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Geochemical and geothermal study of springs in the Ossola-Simplon Region

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Key words: Alps, fast uplift, geochemistry, thermal springs, geothermometry

ABSTRACT

Geological, hydrogeological and geochemical surveys were carried out in the Piedilago area (Ossola-Simplon region) in order to investigate the geothermal resources present in this area. Following these surface exploration efforts an exploratory geothermal well of 248 m was drilled in 1991. It discharges a thermal water with temperatures up to 43°C and calcium (sodium) sulphate composition with a TDS close to 1350 mg/l. Chemical geothermometers suggest a reservoir temperature close to 45°C indicating that the well virtually produces the pure uncooled thermal water. The Piedilago example is here considered as the departure point to establish both general criteria for further geothermal investigations in young mountains chains and taking into consideration all the available data on geology and fluid geochemistry of thermal systems in the Ossola-Simplon region, to constrain a geothermal model for the Lower Pennine Zone.

RIASSUNTO

Studi di tipo geologico, idrogeologico e geochimico sono stati eseguiti per investigare le risorse geotermiche della regione dell'Ossola-Sempione e in particolare dell'area di Piedilago. Agli studi di superficie è seguita la perforazione di un pozzo esplorativo profondo 248 m che produce un'acqua termale con temperatura di circa 43°C, composizione solfato calcico (sodico) e TDS prossimo a 1350 mg/l. Stime geotermometriche su tale acqua forniscono temperature di circa 45°C indicando che il pozzo intercetta l'acquifero termale. Il successo esplorativo di Piedilago viene considerato come il punto di partenza per stabilire dei criteri generali per la prospezione geotermica in catene mountuose recenti. Inoltre tutti i dati di tipo geologico e geochimico disponibili sui sistemi termali della regione ossolana vengono presi in considerazione per ipotizzare un modello geotermico per la zona del Pennidico Inferiore.

ZUSAMMENFASSUNG

Das Gebiet von Piedilago in der Ossola-Simplon Region wurde im Detail mittels geologischer, hydrogeologischer und hydrogeochemischer Methoden untersucht, um das geothermische Potential der Region festzustellen. In der Folge dieser Detailuntersuchungen an der Oberfläche, wurde 1991 ein Bohrloch auf 248 m abgeteuft. Diese Bohrung produziert seither Wasser mit einer Temperatur von 43°C und einer Calcium (Natrium) Sulfat Zusammensetzung bei einer TDS von nahezu 1350 mg/l. Chemische Geothermometer lassen auf Bildungs-Temperaturen nahe bei 45°C schliessen; es kann daher angenommen werden, dass die Bohrung Wasser des thermischen Endgliedes liefert. Das Piedilago Beispiel wird hier sowohl als Ausgangspunkt für die Erarbeitung genereller Kriterien dargestellt, die es erlauben das Modell allgemein auf junge Gebirge anzuwenden; als auch, unter Einbezug sämtlicher geologischer und fluidgeochemischer Daten aus der Ossola-Simplon Region, ein geothermisches Modell für das tiefere Penninikum zu entwickeln.

1. Introduction

Low enthalpy geothermal resources in the central-western Alps are widespread and are represented both by springs with relatively low flowrates and temperatures of 20–70°C (Vuataz 1982; Bortolami et al. 1984) and by inflows in deep alpine tunnels (Schardt 1906, 1914). Chemical and isotopic compositions of these thermal fluids indicate that they are meteoric waters which descend slowly, heat at depth and locally rise up quickly to the surface, preserving part of their chemical and physical characteristics.

The circulation of thermal waters in a mountainous context like the alpine chain is related to the presence of highly permeable zones which allow their rapid upflow, where morphological and structural conditions are adequate. In turn, permeability is mainly governed by dissolution phenomena in

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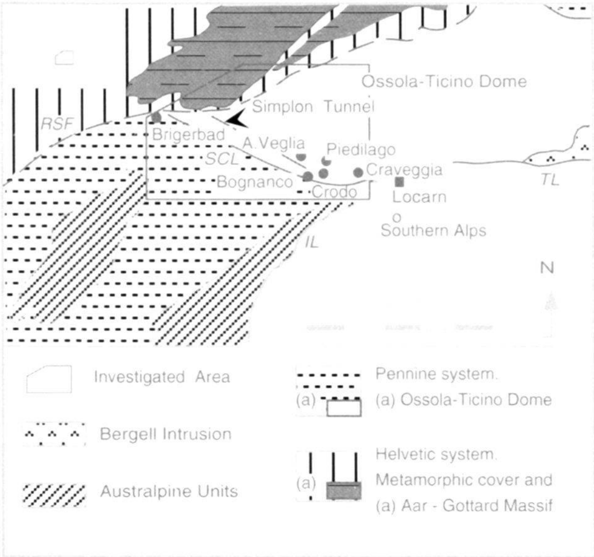

Fig. 1. Geological sketch map of the Ossola Valley, also showing the location of sampled springs. RSF = *Rhone-Simplon Fault*; SCL = *Simplon-Centovalli* Fault; IL = *Insubric Line*; TL: *Tonale Line*.

evaporite-carbonate rocks and by fracturation (Lopez & Smith 1995). Therefore thermal discharges in the central-western Alps are controlled by regional tectonic-stratigraphic setting and tectonic structures (Perello 1997) and secondarily by hydraulics. On the one hand, the regional tectonic-metamorphic setting determinates the geometry of the evaporite-carbonate layers along which meteoric waters can circulate and reach relevant depths. On the other hand the main shear zones control water circulation because they create fracture belts of high vertical permeability.

Moreover the differential uplift of different blocks of the mountain chain along these shear zones induces anomalously high geothermal gradients in the fast uprising blocks (Hunziker et al. 1992).

Geochemical and geothermometric investigations on most alpine thermal springs (e.g. Vuataz 1982; Michard et al. 1989) show that equilibrium temperatures at depth are higher than discharge temperatures due to heat loss through either conduction or mixing with shallow, cold groundwaters during upflow. Therefore detection and tapping of these thermal waters at reservoir conditions can lead to their exploitation for direct uses.

The aim of the present work is to show an example of geological and geochemical prospecting in the Ossola Valley, north-western Italy (Fig. 1) for geothermal purposes, to establish general criteria for future geothermal investigations in young mountain belts.

2. The Geothermal Anomaly of the Ossola Region

In the investigated area, mamed Ossola-Ticino Dome, are exposed the tectonic units which are usually considered as the deepest ones of the Alps. This region was characterised, during Oligocene, by higher metamorphic conditions compared to the adjacent Austroalpine, Middle-Upper Pennine and Helvetic units (Steck & Hunziker 1994). Structurally, it is defined by the concentric pattern of foliations (Merle et al. 1989) and of metamorphic isogrades (Niggli & Niggli 1965; Trommsdorff 1966), which indicate higher metamorphic temperatures (amphibolite facies) in the central part of the dome. Furthermore, concentric patterns are also shown by cooling ages measured on monazite, amphiboles, micas, zircons and apatites (Fig. 2), which are younger in the internal sector (Hunziker et al. 1992). These features have been related to the faster uplift of this region with respect to the adjacent units starting from the Oligocene (monazite U-Pb cooling age) up to recent times (apatite fission tracks) (Fig. 3). The uplift of the Ossola-Ticino dome is related to kinematics of the Rhone-Simplon fault, the Insubric Line and the Engadina Line (Mancktelow 1985; Steck & Hunziker 1994; Merle 1989) that border it. Movements of these shear zones, from Miocene to recent times, caused transtensive-transpressive stress fields, determining the exhumation of this area, with a metamorphic core-complex mechanism (Bradbury & Nolen-Hoeksema 1985). Apatite fission tracks ages attest that the Ossola-Ticino Dome experienced further cooling and rapid uplift, which brought rather hot rocks close to the surface. Underground rock temperatures measured during the excavation of the Simplon railway tunnel (Schardt 1906) indicate that the regional geothermal gradient in the Ossola area is approximately 35°C/km (Clark & Niblett 1956), which is a relatively high gradient with respect to other alpine regions (22°C/km for the Gotthard region; 26°C/km for the Helvetic domain).

