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The use of ^3H and $\delta^{18}\text{O}$ tracers to characterize water inflows in Alpine tunnels

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ABSTRACT

Water inflows in nine tunnels and galleries through the Alpine crystalline massifs have been analysed for their ^3H (tritium) activities and $\delta^{18}\text{O}$ contents. Tritium provides information on water transit times and the dynamics of deep water circulation, whereas $\delta^{18}\text{O}$ contributes to understanding the origin and flow paths of water in such mountainous regions.

Owing to ambiguities arising from the irregularity of the historical ^3H input function since 1945, a univocal and straightforward interpretation of water transit times in Alpine tunnels is not possible. Nevertheless, the ambiguity can be resolved by considering the ^3H data in combination with (a) the generalized hydraulic conductivity of the massif obtained from

discharge data, and (b) the sodium and silica content of the water as an indication of the extent of rock-water interaction. When the data are resolved in this way, the waters that were sampled in the tunnels/galleries can be divided into three age groups, i.e. <15, 15-40 and >40 years. In general, water beneath a rock-cover thickness of <500 m is less than 15 years old, which confirms the active circulation of groundwater in a “decompressed zone” (i.e. a zone of unloading fractures that is expected to have a depth of this magnitude). Moreover, tunnel excavation can radically alter the hydrology, as is shown by the tritium content of a water inflow in the Gotthard gallery.

Oxygen-18 data primarily reflect the recharge altitude, which can be predicted a priori by considering the large-scale geological structures of each massif and the extent to which they control the subvertical paths followed by the groundwater. Anomalous $\delta^{18}\text{O}$ data may reflect local or general departures from this interpretation. A general pattern is that downslope flow in the better jointed “decompressed zone”, which parallels the topography, may divert recharge from a higher to lower altitude before it follows the structural pathways into the tunnel. This results in a somewhat lower $\delta^{18}\text{O}$ value than would be predicted from structure alone, but tends to confirm the existence and role of the “decompressed zone”

indicated by the tritium. More local $\delta^{18}\text{O}$ anomalies reflect recharge from rivers or lakes entering the tunnels, and are illustrated by examples in this paper.

Our study shows that environmental isotopes contribute to a better understanding of the hydrogeology of mountain massifs and of the interactions between tunnels/galleries and groundwater. They provide information not given by other tracing methods and are thus a precious tool for tunnelling engineers and geologists.

Keywords: isotopes, hydrogeology, tunnels, Alps, mountains

INTRODUCTION

The different north-south thoroughfares in the Alps have involved the drilling of several tunnels and galleries through the crystalline massifs. We thus have road tunnels (Tende, Mont Blanc, Great Saint Bernard, Gothard), railway tunnels (Loetschberg, Gothard, Simplon), and various hydroelectric galleries from large dams (EDF hydroelectric installations in France, the Grande Dixence gallery in Swiss Wallis, hydroelectric galleries in the Aar massif). Moreover, further underground projects are planned in these crystalline massifs.

Tunnels have the effect of draining a massif if the drilling is not specifically adapted, although the origin, nature and behaviour of the water inflows are often unknown. In addition, underground works can significantly modify the groundwater circulation regime, even to the extent of causing to dry up in fact, a systematic quantitative study of surface springs is the most reliable method for evaluating the impact of underground works on water resources.

Complementary data useful to engineers for understanding the hydrogeology of the massif can be provided by physico-chemical and isotopic monitoring of water inflows during drilling. As an example, isotopic studies on the water inflows in the Mont Blanc tunnel made it possible to determine not only the recharge areas (Fontes *et al.*, 1979) but also the permeability and porosity of the Mont Blanc massif (Michelot *et al.*, 1983). Jamier *et al.* (1972) used hydroelectric galleries to study the meteoric origin of deep water in the same massif.

Numerous studies have been carried out on the origin and chemical characterization of water inflows in tunnels (cf. Cruchet, 1983; Gourgand, 1983). One method of determining the influence of tunnel drilling on groundwater circulation is through tritium measurements: Polyakov *et al.* (1996), studying the Muya tunnel in the Baikal mountains, showed that water transit times were in the order of 90 years in the non-influenced parts of the massif as against one year for water inflows in the completed sections of the gallery.

In our present study, water inflows in nine tunnels and galleries through the Alpine crystalline massifs (

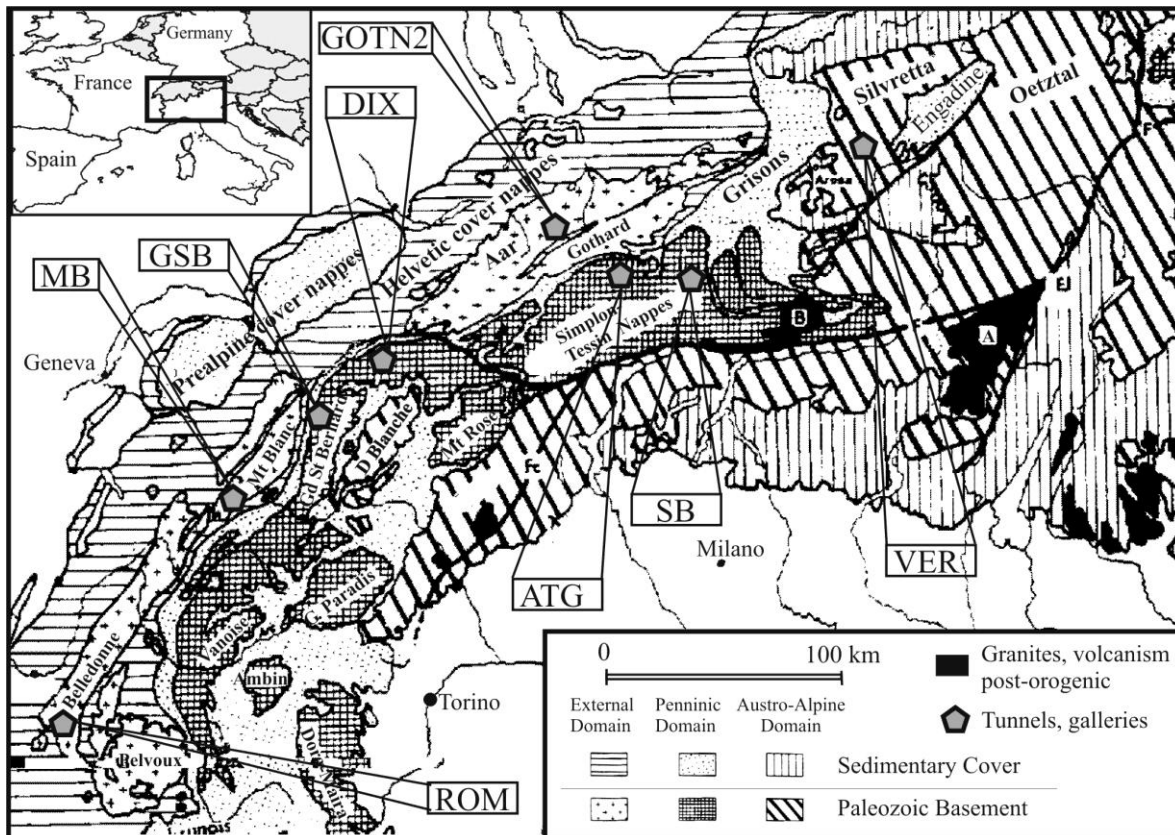


Figure 1) were sampled for chemical and isotopic analysis. The aim was to improve the usefulness of water molecule isotopes for studying the relationship between tunnels and groundwater in Alpine massifs.

CONTEXT OF THE STUDIED ALPINE TUNNELS

The characteristics of the nine tunnels and galleries studied in this paper are summarized in Table 1. Of the four road tunnels, one hydroelectric gallery, one railway tunnel, and three exploratory galleries drilled in the crystalline Paleozoic Basement of the Alps, half were under construction during the study period and the others were already in use. Most of the tunnels/galleries are more than 5000 m long, apart from the two Romanche galleries that do not exceed 750 m in length, and cut through the main Alpine crystalline massifs.

Three of the studied sites (four tunnels/galleries) are located in the External Crystalline Massifs (ECM) made up of Paleozoic basement belonging to the Helvetic Domain (Figure 1):

- The two Romanche galleries, which were being drilled during our study, in the Belledonne Massif near Grenoble, France. These galleries, less than 750 m long in

gneiss and leptynite, are shallow and the discharge rates show a rapid response to rainfall (Maréchal, 1999b).

