Hydrothermal waters from karst aquifer: Case study of the Trozza basin (Central Tunisia)

Younes Hamed[1,2,*] Belgacem Redhaounia[3], Amina Ben Sâad[4], Rihab Hadji[5], Farid Zahri[5], Karim Zighmi[5]

1- Faculty of Sciences of Gafsa. Department of Earth Sciences. City of Zaroug 2100 - Gafsa-Tunisia.
2- Research Unit of Georesources, Geosystems and Geoenvironnemental " 3G "-Gabès-Tunisia.
3- Water Researches and Technologies Center Borj-Cedria (CERTE), BP 273 Soliman 8020, Tunisia.
4- Ministry of Health-Regional Blood Transfusion Center "RBTC" of Gafsa-Tunisia.
5- Farhat Abbas University, Sétif, Algeria.

* Corresponding Author: hamed_younes@yahoo.fr

Received: 12 October 2016 / Accepted: 02 February 2017 / Published online: 05 February 2017

Abstract

Tunisia is rich in geothermal resources from ancient civilizations. Hydrothermal activity in Tunisia has been related to three main stages: magmatic and tectonic activities, eustatisme (Atlantic and Mediterranean coupling) and climate change. The principal factor and the responsable of this phenomenon is the meteoric water by piston flow processes. It constitue the catalyst of volcanism. The Trozza basin, well known since the Roman period for the importance of its thermo-mineral waters, is characterized by a large occurrence of thermal fluid discharges whose main thermal aquifer. Hydrochemical pattern is mainly controlled by the dissolution of evaporitic sediments (halite, gypsum and/or anhydrite) as well as by the incongruent dissolution of carbonate minerals. This reservoir represents the only vapor hydrothermal system in Tunisia. It is constitute the deepest formation cropping out in the study area. The Triassic deposits and the filonic of Pb-Zn/S caused the contamination of the Continental Intercalaire thermal water in this reservoir. The upwelling of the deep groundwater to the shallow level and discharging also in karst caves of the carbonates minerals. This carbonate reservoir of thermal water (≈ 50 °C), consist of emissions of hot air and vapors and represent a unique case gas hydrothermal karst in Tunisia. It plays a role in the attraction for local population and tourists. But the use of geothermal energy is still in its juvenile stage. Presently, the thermal waters are a resort for wellness, fitness and therapeutic purposes. Kairouan basin, in particular, has numerous thermo-mineral springs, the majority of which are used for public baths, swimming pools, and for medical treatments provided by thermal establishments. Previous studies have shown that location and chemical composition of these thermal manifestations are strongly influenced by the regional geology, the tectonic and the climate impact.

Keywords: Thermal water, Karst aquifer, Trozza basin, Tunisia.

1- Introduction

Circulation of hydro-geothermal fluids in the Earth's crust takes place under various tectonic and climatic regimes and geological situation. Recharge and discharge of groundwater systems are highly climate dependent. Both Tunisia and Algeria suffers from limited surface water resources. Consequently, numbers of studies have been carried out in the last decades

(ERESS, 1972; Ben Dhia, 1987; Edmunds *et al*., 1997, 2003; OSS, 2003; Al-Gamal, 2011; Kamel, 2012; Hamed *et al*., 2013) with the main aim of evaluating the potential of groundwater resources in this region.

The northern part of the Sahara comprises the deep "Continental Intercalaire" (C.I.) logged in the continental formations of the lower Cretaceous. With a surface area of approximately 1,000,000 km^2, the C.I., which extends across Algeria, Tunisia, and Libya, constitutes one of the largest groundwater reserves in the world. Nowadays, more than 600 boreholes exploit water from different aquifer levels with the mean productivity equal to approximately 170 Mm^3.y^{-1} (OSS, 2003). This consumption was increased by random access after the Tunisian Revolution of 14 January, 2011. Obviously, this consumption of groundwater was in relation with the consumption of petroleum fluids and shale gas in the Sahara of the North Africa.

