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Compositional multivariate statistical analysis of the hydrogeochemical processes in a fractured massif: La Línea tunnel project, Colombia

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ABSTRACT

Hydrogeochemical and isotopic data were used to improve the understanding of 1) Groundwater flow in a complex fractured aquifer system, 2) Surface water – groundwater interactions, and 3) Groundwater evolution within the La Línea Massif in the Cordillera Central of the Colombian Andes, using two roadway tunnels drilled there as a natural laboratory. The La Línea Massif is a crystalline structure formed by two igneous-metamorphic fractured complexes (Cajamarca Group and Quebradagrande Group), plus andesitic porphyry rocks from the Cenozoic period. The tunnels traverse eight main fault zones, where higher infiltrations of groundwater into the tunnels were reported. Water samples were collected at the surface and within the tunnels in three different sampling rounds in 2010, 2014 and 2015. Major ion concentrations and $\delta^{18}O$ and $\delta^{2}H$ stable isotopic ratios were measured. This database is a unique opportunity to investigate water-rock interaction processes through time in a dewatering crystalline rock massif in such an important area in the Colombian Andes. Compositional data analysis (CoDa) techniques were implemented on the major ion data before a multivariate statistical analysis (MSA). The MSA included a compositional principal component analysis (PCA) and a compositional hierarchical cluster analysis (HCA), combined with more classical graphical methods for the classification of water chemistry data, such as Piper and Stiff diagrams. According to the compositional HCA and PCA, the obtained components and clusters are first related to the location of the samples (surface or tunnel samples) followed by the geochemical processes. The geochemical variability of the massif is associated with the weathering of silicates and pyrite oxidation that generates carbonate dissolution as a result of the drainage caused by the tunnels. A temporal evolution characterized by a decrease in pH, conductivity and Mg^{2+} concentrations was observed. The analysis of the stable isotopes, ^{2}H and ^{18}O, suggests that the sampled groundwater has a common origin: recharge waters with specific signatures for the east and west watersheds that exhibit alterations due to hydration because of the dissolution of plagioclases and rock-water interactions with materials exposed to hydrothermal fluids.

1. Introduction

The La Linea project consists of two tunnels that traverse a highly fractured massif in the Cordillera Central of the Colombian Andes. These tunnels will belong to one of the principal Colombian roadways that connect the main productive centres of the country with the largest port on the Pacific Ocean. In the tunnel area, fault zones express themselves in surface creeks and drainage systems in which surface water flow has decreased since the tunnel works started (IRENA, 2007, 2010; UNAL, 2010, 2015). This change in the hydrogeological regime expresses itself in persistent water ingresses inside the tunnels. Underground tunnelling works such as these generate environmental impacts in the surrounding systems due to these infiltrations (Font-Capó et al., 2011; Maréchal et al., 2014; Perrochet and Dematteis, 2007; Pujades et al., 2015; Valenzuela et al., 2015; Vincenzi et al., 2009; Yang et al., 2011). It causes changes in the hydrogeological regime until a new steady state is reached by the aquifer (by tunnel drainage) and a progressive stabilization of discharge is observed (Adinolfi Falcone et al., 2008; Celico et al., 2005). Tunnelling may also cause alterations in the groundwater chemistry that can be observed and understood using hydrogeochemical and isotopic analyses (e.g., Ii and Kagami, 1997). The present study uses the La Linea tunnels as an opportunity to obtain a better understanding of: 1) Groundwater flow in a complex fractured aquifer system; 2) Surface water-groundwater interactions; and 3)