- The Mont Blanc road tunnel, which was drilled at the end of the 1950s through the Mont Blanc External Crystalline Massif between France and Italy. This high massif, largely covered by glaciers, consists mainly of crystalline schist and granite. From the French portal, the tunnel passes through 3500 m of crystalline schist, 6800 m of granite, and 1300 m of limestone. Large water inflows (1084 L/s the first day) were met when the tunnel intersected cataclastic rock in a strongly tectonized 600-m-wide fault zone that halted drilling progress for four months.
- The Gothard road tunnel, which was drilled through the Gothard and Aar Massifs, in Switzerland, during the 1970s. Cut mainly through granite, crystalline schist and gneiss, it links the Northern and Southern Alps via the N2-National road. Although water inflow rates were fairly low relative to the length of the tunnel, water quality was a major problem for the concrete lining of the tunnel (Keller *et al.*, 1987).

Four of the studied sites are located in the Paleozoic Nappes of the Penninic Domain:

- The Great Saint Bernard road tunnel, which was drilled in 1960 across the Penninic Pontis Nappe (Thélin *et al.*, 1993) to link Swiss Wallis to the Aosta region in Italy. Water inflows in the intersected mica schist and gneiss are very low.
- The Cleuson-Dixence hydroelectric gallery, which was drilled during the study period, crosses the Great Saint Bernard Nappe in Swiss Wallis. It passes through gneiss, mica schist and greenschist. Large water inflows and high water pressures were encountered when drilling behind cataclastic rocks (Buergi *et al.*, 1998).
- The Gothard (AlpTransit) gallery, which was also drilled during the study period, crosses the Penninic Simplon and Tessin Nappes of Leventina (3000 m) and Lucomagno (2500 m). The permeability of these gneissic formations is very low and water inflows are scarce (Schneider, 1997).
- The Gran San Bernardino road tunnel (Switzerland), which crosses the Penninic Nappe of Adula and mainly intersected gneiss. Water inflows are very low but react rapidly to snowmelt.

The last studied site is in the Silvretta Nappe of the Austro-Alpine Domain:

- The Vereina railway tunnel, which was drilled in Switzerland during the study period, crossed 3 km of sedimentary cover and paragneiss before intersecting orthogneiss and amphibolite of the Silvretta Nappe. Water inflows are low.

Isotopic and chemical analyses were carried out on a series of 34 water inflows, some of which were monitored over a period of two years. Tritium analysis was by β - ray scintillation count in the liquid phase after electrolytic enrichment, with measurement precision being a function of the tritium content. Analysis of the stable isotopes (^{18}O and

^2H) was by mass spectrometry with a measurement precision of 0.15‰ for $\delta^{18}\text{O}$ and 1.50‰ for $\delta^2\text{H}$. Anions and cations were measured by classical methods such as ionic chromatography (chloride, sulphates, nitrates), colorimetry (silica), specific electrodes (fluoride) and titration (calcium and bicarbonates). The results are summarized in Table 2.

TRITIUM AS A DATING TOOL

The low hydraulic conductivity of the Alpine crystalline massifs and the long flow paths between the recharge zones and the outlets into tunnels/galleries can result in long transit times. Tritium can be interpreted in terms of groundwater transit time through comparing tritium activities measured at the outlet with simulated activities given by one-dimensional mixing models (Zuber, 1986) for different sets of transit-time parameters. Etcheverry and Perrochet (1999) showed analytically that the transit-time distribution of water inflows in tunnels/galleries corresponds to the 'piston flow' model for a homogeneous steady flow if the hydrodynamic dispersion in the aquifer and the travel time through the tunnel/gallery is ignored. We applied this transfer function to the tritium activity of the precipitation at the Thonon-les-Bains station in the French Alps, near the Mont Blanc tunnel site. The tritium activities simulated for 1995, 1996 and 1997 (Figure 2) show three mean transit-time (T_0) classes: (i) recent waters ($T_0 < 15$ years) with activities between 10 and 20 TU; (ii) old waters, which may show activities greater than 20 TU ($T_0 = 15 - 35$ years), but also between 10 and 20 TU ($T_0 = 35 - 40$ years) due to the bell-shaped tritium evolution in precipitation; and (iii) very old waters ($T_0 > 40$ years) with activities lower than 10 TU. Among the 34 water inflows analysed for tritium in this study, the majority (20) are characterized by an activity ranging between 10 and 20 TU. There is thus a need for a second tracer to determine the age of the water inflows in Alpine tunnels/galleries with a tritium activity in this range.

The hydraulic conductivity of sections of the massifs has been determined on the basis of the measured discharge using steady- and unsteady-state analytical solutions, albeit at the cost of a simplification of the massifs' geometry (Maréchal, 1998, 1999a). This hydraulic conductivity was compared to the tritium activity of the corresponding water inflows (Figure 3).

Very old waters are encountered in tunnel/gallery sections where the hydraulic conductivity does not exceed 10^{-9} m/s and where the mean transit time is greater than 40 years (except for a water inflow in the Great Saint Bernard tunnel, where the mean transit time ranges from 20 to 40 years). Tunnel sections with a hydraulic conductivity greater than $3 \cdot 10^{-7}$ m/s yield recent water with mean transit times of less than 15 years (tritium between 10 and 20 TU). Tunnel/gallery sections with intermediate hydraulic conductivity give either recent or very old waters. The lack of complete correlation between transit time and hydraulic conductivity must be related to the heterogeneity of the massif, with a water inflow corresponding precisely to a structural heterogeneity. The hydraulic gradients and porosity of the massif are also influencing features.

It has been possible to split the studied waters into five hydrochemical groups (Table 3). Even though most of the studied waters are in the Ca-HCO₃ class, the varied geological settings result in certain particularities for each group. Thus, greenschist and Triassic dolomite impart a magnesian character to groups C and E, whilst very old waters belong mainly to Group A and contain more sodium than calcium. This can be generalized to all waters drained by crystalline massifs since old and very old waters are almost systematically Na-rich, which can in part be explained by the tendency to silicate deterioration decreasing in the order Ca-plagioclase, intermediate plagioclase, Na-plagioclase, K-feldspar, muscovite, quartz, i.e. albite is altered after anorthite.

For waters with tritium activities ranging between 10 and 20 TU, the age uncertainty due to the bell-shaped evolution of tritium in precipitation could be reduced on the basis of (a) the Na-concentration of the waters, and (b) the hydraulic conductivity. Figure 4 shows four zones:

- In the foreground are waters with tritium activities in the 10 to 20 TU range: the low Na-concentrations and the high hydraulic conductivity (higher than 10⁻⁸ m/s) are compatible with and typical of recent waters. The mean transit time is unambiguously less than 15 years.
- On the left of the graph and in the background, are waters with tritium activities lower than 10 TU; they also have higher Na. These waters must be more than 40 years old. The high variation in Na-concentrations would be related to the petrography and not to the transit time because the isotopic age given by such tritium activities is unambiguous. The thick rock cover ranging between 1000 and 2000 m corroborates this isotopic age.
- At the middle on the right, are five waters with tritium activities in the 10 to 20 TU range. Two points of this zone have Na-concentrations similar to the water inflows in the foreground, and three have higher Na-concentrations. The hydraulic conductivity is low. The uncertainty of the tritium ages allows one to suspect that the waters with relatively low Na concentrations have shorter transit times than the waters with relatively high Na concentrations. This uncertainty can be removed on the basis of the rock-cover thickness. The two water inflows with low Na concentrations are located below 300 to 400 m of rock cover and are therefore probably recent waters, whereas the three water inflows with relatively high Na concentrations have a rock-cover thickness of about 1000 m and are thus considered as old waters (35 to 40 years old).
- On the right of the graph, a water inflow with a high tritium activity and low conductivity is classified as old water (15 to 35 years old). The low Na concentration must again be related to the petrography and not to the transit time, as with the very old waters.

The above sections show that the mean transit time must be evaluated on the basis of several criteria. Neither the tritium analysis, nor the Na-concentration and hydraulic-conductivity estimation, gives an unquestionable transit-time value. Only a combination of

all these results placed in their hydrogeological context with the rock-cover thickness can yield a good approximation of the water transit time.