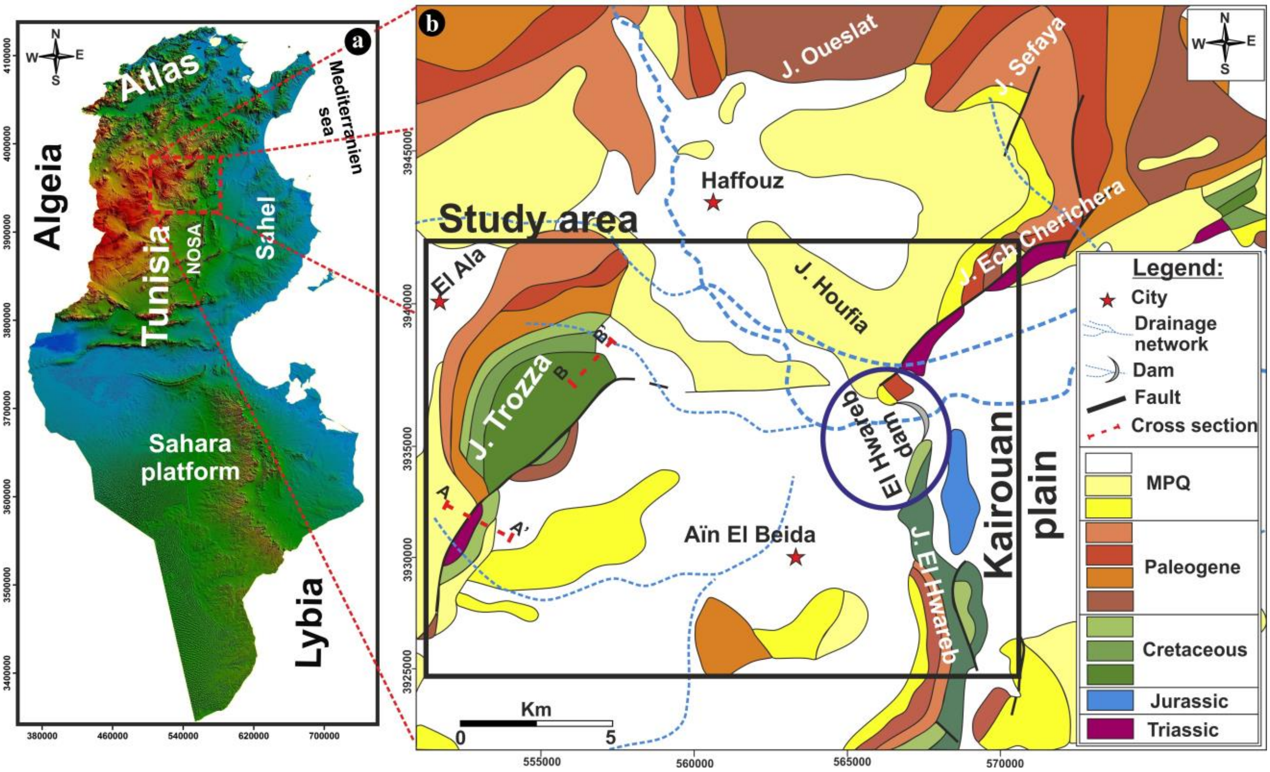

Figure 1a) Geographic location of the study b) Geological map of the study area (Ben Hadj et al., 1985).

The study area is limited to the East and North by the Mediterranean coast, to the West by the Algerian territory and to the South by the Tunisian Sahara Platform (Fig. 1a). In this underground area of Trozza basin, flows are accessible in many natural cavities (speleology) and in galleries of the anticline of J. Trozza. All the flow points (permanent and temporary) are located throughout the gallery (Fig. 1b). This study is based on hydrodynamical flow measurements in a gallery. This artificial gallery intersects arbitrarily fault networks from 10 to 50 m depth in carbonated rocks. In this work, data series of discharge, water temperature, hydrochemistry and geophysical from karst springs located in central Tunisia, have been coupled and used with the aim of characterizing the hydrogeological processes that take place within the carbonate aquifer (Fig. 1b). This permits to define the role of the saturated and the unsaturated zones (including soil and epikarst) in the hydrogeological functioning of this specific aquifer in central Tunisia.

