Deep groundwater circulation in the Alps : relations between water infiltration, induced seismicity and thermal springs : the case of Val d'Illiez, Wallis, Switzerland

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Deep groundwater circulation in the Alps: Relations between water infiltration, induced seismicity and thermal springs. The case of Val d'Illiez, Wallis, Switzerland

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ABSTRACT

The recent occurence (end of 1953) of the thermal springs of Val d'Illiez, Wallis, is linked to exceptional events. During this year indeed, numerous seismic events were felt by the local population. These springs, located on the left bank of the Vièze River, outflow from Tertiary flysch of the Helvetic domain. Since 1988, all thermal and subthermal waters of the study area were measured, sampled and analyzed systematically. Their temperatures reach a maximum of 30 °C and the total discharge of the various exsurgences amounts to 1200 l/mn. The water chemistry of Ca-SO$_4$ type with total dissolved solids of 1850 mg/l is characterized by a low content of alkalis and chlorides.

The thermal springs temperature and discharge are varying with time and the warm fluids are mixed during their ascent by a cold and dilute groundwater, probably originating from a karstic aquifer in the Malm. The calcium and sulphate come from the dissolution of gypsum and anhydrite present in the Triassic cellular dolomite of the autochthonous cover of the Aiguilles Rouges Massif.

The authors present an hypothesis based on the interpretation of hydrogeological, geological, seismic and isotopic data, which suggests a link between these thermal springs and major water losses ($> 1 \text{ m}^3/\text{s}$) at the artificial lake of Salanfe, located 9 km south-east of the spring discharge zone. This hypothesis is supported by several observations:

1) The water losses of the lake of Salanfe do not converge to existing cold springs of the region, as shown by tracer tests carried out during the mid 1950's. This tends to reinforce the hypothesis that the water losses percolate to a deep confined aquifer;

2) The presence in the Salanfe cirque of autochthonous Triassic outcrops from the Helvetic domain, dipping towards the Val d'Illiez area: these layers are responsible for the major water losses of the lake and it is thought that the water flows in the same direction;

3) The abnormally high seismicity recorded in the Val d'Illiez in 1953 at the end of the complete initial filling of the reservoir and the occurence of the thermal springs seem to be contemporaneous;

4) The elevation of the lake catchment basin corresponds to the elevation of the thermal water catchment area, based on stable isotope data;

Chemical geothermometers calculations applied to the thermal springs analyses do not indicate a temperature at depth over 35 °C. Nevertheless, due to their yield (1200 l/min) and emergence temperature (30 °C), the geothermal potential of the springs readily available for an integrated exploitation of water and heat of at least 1.7 MW$_t$ and should not be neglected.

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ZUSAMMENFASSUNG

Das Auftreten der Thermalquellen von Buchelieule im Val d'Illiez, Kanton Wallis, scheint erst einige Jahr-zehnte (Ende 1953) zurückzuliegen und mit aussergewöhnlichen Erscheinungen im Zusammenhang zu stehen. So wurden im Laufe jenes Jahres zahlreiche seismische Stösse durch die Bewohner des Tals verpürt. Seit 1988 wurden die Thermal- und Subthermalwässer der untersuchten Zone mehrmals gemessen und analysiert. Diese am linken Ufer der Vièze gelegenen Quellen treten aus tertiären, parautochthonen, helvetischen Flyschen aus. Die maximale Temperatur beträgt 30 °C und der totale, über alle Austrittspunkte summierte Zufluss 1200 l/min. Der Chemismus vom Ca-SO$_4$ Typ mit einem totalen Mineralgehalt von 1850 mg/l ist durch niedrige Alkali- und Chloridgehalte gekennzeichnet.

Die Temperatur und die Austrittsmenge dieser Thermalwässer schwanken mit der Zeit. Kaltes und wenig mineralisiertes Wasser, wahrscheinlich aus einem Karstaquifer im Malm, mischt sich mit dem emporsteigenden Thermalwasser. Das Kalzium und das Sulfat stammen von der Auflösung von Gips und Anhydrit aus den Trias-Dolomiten der autochthonen Hülle des Aiguilles Rouges-Massivs.

Basierend auf der Interpretation hydrogeologischer, geologischer, seismischer und isotopischer Daten lässt sich eine Hypothese aufstellen, die diese Thermalquellen mit den bedeutenden Wasserverlusten (> 1 m^3/s) des ca. 9 km südöstlich der Quellen gelegenen Stausees von Salanfe hydraulisch verbindet. Mehrere Beobachtungen sprechen für einen solchen Zusammenhang:

1) die Verluste des Salanfer Sees treten bei keiner kalten Quelle der Umgebung aus; Markierungsversuche haben zu keiner Färbung des Wassers dieser Quellen geführt, was darauf hinweist, dass die Seeverluste einen tiefen Aquifer erreichen;

2) im Talkessel von Salanfe sind autochthone helvetische Trias-Einheiten aufgeschlossenen, die gegen Val d'Illiez abtauchen. Es darf deshalb angenommen werden, dass das Wasser in diese Richtung versickert;

3) die anomale Seismizität, die 1953, als der Stausee von Salanfe erstmals vollständig aufgestaut wurde, im Gebiet von Val d'Illiez beobachtet wurde. Wahrscheinlich zu diesem Zeitpunkt erscheinen auch erstmals die Thermalquellen;

4) die topographische Höhe des Auffangbeckens des Sees stimmt mit der Höhe überein, die dank stabilen Isotopen für das Ursprungsgebiet des Thermalwassers geschätzt werden konnte.