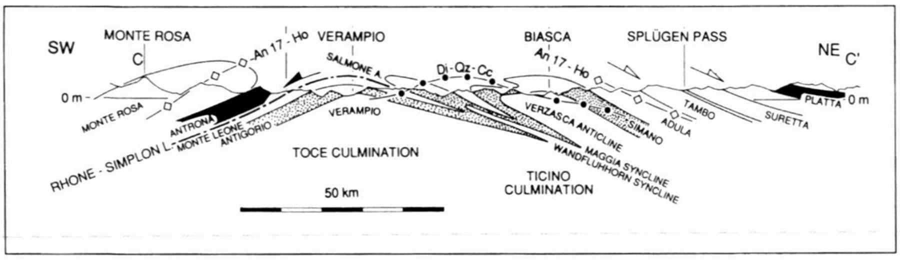

Fig. 2. Geological section of the Ossola-Ticino Dome (after Steck & Hunziker 1994).

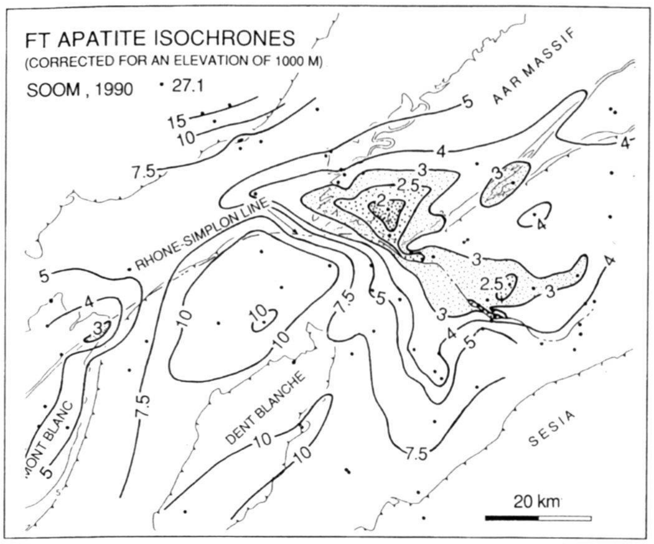

Fig. 3. Apatite fission track isochrons, corrected for an elevation of 1000 m above the sea level (after Soom 1990).

3. Geological and hydrogeological setting of the investigated area

The Ossola-Ticino Dome consists of a series of pre-Triassic basement sheets which are separated by Mesozoic cover sequences (Fig. 2). This geometrical setting pre-dates the onset of movements along the shear zones bordering the dome and is usually referred to the Meso-alpine deformative phase. The core of the dome structure is composed by an orthogneiss (Verampio gneiss) intruded in a pre-Mesozoic meta-sedimentary succession of schists overlaid by a Mesozoic sequence (Baceno syncline) and a crystalline basement (Antigorio gneiss nappe). The upper units are formed by a paragneiss sequence (Lebendun nappe) and by a composite basement-cover nappe (Monte Leone nappe). The Antigorio and Monte Leone basement rocks represent the core of two nappe-folds of kilometric scale with vergence toward NNW. The folding event that created this tectonic setting is related to the development of a pervasive regional schistosity. The nappe-fold event, probably Meso-alpine in age, was followed by late alpine folds related to the transpression-transtension along the shear zones bordering the dome. At present the schistosities plunge toward SE in the south and toward NW in the northern sector. Furthermore the schistosity is dragged toward SW near the Simplon shear zone and is steepened by the Insubric line (Milnes 1974; Huber et al. 1980; Mancktelow 1985).

The Piedilago area, which was studied in detail for geothermal purposes (see below), is located in the Antigorio Valley, where the lower units of the Ossola nappes (Baceno syncline and Antigorio nappe) crop out (Fig. 4). The regional schistosity in this area plunges toward N and NNW with a low angle, like the main contacts between the different units. The geometrical setting of this area is given by the presence of a Mesozoic meta-sedimentary layer, formed by dolomitic marbles, lying between the Baceno schists and the Antigorio gneiss (Figs. 4 and 5). Locally this simple geometrical setting is complicated by hectometric-scale secondary folds.

From the hydrogeological point of view, the Baceno schists have low permeability since the high mica contents attribute them a plastic behaviour. The Mesozoic sequence consists of carbonate-evaporite rocks, which are characterised by high

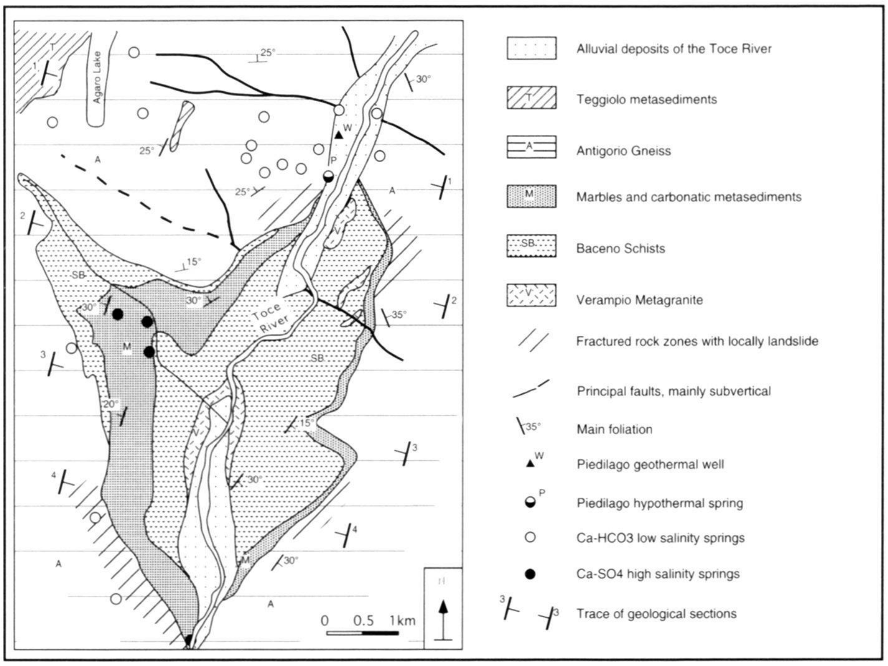

Fig. 4. Geological map of the Piedilago area.