The decompressed zone

The existence of a decompressed zone in the Alpine crystalline massifs is already known (Cruchet, 1985; Maréchal, 1999b). This superficial part of the Alpine massifs has a higher hydraulic conductivity and thus shorter transit times, as shown by Figure 5. Tritium activities of the water inflows under a rock-cover thickness of less than 500 m are almost systematically in the 10 to 20 TU range; this is typical of recent waters if hydraulic conductivity and sodium concentrations are taken into account (see above). Only a small water inflow from the low-permeability Gothard's paragneiss, encountered at PM-10140 in the Gothard tunnel, has a tritium activity of about 8 TU below a rock-cover thickness of 400 to 500 m.

Conversely, old, and even very old, waters are often encountered under a rock-cover thickness of more than 500 m. This fact is related to the decrease in hydraulic conductivity with depth and the increased flow-path lengths. In the Mont Blanc tunnel, water inflows below a rock-cover thickness in excess of 1500 m are outlets of high-permeability zones and therefore have short transit times (Figure 5). In this case, the cover thickness has no influence because of the structural context. In the Great Saint Bernard tunnel, the water inflow at PM-1016 is moderately old because of the low permeability of the mica schist making up the massif. The inflow water's tritium activity at PM-5540 in the AlpTransit Gothard gallery must be related to the water put into circulation when drilling the gallery.

Effect of tunnel drilling on groundwater

The AlpTransit Gothard gallery at Polmengo was drilled to test the Piora Mulde zone - a dolomite syncline pinched between the Penninic gneiss zone (Leventina and Lucomagno gneiss) and the Gothard massif - for the future Gothard AlpTransit tunnel. The aim of the gallery is to determine the geometry of the dolomite zone, as well as its geological, hydrogeological and geotechnical features.

From its entry at Polmengo, the 5552-m-long gallery crosses the Leventina Gneiss over a distance of about 3000 m and then the Lucomagno Gneiss over 2500 m (Figure 6a). Progress was normal up to 5251 m from the entry. Being close to the Piora zone, the tunnel boring machine was preceded by sounding boreholes some 100 m long. The Piora dolomite was encountered in the 5th borehole and gallery excavation was stopped at 5552 m.

Particularly low tritium activities (<10 TU) for most of the inflow waters in this gallery show that the waters were very old (e.g. PM-1163 to PM-5406 in Table 2); for example, a water with an activity of less than 0.8 TU is older than the first nuclear tests of 1952. Some

months after the excavation of the gallery and the drilling of the water-productive boreholes in the Piora zone, tritium activity close to this area increased significantly (Figure 6b). In a borehole drilled into the Piora dolomite in March 1996, tritium activity measured increased from 1.4 TU on the first day that the zone was intersected, to 3.3 TU on the third day, to finally reach values in excess of than 10 TU one year later (Figure 6b). In the main gallery, 5540 m from the entry portal, tritium activity one year after the drilling of the tunnel was 13.3 TU; this is the only recent water observed within the gneiss in this gallery. The tunnel drilling had thus generated very important hydraulic gradients that reactivated groundwater circulations in the Piora dolomite; these then passed through the Lucomagno Gneiss toward the gallery, and the old waters initially encountered in the gallery were replaced progressively by increasingly younger waters. A tracer test in September 1997 showed that the surface waters reached the gallery through the Piora dolomite after only 24 days (Schneider, 1997). This implies that a previously slow circulation that was restricted to the dolomite in the core of the syncline has been reorganized into a system of rapid near-vertical flow.

OXYGEN-18 FOR DETERMINING RECHARGE AREAS

Knowledge of the altitude gradient in a given area makes it possible to determine the recharge altitude of water according to its $\delta^{18}\text{O}$ content (Clark and Fritz, 1997). For the Alps, it is necessary to take into account two altitude gradients because of the climatic contrast between the northern and southern sides of the mountains. In the Northern Alps, the calculated altitude gradient between the stations at Thonon-les-Bains (alt. 385 m) and Grimsel (alt. 1980 m) is less than 0.27‰/100 m, whereas Novel (1995) calculated a gradient of 0.23‰/100 m on eight stations lying between 350 and 3500 m in the Aoste valley during the 1993-1994 period. The relationship between the $\delta^{18}\text{O}$ of precipitation and altitude is thus:

- Northern Alps: $\delta^{18}\text{O} = -0.0027 \cdot h - 8.4$
- Southern Alps: $\delta^{18}\text{O} = -0.0023 \cdot h - 8.0$

with $\delta^{18}\text{O}$ [‰] and h [m]

On the basis of these gradients, it is possible to evaluate not only the mean altitude of the recharge area of a water inflow in a tunnel from its $\delta^{18}\text{O}$ content, but also its location due to the high fluctuations of altitude in this mountainous region. However, as with tritium, care must be taken to recognize possible mixing.

Because tunnels and galleries through the Alpine massifs are designed to allow communication between valleys, most cross very steeply dipping –near vertical– geological structures. In the Mont Blanc road tunnel, Fontes *et al.* (1979) observed that the large hydraulic gradients between the recharge areas and the tunnel induce subvertical water circulation along the Alpine geological structures, such that the recharge altitude of each

water inflow may be evaluated. In our study, these altitudes are generally consistent with the $\delta^{18}\text{O}$ of water inflows as shown in Figure 7. The observed data fit well with the above $\delta^{18}\text{O}$ /altitude lines for the Northern and the Southern Alps. The water inflows of the Mont Blanc tunnel (southern part), Great Saint Bernard tunnel (southern part) and San Bernardino tunnel (southern part) fall into the Southern Alps line, and the data observed in other galleries give a better fit with the Northern Alps line. Three particular hydrogeological configurations may be considered.

Effect of the decompressed zone and Quaternary cover

The decompressed zone, especially the ‘down-bending’ zone, and the Quaternary rocks generally show higher hydraulic conductivity than the underlying massif. Considering their position close to the valley-side slope, the strong hydraulic gradients facilitate circulation parallel to the slope. This indicates higher recharge areas than those estimated by simple geological extrapolation. Consequently, the sampled gallery and tunnel waters seem impoverished in $\delta^{18}\text{O}$. This is the case for PM 936 and 1600 in the AlpTransit Gotthard gallery of Polmengo (Figure 6a) where the isotopic data (Schneider, 1997) indicate higher recharge altitudes (Table 4 and Figure 8).

Regional groundwater circulation

A regional flow system drained by the Gotthard road tunnel under the Reuss river is indicated by the waters impoverished in $\delta^{18}\text{O}$ (zone 1; Figure 9). The tunnel drains a regional flow system, while the local flow system supplies the Reuss river.

Waters coming from the Piora dolomite and the Lucomagno Gneiss near the Piora zone in the AlpTransit Gotthard gallery (Figure 8) are enriched in $\delta^{18}\text{O}$ (highest values about -12‰). Therefore, their recharge altitude could be lower than the altitude of the surface just above the gallery. The Piora Valley, just above the massif, is characterized by lower altitudes (Ritom lake, for example, at 1800 m). Thus, the Piora could be recharged from this zone, as indicated by tracer tests in this region (Schneider, 1997) and by the tritium data indicating a rapid near-vertical flow from the lake.

Relationship between tunnels and surface water

Figure 9b shows that the $\delta^{18}\text{O}$ enrichment of the inflow water from zone 2 of the Gotthard road tunnel is very similar to that of lake water. A recharge from the Lucendro and Sella lakes is thus suspected in the southern part of the tunnel.

Close to the tunnel's northern entrance (zone 3), a water inflow with $\delta^{18}\text{O}$ compositions similar to the Reuss river waters, indicates partial recharge from the overlying Reuss river. It would be useful to confirm this hypothesis with the help of isotopic and chemical data on local precipitations.

Tritium activity (13-15 TU) of the inflow in zone 3 is also compatible with this statement, indicating young water.

The above examples show how local $\delta^{18}\text{O}$ anomalies reflect recharge through the decompressed zone, or from regional systems, rivers and lakes.

CONCLUSIONS

The use of artificial tracers to study groundwater circulation around Alpine tunnels is difficult, or even impossible, because of the amount of required tracers, the long transit times, and uncertainties concerning the flow paths. However, the isotopes of oxygen and hydrogen, as conservative tracers, are well suited to this purpose.