Die Anwendung der geothermometrischen Methoden zeigt, dass das Wasser in der Tiefe nicht viel wärmer sein kann als das Wasser beim Austritt. Dennoch steht wegen der hohen Austrittsmenge (1200 l/min) und der Temperatur (30 °C) ein nicht vernachlässigbares Wärmepotential (1.7 MW$_t$) für eine eventuelle integrierte Wasser- und Wärmenutzung in Val d'Illiez zur Verfügung.

RÉSUMÉ

L'apparition des sources thermales de Buchelieule dans le Val d'Illiez, canton du Valais, semble être récente (fin 1953) et liée à des circonstances exceptionnelles. En effet, au cours de cette année, de nombreuses secousses sismiques ont été ressenties par la population locale. Toutes les eaux thermales et subthermales de la zone d'étude ont été mesurées, échantillonnées et analysées à de nombreuses reprises à partir de 1988. Ces sources, situées sur la rive gauche de la Vièze, émergent de flyschs tertiaires parautochtones helvétiques. Elles ont une température de 30 °C au maximum et le débit total des divers exutoires est de 1200 l/mn. Le chimisme, de type Ca-SO$_4$ avec une minéralisation totale de 1850 mg/l, est caractérisé par de faibles teneurs en éléments alcalins et en chlorure.

La température et le débit de ces eaux thermales varient au cours du temps et celles-ci subissent une dilution, lors de leur remontée, par des eaux plus froides et peu minéralisées, vraisemblablement originaires d'un aquifère karstique du Malm. Le calcium et le sulfate dans l'eau proviennent de la dissolution de gypse et d'anhydrite présents dans les cornieules triasiques de la couverture autochtone du Massif des Aiguilles Rouges.

Les auteurs présentent une hypothèse, basée sur l'interprétation des données hydrogéologiques, géologiques, sismiques et isotopiques, qui tend à démontrer qu'il existe une liaison hydraulique entre ces sources thermales et les importantes pertes (> 1m^3/s) du lac artificiel de Salanfe, situé environ 9 km au sud-est des sources. Cette hypothèse est corroborée par plusiers observations:

1) les fuites du lac de Salanfe n'aboutissent pas à des sources froides de la région, et des essais de coloration ont montré l'absence de traceurs dans l'eau de ces sources. Ce fait tend à démonter que les pertes du lac atteignent un aquifère captif profond;

2) la présence dans le cirque glaciaire de Salanfe de niveaux affleurants de Trias autochtone helvétique, par lesquels s'opèrent les fuites du lac, et qui plongent en direction du Val d'Illiez, laisse supposer que l'eau s'infiltre dans cette direction;

3) la sismicité anormale, relevée dans le Val d'Illiez en 1953, à la fin du premier remplissage complet de la retenue. L'apparition des sources thermales semble être contemporaine;

4) l'altitude du bassin versant du lac correspond à l'altitude d'origine des eaux thermales estimée à partir des données en isotopes stables de l'eau.

L'application des méthodes géothermométriques ne permet pas d'envisager que la température de l'eau thermale en profondeur soit supérieure à 35 °C. Néanmoins, en raison du débit élevé (1200 l/mn) qui s'écoule en surface dans la zone d'émergence, un potentiel thermique non négligeable (1,7 MW$_t$) est disponible pour une éventuelle exploitation de la chaleur à Val d'Illiez.

1. Introduction

The thermal springs area is located in the Val d'Illiez valley, Wallis, Switzerland, north-east of the Val d'Illiez village, at the locality of Buchelieule (coordinates 558.400/ 117.500 and 790 masl, Office Fédéral de Topographie 1980). All the springs discharge from the left bank of the Vièze River, the major stream of the valley which flows into the Rhône in the town of Monthey. This study of the thermal springs of Val d'Illiez, which were still relatively unknown a few years ago, was carried out within the framework of GEOTHERMOVAL, an extensive geothermal exploration program in the canton of Wallis (CRSFA 1988).

2. Historical background

Thermal spring occurence seems to be recent, because no recorded activity could be found in the literature before 1953, although geologic studies of the Val d'Illiez region were carried out in the 1920's. At the most Marietan (1953) says that a spring with a temperature of 18 °C was known from the time immemorial. The same author is the first to describe the circumstances under which the present thermal springs appear for the first time : "In September 1953, warm springs gushed forth below the village of Val d'Illiez... near the bridge on the Vièze River (780 masl)... Since last year, one could hear underground noises and one could feel weak earth tremors. But during the summer, these noises became louder. From October 26 to November 2, nine earth tremors were recorded; the one from November 2 shook doors and windows in the village of Val d'Illiez..." These seismic events were also recorded in the annual report of the Swiss Meteorological Office (Wanner 1954). Marietan (1953) also gives a description of the springs: "... the thermal springs are spread out 70–80 m, emit a hydrogen sulfide smell and their temperature reaches 28 °C...". The total flow rate was estimated around 1300 l/mn (Wanner 1954) and the first chemical analysis (Schroeder & Ducloz 1955) carried out in October 1953 revealed mainly a calcium-sulphate composition.