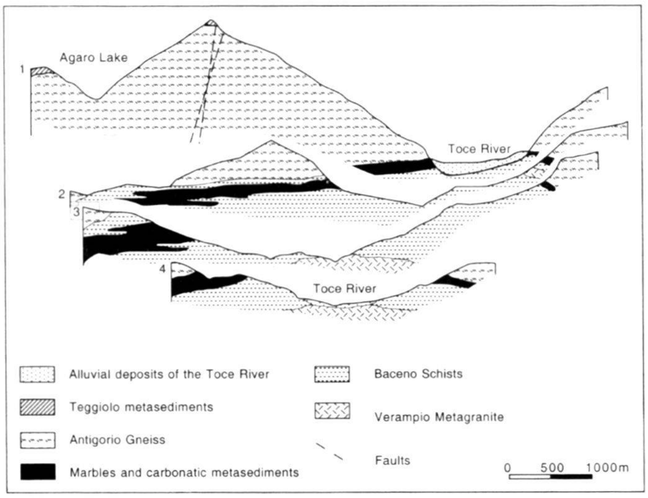

Fig. 5. Geological sections showing the geometrical setting of the Piedilago area.

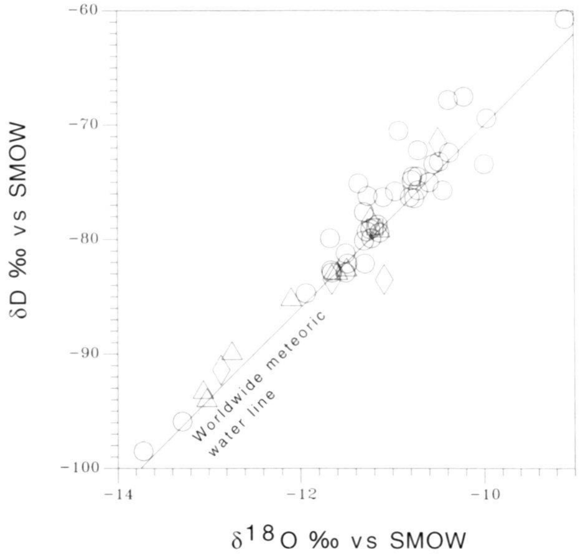

Fig. 6. δD vs $\delta^{18}O$ plot. Symbols are as follows: circles= bicarbonate waters; diamonds = calcium sulfate-bicarbonate type of intermediate TDS; triangles = calcium sulfate type of high TDS; squares= sodium-sulfate and calcium sodium-sulfate waters. The meteoric water line $\delta D = 8\delta^{18}O + 10$ is plotted as reference.

permeability related to karstic phenomena. The Antigorio gneiss are strongly fractured near the contact with the underlying Mesozoic rocks in a ~50 m-thick zone. This narrow zone is related to gravitational collapses induced by volume losses inside the underlying marble layer, which are caused by dissolution processes. Increased permeability characterizes this zone of the Antigorio nappe with respect to the normal features of this orthogneiss.

4. Fluid geochemistry

4.1. Field work and laboratory analyses

A total of 63 springs were sampled as part of two geochemical surveys, which were recently carried out in the Ossola valley. The aim of the first one, performed in 1988, was to evaluate the geothermal potential of the area (Geotermica Italiana 1989; Hunziker et al. 1990), whereas the second one was executed in 1992 in the framework of the project for a new railway tunnel through the Alps (Geotermica Italiana 1992).

Raw, filtered (through a 0.45 μm membrane) and filtered-acidified (with HCl 1:1) aliquots were collected from thermal and cold springs and stored in polyethylene bottles. Outlet temperature, pH and alkalinity were measured in the field. Water samples were analysed in the laboratory as follows: (1) Na, K, Li, Ca, Mg: atomic absorption spectrophotometry and/or atomic emission spectrophotometry; (2) Cl, SO_4, NO_3: ion chromatography; (3) B, SiO_2: visible spectrophotometry; (4) F, NH_4: ion-selective electrode. The $D/^1H$ and $^{18}O/^{16}O$ isotope ratios were also measured in most water samples by using the Finnigan MAT 251 mass spectrometer of the Institut de Minéralogie et Pétrographie of Lausanne University. Analytical results are reported in Table 1.

4.2. The δD and δ18O values

Inspection of the δD vs $\delta^{18}O$ plot (Fig. 6) for the waters of the Ossola Valley shows that sampled springs fit the following regression line:

$$\delta D = 8.00\,\delta^{18}O + 11.02$$

which is not significantly different from the worldwide meteoric water line with the equation :

$$\delta D = 8\delta^{18}O + 10$$

Not surprisingly, natural waters of the Ossola Valley are therefore meteoric in origin. No enrichment in δD and $\delta^{18}O$ values is evident, a fact excluding the occurrence of both water-rock oxygen isotope exchanges and surface evaporation processes.

Admitting that the spread of δD and $\delta^{18}O$ values is mostly linked to differences in the average elevation of infiltration zones, h_i, it is possible to derive a local $\delta^{18}O$ -elevation relationship. We assume that the thermal and cold waters sampled in the Simplon tunnel (that have δD and $\delta^{18}O$ values of –89.7 to –93.8 ‰ and –12.74 to –13.06 ‰, respectively) infiltrate where the carbonate-evaporite rocks outcrop above the tunnel. If so, h_i's are close to 2300 m asl. Then, in the $\delta^{18}O$ vs elevation plot (Fig. 7), we may draw a line passing through the samples of the Simplon tunnel and the springs of highest elevations, obtaining the following equation:

$$h_i = -840.09 - 245.47\,\delta^{18}O$$

which can be used to evaluate the infiltration altitude of local groundwaters of meteoric origin.

Table 1. Results of selected chemical and isotopic analyses of waters. Concentrations are in mg/l, δD and δ18O values are in ‰ vs SMOW.

* = distance from the northern portal.

