermal end-members and cold shallow groundwater with a selection of physico-chemical parameters correlated. Recent historical data used in the graphs are documented in Sonney (2010).

thermal and cold springs, and tritium was analysed by scintillation spectrometry at Hydroisotop analytical laboratory, Germany. This allows the groundwater residence time for the Val d'Illiez deep flow system to be better discussed, using the piston flow model. This method takes into account the simplest case study of pathway assuming that water infiltrates in a well defined area and flows like in a pipe towards the spring without mixing process. This case is probably over-simplifying the deep flow system of Val d'Illiez. Previous measurements made on the three hydrothermal sites by Vuataz (1982), Bianchetti (1993), Sonney (2007, 2010), and Bianchetti et al. (2006) were also used (Fig. 6). The present day tritium content in precipitation is several orders of magnitude lower than the peak reached during the period of atmospheric nuclear weapons testing (Pearson et al. 1991), and for the last 10 years tritium content in precipitation has stabilized around 10 T.U. (Tritium Units). Alpine hydrothermal systems in crystalline rocks have often relatively long underground residence times (mostly older than the first nuclear weapons tests in 1953), the method using tritium content in water makes possible the detection of younger waters (Fontes 1980).

## 5. Circulation systems

Three circulation systems are proposed in the paper starting with the deepest to end with the shallowest. These follow geology and are: Aiguilles Rouges Massif circulation system, autochthonous sedimentary cover circulation system and shallow circulation system in Quaternary formations. Chemical and isotopic properties of thermal, subthermal and cold waters represent these mixes of three systems as follows (Fig. 4):

- Lavey-les-Bains: Aiguilles Rouges Massif circulation system and Quaternary formations.
- Saint-Gervais-les-Bains: mix of all three.
- Val d'Illiez: Autochthonous sedimentary cover circulation system and Quaternary formations.

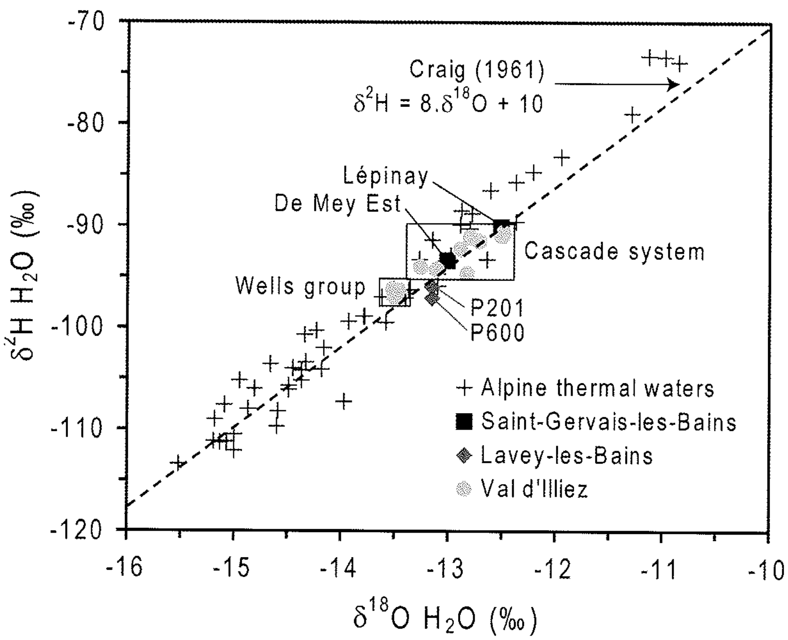



Fig. 5: Water stable isotopes plot for Alpine thermal waters. Data for Lavey-les-Bains, Saint-Gervais-les-Bains and Val d'Illiez are provided from Sonney (2010).