The low hydraulic conductivity of the Alpine crystalline massifs and the long flow paths between the recharge zones and the outlets in tunnels/galleries can result in long transit times. Tritium can therefore be interpreted in terms of groundwater transit time, although ambiguities arising from the irregularity of the historical 3H input function since 1945 do not permit a univocal and simple interpretation. The ambiguity can nevertheless be resolved by considering the 3H data in combination with (a) the generalized hydraulic conductivity of the massif, obtained from discharge data, (b) the Na and Si contents of the water as an indication of the extent of rock/water interaction, and (c) the rock cover thickness. When the data are resolved in this way, the sampled waters in tunnels/galleries can be divided into three age groups, i.e. <15, 15-40 and >40 years. In general, waters beneath a rock-cover thickness of <500 m are less than 15 years old: this confirms the active circulation of groundwater in a “decompressed zone” (i.e. a zone of unloading fractures, which is expected to have a depth of this magnitude).

The excavation of a tunnel may radically alter the hydrology, especially of highly permeable rocks, by providing a flow outlet where none previously existed. The corollary of the case study presented in this paper is that, for samples to reflect the undisturbed groundwater system, they must be taken as soon as possible following penetration of the rocks during excavation.

Oxygen-18 data primarily reflect recharge altitude, which can be predicted a priori by considering the large-scale geological structures of each massif and the extent to which they control the subvertical paths followed by groundwater. Anomalous $\delta^{18}\text{O}$ data may reflect local or general departures from this interpretation. A general pattern is that downslope flow in the better jointed “decompressed zone”, which parallels the topography, may divert recharge from a higher to lower altitude before it follows the structural pathways into the

tunnel. This leads to a somewhat lower $\delta^{18}\text{O}$ value than would be predicted from structure alone, but tends to confirm the existence and role of the “decompressed zone”, as shown by tritium. More local $\delta^{18}\text{O}$ anomalies reflect recharge from rivers or lakes entering tunnels, and are illustrated by examples in this paper.

Our study has shown that environmental isotopes contribute to a better understanding of the hydrogeology of mountain massifs and of the interactions between tunnels/galleries and groundwater. They provide information not given by other tracing methods and are thus a precious tool for tunnelling engineers and geologists.

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FIGURE AND TABLE CAPTIONS

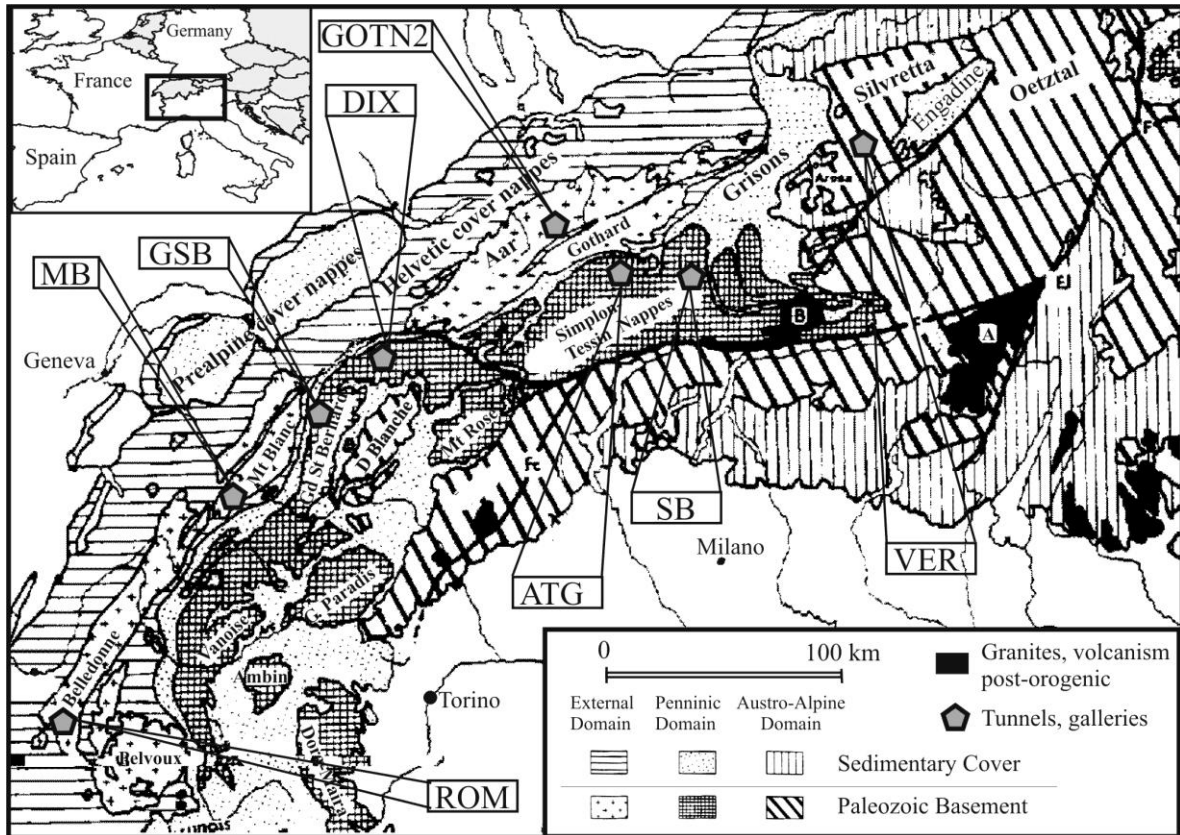


Figure 1 - Simplified geological map of the Western Alps showing the studied tunnels/galleries.

ATG: AlpTransit Gothard gallery; DIX: Cleuson-Dixence gallery (Part AB or C); GOT N2: Gothard road tunnel; GSB: Great Saint Bernard road tunnel; M-B: Mont Blanc road tunnel; ROM: Romanche (Livet or Gavet gallery); SB: San Bernardino road tunnel; VER: Vereina railway tunnel.

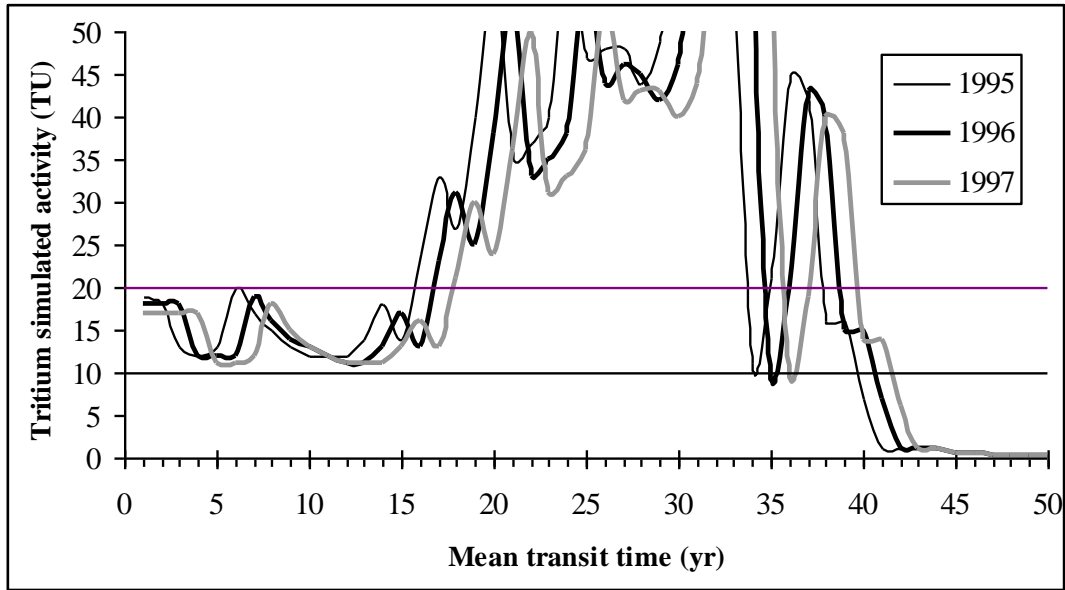


Figure 2 - Relationship between mean transit time of water in the massif and tritium activity at the outlet, simulated during the study period (1995 – 1997) with a 'piston flow' model.

