Journal of Hydrology 547 (2017) 690–707

Contents lists available at ScienceDirect

Journal of Hydrology

journal homepage: www.elsevier.com/locate/jhydrol

Research papers

Respective roles of the weathering profile and the tectonic fractures in the structure and functioning of crystalline thermo-mineral carbo-gaseous aquifers

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A R T I C L E I N F O

Article history:
Received 7 September 2016
Received in revised form 13 February 2017
Accepted 14 February 2017
Available online 16 February 2017
This manuscript was handled by Corrado Corradini, Editor-in-Chief, with the assistance of Brian D. Smerdon, Associate Editor

Keywords:
Crystalline rocks thermo-mineral and carbo-gaseous aquifers
Weathering profile
Deep fractures
Geology
Hydraulic tests
Hydrochemistry

A B S T R A C T

Crystalline thermo-mineral and carbo-gaseous (CTMCG) hydrosystems are well known for their economic importance in fields such as thermal, spa activities and natural mineral water (NMW) bottling. Such systems are usually associated with strong structural complexity, which is rarely characterised in detail or robustly. This research focuses on a CTMCG hydrosystem associated with a peri-alpine graben. A multidisciplinary approach with a very large set of data and methods – geological modelling with geophysics and geological data from outcrops and several boreholes, hydrodynamic data, hydrochemistry, hydrogeological and geochemical modelling – reveals very novel results and allows a robust conceptual model to be constructed. The aquifer at the origin of the carbo-gaseous natural mineral water is the 100–125 m-thick fractured stratiform layer of the weathering profile of the crystalline rock (granite). It forms a rather large and thick inertial aquifer that can be numerically modelled, in a similar fashion to a porous medium. The majority of tectonic faults length act as impervious boundaries that divide this aquifer into around ten elongated compartments that were precisely delineated. These tectonic faults are permeable only along two small areas that were also precisely located. These permeable zones feed some aquifer compartments with deep, highly mineralised carbo-gaseous water, which mixes with "fresher" water and forms the exploited NMW. These results can be generalised and in particular show a strong opposition between low-inertia CTMCG hydrosystems without a subsurface reservoir, as the weathering profile was eroded, and high-inertia hydrosystems such as the one studied.

1. Introduction

Thermo-mineral and carbo-gaseous hydrosystems, well known for their economic importance, have been exploited for centuries for thermal and spa activities. Sparkling natural mineral waters, bottled in Europe since the early 17th century (Lopoukhine, 1998), still constitute a dynamic industry (Renac et al., 2009; Cinti et al., 2014). These hydro-systems are associated with specific geological structures, such as faults and fractures in crystalline bedrock, that allow deep (hot) fluids and/or gases to flow to the ground-surface. Case studies are scarce in geological sedimentary contexts where gaseous fluxes are often masked by the sediments. These high heat/gas flow areas are generally associated with recent volcanism and/or extensional tectonics such as graben or back-arc basins (Barnes et al., 1984; Kerrick et al., 1995; Matthews et al., 1987; Weinlich, 2005).

Despite their economic importance, structurally complex, crystalline thermo-mineral and carbo-gaseous (CTMCG) hydrosystems have rarely been characterised in detail (Maréchal et al., 2014). In the absence of a better alternative, groundwater fluxes are often

Abbreviations: BRGM, Bureau de Recherches Géologiques et Minières; CGG, Compagnie Générale de Géophysique; CTMCG, Crystalline Thermo-Mineral and Carbo-Gaseous; EMMA, End-Member Mixing Analysis; GW, GroundWater; MARTHE, Modelling of Aquifers with Rectangular grid in Transient state for Hydrodynamic calculations of hEads and flows; PCA, Principal Component Analysis.

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http://dx.doi.org/10.1016/j.jhydrol.2017.02.028
0022-1694/

considered to be limited to fractures and faults related to the tectonic regime (Forster and Smith, 1989; Stober and Bucher, 1999) in hydraulically active faults whose geometries are poorly understood. Moreover, in many descriptions, faults are assimilated to pervious structures, often without any hydrodynamic description, even if several studies demonstrate that they are often impervious due to rock crushing and formation of sealing minerals (Mohamed and Worden, 2006; Lachassagne et al., 2011; Petrella et al., 2015; Tokan-Lawal et al., 2015).

Groundwater flow in crystalline aquifers may not be limited to tectonic fractures alone. Such aquifers often derive their hydrodynamic properties from weathering processes (Acworth, 1987; Chilton and Foster, 1995; Dewandel et al., 2006; Lachassagne et al., 2011, 2017), resulting in weathering profiles composed of several stratiform layers. From top to bottom, where not eroded, they include: i) several tens of metres thick unconsolidated saprolite layer and laminated saprolite layer, together forming the "regolith". Given its clayey–sandy composition, this superficial layer may have a high porosity (up to several percents, depending on the lithology of the parent rock) but low hydraulic conductivity. ii) an underlying "Stratiform Fissured or Fractured Layer (SFL)" (Lachassagne et al., 2011, 2017) forming the transmissive part of the aquifer. Within this layer, fracturing is induced by prolonged weathering processes, as a consequence of the chemical weathering stresses induced by swelling minerals such as biotite (Wyns et al., 2004; Dewandel et al., 2006; Lachassagne et al., 2011, 2017). Below the weathering profile (saprolite + SFL), (iii) the fresh basement is only permeable where discontinuities (ancient tectonic fractures, joints, veins, dykes, lithological contacts, etc.) induce the local deepening of the weathering front and, consequently, the development of some pervious fractures within ancient structures (Dewandel et al., 2011; Lachassagne et al., 2011, 2017).

