ORIGINAL ARTICLE

Natural controls validation for handling elevated fluoride concentrations in extraction activated Tóthian groundwater flow systems: San Luis Potosí, Mexico

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Abstract

Fluoride concentration in groundwater supply above the guideline value of 1.5 mg/L is a health hazard for the population living in two thirds of the Mexican territory. Enhanced groundwater extraction in the city of San Luis Potosí (SLP), Mexico, led to a substantial territorial increase in water with high fluoride (F^-) which originates from thermal water–rock interaction with regional rhyolites. Previous knowledge of the Tóthian groundwater flow systems around SLP City and their F^- concentrations from 1987 data provided an insight into natural F^- controls for the construction and operation of boreholes. During the period 1987–2007, the number of new boreholes increased as well as the relocation of boreholes whose production diminished. Overall estimated extraction augmented from 2.6 to 4.1 m^3/s. Results obtained for 2007 suggest that F^- controls defined for 1987 data (e.g., variable portions of F^--rich deep thermal water in borehole yields) are also valid in newly constructed boreholes. Water authority actions related to groundwater extraction lack consideration of proposed F^- controls, so constructed boreholes progressively tapping the high F^- groundwater flow system resulted in a 85% increase in the F^- affected territory (> 2 mg/L) between 1987 and 2007. Reduction in F^- extraction following the proposed natural control mechanisms (e.g., fluorite precipitation) was also confirmed. Applying geochemical and mineralogical analysis, rhyolites surrounding the SLP graben basin and contributing to its volcano-clastic sedimentary filling were identified as the primary F^- source for elevated concentrations in groundwater of the area under investigation.

Keywords Hydrochemistry · Fluorosis · Arid regions · Volcanic aquifer · Groundwater management · Mexico

Introduction

Importance of fluoride management

Groundwater is the major source of potable water supply in arid and semiarid regions. However, its availability may be threatened not only by the introduction of contaminants through human activities but also by natural processes (McArthur et al. 2012; Nicolli et al. 2012; Jia et al. 2014; Edmunds et al. 2015; Banning and Rüde 2015). The contribution of some minor and trace elements (e.g., fluoride, iron, arsenic, uranium, lead, and cadmium) that change the quality of extracted groundwater is a substantial health hazard in many groundwater regions worldwide (e.g., Edmunds and Smedley 1996; Fendorf et al. 2010; Guo et al. 2014; Jia et al. 2014, 2017; Bjørklund et al. 2017). Recently, the impact of trace elements in the water supply of Mexico has started to be given consideration in groundwater management.