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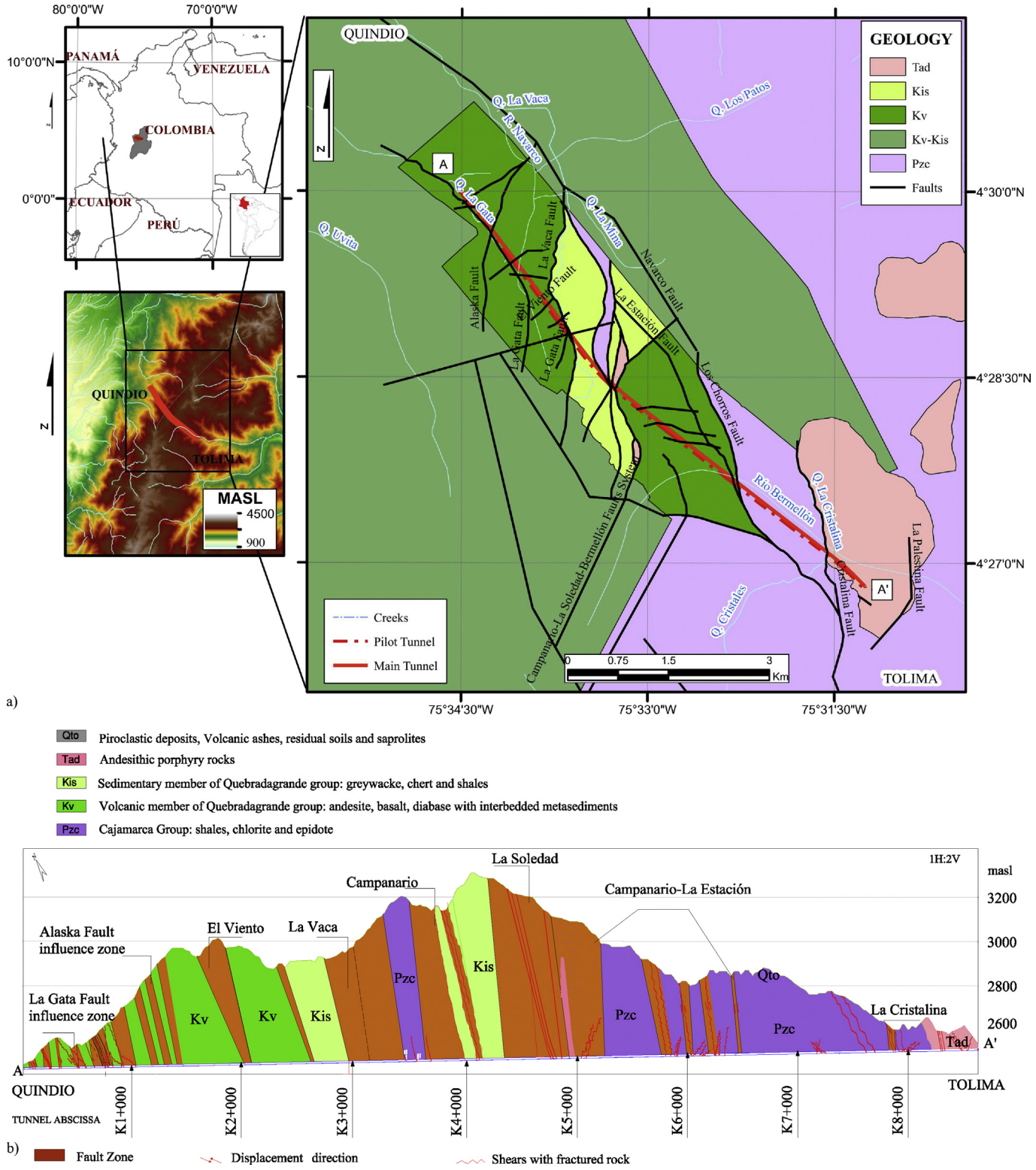

Fig. 1. The La Línea tunnels study area: (a) geographical situation, the La Línea tunnels location (−75.52W, 4.45N and −75.57W, 4.50N) and local geology description, (b) geological cross section A-A'; the elevation of the tunnel beneath the land surface is indicated by the blue line. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

Groundwater evolution in a crystalline massif, by analysing hydrogeochemical data from water samples collected in the La Linea influence zone (groundwater and surface water), combined with classical graphical methods, such as Piper and Stiff diagrams, stable isotope analyses and electrical conductivity (EC) measurements. This database provides a unique opportunity to investigate water-rock interaction processes through time in a dewatering crystalline rock massif (and assess implications for the local environment) in such an important area in the Colombian Andes.

Hydrogeochemical analysis techniques and stable isotope analysis (e.g., ^{18}O and ^{2}H) have been widely used for a better understanding of hydrogeological systems (Smellie et al., 1995; Jayakumar and Siraz,