# HYDROGEOLOGICAL IMPACT OF FIRENZUOLA RAILWAY TUNNEL (ITALY): INFERENCES FROM THE CHEMICAL AND ISOTOPE COMPOSITION OF SURFICIAL AND GROUND WATERS

**Luca Ranfagni [1], Fabrizio Gherardi [2] and Stefano Rossi [1]**
[1] Environmental Protection Agency of Tuscany (ARPAT ), Via Porpora 22, Firenze, 50144, Italy, luca.ranfagni@arpat.toscana.it
[2] Consiglio Nazionale delle Ricerche (CNR), Istituto di Geoscienze e Georisorse (IGG), Via Moruzzi 1, Pisa, 56124, Italy, f.gherardi@igg.cnr.it

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## Introduction

The Firenzuola tunnel is part of the new Bologna-Firenze high-speed railway, opened in 2009. This tunnel, located approximately 29,2 to 44,5 km northwards of Firenze, was excavated at an elevation of 300-350 m a.s.l, below the main apenninic watershed (mean elevation 1000-1100 m a.s.l.; Rodolfi et alii, 2004).
The excavation of the Firenzuola tunnel caused a significant drop of groundwater levels, and the drying out of springs and creeks regionally, due to the seepage of surrounding groundwater into the tunnel (AA.VV. 2008). About 250 L/s of groundwater currently discharge into this tunnel during the low-flow season, but a maximum inflow of 900 L/s was estimated, along the whole tunnel, during the digging.
The main purpose of this study was to elaborate an integrated hydrogeological and geochemical model of the area impacted by the tunneling works, and possibly identify the main structures connecting the tunnel with streams and surficial aquifers.

## Methods

Samples were repeatedly collected on a total of 46 water points during the period 2004-2009, and an additional point was sampled in 2011 and 2012. Temperature, pH, electric conductivity were measured in the field. The concentration of major (Ca, Mg, Na, K, Cl, $HCO_3$, $SO_4$) chemical constituents was determined in the ARPAT laboratories of Firenze, whereas the isotopic composition of water ($\delta^{18}O$, $\delta^2H$, $^3H$) was measured in the CNR-IGG laboratories of Pisa.

## Results and discussion

Three main types of waters were considered for this study: i) creeks and streams, ii) springs and wells; iii) tunnel seeps. All the sampled waters have pH values between 6.7 and 10, with the most alkaline values associated to tunnel seeps. Waters inflowing in the Firenzuola tunnel are generally more saline (up to 848 mg/L) than waters from springs (238-508 mg/L) and streams (314-574 mg/L). Surficial waters have a Ca-$HCO_3$ signature, whereas the chemical composition of tunnel inflows varies from Ca-$HCO_3$ to Na-$CO_3$–$HCO_3$ with increasing salinity. The prolonged interaction of meteoric waters with host rocks causes $Na_{TOT}$ concentrations to increase and $Ca_{TOT}$ to decrease in tunnel seeps (Figs. 1 and 2). Decreasing tritium contents ($^3H$ <4 UT; Fig. 1) are good tracers of i) prolonged underground residence times, and ii) of the lack of mixing with meteoric waters ($^3H$ >5 UT) rapidly infiltrating in the Marnoso Arenacea flysch.

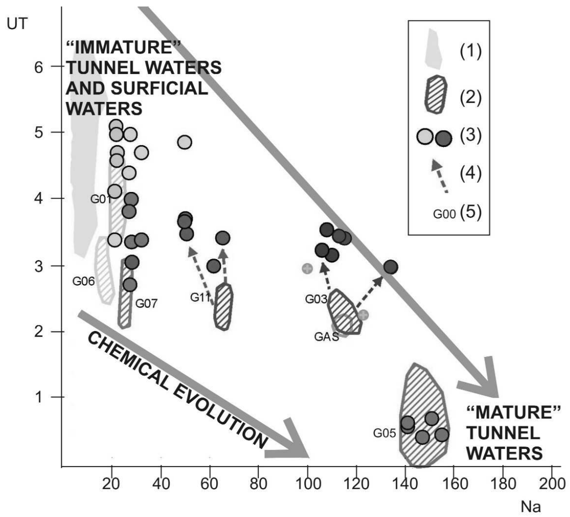


*Fig.1 – Tritium (UT)-Na correlation for streams and springs (1), 2004 (2) and 2007/08 tunnel seeps (3). Dotted arrows (4) indicate major variations over the period 2004 to 2007/08. Labels (5) identify tunnel water points (Gxx = Firenzuola, GAS = Allocchi).*

A reaction-path modeling approach was applied to simulate water-rock interactions likely occurring in the Marnoso Arenacea aquifer. Numerical outputs indicate that most saline and alkaline waters sampled in the inner part of the Firenzuola tunnel (Southern sector, zone I of Fig. 3) can be produced by hydrolysis of the Marnoso Arenacea flyschs.
The stable isotope composition of waters indicates that tunnel seeps have a common meteoric origin, compatible with precipitations

falling in Central Italy (d-excess = 15).