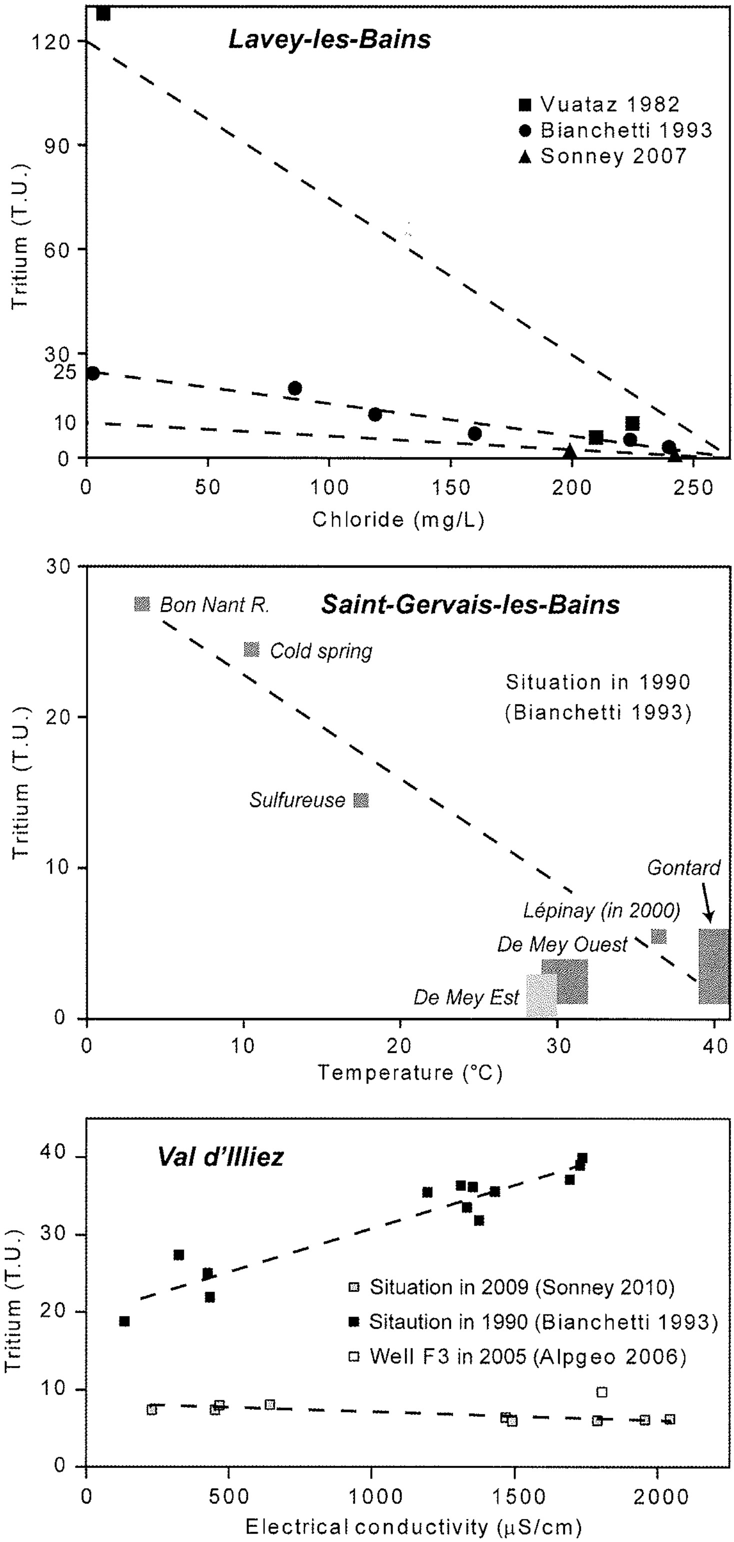



Fig. 6: Chloride-tritium, temperature-tritium and electrical conductivity-tritium relations for Lavey-les-Bains, Saint-Gervais-les-Bains and Val d'Illiez respectively. Data are documented in Sonney (2010).

## 5.1 Aiguilles Rouges Massif circulation system

One geochemical end-member (Fig. 3) includes Na-$SO_4$ thermal water rich in chloride and Na-Cl water representing the deep thermal component circulating in the crystalline rocks of the Aiguilles Rouges Massif. Waters in the P600 and P201 wells at Lavey-les-Bains and in the Lépinay and De Mey Est wells at Saint-Gervais-les-Bains are characteristic of this geochemical type. Total mineralization ranges around 1.3–1.5 g/L for Lavey-les-Bains and around 4.2–4.9 g/L for Saint-Gervais-les-Bains and the main chemical compounds, considered as natural markers of the thermal component, are Li, Na, K, Cl, $SO_4$, F and $SiO_2$.

At Lavey-les-Bains, the geochemical investigation infers the existence of a purely thermal component of around 68 °C and 1.5 g/L circulating in the basement where dissolution of feldspar, oxidation of sulphides as pyrite and leaching of small amounts of rich Na-Cl fluid occur. The hydrolysis of biotite from the crystalline rocks (Edmunds et al. 1985), and the leaching of fluid inclusions were also assumed to explain the origin of the high chloride concentrations in thermal water. This end-member is strongly undersaturated with respect to the feldspar, but clearly in equilibrium with calcite and aragonite which are controlled by their solubility in relation to temperature. It is also undersaturated with respect to dolomite, gypsum and anhydrite because sulphate and dolomite contents are not high enough to reach equilibrium, and is slightly over-saturated with respect to the quartz and chalcedony.