Sampling site	Code	Elevation m asl	T °C	pH	Li	Na	K	Mg	Ca	Alk meq/L	SO_4	Cl	F	NO_3	SIO_2	δD	$\delta^{18}O$
Fontana di Varzo	1	570	9.7	7.86	–	1.9	4.7	7.3	82.4	1.95	129.3	1.5	0.17	5.05	5.2	–78.5	–11.24
Cangelli	2	970	9.1	7.82	–	1.6	3.5	2.1	32.5	1.42	24.0	0.5	–	0.55	6.1	–76.2	–11.27
San Bernardo Cairasca	3	1165	9.4	7.67	–	2.9	3.3	2.5	34.9	1.28	39.2	1.3	–	1.08	5.7	–82.9	–11.66
Trasquera	4	1160	4.9	7.55	–	1.2	2.2	0.6	6.5	0.29	7.3	1.3	–	2.26	3.5	–73.2	–10.49
Torre Bugliaga	5	1390	8.1	7.84	–	1.2	1.6	0.5	9.9	0.56	4.4	0.5	–	1.41	3.9	–82.1	–11.30
Mugnè	6	1450	6.8	7.75	–	1.1	1.2	0.4	10.0	0.49	4.2	0.4	–	0.81	4.4	–79.3	–11.28
km 3.7 Domo–Bognanco	7	421	10.7	7.28	–	3.1	1.0	2.7	24.3	0.94	27.5	0.6	–	0.81	5.7	–67.8	–10.39
Foibello	8	680	9.3	6.97	–	2.2	2.4	6.6	14.1	1.00	17.6	1.1	–	1.06	11.4	–69.4	–9.97
Alpe Manzano	9	1360	4.9	7.22	–	1.4	0.8	0.9	4.5	0.22	5.4	0.2	–	3.65	5.5	–74.5	–10.73
Graniga	10	1150	9.0	7.74	–	2.2	1.2	1.5	13.8	0.66	11.9	0.5	0.16	2.16	6.5	–75.7	–10.45
San Bernardo Bognanco	11	1725	4.3	7.86	–	0.7	0.4	6.1	9.4	0.73	12.8	0.1	–	1.66	2.5	–74.5	–10.78
Pragio	12	1670	4.2	7.64	–	0.6	0.3	1.7	5.4	0.25	10.4	0.2	–	1.02	5.0	–76.3	–11.10
Iselle	13	710	7.6	7.74	–	0.8	1.2	2.6	15.4	0.89	7.4	0.2	–	3.76	3.1	–72.2	–10.72
Iselle FFSS	14	670	12.3	7.74	–	2.0	2.8	1.1	13.9	0.71	8.9	1.5	–	1.89	5.2	–60.7	–9.10
Iselle	15	680	14.2	7.40	–	1.1	1.2	1.1	15.1	0.75	9.0	0.3	–	2.52	3.5	–75.0	–10.60
Molino di Varzo	16	500	8.6	7.68	–	2.2	2.3	4.7	33.3	1.03	51.0	1.8	0.19	2.49	5.2	–71.5	–10.50
Crevola d'Ossola	17	430	16.0	7.22	–	5.5	4.0	6.6	44.9	2.19	18.6	5.2	0.13	11.80	8.7	–67.5	–10.22
Burra	18	560	9.0	8.01	–	1.3	1.3	3.4	19.1	1.05	9.8	0.3	–	3.42	4.8	–	–10.44
Preglia	19	530	11.8	6.75	–	2.9	1.1	1.1	10.6	0.52	12.7	0.4	0.18	1.09	9.2	–73.4	–10.00
Oira	20	510	10.5	7.14	–	1.8	1.4	1.2	19.1	0.73	16.6	0.7	–	5.18	5.1	–70.5	–10.93
Alpiano Superiore	21	675	10.0	7.07	–	2.6	1.3	1.0	10.1	0.53	10.1	0.5	0.13	1.40	7.9	–72.4	–10.38
Mozzio	22	835	9.0	6.66	–	2.3	2.3	1.5	13.0	0.74	7.9	0.5	–	1.93	6.5	–75.8	–10.97
Viceno	23	860	7.3	7.27	–	1.5	3.0	1.0	10.3	0.54	9.3	0.6	–	1.87	6.5	–75.7	–10.72
Foppiano	24	1260	6.5	7.90	–	0.6	1.9	0.9	26.6	1.23	6.9	0.2	–	3.04	2.8	–79.9	–11.68
Oratorio Salera	25	1180	6.8	6.46	–	0.9	1.0	0.6	4.7	0.30	2.9	0.3	–	0.74	5.6	–77.6	–11.31
Alpe Monscera	26	2050	4.9	7.10	–	1.2	0.3	5.1	13.1	0.82	16.1	0.1	–	2.98	2.6	–75.1	–11.37
Alpe Monscera	27	1965	5.1	6.55	–	0.7	0.6	0.3	4.1	0.19	4.1	0.1	–	1.81	2.1	–78.7	–11.16
Arza	28	1830	6.9	5.80	–	0.7	0.4	0.2	2.4	0.09	4.3	–	–	0.99	2.6	–83.5	–11.09
Alpe Lusentino	29	1080	10.8	5.93	–	2.0	1.5	2.5	3.2	0.36	1.6	0.5	–	3.93	11.9	–79.1	–11.24
Bognanco Ausonia	AU	*600*	*10.5*	*5.60*	*0.21*	*48.3*	*7.9*	*109.0*	*91.2*	*13.20*	*128.0*	*15.6*	*0.27*	*0.88*	*40.9*	*–73.4*	*–10.55*
Bognanco S. Lorenzo	SL	600	12.3	6.12	0.60	153.0	13.7	339.0	239.0	37.20	362.0	31.6	0.11	–	65.5	–74.8	–10.79
Bognanco Gaudenziana	32	–	9.5	7.82	–	1.6	1.6	2.0	25.2	1.19	12.3	0.3	–	2.24	9.0	–76.3	–10.81
Alpe Veglia	AV	1820	7.2	5.55	0.15	24.6	3.8	25.5	195.0	8.27	228.0	0.8	0.27	–	27.3	–95.9	–13.29
Alpe Veglia	34	1820	7.2	5.65	–	0.3	0.9	0.6	10.4	0.51	6.3	–	–	0.93	1.6	–98.5	–13.72
Alpe Veglia road	35	1590	5.9	7.38	–	0.6	2.3	2.8	25.2	1.18	12.2	0.1	–	6.30	4.8	–80.1	–11.31
Crodo Lisiel	LI	400	9.7	7.73	–	5.4	3.1	7.2	57.9	1.68	96.4	1.6	0.11	3.45	7.3	–83.5	–11.66
Crodo Valle d'oro	VO	405	11.8	7.57	–	2.0	5.7	49.7	510.0	1.24	1384.0	0.4	0.29	–	7.2	–85.0	–12.10
S. Rocco di Premia	38	775	12.0	7.33	–	1.1	1.7	1.1	16.8	0.77	7.5	0.4	–	–	5.4	–84.7	–11.94
Pianez	39	1150	8.3	7.27	–	1.3	1.5	0.6	9.7	0.47	6.0	0.5	–	1.70	5.7	–76.4	–10.76
Pianez	40	1150	8.2	7.21	–	1.3	1.5	0.6	9.6	0.47	5.8	0.4	0.80	1.71	5.3	–79.4	–11.14
D'Antin	41	790	9.4	7.09	–	1.1	0.9	1.3	7.0	0.35	6.8	0.4	–	2.45	1.1	–81.2	–11.51
Valle Devero	42	980	9.1	7.95	–	1.1	2.4	3.6	46.7	1.52	58.0	0.6	–	2.43	3.9	–82.1	–11.49
Piedilago	PS	740	16.1	7.25	0.02	21.3	3.6	9.5	67.3	0.76	206.0	1.5	0.33	2.11	10.3	–78.9	–11.19
Baceno S	BS	620	11.3	7.41	0.05	2.1	5.1	41.4	484.0	1.19	1265.0	0.3	0.18	–	3.1	–79.0	–11.14
Baceno N	BN	635	12.4	7.85	0.04	2.5	4.3	26.3	313.0	1.25	828.0	0.4	0.14	0.79	5.7	–82.7	–11.60
Uresso	UR	750	9.7	7.65	0.03	2.5	3.9	22.5	264.0	1.16	656.0	0.6	0.16	0.63	5.1	–82.4	–11.50
Valle Devero	47	950	6.6	7.70	–	0.9	1.2	1.2	19.0	0.77	15.2	0.4	–	1.70	5.3	–79.9	–11.23
Valle Devero	48	990	8.1	7.90	–	0.9	2.6	3.7	47.5	1.52	56.5	0.3	–	1.88	5.3	–82.9	–11.51
Spotigene	49	1750	5.0	6.98	–	0.4	0.7	0.2	3.1	0.14	2.7	–	–	0.86	4.0	–82.7	–11.67
Almaio	50	1305	7.3	7.48	–	3.3	2.1	1.5	10.1	0.63	8.0	1.0	–	0.80	11.3	–75.0	–10.60
Simplon T. 9620 m*	G1	700	35.0	7.49	–	2.3	3.2	25.9	318.0	1.29	815.0	0.1	0.23	–	6.4	–93.8	–13.02
Simplon T. 10365 m*	G2	700	37.6	7.39	0.02	9.1	3.0	40.9	488.0	1.32	1272.0	0.3	0.27	–	17.3	–	–
Simplon T. 10362 m*	G3	700	40.8	7.47	0.02	9.2	3.0	45.7	498.0	1.34	1285.0	0.3	0.26	–	13.2	–89.7	–12.74
Simplon T. 10162 m*	G4	700	20.7	7.64	–	1.7	3.0	26.1	345.0	1.27	830.0	0.1	0.19	–	5.1	–	–
Simplon T. 9827 m*	G5	700	31.9	7.59	–	1.9	3.0	24.6	345.0	1.27	844.0	–	0.20	–	5.6	–93.1	–13.06
Simplon T. 15335 m*	G6	650	7.2	7.57	–	1.5	3.4	9.1	175.0	1.35	394.5	0.2	–	–	5.3	–91.4	–12.86
Piedilago	PW1	–	42.7	7.14	0.02	87.2	7.5	39.6	244.0	0.70	890.0	5.7	1.00	–	24.0	–	–
Piedilago	PW2	–	42.7	7.05	0.02	86.3	7.0	39.6	242.0	0.70	880.0	5.7	1.00	–	25.0	–	–
Piedilago	PW3	–	42.7	7.54	0.02	89.0	6.8	40.6	252.0	0.72	895.0	5.7	1.04	–	29.0	–	–
Bagni di Craveggia	BC	1000	29.0	9.25	–	62.9	1.5	–	19.0	0.42	148.0	0.8	2.89	–	43.8	–	–
Pian di Sale	61	945	9.0	5.54	–	1.4	0.5	1.0	8.2	0.39	5.3	1.6	0.03	2.58	7.5	–	–
Coimo	62	710	14.3	6.46	–	2.8	2.4	2.5	9.9	0.49	7.1	2.9	0.06	8.28	18.6	–	–
Gagnone	63	800	11.5	6.12	–	2.1	1.3	1.9	5.8	0.40	5.3	0.6	0.17	2.70	10.6	–	–