The hydroelectric Salanfe dam was completed in 1952; it is located at an elevation of 1900 masl, about 9 km south-east of the village of Val d'Illiez: the reservoir lake is rather large compared to other Swiss reservoirs (40 millions cubic metres), but the height of the dam is moderate (52 m). The first partial filling of the lake was carried out during the same year and, in September 1953, the maximum level (1917,33 masl) was reached. Rather quickly major water losses through the lake basin were noted by the dam supervisors.

Between 1953 and 1962, the thermal springs were utilized by means of a warm water basin for the local inhabitants. In 1980, the Société des Bains de Val d'Illiez drilled subhorizontal drainage boreholes and built a swimming-pool. Since 1988, the Centre de Recherches Scientifiques Fondamentales et Appliquées de Sion (CRSFA) is carrying out a geothermal and hydrogeological study of the thermal zone of Val d'Illiez, within the framework of a research project on the thermal waters in Wallis, sponsored by the Swiss National Science Foundation (Bianchetti, in prep.) and of the GEOTHERMOVAL programme. In a study on the Triassic aquifers in the alpine environment, Mandia (1991) also investigated the geochemistry of the Val d'Illiez thermal water.

3. Geologic and hydrogeologic setting

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 (Fig. 1). The Helvetic domain, in which the area under study is included, is formed by the following units (Lanterno 1954; Schroeder & Ducloz 1955):

- The crystalline basement of the Aiguilles Rouges Massif: a Hercynian unit mainly composed of paragneiss, biotite or chlorite hornfels and orthogneiss. These rocks outcrop in the Salanfe area and disappear toward the north-west with a dip of 20 to 30° (Fig. 2).
- The Autochthonous Mesozoic: the sedimentary cover of the crystalline basement, of Triassic to Cretaceous age. The Triassic layers are an important unit in this context, because of their petrology (coarse sandstone, quartzite, argilite, dolomitic limestone and gypsiferous cellular dolomite), as well as of their hydrogeologic characteristics. Gypsum dissolution indeed creates preferential pathways for surface water infiltration and deep groundwater circulation. The other layers consist of limestone and marly limestone for the Jurassic, and of limestone, sandstone and marly shale for the Cretaceous series.
- The Parautochthonous: several sedimentary thrust slices, composed of formations ranging from the Triassic to the Tertiary, with a petrology similar to that of the Autochtonous.
- The Morcles nappe: a unit tectonically thrusted over the Parautochthonous. Its formations are not different from those described for the Autochthonous.

The thermal springs are located in the zone of the parautochthonous Tertiary flysch sediments. The subhorizontal drainage boreholes encountered sandstones and argilites with a vertical dip, and locally crushed zones (Geotechnisches Institut 1980). The lake of Salanfe however, is mainly nested on the autochtonous Triassic sediments, and major water losses ($> 1 \, \text{m}^3/\text{s}$) have been noticed along the north to the north-east shoreline (Schneider 1982).

Aerial photographs in the Val d'Illiez region show the presence of a NNW-SSE fracture pattern (Vergain 1991). Moreover, the secondary hydrologic network of the valley is oriented in the same direction. In the Salanfe area, two preferential fracture directions are observed: N-S and NNW-SSE. From a hydrogeological point of view, it can be concluded that regional tectonic structures favor water circulation from the

QUATERNARY

Alluvial deposit

PREALPS

Mesozoic cover nappes

Thermal spring

HELVETIC

Morcles nappe

Autochthonous Tertiary
and Parautochthonous

Parautochthonous thrust slices

Autochthonous Mesozoic
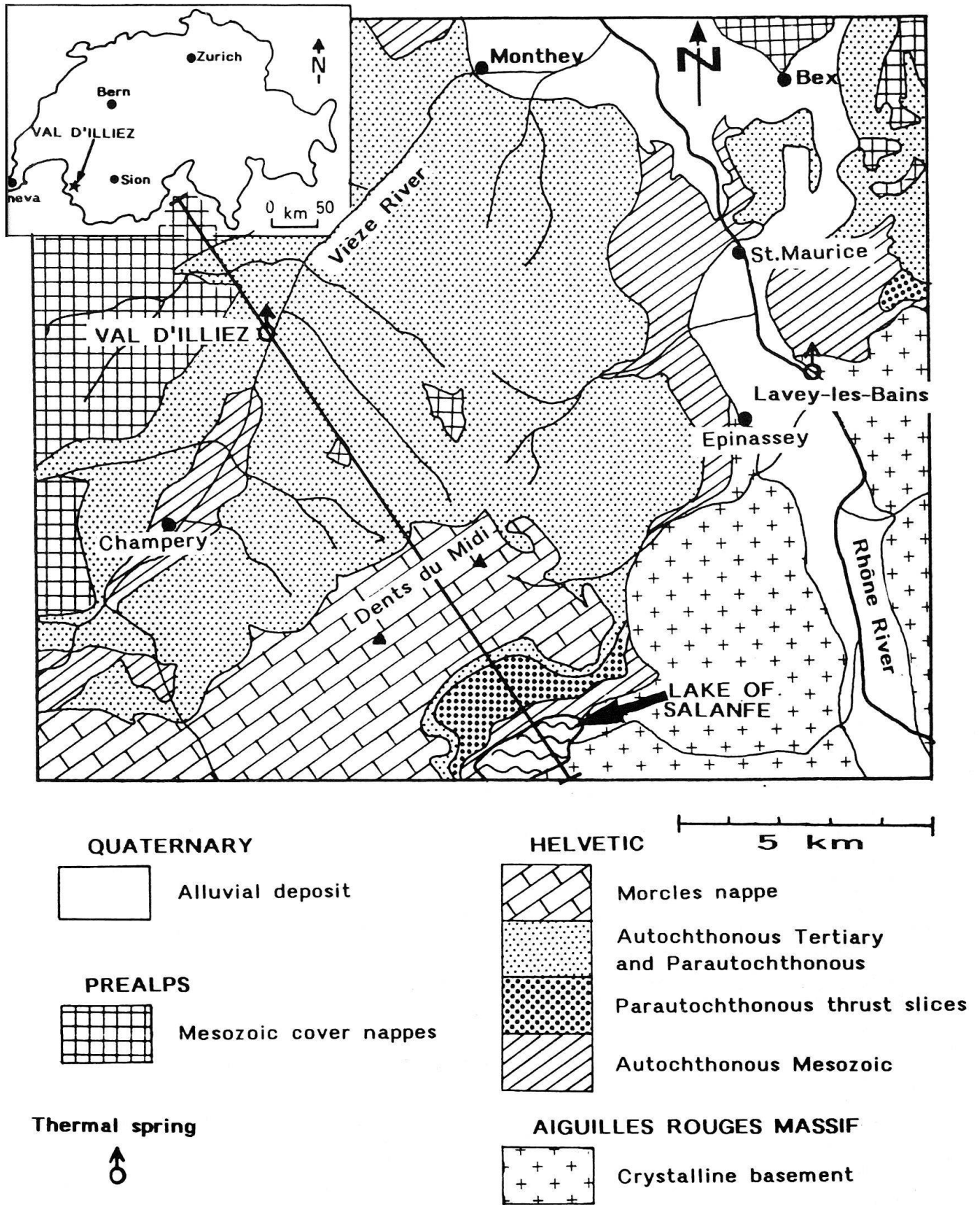
AIGUILLES ROUGES MASSIF