By combining hydrogeological and geological information with data on chemical and isotope composition of waters, we derived a model of underground water circulation which considers two main hydrogeological sectors in the tunnel (Fig. 3). The northern sector of the tunnel is dominated by the rapid infiltration of meteoric waters, as testified by the direct drainage from Veccione stream (Vincenzi et alii, 2013).

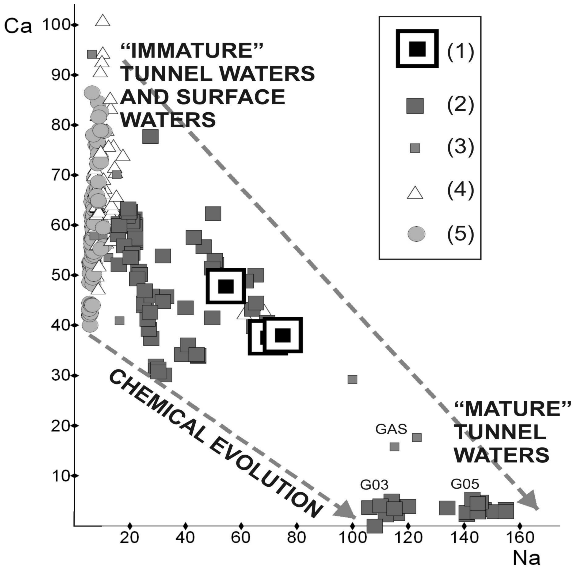


*Fig.2 – Ca-Na correlation diagram. 1) Firenzuola tunnel, southern entrance, 2012; 2) Firenzuola tunnel, 2004-2007; 3) Allocchi tunnel; 4) streams; 5) springs.*

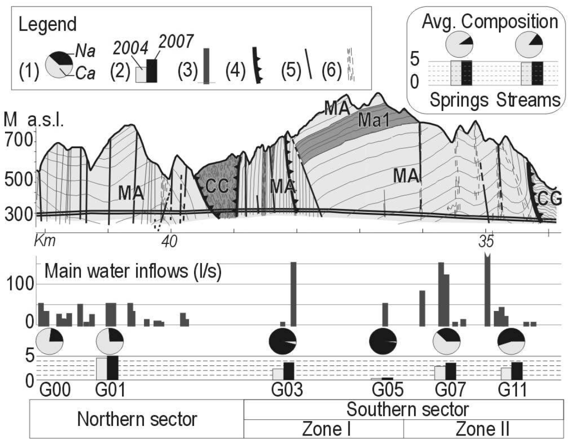


*Fig. 3 – Projection of selected geochemical parameters over the geo-structural cross-section of the Firenzuola Tunnel. (1) Ca/Na ratio; (2) tritium content in 2004 and 2007; (3) inflow rates (L/s) during the excavation; (4) thrusts; (5) faults or main fractures; (6) fractured belts; (MA); Marnoso-Arenacea fm.; (MA1) marl-rich member of Marnoso-Arenacea fm.; (CC) Caothic Complex; (CG) Castel Guerrino fm.*

The southern sector comprises two sub-zones: the first one (Zone I), adjacent to the olistostrome, is dominated by relatively ancient waters (likely older than 100 years; $^3H$ generally <2 UT), having high pH values, and Na-$CO_3$-$HCO_3$ composition. In this zone, the occurrence of marl-rich, relatively impermeable strata of the Marnoso-Arenacea fm. above the tunnel (MA1 in Fig. 2) prevents meteoric precipitation from infiltrating in the excavated area. The remaining zone (Zone II), is characterized by the occurrence of the same "old" waters of Zone I, locally mixed with waters rapidly percolated in the aquifer through well-defined fractures zones.

The occurrence of long residence water circuits, is further supported by: (i) the presence of low-$^3H$ waters in the Allocchi tunnel, a railway tunnel excavated at the end of XIX century in the same flysch formation of the Firenzuola tunnel, not far (8 km) from the area of study; (ii) the measurable contribution of waters with prolonged residence times during the low-flow season in the water points sampled in 2011 and 2012 at the southern entrance of the Firenzuola tunnel.

## Conclusions

Combined with geological and hydrogeological information, a detailed chemical and isotope survey of 47 water points (streams, springs, wells and tunnel seeps) during the period 2006-2012 contributed to the definition of an integrated hydrogeochemical model of an area impacted by the tunneling works for the Bologna-Firenze high-speed railway. Water isotopes revealed that waters of different age are drained by the Firenzuola tunnel, with the oldest groundwater component likely being older than 100 years. The chemical characteristics of tunnel seeps are controlled by the extent of interactions with aquifer rocks (Marnoso Arenacea flysch). More prolonged residence times and/or effective water-rock interactions lead to more saline, pH alkaline waters of Na-$CO_3$-$HCO_3$ composition.

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