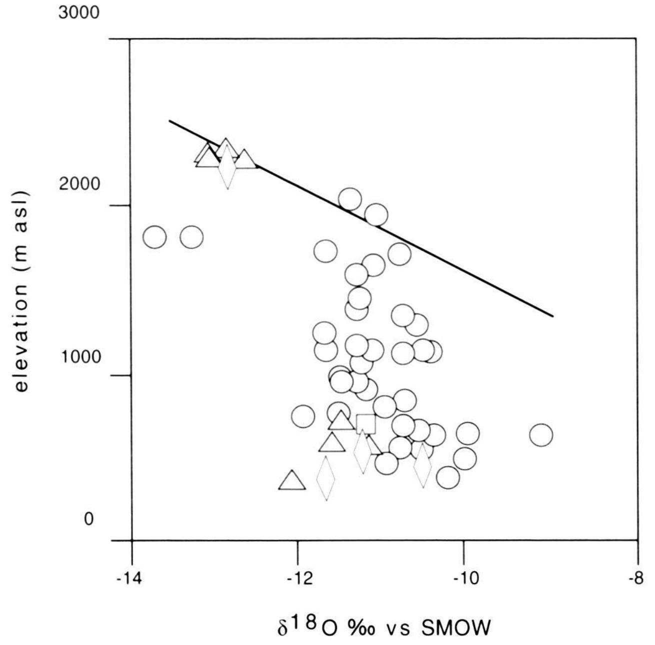

Fig. 7. Plot of $\delta^{18}O$ vs discharge elevation at sampling points. The presumed elevations of the infiltration zones are considered for the water inflows in the Simplon tunnel. Symbols as in Fig. 6.

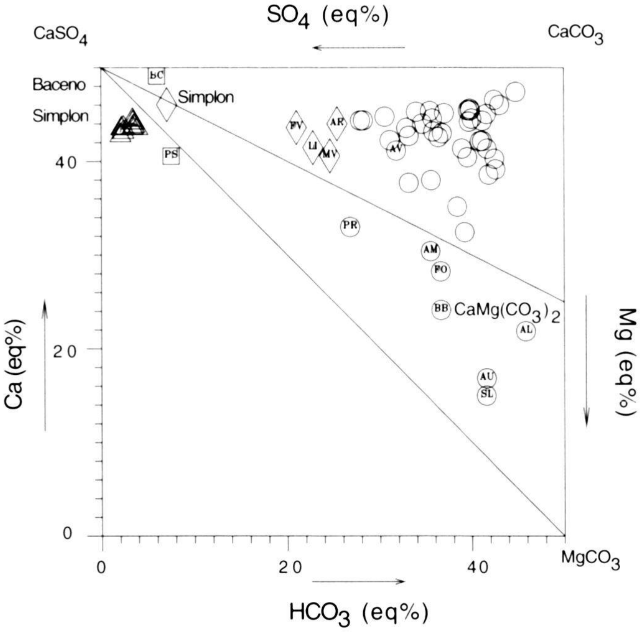

Fig. 8. Plot of 50 $C_{Ca}/(C_{Ca} + C_{Mg})$ ratio versus 50 $C_{HCO3}/(C_{HCO3} + C_{SO4})$ ratio (C_i in eq/l). Symbols as in Fig. 6.

4.3. Water chemistry and discussion of hydrochemical types

The springs of Bagni di Craveggia and Piedilago excluded, which have Na-SO_4 and Ca-(Na)-SO_4 compositions, respectively, the main ionic solutes of all the other sampled waters are Ca, Mg, HCO_3 and SO_4. As these dissolved constituents generally account for more than 90% of total ionic salinity, only their meq/l-percentages have been plotted in Fig. 8, which is a modified Langelier-Ludwig diagram. Most springs plot into the calcite-dolomite-anhydrite triangular field suggesting that their composition is largely affected by dissolution of these three minerals. Some springs plot outside this field, due to either precipitation of calcite, a phenomenon that shifts water composition away from the calcite vertex, or leaching of ophiolites, a process that moves water composition towards the magnesite vertex. Inspection of Fig. 8 allows to characterise the hydrogeochemical types occurring in the Ossola valley. The springs of Craveggia and Piedilago will be considered afterwards.

a) The *calcium bicarbonate type of low TDS* comprises most cold springs, whose temperatures range from 4 to 12 °C and whose TDS is in the interval 20–240 mg/l. These waters are related to shallow, comparatively quick hydrogeological circuits hosted into gneissic rocks.

b) The *magnesium bicarbonate type of low TDS.* Only few springs (labelled AL, BB, FO and AM) are attributed to this family. They are similar to the previous type in TDS (50–120 mg/l) and temperature (4–11°C). In these waters Mg prevails over Ca likely because of leaching of ophiolites, that actually crop out nearby these springs. These waters are therefore linked to shallow, relatively quick circuits mainly developed into these lithotypes.