At Saint-Gervais-les-Bains, the Na-Cl thermal component is most likely related to the remobilization of trapped saline water by deep flow systems reaching the thrust fault of the Aiguilles Rouges Massif on the Infra-Aiguilles Rouges Massif (Arthaud & Dazy 1989, Sonney & Vuataz 2010a). However, the hydrolysis of biotite coupled to the leaching of fluid inclusions may explain partially the presence of high chloride concentrations reaching 1 g/L in thermal waters at Saint-Gervais-les-Bains. This assumption has to be considered especially as the deep flow system occurs in a crystalline environment (Gascoyne & Kamineni 1994; Stober & Bucher 1999; Perello et al. 2001). The leaching of residual brines would be the main source of Na-Cl as observed in calculating a Cl/Br molar ratio at Saint-Gervais-les-Bains lower than 655 (Alcalá & Custodio 2008; Sonney & Vuataz 2010b). The Na-Cl end-member does not result from halite dissolution in Triassic formations. Water-rock interactions occur during the uprising of this thermal component through N-S strike-slip faults in the basement and later on in the autochthonous sedimentary cover.

For the Aiguilles Rouges Massif circulation system, the average elevation of the recharge zone reaches about 1700–2100 metres according to the water stable isotopes data. This estimation is consistent because the Aiguilles Rouges basement has an average elevation of 1800–2200 metres. The origin of the deep flow systems probably comes from infiltration and circulation through the fractures in the north-eastern and south-western parts of the Aiguilles Rouges basement for Lavey-les-Bains and Saint-Gervais-les-Bains, respectively. Using the total dissolved silica in the Na-$SO_4$ thermal end-member, reservoir temperatures can be evaluated of around 100–110 °C and 70–80 °C for Lavey-les-Bains and Saint-Gervais-les-Bains, respectively. The plots of tritium values versus chloride and temperature for Lavey-les-Bains and Saint-Gervais-les-Bains in Figure 6 show that the Na-$SO_4$ and high-Cl thermal end-member is devoid of tritium, and therefore infiltrated before the first nuclear weapons tests (< 1953). In addition to this, carbon-14 analyses were performed at Lavey-les-Bains (Bianchetti 1993; Sonney 2007) showing that the average residence time for Aiguilles Rouges Massif circulation system should be higher than

8000 years (Sonney & Vuataz 2009; Sonney 2010). The Aiguilles Rouges Massif circulation system leading to the Lavey-les-Bains and Saint-Gervais-les-Bains thermal waters is most likely related to the presence of a large thrust fault system at 2-3 kilometres below the surface putting in contact two external crystalline massifs: Aiguilles Rouges and Infra-Aiguilles Rouges (Fig. 1). The thrust fault should collect infiltrated waters circulating in vertical permeable faults in the basement. However, it remains difficult to locate exactly where the thrust fault drains the deep fluid, and moreover it dips to the south-east, what brings complications in evaluating the depth of the reservoir.

### 5.2 Autochthonous sedimentary cover circulation system

The second geochemical end-member (Fig. 3) includes Ca-$SO_4$ waters with medium salinity (1.7-1.8 g/L) representative of waters circulating inside gypseous formations of the autochthonous cover. Three wells at Val d'Illiez and two cold springs at Saint-Gervais-les-Bains («Ferrugineuse» and «Magnésienne») belong to this group. This group also has low chloride content, around 20 mg/L at Saint-Gervais-les-Bains and around 4 mg/L at Val d'Illiez and high magnesium concentrations reaching 80 mg/L.

At Saint-Gervais-les-Bains, the Ca-$SO_4$ and low-Cl end-member in the autochthonous sedimentary cover dilute the uprising Na-$SO_4$ and high-Cl thermal water from the Aiguilles Rouges basement. This occurs in the lower Triassic-Permian quartzite as evidenced by De Mey boreholes (27-36 °C) and in the imbricated structure zone crossed as evidenced by Lépinay well (39 °C). For the autochthonous sedimentary cover circulation system, gypsum dissolution is occurring with cationic exchanges involving Na and low-temperature Mg dissolution from dolomite. The elevation of recharge area for the autochthonous sedimentary cover circulation system at Saint-Gervais-les-Bains, given by the water stable isotope data, is at about 900-1300 metres. This corresponds to the mean elevation of Triassic formations outcropping in the sector of Mont d'Arbois and Mont Joly Massifs, located towards the south-west (Fig. 1). Unfortunately, the residence time of this system cannot be evaluated due to the lack of isotopic data. Further isotopic analyses, especially on the «Ferrugineuse» and «Magnésienne» springs which belong to this system, should be performed.