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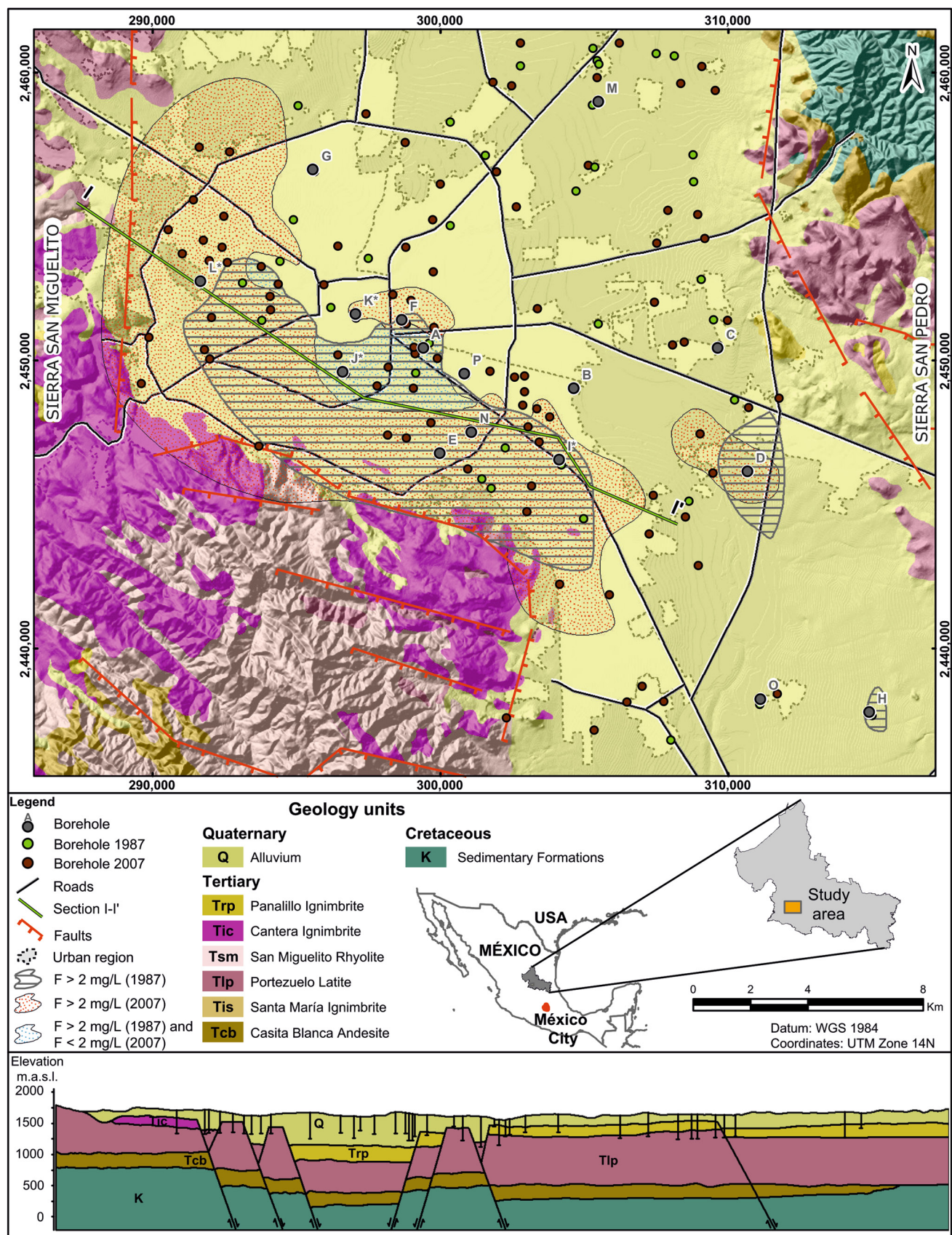5 Institute of Hydrogeology, RWTH Aachen University, Lochnerstr. 4-20, 52064 Aachen, Germany

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Carrillo-Rivera et al. (2002) proposed feasible natural F^- management controls at borehole site without the need of a water treatment plant. These management approaches might be applied elsewhere as F^- is a common natural constituent that threatens groundwater supply in both industrialized and developing countries (e.g., Lucas 1988; Gaciri and Davies 1993; Valenzuela-Vásquez et al. 2006; Amini et al. 2008; Nicolli et al. 2012; Guo et al. 2012; Navarro et al. 2017; Raju 2017). In the semiarid eastern part of the Sierra Madre Occidental alone, at least some 15% of the total Mexican population (estimated to be in excess of 110 million people), are supplied with regional F^--rich groundwater.

Study area

The investigation area is located around San Luis Potosí (SLP) City, capital of the homonymous state, in the semi-arid north-central part of Mexico (Fig. 1). It hosts one of the conurbations of the country with the highest population growing rate (broadly 5–7% p.a.), and presently has around one million inhabitants.

The study area is part of one of the several closed basins existing in the north-central part of Mexico. The steep surrounding mountain ranges of Sierra de San Miguelito (SSM, west of SLP) and Sierra de San Pedro (SSP, east of SLP) consist of Tertiary felsic volcanic and Cretaceous calcareous rocks, respectively (Fig. 1). These sierras have an elevation exceeding 2300 m a.m.s.l. and slope toward the plane of the drainage basin which has an altitude of about 1900 m a.m.s.l. The mean annual air temperature is around 17.5 °C, while the summer mean temperature is around 21 °C.