c) The *calcium bicarbonate type of high TDS* and the *magnesium bicarbonate type of high TDS.* Only the CO_2–rich water spring of Alpe Veglia (AV, temperature 7.2 °C, TDS 1010 mg/l) is attributable to the former, while the latter comprehends the CO_2–rich springs of San Lorenzo (SL, temperature 12.3 °C,TDS 3470 mg/l) and Ausonia (AU, temperature 10.5 °C, TDS 1250 mg/l), both at Bognanco. Compositional differences reflect the different lithotypes interacting with these waters, e.g. gneisses are responsible of the Ca-character of the Alpe Veglia water, whereas ophiolites determine the Mg-character of Bognanco waters. All these waters have CO_2 partial pressures (calculated at outlet conditions on the basis of pH, carbonate alkalinity and temperature) close to or slightly higher than 0.1 MPa, e.g. 0.11 and 0.14 MPa at Bognanco, 0.095 MPa at Alpe Veglia. These high P_{CO2} values are due to input in shallow waters of deep, CO_2-rich gases uprising along important tectonic structures, such as the Simplon-Centovalli line, at Bognanco, and the Alpe Veglia fault. High P_{CO2}'s make these waters particularly aggressive in rock interaction and are responsible of the high concentrations of HCO_3 and cations. Therefore, the CO_2-rich springs of Alpe Veglia and Bognanco are essentially fed by shallow hydrogeological circuits receiving the contribution of deep, CO_2–rich gases. However, the presence of a deep, Cl-rich component at Bognanco cannot be ruled out.

d) The *calcium sulfate type of high TDS* comprises 5 thermal water springs of the Simplon tunnel (temperature 20.7 to 40.8 °C, TDS 1250–1940 mg/l), the Valle d'Oro spring of Terme di Crodo (temperature 11.8 °C, TDS 2040 mg/l) and the springs of Baceno-Uresso (temperature 9.7 to 12.4 °C, TDS 1030–1870 mg/l). The chemical characteristics of these waters are due to dissolution of anhydrite and/or gypsum contained into carbonate-evaporite metasedimentary rocks. As a matter of fact these lithotypes outcrop nearby these springs (Fig. 4) and are associated with the thermal water inflows in the Simplon tunnel (e.g. Schardt 1906).

e) The *calcium sulfate-bicarbonate type of intermediate TDS*. To this groups belong the cold water inflow in the Simplon tunnel (G6) and the springs Lisiel of Crodo (LI), Fontana di Varzo (FV) and Molino di Varzo (MV), which have temperatures of 7 to 10 °C and TDS of 170–670 mg/l. Chemical and physical charactericties of these waters are probably due to mixing of calcium bicarbonate waters of low salinity with calcium sulfate waters of high salinity.

f) In addition to these different types of cold waters, there are two mildly thermal springs. One is the thermal spring of Bagni di Craveggia (BC, temperature 26.8–28 °C, TDS 300 mg/l), which is a *sodium sulfate water of intermediate TDS*. The high pH values, from 8.65 to 9.45, reflect low P_{CO_2}'s, that is the absence of CO_2 sources at depth underneath this area. Physical and chemical characteristics indicate that this spring represents the discharge of deep circuits hosted into crystalline rocks only, likely gneisses of pre-Triassic age (Vuataz 1982). According to this hypothesis, sulfate would originate through dissolution of sulfide minerals, mostly pyrite, contained into crystalline rocks and oxidation of dissolved sulfide to sulfate. Data on the $^{34}S/^{32}S$ ratios are needed to prove this mechanism.

The other is the hypothermal spring of Piedilago (PS, temperature 16.1 °C, TDS 370 mg/l) which discharges a *calcium (sodium) sulfate water of high TDS*, diluted through addition of cold, calcium bicarbonate waters of low mineralization. The chemical characteristics of the thermal endmember of Piedilago are intermediate between those of the waters circulating into carbonate-evaporite metasedimentary rocks only (calcium sulfate waters) and those of the waters interacting with crystalline rocks only (sodium sulfate waters). Therefore, calcium (sodium) sulfate waters likely have interacted with both crystalline rocks and carbonate-evaporite metasedimentary rocks during their deep-reaching circulation.

4.4. Geothermometry of the thermal waters of the Ossola Valley

Based on the above discussion, the only waters that might have achieved the condition of thermodynamic equilibrium with relevant minerals in the thermal reservoirs of provenance are the sodium sulfate water of Bagni di Craveggia and the calcium (sodium) sulfate thermal endmember of Piedilago. Therefore geothermometers have been applied to these waters only, taking into account the effects of mixing (Chiodini et al. 1996) at Piedilago.

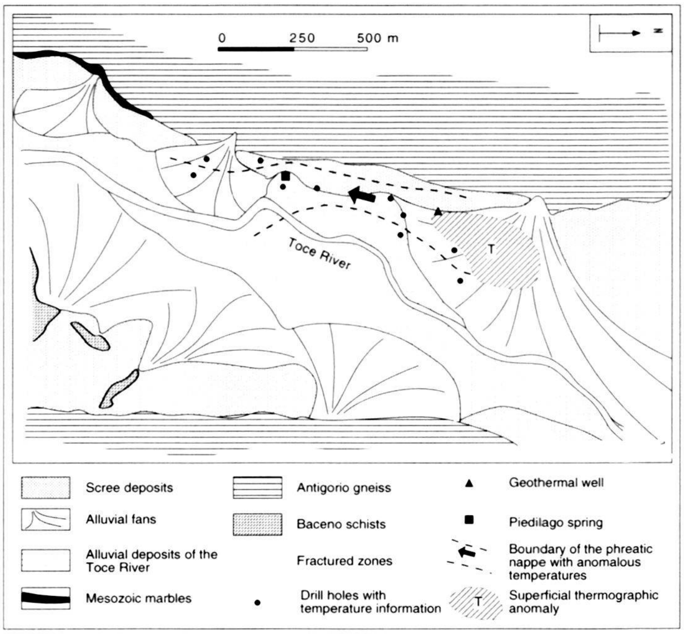

Fig. 9. Detailed geological map of the Piedilago area, showing an underground flow of thermal water.

Bagni di Craveggia. If the pH at depth were similar to that measured at the surface (9.15–9.45), the equilibrium temperature evaluated by means of the quartz geothermometer would be close to 45 °C, since the solubility of silica increases with pH in akaline aqueous solutions. If the pH at depth were lower than outlet values, quartz solubility (Arnorsson et al. 1983) would indicate equilibrium temperatures close to 85 °C. These values are consistent with the equilibrium temperatures provided by the K-Mg geothermometer (Gigggenbach 1988; data by Vuataz 1982), 85–88 °C, and the Na-K geothermomether for low-temperature geothermal waters (Arnosson et al. 1983), ~80°C.

An other approach to geothermometry is to calculate, at varying temperatures, the saturation indices with respect to a number of hydrothermal minerals potentially in equilibrium with the aqueous solution. This exercise was done by means of the Solveq computer code (Reed & Spycher 1984) assuming that Al concentration is constrained by equilibrium with K-feldspar, since Al was not analysed in collected samples. Saturation indices with respect to Na-beidellite, kaolinite, paragonite and, obviously, quartz converge to 0 close to 80°C. The calculated pH value at this temperature is 8.21 and undissociated H_4SiO_4 represents 85.9% of total dissolved silica.

Therefore, it seems likely that temperatures in the geothermal reservoir connected with the Bagni di Craveggia spring are close to 80–85 °C.