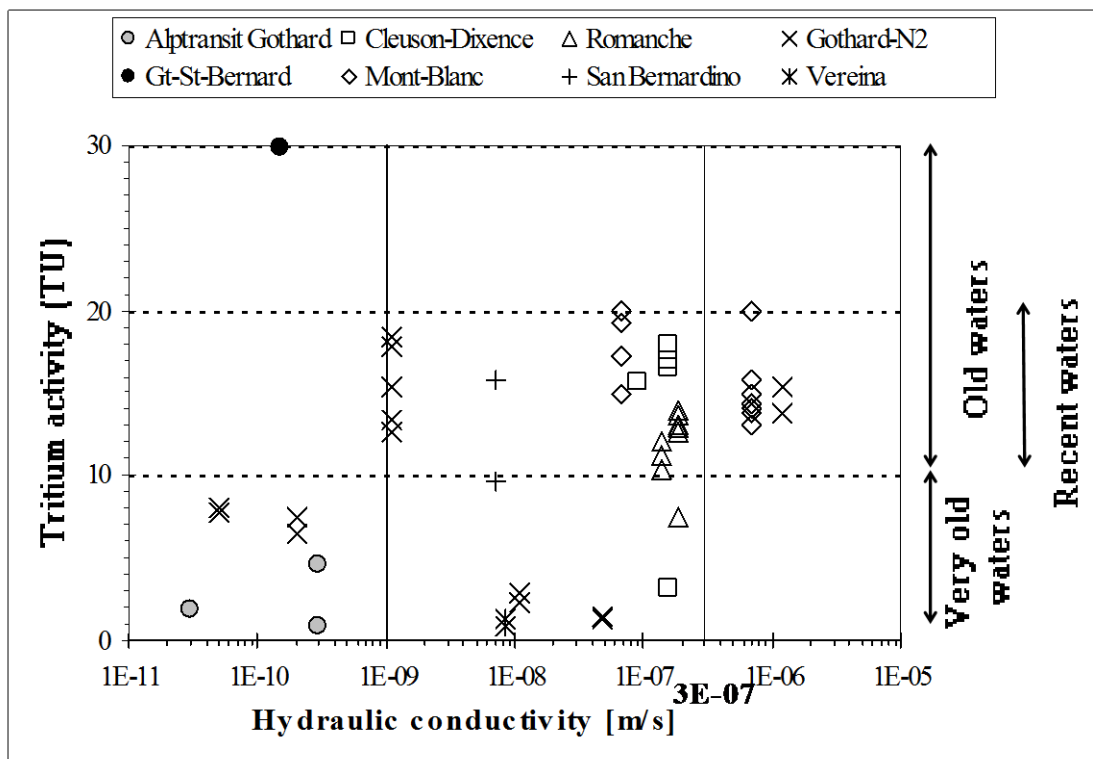


Figure 3 – Relationship between tritium activity of the water inflows and hydraulic conductivity of the corresponding tunnel/gallery sections.

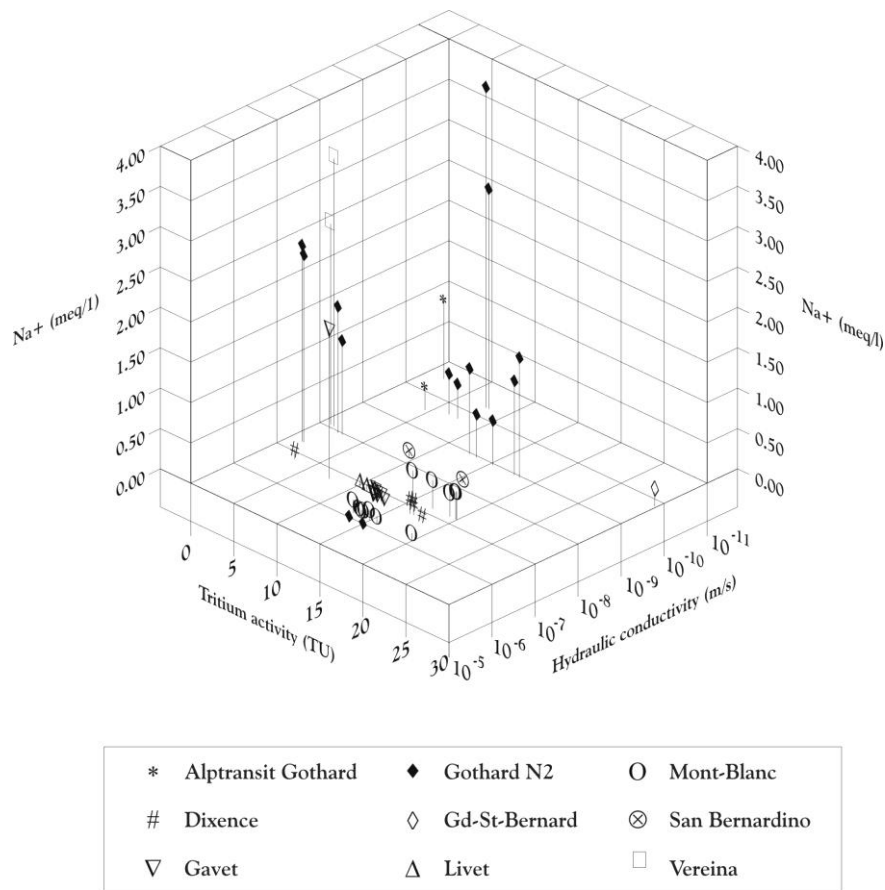


Figure 4 – Relationship between sodium content and tritium activity of the water and hydraulic conductivity.

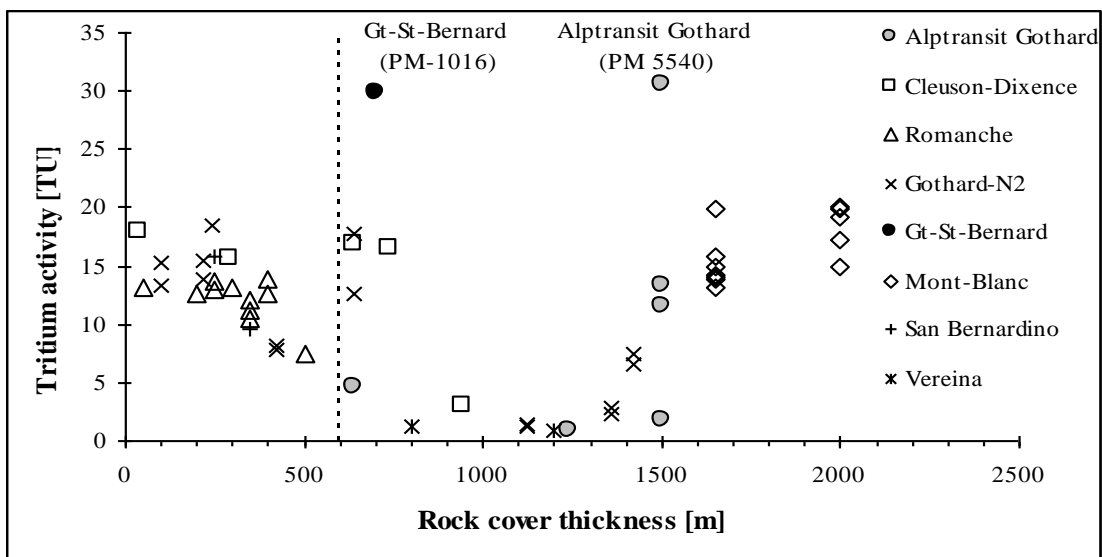


Figure 5 – Relationship between tritium activity of the water and rock-cover thickness above the water inflows.