The San Luis Potosí Volcanic Field (SLPVF) is located between the morphotectonic province of Sierra Madre Oriental, and the volcanic province of Sierra Madre Occidental (Guzmán and De Cserna 1963), in the southern part of the Mesa Central. The main local geological features are associated with a thick (> 1500 m) sequence of extrusive tertiary volcanic rocks and alluvial materials, covering a Cretaceous limestone and calcareous mudstone sequence outcropping in folded NW–SE-striking structures in SSP (Fig. 1, cross section); suchlike features are typical for a number of similar basins in the Sierra Madre Occidental (400 km wide and 1500 km long, hosting volcanic rocks with a total thickness of 2–3 km) and other regions of northwestern Mexico and the southwestern USA. The Tertiary volcanic units relevant

for this study were generated in several stages and are briefly presented in the following paragraph, according to the volcano-stratigraphy developed by Labarthe-Hernández et al. (1982; cf. Fig. 1).

The emplacement of the SLPVF began with the *Casita Blanca Andesite* which is composed of basaltic to andesitic lava flows of porphyric texture with ~ 5 vol.% of biotite and plagioclase phenocrystals; ages obtained for this unit are between 43.7 and 36.5 Ma (Tristán-González et al. 2009). The subsequent *Santa María Ignimbrite* yields welded ash-flow tuffs with 30–40 vol.% of mainly quartz and sanidine phenocrystals and collapsed pumice (Tristán-González et al. 2006, 2009). The *Portezuelo Latite*, generated around 30.6 Ma, consists of different lava flows with porphyric texture (30 vol.% of sanidine, albite, and quartz phenocrystals). It overlies some Mesozoic marine formations with discordant contact and is stratigraphically followed by the *Panalillo Ignimbrite* (Tristán-González 1986). The latter unit is composed of two members with the inferior member consisting of pyroclastic flows filling small tectonic structures and the superior one of co-ignimbrite and welded ignimbrite; their age is between 26.8 and 28.0 Ma (Tristán-González et al. 2009). The *San Miguelito Rhyolite* was named after the outcrop of the lava flows in the Sierra de San Miguelito. This widespread unit is composed of highly viscous, topaz-bearing lava flows that formed dome structures showing flow foliation, shrinkage fractures and tephra surges similar to structures reported from the USA by Christiansen et al. (1983). This rock has 5–20 vol.% of phenocrystals of quartz and feldspar in the devitrified matrix (Aguillón-Robles et al. 1994; Tristán-González et al. 2009). The *Cantera Ignimbrite* was described as a violet to gray colored rock with 5–10 vol.% of phenocrystals (quartz and sanidine) and uncollapsed pumice. It is associated with the main volcanic event of the Sierra de San Miguelito. The *El Zapote Rhyolite* (not sampled for this study) represents the latest volcanic event of the Sierra de San Miguelito and is composed of gray colored lava flows with ~ 30 vol.% of phenocrystals (quartz, sanidine) and an isotopic age of 27.0 Ma (Nieto-Samaniego et al. 1996). Overall, the studied volcanic rocks are geochemically well differentiated (felsic to intermediate).

Expansive structures (mainly normal faults) bound a regional horst and graben structure and were used as conduits for volcanism (Tristán-González 1986). Based on geochemical variations, Orozco-Esquivel et al. (2002) divided the described succession into a lower and an upper volcanic sequence. The younger (upper) one consists of mainly rhyolitic lavas that contain topaz and are enriched in F and incompatible lithophile elements. This subdivision was adopted for geochemical interpretations in the present study (cf. "Geochemical and mineralogical characterization of the fluoride source" section). The allocation of the sampled lithologies for the two sequences can be found in Table 1.