At Val d'Illiez, the autochthonous sedimentary cover circulation system leads to a Ca-$SO_4$ and low-Cl thermal end-member at 30 °C and 2 g/L. The thermal component acquires its mineral composition from the dissolution of gypsum and dolomite, is clearly in equilibrium with carbonate minerals and is slightly under-saturated with respect to gypsum and anhydrite. An excess of sulphate concentration in relation to calcium occurs in the thermal end-member (about 26.7 meq/L against 21 meq/L) and would be related to carbonate equilibrium in the reservoir. Looking at the typology of Triassic evaporitic aquifers from the Western Alps in Switzerland (Wallis) and according to chemical analyses made on more than 100 springs, documented in Mandia (1991), the Val d'Illiez water is clearly in the family of waters circulating in a gypseous karstified environment. The deep flow system of Val d'Illiez starts from infiltration in the autochthonous sedimentary cover in the Salanfe Lake area (Fig. 1), located at about 1900 metres of elevation. The water stable isotope values in thermal water agree with that. The location of the recharge area was initially highlighted by Bianchetti et al. (1992) who studied the relation between levels of the Salanfe Lake, induced seismicity and natural flow rates of the Val d'Illiez thermal springs. The Triassic rocks outcropping in Salanfe area and along the north-western edge of the Aiguilles Rouges basement are dipping at about 30° towards the north-west. Assuming that these layers are homogeneous at depth, the Triassic reservoir should be deeper than 1500 metres below the Val d'Illiez thermal area. However, the presence of Cretaceous limestones in the Champéry region (Lanterno 1954), belonging to the upper part of the autochthonous cover, requires the existence of an anticline at depth having a fold axis more or less parallel to the valley axis. This anticline would raise the Triassic rocks less than 1000 metres below the Val d'Illiez spring zone. According to the geological cross section in Figure 1, this anticline should thrust younger formations with a fault system probably related deeply to the thrust fault putting in contact the Aiguilles Rouges and Infra-Aiguilles Rouges Massifs. To estimate the reservoir temperature for the autochthonous sedimentary cover circulation system, the use of silica geothermometers is not appropriate because of the geological context. Indeed, the deep flow system occurs in sedimentary formations and thermal waters discharge low silica concentrations (< 15 mg/L). Bianchetti et al. (1992) indicated that the reservoir temperature at Val d'Illiez should probably not exceed 35-40 °C, not significantly warmer than the emergence temperatures. The residence time was initially evaluated by Bianchetti et al. (1992) who proposed 10-15 years according to tritium isotope measurements in thermal and cold waters in 1990. Indeed, at that time the thermal end-member had an average tritium content of around 40 T.U. greater than the cold groundwaters (about 24 T.U., Fig. 6). In June 2009, the new sampling campaign allowed the residence time to be better discussed, and the trend is reversed because the thermal end-member in the Val d'Illiez contains slightly less tritium (6 T.U.) than cold waters mixing (8 T.U., Fig. 6). This can be explained assuming that the thermal end-member had been infiltrated with tritium values between 8 and 15 T.U., during the early 2000's. The tritium concentration in the thermal end-member is only modified by the radioactive decay process and then, the piston-flow model makes possible to estimate the residence time for the thermal end-member at about 5 years.