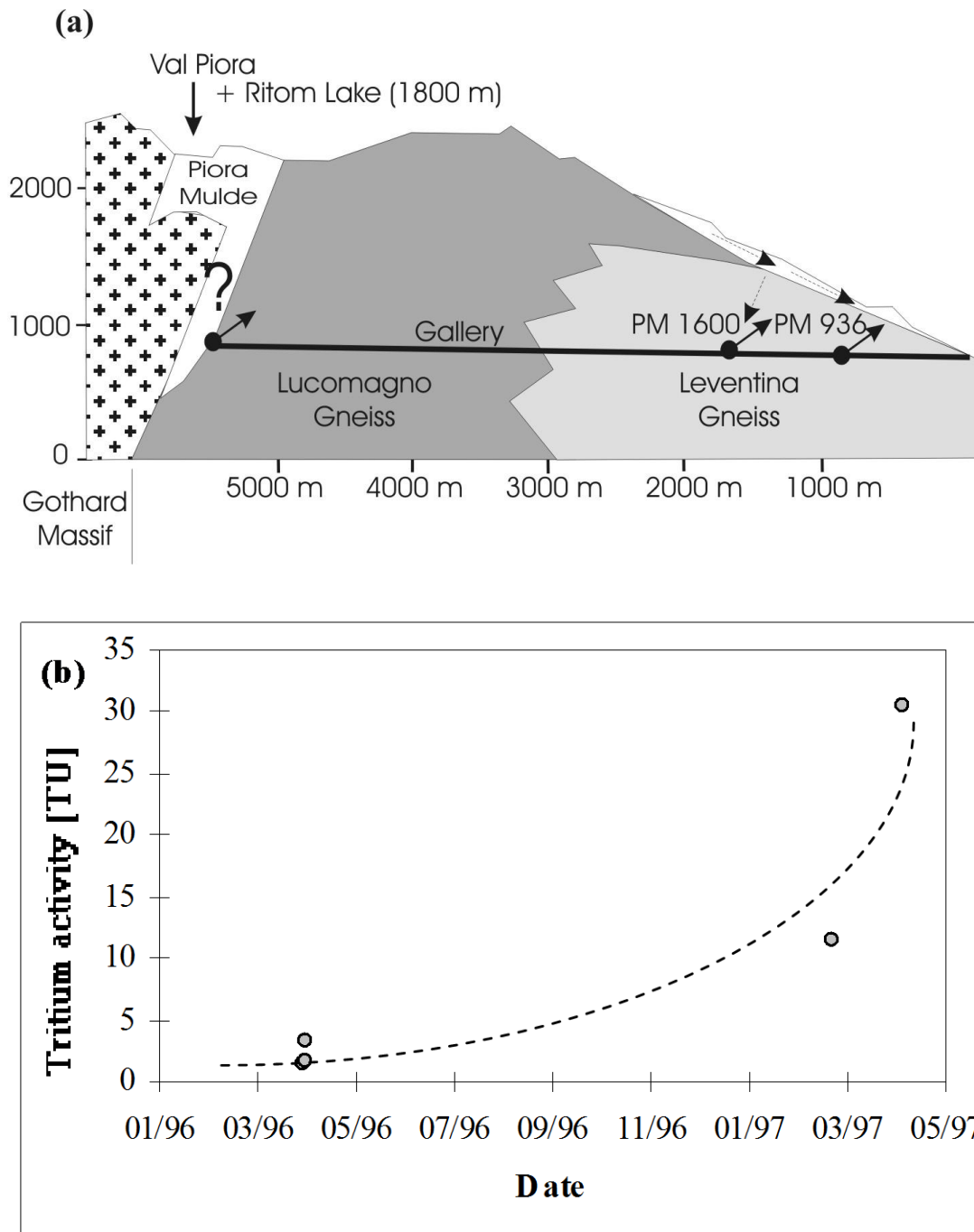


Figure 6 – (a) Geological context of the Polmengo gallery. (b) Evolution of the tritium activity in boreholes reaching the Piora Mulde zone.

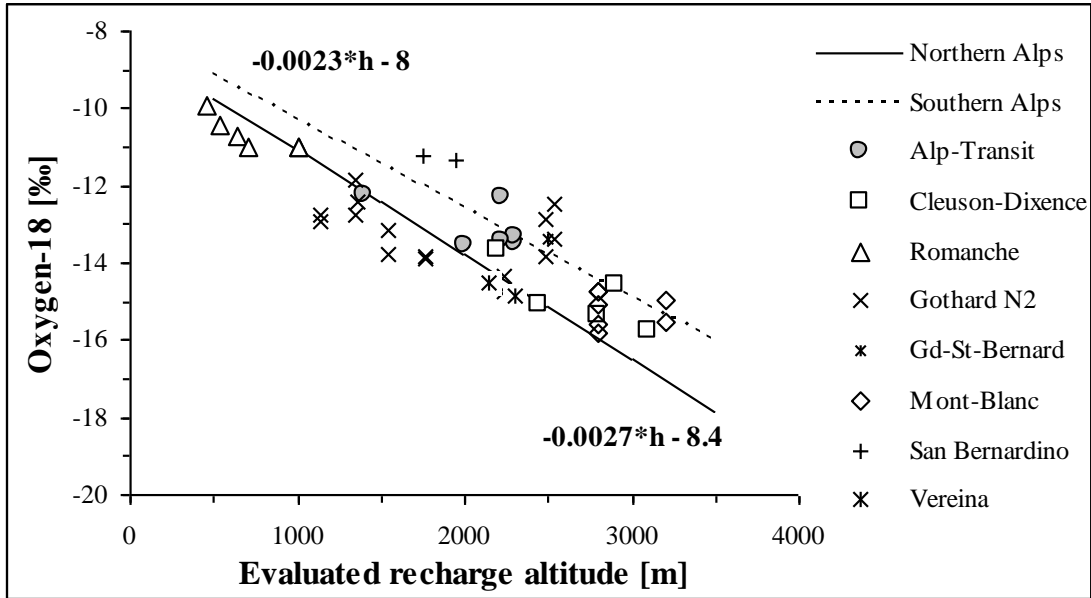


Figure 7 – Relationship between $\delta^{18}\text{O}$ of the water inflows and recharge altitude of the water evaluated on the basis of structural geology. Comparison with precipitation gradients observed in the Northern and Southern Alps.

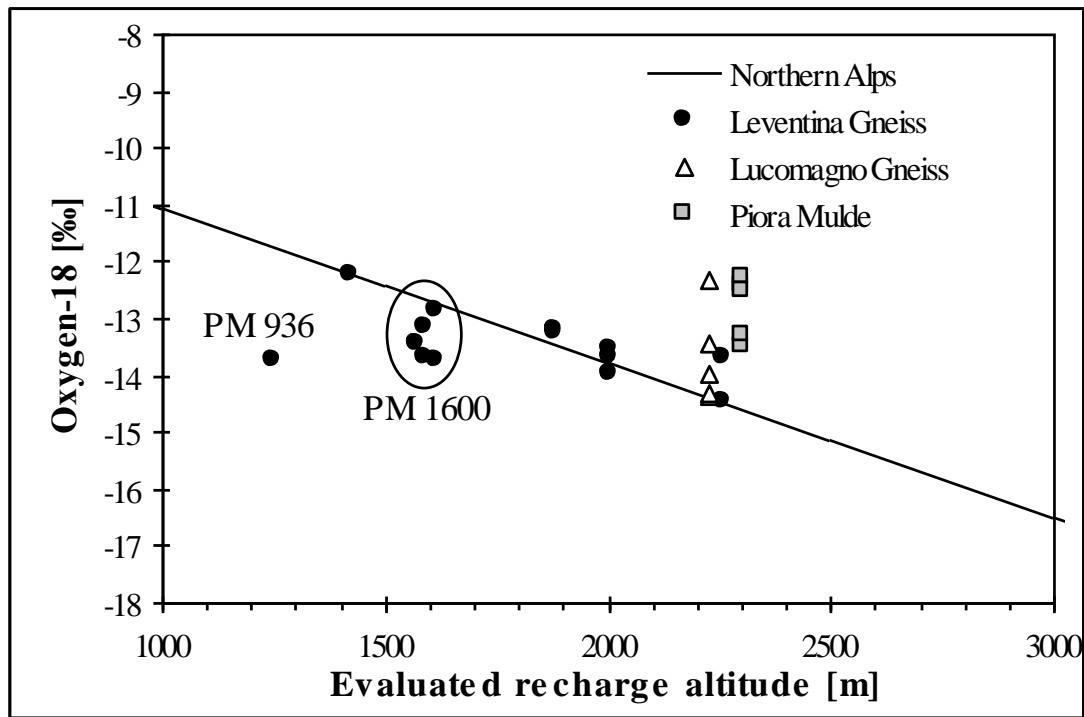


Figure 8 – Relationship between $\delta^{18}\text{O}$ of the water inflows in the AlpTransit Gothard gallery and evaluated recharge altitude.