Crystalline basement

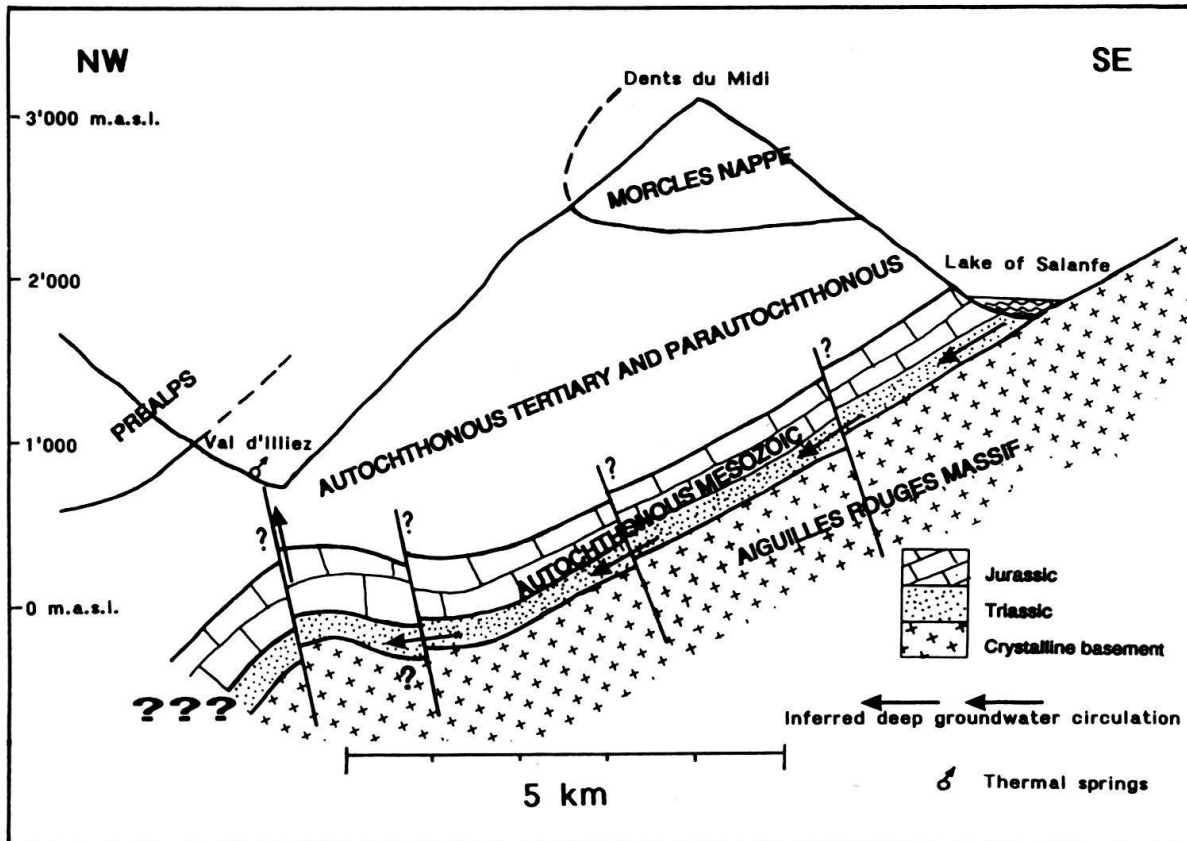Figure 1. Geological sketch map of the Val d'Illiez and Salanfe regions (simplified after Gagnebin et al. 1934).