### 5.3 Shallow circulation system in Quaternary formations

The third geochemical end-member includes Ca-$HCO_3$ cold waters with low salinity (< 0.5 g/L) representative of waters circulating at shallow depth (< 500 m) inside Quaternary formations covering the Aiguilles Rouges basement and autochthonous sedimentary cover. At Lavey-les-Bains, the cold end-members dilute the thermal water in all wells at different rates. The dilution is marked by a reduction in Li, Na, K, Cl, $SO_4$, F and $SiO_2$, compensated by an increase in Ca, Mg, $HCO_3$ and tritium in thermal water (Bianchetti 1994; Sonney & Vuataz 2009). This evolution is also accompanied by a decrease in the total mineralization and of the temperature. The P600 and P201 wells are the least diluted, 20% and 5% of Ca-$HCO_3$ cold water, respectively. Two cold end-members are present and circulate in the Rhone alluvial deposits and in the fissured gneissic massif of the mountain slope (decompressed area). The last one is confirmed by springs inside the gallery of the Lavey power plant. At Saint-Gervais-les-Bains, the shallow circulation system in Quaternary formation of the Bon Nant valley dilutes all the springs and wells. The sulfureuse spring located close to De Mey wells is discharging a Ca-$HCO_3$ cold water at about 8-10 °C, but discharged in the past a Na-$SO_4$ thermal water rich in chloride. Finally, at Val d'Illiez, a Ca-$HCO_3$ cold water dilutes the uprising Ca-$SO_4$ and low-Cl thermal end-member and acquires its composition with circulation at a shallow depth in the moraine deposits on the slopes and in the Quaternary formations of the Vièze valley. For each site, waters of the shallow circulation system in Quaternary formations have higher values of water stable isotopes. This indicates that the Ca-$HCO_3$ cold end-members infiltrate at lower elevation compared to the deep flow systems leading to thermal waters. The residence time for the shallow circulation system in Quaternary formations cannot be precisely evaluated, but the measured tritium values in Val d'Illiez cold waters in 2009 (average of 8 T.U.) and the previous tritium measurements carried out by Vuataz (1982) and Bianchetti (1993) would indicate that the residence time for this system does not exceed a few months.

## 6. Conclusions and perspectives

The comparison of the geological, hydrogeological, geochemical and isotopic properties of the three studied low-enthalpy geothermal systems enabled to better understand the deep flow systems occurring in the Aiguilles Rouges basement and its autochthonous sedimentary cover. From a regional view, the two sites of Lavey-les-Bains and Saint-Gervais-les-Bains are positioned at the two low-elevation parts of the Aiguilles Rouges crystalline Massif, on each side. These positions are certainly no coincidence because the geological structure of the Aiguilles Rouges Massif could be considered as a volume having distinct boundaries, which play an important role in the circulation of the deep fluids: 1] at the front and at the bottom, the thrust fault system of the Aiguilles Rouges Massif overlapping the Infra-Aiguilles Rouges Massif; 2] behind, the thrust fault system of the Mont Blanc Massif overlapping the Aiguilles Rouges Massif and 3] on both sides, two NNW-SSE valleys, Rhone and Bon Nant Valleys, where major vertical faults are present. Considering infiltrations inside this enclosed volume, the generated deep regional flow systems have to exit the massif via the two low-elevation points. This complex geological structure with distinct boundaries could explain the occurrences of the hydrothermal systems of Lavey-les-Bains and Saint-Gervais-les-Bains.
The deep flow system leading to the thermal springs in the Val d'Illiez occurs at the bottom of the autochthonous cover of the Aiguilles Rouges basement, mainly inside the Triassic formations. The structure of the cover is a great recumbent anticline with an axial plane plunging towards the south-east which would be limited by a basal thrust fault related to the thrust system between the Aiguilles Rouges and Infra-Aiguilles Rouges basements. The thermal component acquires its mineral composition from the dissolution of gypsum and dolomite occurring in the Triassic formations, in a different way compared to Lavey-les-Bains and Saint-Gervais-les-Bains. The thermal component has an infiltration area close to the elevation of the Salanfe Lake, at about 1900 meters, and the reservoir temperature of the deep flow system should probably not exceed 35–40 °C. New tritium data on Val d'Illiez thermal and cold springs allowed the groundwater residence time to be estimated at about 5 years, much smaller than estimated for Lavey-les-Bains and Saint-Gervais-les-Bains (> 8000 years).
The knowledge gained through this study is also useful to improve the knowledge of other geothermal systems in external crystalline massifs, such as Brigerbad in Switzerland, Uriage-les-Bains in France, etc. We could also cite other examples but generally, the density of hydrothermal sites is often higher in the Western Alps where the basement outcrops. Indeed, the vertical faults in the basement facilitates a deep infiltration of water leading to deep flow systems, whereas in sedimentary domain the superposition of nappes tends to generate shallower flow systems. Consequently, it would be interesting to investigate other low-elevation zones bordering the external crystalline massifs where the Quaternary filling could mask areas of uprising thermal waters. Since deep uprising thermal waters are often more mineralized than cold shallow water in the Quaternary filling, geophysical methods would help us to decipher the uprising areas. The use of geophysical tools in our case study could have improved the knowledge on the

hydrogeological processes occurring in the discharged thermal areas and even better, these tools could have detected new uprising zones.

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