Hypothermal spring of Piedilago. Application of the binary mixing model based on chalcedony and K-Mg geothermometers gives an equilibrium temperature of 43°C and a Cl concentration of 4.6 mg/l for the thermal endmember.

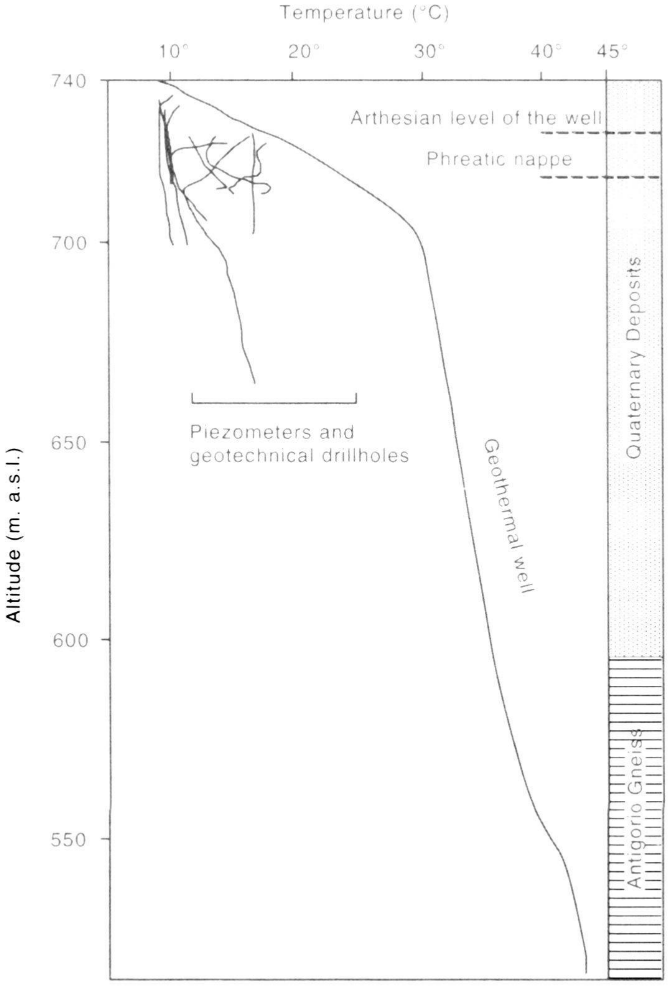

Fig. 10. Temperature logs measured in geotechnical drill-holes already present in the Piedilago area.

5. Geothermal exploration in the Piedilago Area

The Piedilago area has been investigated in detail during evaluation for the feasibility study of a new hydroelectric power plant (ENEL DCO). Geological, hydrogeological and geochemical studies have been carried out by G. Martinotti, L. Marini & P. Perello. Since this power plant had to include relevant excavations into the Antigorio Gneiss, near the hypothermal spring of Piedilago, a detailed geothermal investigation has been performed to verify possible interference patterns.

Water temperatures measured in earlier geotechnical drillholes delineate an underground flow in the phreatic nappe of water warmer than the average (Fig. 9). The temperature logs of these wells are displayed in Fig. 10. Steep temperature gradients are present outside of the perturbed area while more irregular patterns, due to thermal differences related to variations of permeability conditions inside the anomalous area, characterise the Quaternary sequence. A thermography survey performed in winter and during the early morning, in order to have the lowest thermal irradiation from ground, revealed a slight temperature anomaly (1–2°C) in a restricted zone of the alluvial fan, approximately 500 m to the N of the Piedilago spring.

In this area an exploratory well was drilled to the total depth of 248 m below the topographic surface. It is a vertical well with a diameter varying from 140 to 100 mm. The base of the quaternary sequence, which is made up of alluvial and lacustrine sediments, was encountered at a depth of 138 m. It is followed by the Antigorio gneiss, which shows a high permeability due to the presence of open fractures systems. Drilling operations were stopped at a final depth of 248 m due to technical problems (a deeper production well is in project). The carbonate aquifer was not attained but probably is not much deeper (some ten of meters), as suggested by nearby outcrops. The intense fracturation of the gneiss, which is due to dissolution in the underlying marble layer, points in the same direction. The static level of the phreatic nappe is –26.70 m, in agreement with those displayed in the other boreholes and with the Toce river. The level in the hard rock (that has been isolated from the quaternary sequence by a casing pipe) is higher, at –13.50 m, displaying an artesian behaviour. The temperature log of the well shows a regular increasing pattern below the first 40 m, where the influence of shallow groundwaters is pronounced. The temperature of the water, after stabilisation during the pumping test, is 42.7°C. The discharge is limited by the diameter of the hole and consequently of the pump potential. The installed pump produces 5 l/s with a stable level at –3.3 m from the static level. The well is pumping continuously since December 1992, without any variation in temperature and hydrodynamic parameters. Furthermore, a deeper production well is in project in summer 1999.

The thermal water discharged from the Piedilago well exhibits calcium (sodium) sulfate composition, TDS close to 1350 mg/l and Cl content of ~6 mg/l. The equilibrium temperatures inferred for this thermal water through the chalcedony solubility and the K-Mg geothermometer is, with 45°C, very close to the measured temperature, indicating that the well produces the virtually uncooled thermal water. Observed temperature and Cl content are also close to those inferred through early application of the SiO_2-K-Mg geothermometric mixing model to the hypothermal spring of Piedilago (43°C, 4.6 mg/l, see above).

6. Conclusions

The Piedilago geothermal exploration represents a good example for an Alpine type geothermal anomaly related to fast uplift. An attempt to generalise the situation follows in order to apply these inferences to similar cases in the Alps and in other young mountain chains.

The lower Pennine situation, from the geothermal point of view, is characterised by a recent and fast uplifting phase, in combination with the recent activity of main shear zones, like