Although the previously developed conceptual models based on groundwater flow through faults and tectonics fractures may be relevant, the hydrodynamic properties of such fractured aquifers are rarely characterised in detail, nor are their geometry or functioning described in 3D. Moreover, extensive SFL occur in shallow crystalline aquifers, while faults are not always, or rarely, permeable.

The aim of this work is to characterise in detail a CTMCG hydrosystem associated with a peri-Alpine graben to understand its geological structure and hydrogeological functioning. A multidisciplinary approach is developed using complementary methods: geological modelling with geophysics and geological data from outcrops and boreholes, hydrodynamic data and hydrochemistry, as well as hydrogeological and geochemical modelling. The combined results allow better conceptualisation of the hydrogeological system. The strengths of this work rely on the density of available information, rarely available in such a context, and the transferability of the resulting conceptual scheme.

2. Material and methods

2.1. Study site. Location, geological and hydrogeological description of the study area

The CTMCG system of Saint-Galmier, France, is located at the boundary between two distinct geomorphological and geological areas: the Forez plain to the West, with outcropping Oligocene to Quaternary sediments, and the Hercynian crystalline massif of the Monts-du-Lyonnais to the East (Fig. 1), separated by a major roughly N-S oriented tectonic fracture zone.

Structurally, the Forez Plain occupies a N-S elongated graben, the result of Cenozoic rifting associated with early stage Alpine orogeny (Fig. 1a). This extensive phase is highlighted by normal faults bordering the plain on both sides (Fig. 1b).

At Saint-Galmier, the N-S oriented border fault separates the Forez plain from the Monts-du-Lyonnais plutonic and metamorphic rocks. The city of Saint-Galmier lies on porphyritic calc-alkaline granite with biotite. The granite, where weathered at outcrop and in boreholes, exhibits:

(i) a thin layer of sandy saprolite, a clay-rich material with coarse sand-size clasts, thinned by Plio-Quaternary erosion,
(ii) a thick laminated saprolite layer (15 m to >30 m-thick). This layer is comprised of a consolidated highly weathered parent rock with a coarse sand-size clasts texture and a millimetre-scale dense horizontal lamination crosscutting the largest minerals,
(iii) and a stratiform fractured layer (SFL), met in boreholes but rarely seen at ground-surface. This layer is characterised by several fractured zones with a depth-decreasing density. Some of these zones include highly weathered materials similar to the sandy saprolite.

The rift basin of the Forez Plain is a relic of the system of the Loire's Limagne that belongs to the European Cenozoic peri-Alpine grabens (Fig. 1a). The graben is filled with Late Eocene to Miocene clayey-sandy sedimentary deposits up to 800 m thick in the central part of the basin (Ech-Cherif El Khetani, 1996; Briot et al., 2001). These sediments are continental, showing strong spatial heterogeneity at the basin scale with:

(i) a dominant clayey-conglomeratic and -sandy facies close to the borders and in the northern part, with piedmont facies derived from bordering high relief,
(ii) claystone and marl dominant facies in the central and southern areas with floodplain and lacustrine deposits (Gerbe et al., 1998). Quaternary alluvium of the Loire River and its tributaries – both recent and old –, covering the Forez plain, mask the Tertiary sediments described above (Fig. 2).

Several sparkling natural mineral waters (NMW) occur peripheral to the basin, the south-eastern border fault of the graben (Fig. 1) being the discharge point of the studied deep mineral carbo-gaseous system, the Saint-Galmier natural mineral water. The historical "Fontfort" spring (Fig. 4) has been exploited since historical times, being first bottled at Saint-Galmier in 1837. The commercial development of this source began with the digging and exploitation of deep large diameter wells, followed by the drilling of borewells during the second half of the 20th century. This caused the lowering of piezometric levels and the drying up of the spring during the 19th century. A hydrodynamic steady state was reached during the 20th century, with stable piezometric levels during the last several decades. The previous historic unsteady state is not documented within any databases.

2.2. Methods and data

In this research, a multidisciplinary approach was applied to obtain clues from each applied method. Results from the complementary methods were compiled to conceptualise the aquifer geologic structure and its hydraulic functioning. These various methods are described below.

2.2.1. Geological data (re)interpretation

Data from 254 boreholes (including 60 boreholes located in the narrow study area – Figs. 1 and 2) were analysed for geological and structural interpretation. Additional geological, weathering and structural (e.g. fractures, joints and faults) observations were carried out on 27 outcrops and on a 70 m-deep cored drill