This paper combines a synthesis of relevant published information with new data (hydrochemistry data of boreholes, lithostratigraphic lithology of the boreholes, direct data observation…) to reinterpret, and reviews the hydrogeological features of the karst aquifer systems from central Tunisia that may be used more widely in thermal water source evaluation across the country.

2- Study area

The Trozza basin is located approximately 40 km northwest of the Kairouan city. This study area comprehends a sector of Tunisia located between latitudes 55000 mE and 570000 mE, and longitudes 3925000 mN and 3945000 mN, and incorporates a total area of 625 km^2 (Fig. 1b). Elevations increase from 265 m above mean sea level in the Haffouz plain to 985 m at Trozza Mountain. This region is incised by principal drainage system "Merguellil wady", that constitute the principal input surface water of Kairouan basin. It is distinguished by an arid climate with mean annual precipitation of 100 mm, mean annual temperature of 20 °C and potential evapotranspiration of 1750 mm.year-1 (Ben Ammar, 2007; Mejri, 2010).

3- Geological and hydrogeological setting

In this study, we are mainly interested in the geological structures associated with the Tertiary formations, which constitute the main fractured carbonate reservoirs of Cretaceous. The outcropping formations of the study area are showing a lithological variety, ranging from the Triassic to the Quaternary (Ben Hadj, 1985).

Hydrogeology plays a major role in all aspects of environmental planning, execution and implementation. Without a safe sustainable water supply, life cannot exist and hopes for prosperity are limited. In arid/semi-arid of North Africa countries, issues related to water resources are of growing concern due to different environmental, economic and social factors. Karstic aquifers are of particular interest and importance to Southern Mediterranean countries, because they contain most of their groundwater resources. Their structure and dynamics are complex (Bakalowicz, 1995), because they modify various hydrodynamic features and flow conditions (Al-Fares *et al*., 2002; Vouillamoz *et al*., 2003).

The northern part of the Sahara comprises the deep "Continental Intercalaire" (C.I.) logged in the continental formations of the Lower Cretaceous. With a surface area of approximately 1,000,000 km^2, the C.I., which extends across Algeria, Tunisia, and Libya constitutes one of the largest groundwater reserves in the world.

Continuously increasing abstraction of groundwater resources to meet rising industrial, agricultural, domestic and touristic needs, coupled with severe drought periods during the past decades leads to growing deficit of water. The drawdown of piezometric levels (0.5-1 m/y), progressing degradation of water quality, extinction of the artesianism and the geothermic groundwater are the main consequences of such intensive exploitation of deep aquifers in central Tunisia (Kairouan basin, Fig. 1) and also, the climate impact on groundwater (quality and quantity). Most climate models forecast an increase in temperature and a decrease in precipitation at the end of the 21st century as a consequence to climatic changes and climatic variability according to the specialist of the domain.

4- Materials and methods

The data used in the present study are the geophysical profils, lithostratigraphic logs of boreholes, direct observations and the hydrochemical study of groundwater and surface water (deep and shallow boreholes and dam). The groundwater samples were collected from the multi-aquifers wells from water-supply, El Hwareb Dam and agricultural wells, and nearby low thermal discharges (Fig. 1).

Water samples for Laboratory analyses were collected at the humid season (March, 2013).

Prior to sampling, all wells were purged in order to remove the stagnant portion and collect representative water samples. Total Dissolved Solids (TDS), Temperature, pH, and specific electrical conductance (SEC) of the discharge water were measured *in situ* using a Consort C535 multi-parameter analyzer. After that, sample bottles were filled and kept in a refrigerator (4 °C) upon collection. Samples revealing relatively high salinity (exceeding 3 g.l^{-1}) were diluted before analysis. The ionic balance for all samples is within ± 5 %.

5- Discussions and conclusions

The interaction of hydrothermal fluids with wallrocks and changes in their composition through time and space, contribute to the formation of a wide range of mineral deposit types and associated wallrock alteration. The Trozza mine represents one of the famous significant Pb-Zn/S ore deposits of the overthrust Kairouan zone in central Tunisia exploited since 1900 by the French society.