Figure 2. Schematic tectonic profile of the Val d'Illiez and Salanfe regions (after Geotechnisches Institut 1980) and inferred deep circulation pathways (CRSFA 1990).

south-east toward the north-west and that fluid pathways develop through the Triassic sediments.

4. Main characteristics of the thermal waters

There are five main thermal and subthermal springs (Vergain 1991). The emergence zone is located within a narrow N-S oriented strip, of about 10 metres wide and 300 metres long:

- two thermal springs (A and B), produced from 10 subhorizontal drainage boreholes, feeding the swimming-pool;
- the large Cascade thermal spring (C), produced from 11 subhorizontal drainage boreholes, still unused;
- one small thermal spring (ZR), undeveloped;
- one small subthermal spring (ST), undeveloped, flowing outside the main emergence area.

These springs, with a total yield of 1115–1230 l/min, can be separated in two groups (Table 1):

- group 1: the warmest and most mineralized thermal springs (A, B and ZR), located in the southern part of the emergence zone;

	GROUP 1		GROUP 2	
SPRING	A + B	ZR	C	ST
Temperature (°C)	29.3 – 29.6	27.3 – 28.5	22.6 – 23.1	14.0 – 22.5
pH	6.7 – 7.2	7.1 – 7.4	6.8 – 7.4	6.7 – 7.9
Conductivity (μS/cm) (1)	1650 – 1740	1650 – 1730	1190 – 1430	1090 – 1370
TDS (mg/l) (2)	1850 – 1870	1850 – 1870	1270 – 1400	1100 – 1390
Discharge (l/mn)	400 – 450	∼5 – 10	∼700 – 750	∼10 –20

(1) Electrical conductivity corrected at 20°C   **(2) Total Dissolved Solids**

Table 1. Main physical characteristics of the thermal waters. The two values represent respectively the minimum and maximum observed in 1990.

– group 2: the colder and more dilute thermal springs (C and ST), located in the northern part.

The thermal springs of Val d'Illiez reach 29,5 °C and have a low content of hydrogen sulphide (about 1,5 mg/l). They are mainly calcium and magnesium-sulphate waters (Table 2), these three major ions forming 90% of the total mineralization (1850 mg/l). Such a specific chemical composition, as well as the high content of strontium (8,5 mg/l) and the low concentration of potassium, sodium and chloride, are typical for Triassic waters (Mandia 1991). Moreover, the low contents in alkaline elements allow to preclude that these waters flow within crystalline rocks. Thermodynamic calculations carried out with the computer code PHREEQE (Parkhurst et al. 1980) indicate that the warmest fluid is in chemical equilibrium with gypsum and slightly oversaturated with calcite. It is believed that calcium and sulphate contents derive from the dissolution of gypsum and anhydrite contained in the cellular dolomite of the autochthonous Triassic sediments.

Since the first chemical analysis carried out in 1953 (Schroeder & Ducloz 1955), a decrease of the total mineralization as well as of the calcium and sulphate content has taken place in springs A and B (Table 3). This phenomenon could be explained by a velocity increase of the underground flow inside the deep thermal aquifer, induced by major changes in hydrogeologic conditions (see 5.).

During the observation period, temperature and chemistry of the springs A and B have shown smaller variations than the discharge (Table 1). The waters of group 2, with higher variations of their physical and chemical parameters, lower temperature and total dissolved solids (TDS), undergo an important mixing process between the warm mineralized fluid and a cold dilute component. Since the range of chemical variations with time is moderate, this mixing process is not necessarily bound to the emergence spring zone but can take place in an intermediate aquifer. The regional geology suggests that the thermal fluid rising from the Triassic layers could intercept the cold bicarbonate water of a karstic aquifer in the Malm.

Sample n°	109	110	111	112	315
Name	Main Spring (A+B)	Cascade Spring (C)	Subthermal Spring (ST)	Vièze River	Salanfe Lake
Sampling date	05–Feb–1990	05–Feb–1990	05–Feb–1990	05–Feb–1990	12–Sep–1990
FIELD MEASUREMENTS					
Temperature (°C)	29,5	23,1	14,0	2,3	11,9
Conductivity (µS/cm)	1727	1430	1374	432	134
Discharge (l/mn)	435	~700	20		
pH	7,02	6,8	6,71	8,11	8,35
Eh (mV)	–200	129	178	145	10
CHEMISTRY					
TDS (mg/l)	1872	1405	1389	394	125
CATIONS	mg/l	mg/l	mg/l	mg/l	mg/l
Li	0,15	0,10	0,08	0,007	0,001
Na	21,4	22,3	20,8	3,1	0,1
K	1,5	1,8	1,7	1,2	0,1
Rb	0,004	0,003	0,000	0,001	0,000
Cs	0,003	0,002	0,000	0,000	0,000
Mg	83,0	69,5	59,0	9,3	3,0
Ca	375	285	268	82,7	27,5
Sr	8,5	6,0	5,6	0,8	0,2
Ba	0,012	0,031	0,037	0,018	0,006
Al	0,008	0,082	0,000	0,000	0,000
U	0,000	0,000	0,000	0,000	
Ge	0,001	0,000	0,000	0,000	0,000
Pb	0,000	0,000	0,000	0,000	0,000
As	0,023	0,003	0,000	0,000	0,000
W	0,000	0,000	0,000	0,000	0,000
Mn	0,067	0,017	0,000	0,001	0,000
Fe	0,057	0,080	0,002	0,011	0,000
Zn	0,465	0,230	0,189	0,250	0,001
ANIONS	mg/l	mg/l	mg/l	mg/l	mg/l
F	1,7	1,1	1,1	0,1	0,1
Cl	4,1	5,3	4,7	4,3	1,0
Br	0,090	0,079	0,074	0,006	0,005
I	0,068	0,016	0,012	0,001	0,001
SO4	1240	846	847	99,0	8
HCO3	122	156	171	189,0	84
NON DISSOCIATED	mg/l	mg/l	mg/l	mg/l	mg/l
SiO2	13,8	11,7	9,3	4,3	0,9
B	0,192	0,138	0,149	0,045	0,000
IONIC BALANCE					
Sum cations (meq/l)	26,73	21,11	19,31	5,08	1,63
Sum anions (meq/l)	28,02	20,38	20,63	5,29	1,58
CLASSIFICATION					
Geochemical type	Ca > Mg ; SO4	Ca > Mg ; SO4	Ca > Mg ; SO4	Ca ; HCO3 > SO4	Ca ; HCO3
ISOTOPES					
Tritium (TU)	39.0 ± 3.2	35.6 ± 3.6	31.9 ± 2.4	21.9 ± 2.4	
Deuterium (‰)	–97.1 ± 1.5	–91.8 ± 1.5	–86.9 ± 1.5	–76.2 ± 1.5	–96.7 ± 1.5
Oxygen–18 (‰)	–13.56 ± 0.15	–13.01 ± 0.15	–12.34 ± 0.15	–10.89 ± 0.15	–13.33 ± 0.15