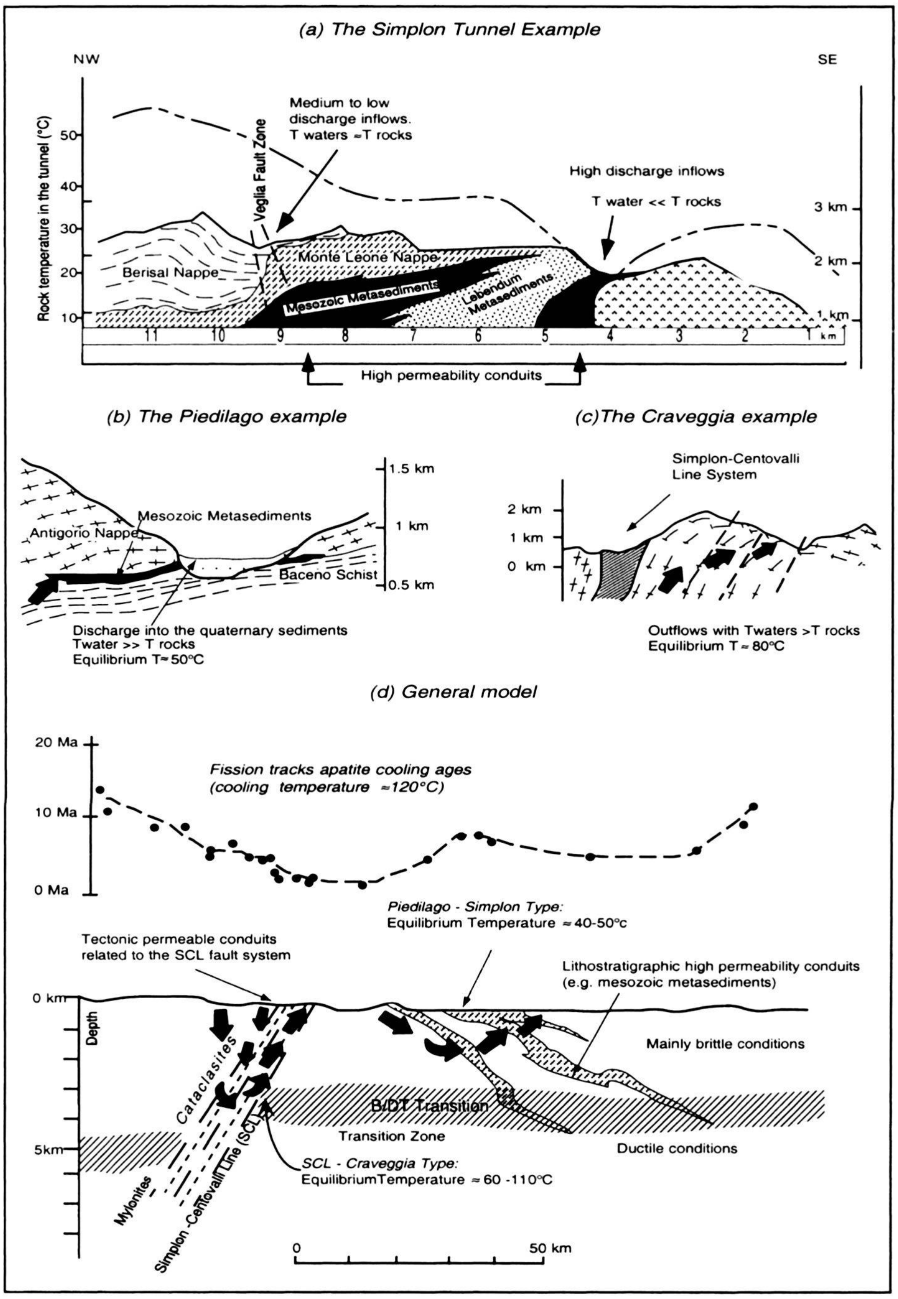

Fig. 11. Geothermal frameworks of (a) the Simplon Tunnel, (b) the Piedilago area, (c) the Craveggia area and (d) geothermal model for the Lower Pennine Zone.

the Simplon-Centovalli Line. Similar situations are present in other mountain chains as the NW sector of the Pakistan Himalayas (Zeitler 1985) or the Southern Alps of New Zealand (Koons 1987). In all these regions the last uplift rates have been measured with isotopic techniques.

As a general rule for the geothermal exploration, first of all, regions with fast uplift have to be evidenced by means of radiometric dating combining different methods like Rb/Sr, Ar/Ar and fission track on zircons and apatites, together with structural, neotectonics and quaternary investigations. These preliminary studies serve to determine a target area where to perform isotopic and geochemical water analysis of all the available spring waters.

In this phase it is also very important to reassemble all the available pre-existing data on precipitations, springs, tunnels inflows and drill holes which can give information on the thermal state of the water table.

Chemical and isotopic analyses reveal the origin of thermal waters, the lithology of the thermal aquifer, the possible occurrence of mixing processes between thermal waters and shallow groundwaters. Equilibrium temperatures presumably present at depth are obtained through geochemical thermometry, taking into account the effects of mixing processes where needed.

Once the water types of geothermal interest have been individuated and studied, the following step is to discover and characterise the litho-structural traps with suitable geometry and permeability to allow the build up of geothermal circuits. We stress the importance of the study of the intersection of the quaternary deep infilling of the alpine valleys with the evidenced structural traps. In most cases the geothermal outflows are located in the bottom of valleys with an impermeable quaternary infilling.

All the available data on geology and fluid geochemistry of the Piedilago, Simplon and Craveggia area allow to constrain a detailed geothermal model for the Lower Pennine Zone (Fig. 11).

In the Simplon tunnel (Fig. 11a) there are two main types of water circuits: one with a very high discharge value (1000 l/s in the tunnel, since 1898), related with a negative thermal anomaly in the surrounding rocks, the second with a moderate to low flowrate (0.1–10 l/s), that allow the water to reach thermal equilibrium with the rocks at the tunnel level. This situation have been confirmed during recent drilling investigations in the Simplon tunnel carried out as part of the Programme Geothermoval, CRSFA (Bianchetti et al. 1993; Hayoz & Zuber 1990). The geochemical temperatures of these waters show that they are close to equilibrium with the temperature of the rock (Geotermica Italiana 1989). Both circuits are related to lithostructural traps, associated to Mesozoic metasediments.

In the Piedilago example (Fig. 11b) there is a good evidence of ascending thermal waters, whose temperatures are much higher than those of surrounding rocks. The water equilibrium temperature (45°C), calculated with geothermometric techniques, is not much higher than the water temperature measured in the geothermal well (43°C). The lithostructural trap is, in this case, made up of the Mesozoic metasediments between the Antigorio gneiss and the Baceno schists. The thermal outflow is masked by the quaternary infilling of the Toce Valley.

The Craveggia example (Fig. 11c) differs from the previous ones because the thermal spring, (27–28°C with a discharge <0.02 l/s) is related to minor tectonic features (faults and open fracture systems) linked to the near Simplon-Centovalli Line. Moreover the equilibrium temperature (80–85 °C) is higher than the temperature measured at Piedilago.

In Fig. 11d we try to correlate the geothermal features observed in the Simplon tunnel and in the Piedilago and Craveggia areas with the recent geological evolution of the Lower Pennine.

The Simplon-Centovalli Line represents the southern tectonic boundary of this zone. The sector north of the line experienced a fast and recent uplift that brought up to the surface rocks of amphibolite grade that did not attained thermal equilibrium.

The brittle-ductile transition (B/DT) into the crust represents a boundary between an upper part in which the rock masses deform under brittle regime and a lower part in which deformation has a ductile style. This transition zone, depending on the geothermal gradient, is located at depths ranging from 5 to 8 km. When, as is the case of the Ossola region, portions of the crust are quickly uplifted as a unique block in recent time, the old brittle-ductile boundary is moved at rather high levels, where it behaves as an aquiclude in the absence of seismically induced fracturing (Fig. 11d). The same situation does not apply to the Simplon-Centovalli Line, where still ongoing movements create zones of high vertical permeability through fracturing. There the old B/DT does not act as a permeability boundary.

The waters of the Piedilago-type situation are located in an area where the permeability barrier related to the old B/DT is on higher crustal position and is also unaffected by fracturing. Therefore their possible attainable circulation depth is limited and consequently they cannot reach high temperatures (60°C maximum).

Waters connected with the Simplon-Centovalli Line permeability circuits can infiltrate to greater depth as the permeability barrier related to the old B/DT is not effective due to recent and ongoing fracturing. This fact is in agreement with the higher geothermal temperatures calculated for the Craveggia thermal spring.

Summing up, it seems likely that in areas of quick uplift geothermal resources are located at shallower depths than in areas of slow uplift, but the maximum temperatures attainable by deep-circulating fluids are smaller in the fast-uplifting areas, because the permeability boundary imposed by the old B/DT is also shallower than in slow-uplifting areas.

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