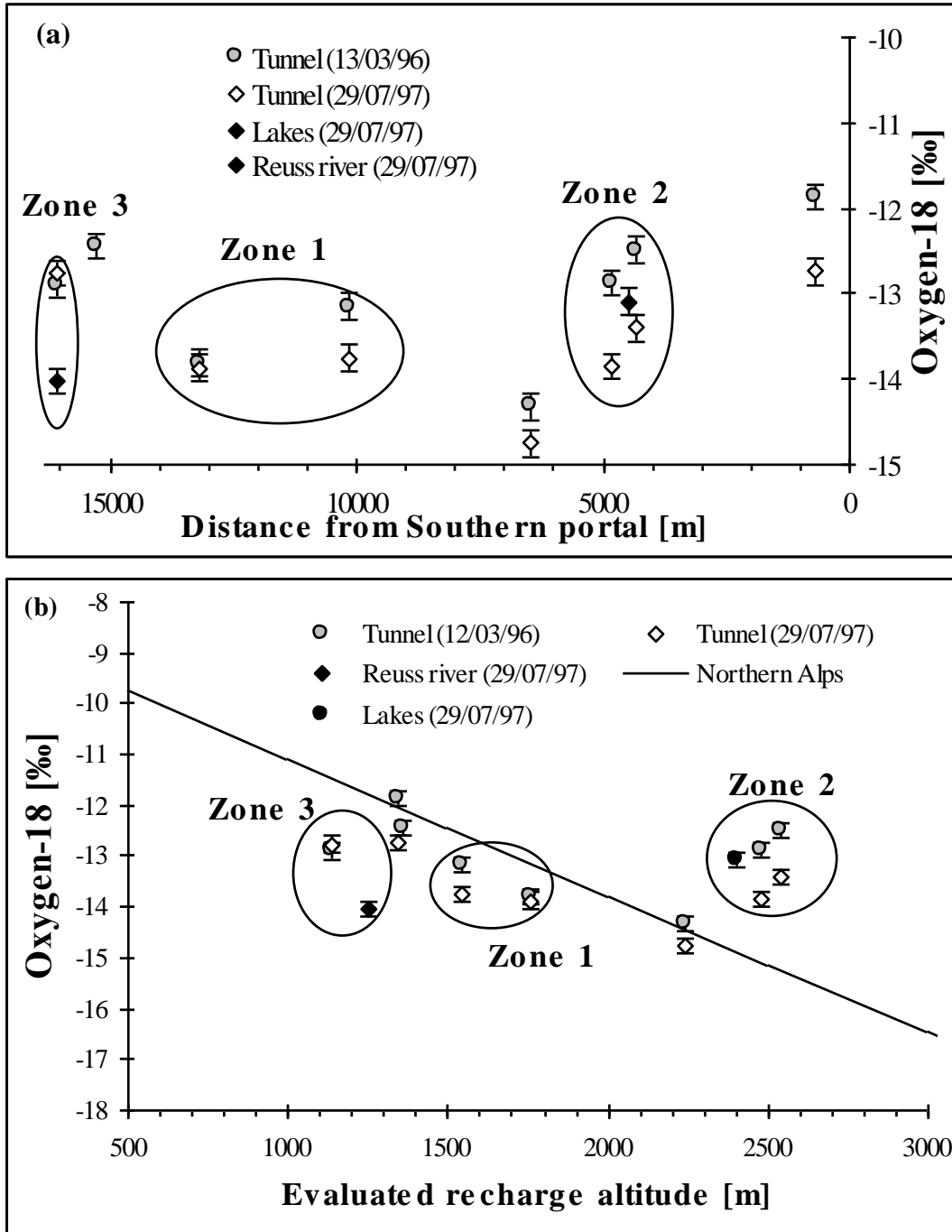


Figure 9 - Oxygen-18 of the water inflows in the Gotthard road tunnel. (a) Results along the tunnel section. (b) Relationship between $\delta^{18}\text{O}$ and evaluated recharge altitude.

Tables

Site	Tectonic unit	Lithology	Altitude [m]	Maximum cover [m]	Gallery	Length [m]	Discharge [l/s]	U – P
Mont Blanc (F-I)	ECM: Mont Blanc	Granite and crystalline schist	1300	2600	RT	11600	400	U
Romanche (F)	ECM: Belledonne	Leptynite, amphibole gneiss	710 + 440	360 + 460	2 SG	300 + 717	10 + 13	P
Great Saint Bernard (CH-I)	Penninic D: Great St Bernard N.	Mica schist and gneiss	1900	780	RT	5855	0,3	U
Cleuson-Dixence (CH)	Penninic D: Great St Bernard N.	Greenschist, gneiss, mica schiste	2160	860	HG	15957	330	P
Gothard-N2 (CH)	ECM: Aar and Gothard	Gneiss, granite, mica schist	1100	1450	RT	16322	270	U
Gothard (AlpTransit-CH)	Penninic D: Lucomagno, Leventina N.	Gneiss	760	1600	SG	5500	8	P
San Bernardino (CH)	Penninic D: Adula N.	Gneiss	1630	500	RT	6596	5	U
Vereina (CH)	Austro-Alpine D. (Silvretta N.)	Gneiss and amphibolite	1350	1750	RWT	19048	80	P

Table 1 – The studied galleries

RT: Road tunnel – HG: Hydroelectric gallery – SG: Sounding gallery - RWT: Railway tunnel. Gallery in use (U) or in progress (P) during the study period. Water discharges are indicative. Tectonic units: ECM: External Crystalline Massif – D: Domain – N: Nappe.