Table 2. Physical, chemical and isotopic parameters of the waters in Val d'Illiez and Salanfe areas.

YEAR	1953	1963	1980	1990
Sulphate (mg/l)	1642	1387	1270	1240
Calcium (mg/l)	708	414	405	375
Mineralization (mg/l)	2456 (1)	2012 (2)	1955 (1)	1872 (2)

(1) Dry residue   (2) Total Dissolved Solids

Table 3. Time evolution of the mineralization of the Main Spring (A + B).

5. Recharge zone and deep circulation of the thermal springs

Hydrothermal circulations in the Alpine environment

The presence of a thermal spring requires either a connection to a deep "reservoir" or, more probably in a fissure-controlled envirnonnement, to a fracture network. A complete hydrothermal circulation system can be subdivided into three zones.

– *Recharge zone*. Rain water and snow melt of the catchment basin infiltrate partially through the fracture network or through dissolution pathways and percolate downwards into the massif.
– *Deep circulation zone*. The groundwaters can reach a depth of several hundreds metres up to several kilometres. This limit is controlled by the decreasing permeability of the rock with depth, or by an impervious geological barrier. The geothermal gradient and the decreasing velocity of the fluid circulation cause the warming up of the groundwater and the increase of geochemical reactions. For alpine topographic and geologic environments, the underground transit time of hydrothermal circulations are usually in the range of ten to thousand years (Dazy et al. 1987; Vuataz 1982).
– *Rise and emergence zone*. Due to the great depth reached by the thermal fluid and the frequent high elevation of the recharge zone, an important hydraulic head exerts a pressure on the lower part of the circuit. Subvertical fractures or tectonic contacts create preferential pathways for the rapid ascent of the hydrothermal fluid towards the surface. Part of this flux generates springs, but an important amount of warm water may remain as flow in shallow aquifers.

Inferred recharge zone of the Val d'Illiez thermal springs

Unlike most thermal springs in the Alps, which are known since Roman times, the warm springs of Val d'Illiez seem to have appeared recently following the exceptional events described previously (see 2.). The question can be raised whether these seismic events were not caused by a drastic modification of the regional groundwater hydrology.

Due to its chemical composition, it is obvious that the deep thermal water percolates through evaporitic rocks, which in this region are solely located in the autochthonous sedimentary cover of the Aiguilles Rouges massif or in a regional prealpine overthrust. The recharge zone of the thermal circulation should be included in the Triassic outcrops extending from Epinassey (Fig. 1) to the south-west (Norbert 1987). Several independent observations and investigations substantiate this hypothesis and indicate that the infiltration zone occurs in the basin of Salanfe area (CRSFA 1990).

– *Coincidence of the events*. The Salanfe dam was built between the years 1948 and 1952. The initial filling of the lake started in 1952 and reached its maximal height (1917 m) in September 1953. These events are contemporaneous with the abnormal seismicity recorded in the Val d'Illiez (see 6.) and with the appearance of the thermal springs (end of September 1953). For the first time the hydraulic head of the lake caused a strong pressure on the dissolution conduits of the Triassic rocks, apparently linked to the seismic activity. These phenomena may have lead to the opening of a subvertical fracture network below Val d'Illiez, allowing the rising of warm water to the surface.

- *Water losses in the Salanfe lake.* Significant water losses are reported from its north to north-east shoreline (about 1 m^3/s for a lake elevation of 1910 masl), and begin as soon as lake level reaches 1890–1895 masl (Schneider 1982). Several sink holes beneath the moraine indicate the presence of dissolution phenomena in the underlying Triassic cellular dolomite. These sink holes form preferential infiltration points for the runoff water and for the lake water.
- *Geologic conditions.* The Triassic layers outcropping in the Salanfe region are dipping about 30° towards the north-west (Fig. 2). Due to their fractured zones and their sink holes, these sediments represent the ideal pathway for infiltration of runoff water. Assuming this layer is homogenous at depth, the Triassic reservoir should be deeper than 1500 metres under the Val d'Illiez. However, the presence of Cretaceous limestones in the Champéry region (Lanterno 1954) requires the existence of an anticline at depth, the culmination of which should correspond to the valley axis. This anticline would raise the Triassic rocks less than 1000 metres below the Val d'Illiez spring zone. This geologic feature is in accordance with the inferred depth of the thermal water resource (see 8.). Finally, the direction of the main fracture systems favors fluid circulation from south-east to north-west (Vergain 1991).
- *Tracer tests.* Three tracer tests were carried out with dyes during the years 1944–46, 1953–54 and in 1954 by N. Oulianoff, but not the slightest content of the tracer injected in the lake was recovered in any of the springs monitored. Schneider (1982) suggested two possibilities. The first one is based on geohydrologic criteria and postulates that the water losses of the lake would not reappear at the surface, but flow through "the alluvial aquifer of the Rhône or of the Arve valley, or through any flow paths to the phreatic water-table under the Plateau, in the region of the Geneva lake". The second possibility is based on the technical conditions of the tracer tests, namely the amount of the dye injected (apparently a maximum of 28 kg), which was too small to be detected by the analytical methods available in the period of the tests, after the strong dilution occuring in the lake. Even though the investigations of the present study indicate that the water infiltrates in the Salanfe basin and percolates through a shorter and shallower pahtway than the one proposed by Schneider (1982), the underground transit time needed to reach the Val d'Illiez area would be too long to be successfully evaluated by means of a tracer test with dyes. Tritium isotope data indeed show that the underground transit time of the deep thermal fluid ranges between 10–15 years (Bianchetti, in prep.).
- *Agreement of the isotopic data.* The comparison of stable isotope data (oxygen-18 and deuterium) between the surface water of the inferred recharge basin and the thermal springs of Val d'Illiez indicates a similar origin in terms of elevation. The average value of oxygen-18 for the Salanfe lake reaches -13.35‰ while thermal springs A + B and C values give respectively -13.56 and -13.01‰.

Tentative correlations have been tried between the lake water level and the springs discharge. The flow of the thermal springs A and B in Val d'Illiez has been monitored on a daily basis since May 1988 with a precision of 5% indicating discharge variations of about 30%. Low discharge values occur in summer, whereas the high values are prevailing in winter, out of phase with the majority of the alpine springs with a nival or glacio-nival regime. The water level of the Salanfe lake has also been monitored daily

since 1952. In accordance with the exploitation programme of the dam, it rises during the spring and summer and starts to decrease around the beginning of the fall. For the observation period, the maximum variation of range between the highest and the lowest water level equals 19 metres.

In several thermal spring studies in Switzerland, the analysis of time-data series of flow discharge and precipitation input in the infiltration zone has shown short- or mid-term flow rate variations due to pressure transmission (Vuataz 1982; Zorn & Jaffé 1983). These hydraulic changes are independent of mixing processes in the discharge zone and much faster than the average underground transit time.

In the case of Val d'Illiez, time series correlations between the spring discharge and the water level of the Salanfe lake have been tested. The two sine curves with a one-year long wavelenght do not present any exceptional events which might disturb the input. However for the period of observation 1988-90, the best-fit of the two curves gives a time-lag of 142 days. This represents a reasonable period of time for the diffusion of pore pressure variations from the lake to the springs regarding the evaporitic environment (see 6).

Presently all the observations and data acquired lead to this hypothetical hydraulic relation between the Salanfe lake and the thermal springs. However, only long range monitoring of the springs discharge as well as the lake level may allow to confirm or to invalidate this hypothesis. Since summer 1991 important underground works have been undertaken in the Salanfe area by the owner of the dam. A gallery is drilled along the north-east shoreline of the lake and a grout curtain is injected in order to decrease the water losses. These works will certainly bring new informations and ideas on the deep groundwater circulation.

6. Induced seismicity

In the village of Val d'Illiez, several detonations and vibrations had been felt since the beginnig of 1953 (Wanner 1954). Seismic activity reached a maximum in September with more than ten events a day causing considerable anxiety by the local population. After the springs first appeared (27th September) the seismic activity decreased rapidly. Unfortunately date and time of the different earthquakes were not noted prior to the 12th of October. After this date ten events were felt in October, four in November, five in December, and three in Januar 1954. In 1953 only four seismographs were in operation in Switzerland. Only two events felt at Val d'Illiez were recorded by these stations (local magnitude $M_L = 3.5$). For the other earthquakes only macroseismic information is available. The Swiss Seismological Service was only informed when the activity was already strongly decreasing, and hence no portable station was installed in the region. Because of the small extension of macroseismic observations, the events are believed to be shallow.

Generally, seismic activity in Wallis is rather high compared with other regions in the country (Pavoni 1977), but the region of Val d'Illiez do not belong to the most active zone in Wallis. During the ten years preceding 1953, no earthquake had been recorded or felt. Hence, there is no doubt that the activity described above is far beyond to what can be considered as a background seismicity.

The association of a significant increase in seismic activity with the impoundment of some reservoirs (artificial dams) has been well documented and investigated by several authors (e.g. Gupta & Rastogi 1976; Simpson & Negmatullaev 1981). Cases are also known from Switzerland (Mayer-Rosa & Deichmann 1979). Simpson et al. (1988) distinguish two types of reservoir-induced seismicity:

(1) A rapid response which lags behind changes in water level by only few hours or days. This activity is usually shallow and occurs in the immediate vicinity of the dam.