Gallery	Water inflow	Date	Water type	O-18 [‰]	Tritium [TU]	Na [meq/l]	H ₄ SiO ₄ [mg/l]
ATG	PM-1163	12/03/96	<u>Ca</u> -HCO ₃ -SO ₄	-12.2	4.6	0.28	22.2
ATG	PM-2370	12/03/96	-	-13.5	0.8	-	-
ATG	PM-5406	21/02/97	<u>Ca</u> -Mg-SO ₄ -(HCO ₃)	-12.3	1.8	0.97	18.1
ATG	PM-5540	21/02/97	<u>Ca</u> -Mg-SO ₄	-13.4	13.3	0.34	16.2
ATG	BO2	21/02/97	<u>Ca</u> -Mg-SO ₄ -(HCO ₃)	-13.5	11.5	0.56	13.0
ATG	BO3.2	7/04/97	<u>Ca</u> -Mg-SO ₄	-13.3	30.5	0.03	10.6
DIX (AB)	PM-750 S	21/06/95	<u>Ca</u> -Mg-HCO ₃ -(SO ₄)	-	17.9	0.06	3.5
DIX (AB)	PM-1710 S	21/06/95	<u>Ca</u> -(Mg)-HCO ₃ -SO ₄	-	16.9	0.15	9.3
DIX (AB)	PM-2020 S	21/06/95	<u>Ca</u> -(Mg)- HCO ₃ -SO ₄	-14.6	16.5	0.18	11.4
DIX (AB)	PM-3060 S	21/06/95	<u>Ca</u> -Mg- HCO ₃ -SO ₄	-15.8	3.1	0.13	23.5
DIX (C)	PM-2840 E	2/10/95	<u>Ca</u> -Mg-HCO ₃ -(SO ₄)	-15.1	15.6	0.07	4.5
GOT N2	PM-691 S	13/03/96	<u>Ca</u> - HCO ₃ -SO ₄	-11.9	15.4	0.06	8.2
GOT N2	PM-691 S	29/07/97	<u>Ca</u> -Mg- HCO ₃ -SO ₄	-12.8	13.8	0.07	11.4
GOT N2	PM-4335 S	13/03/96	<u>Ca</u> -Na- HCO ₃ -SO ₄	-12.5	7.5	0.45	25.6
GOT N2	PM-4335 S	29/07/97	<u>Na</u> -Ca- HCO ₃ -SO ₄	-13.4	6.5	0.52	22.6
GOT N2	PM-4819 S	13/03/96	<u>Na</u> -(Ca)- HCO ₃ -SO ₄	-12.9	2.3	1.58	37.6
GOT N2	PM-4819 S	29/07/97	<u>Na</u> - HCO ₃ -SO ₄	-13.8	2.8	1.18	34.2
GOT N2	PM-6454 S	13/03/96	<u>Na</u> - HCO ₃ -SO ₄	-14.3	1.5	2.33	57.1
GOT N2	PM-6454 S	29/07/97	<u>Na</u> - HCO ₃ -SO ₄	-14.7	1.3	2.45	58.2
GOT N2	PM-10140 S	13/03/96	<u>Na</u> -HCO ₃	-13.1	8.1	2.74	18.9
GOT N2	PM-10140 S	29/07/97	<u>Na</u> -HCO ₃	-13.7	7.8	3.99	17.4
GOT N2	PM-13189 S	13/03/96	<u>Na</u> -Ca- HCO ₃ -SO ₄	-13.8	17.8	1.19	3.8
GOT N2	PM-13189 S	29/07/97	<u>Na</u> - HCO ₃ -SO ₄	-13.9	12.6	1.08	27.0
GOT N2	PM-15260 S	13/03/96	<u>Ca</u> -Na- HCO ₃ -SO ₄ -(Cl)	-12.4	18.4	1.50	12.6
GOT N2	PM-15260 S	29/07/97	<u>Ca</u> -Na-SO ₄ -HCO ₃ -(Cl)	-	-	1.21	20.2
GOT N2	PM-16070 S	19/12/95	<u>Ca</u> -Na-HCO ₃ -SO ₄	-12.9	13.4	0.55	13.4
GOT N2	PM-16070 S	29/07/97	<u>Ca</u> -Na-HCO ₃ -SO ₄	-12.8	15.3	0.57	12.6
GSB	PM-1016 S	24/04/96	<u>Ca</u> -(Mg)- HCO ₃ -SO ₄	-13.4	29.8	0.18	14.1
M-B	PM-3369-S	26/03/96	<u>Ca</u> -(K)- HCO ₃ -SO ₄	-14.7	14	0.08	3.8
M-B	PM-3369-S	3/06/96	<u>Ca</u> -(Na)- HCO ₃ -SO ₄	-	19.9	0.09	5.0
M-B	PM-3369-S	9/09/96	<u>Ca</u> -(Na)- HCO ₃ -SO ₄	-	15.8	0.09	2.9
M-B	PM-3369-S	10/02/97	<u>Ca</u> -(Na)- HCO ₃ -SO ₄	-14.7	14.3	0.09	0.8
M-B	PM-3369-S	12/05/97	<u>Ca</u> -(Na)- HCO ₃ -SO ₄	-15.1	13.8	0.09	0.6
M-B	PM-3667-S	10/02/97	<u>Ca</u> -(Na)- HCO ₃ -SO ₄	-15.8	15	0.13	6.6
M-B	PM-3667-S	12/05/97	<u>Ca</u> -Na- HCO ₃ -SO ₄	-15.6	13.1	0.16	0.8
M-B	PM-5491-S	26/03/96	<u>Ca</u> -Na- HCO ₃ -SO ₄	-14.9	19.2	0.30	18.4
M-B	PM-5491-S	3/06/96	<u>Ca</u> -Na- HCO ₃ -SO ₄	-15.5	14.9	0.36	10.6
M-B	PM-5491-S	9/09/96	<u>Ca</u> -Na- HCO ₃ -SO ₄	-	19.9	0.34	23.8
M-B	PM-5491-S	10/02/97	<u>Ca</u> -Na- HCO ₃ -SO ₄	-	17.2	0.36	11.2
M-B	PM-5491-S	12/05/97	<u>Ca</u> -Na- HCO ₃ -SO ₄	-	20	0.35	9.9
ROM (Gav)	PM-0	2/04/97	<u>Ca</u> - HCO ₃ -SO ₄	-	13.1	0.13	8.2
ROM (Gav)	PM-42	1/06/95	<u>Ca</u> -HCO ₃ -(SO ₄)	-9.9	13.1	0.08	11.7
ROM (Gav)	PM-201	10/07/95	<u>Ca</u> -HCO ₃ -(SO ₄)	-	12.6	0.07	12.3
ROM (Gav)	PM-254	1/06/95	<u>Ca</u> -(Mg)- HCO ₃ -SO ₄	-10.4	13.6	0.13	16.8
ROM (Gav)	PM-254	24/04/95	<u>Ca</u> -(Mg)- HCO ₃ -SO ₄	-	12.9	0.16	17.4
ROM (Gav)	PM-540	10/07/95	<u>Ca</u> -HCO ₃ -(SO ₄)	-10.7	13.9	0.08	11.8
ROM (Gav)	PM-540	15/12/95	<u>Ca</u> - HCO ₃ -SO ₄	-	12.7	0.09	2.4
ROM (Gav)	PM-717	6/10/95	<u>Ca</u> -(Na)- HCO ₃ -SO ₄	-11.0	7.5	1.86	16.8

ROM (Liv)	PM-0	1/06/95	<u>Ca</u> -(Mg)- <u>HCO₃</u> -SO ₄	-11.0	11.2	0.09	9.4
ROM (Liv)	PM-0	6/10/95	<u>Ca</u> -(Mg)- <u>HCO₃</u> -SO ₄	-11.0	12.1	0.09	18.4
ROM (Liv)	PM-0	2/04/97	<u>Ca</u> - <u>HCO₃</u> -SO ₄	-	10.4	0.10	15.2
SB	PM-2200 S	8/05/96	<u>Ca</u> - <u>HCO₃</u> -(SO ₄)	-11.3	9.6	0.09	4.0
SB	PM-650 S	8/05/96	<u>Ca</u> - <u>HCO₃</u> -SO ₄	-	15.8	0.04	5.9
VER	PM-4180 N	12/08/96	<u>Na</u> - <u>HCO₃</u> -(SO ₄)	-14.5	1.3	3.32	16.3
VER	PM-7165 N	12/08/96	<u>Na</u> -(Ca)- <u>HCO₃</u> -SO ₄	-14.8	0.9	2.49	19.2

Table 2 – Synthesis of isotopic and chemical analyses results for the studied water inflows.

ATG: AlpTransit Gotthard gallery; DIX: Cleuson-Dixence gallery (Part AB or C); GOT N2: Gotthard road tunnel; GSB: Great Saint Bernard road tunnel; M-B: Mont Blanc road tunnel; ROM: Romanche (Livet or Gavet gallery); SB: San Bernardino road tunnel; VER: Vereina railway tunnel. PM-x-S(N) is the name of the water inflow situated at x meters from the South(North)ern portal of the gallery. The water types are related to the Jäckli classification (1970).

Group	Type	Geological origin	Range [TU]	Mean [TU]
Group A	<u>Na-HCO₃</u>	Crystalline rock	0.9-17.8	5.7
Group B	<u>Ca-HCO₃</u> -SO ₄	Metamorphic rock	4.6-15.8	12.1
Group C	<u>Ca-Mg-HCO₃</u> -SO ₄	Greenschist	3.1-29.8	14.8
Group D	<u>Ca-Na-HCO₃</u> -SO ₄	Granitic rock (granite and orthogneiss)	0.8-19.9	15.2
Group E	<u>Ca-Mg-SO₄</u>	Triassic dolomite	1.8-30.5	14.3

Table 3 – Tritium activity of waters classified according to their hydrochemical group.

Water inflow	Geology	Date	$\delta^{18}\text{O}$ [‰]
PM 936	G. Leventina	28/04/94	-13.7
PM 1590	G. Leventina	27/06/94	-13.7
PM 1590	G. Leventina	15/09/95	-13.1
PM 1550	G. Leventina	20/10/94	-13.4
PM 1550	G. Leventina	15/09/95	-13.5
PM 1619	G. Leventina	29/06/94	-13.7
PM 1619	G. Leventina	15/09/95	-12.9
PM 2110	G. Leventina	20/10/94	-13.2
PM 2110	G. Leventina	15/09/95	-13.2
PM 2370	G. Leventina	27/10/94	-13.7
PM 2370	G. Leventina	15/09/95	-13.9
PM 2840	G. Leventina	13/12/94	-13.7
PM 2840	G. Leventina	15/09/95	-14.5
PM 5406	G. Lucomagno	19/02/96	-14.4
PM 5406	G. Lucomagno	21/02/96	-14.3
PM 5406	G. Lucomagno	21/02/96	-13.9
PM 5552	Piora	30/03/96	-12.4
PM 5552	Piora	31/03/96	-12.3
PM 5552	Piora	01/04/96	-12.5

Table 4 - Isotope analyses results for the AlpTransit Gothard gallery (data from Schneider, 1997).