(2) A delayed response characterized by earthquakes occurring months or years after reservoir filling. These earthquakes can occur several kilometres away from (or below) the reservoir.

The rapid response is thought to be primarily the result of changes in stress and pore pressure caused by elastic loading, the so-called coupled poro-elastic effect (Rice & Cleary 1976). Diffusion-controlled increases in pore pressure are believed to be the dominant factor in the delayed response.

Unfortunately, in the region of Salanfe the type of response cannot be defined accurately any more. The problem arises from the difficulty to ascribe to the seismicity a certain phase of the lake filling. At first glance it seems that all events took place at the same time: in September 1953 the lake reaches its maximum level, the thermal springs appear and a maximum in seismic activity is reported. However, at times the rate of filling and not the lake level seems to have been responsible for the increased seismicity (Simpson 1976). Hence it is also possible that the rapid filling between May and June 1953 is responsible for the maximum in seismic activity in September 1953. The corresponding time-lag would then be compatible with the diffusion of pore pressure increases from the lake bottom to the nearby Val d'Illiez valley. However, one can only speculate as the earthquake location is not known precisely: according to the observations made by the local population, the epicentre is near Val d'Illiez, while the instrumental determination of this epicentre (which, calculated by four distant stations, is not very accurate) is closer to the dam (Wanner 1954). Nevertheless, the causal relationship between Salanfe impoundment and anomalous seismic activity seems plausible.

Clearly, the relatively small pore pressure increases discussed can only trigger earthquakes in a crust already tectonically stressed to a point close to failure. That this may have indeed been the case in Val d'Illiez is indicated by the absence of recorded events in that seismically active region in the years preceding the impoundment. According to Scholz (1990), the different cases of reservoir-induced seismicity indicate that often the shallow part of the earth crust is stressed near to its failure strength.

7. Geothermal aspects

The fluid temperature existing at depth and therefore the geothermal potential of the Val d'Illiez resource have been calculated by several methods. Time and space variations of the fluid chemistry indicate that the thermal waters are mixed by cold and dilute water during their ascent towards the surface. A mixing model established after repeated measurements of parameters such as dissolved oxygen, electrical conductivity and temperature at the emergence indicates that the dilution rate of springs A and B can reach

20 % and that the temperature of the fluid at depth before mixing may not exceed 35 °C (Vergain 1991).

Cations and silica geothermometers have been applied in order to quantify a possible conductive cooling of the geothermal fluid before mixing at shallow depth, but no indication of a temperature higher than 35 °C at depth could be obtained. This relatively low calculated temperature at depth can be explained in different ways. First of all, the geothermal fluid is probably never in contact with crystalline rocks and consequently cannot dissolve enough silicate minerals on which the main geothermometers are based. Furthermore, a relatively short underground transit time and a rather low reservoir temperature reduce significantly the velocity and the intensity of all the water-rock interaction processes. Unlike several other hydrothermal circulations in the alpine environment, which can reach temperatures at depth up to 100 °C (Vuataz 1982), the temperature of this system is rather low. However, the discharge of the thermal springs is quite important: 450 l/min for the warmest springs (A + B) and a total of 1200 l/min for all the emergences. This high yield, on a steady state basis, should prevent major conductive cooling, and therefore it is possible to estimate the geothermal potential of the area using the emergence temperature (T = 30 °C) and total rate of the springs (Q = 1200 l/min). Considering a cooling of the fluid by exploitation arbitrarily set at the temperature of 10 °C, the gross geothermal potential $[P(MW_t)]$ is calculated as follows, $P(MW_t) = Q(m^3/h)*[T(°C) - 10 °C]/861$, and amounts to 1,7 MW_t.

8. Conclusions

The results of the hydrogeologic and isotopic investigations of Val d'Illiez thermal springs indicate that the recharge zone is most likely located in the Salanfe basin. After infiltration, the groundwater percolates essentially within sedimentary rocks, especially the autochthonous Triassic evaporites of the cover of the Aiguilles Rouges massif. Sulphate minerals are dissolved, giving the groundwater typical Ca-SO_4 chemical characteristics. At depth, the fluid temperature does not seem to exceed 35 °C, and if assuming a regional geothermal gradient of 30 °C/km, a depth of about 1 km could be reached below Val d'Illiez by the hydrothermal circuit.

Scarce seismic data collected between 1953 and 1954 indicate that the initial filling of the artificial lake of Salanfe could have induced an intense seismic activity as a response to the change of stress and pore pressure. The hydraulic relation between the lake water and that of the thermal springs may never be proved beyond doubt, due to the lack of hydrogeological and seismic observations during the crucial period of the first appearance of the springs, as well as the initial filling of the lake. Nevertheless, the convergence of several independent observations points to the probability of this hypothesis. Regular measurements on a long-term basis of the springs discharge and of the lake level, as well as the works in progress of tightening the water losses, may bring new elements to confirm or to invalidate this hypothesis. Drastic events, such as the complete drain of the lake, as well as earthquakes will also be significant elements for this purpose.

From a geothermal point of view, the heat potential of 1.7 MW_t currently available at the emergence zone of the thermal springs should be noted. It is believed that the known discharge of thermal fluid may be only a fraction of the whole accessible warm water resource at Val d'Illiez.

Acknowledgements

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