After the independence this mine has been non exploited view the non rentability. The rest of the operation (sterile deposit) remains stalled near the hydrographic network. After the period of precipitations these deposits will eventually be transported to power after dissolution to the surface water of El Hwareb dam and of course after infiltration will be the main cause of the deterioration of groundwater in Kairouan plain.

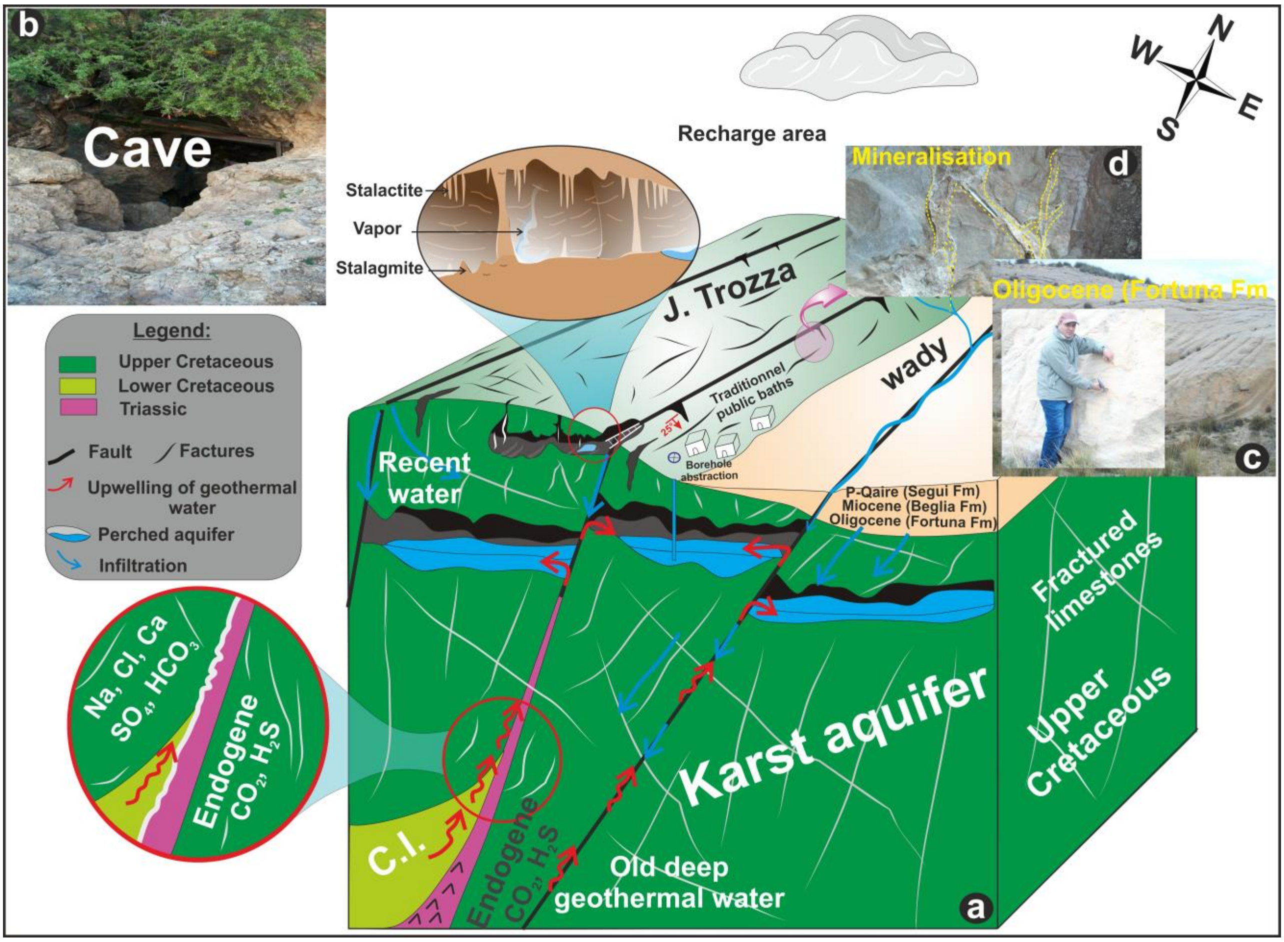

Figure 2) Conceptual model of the functioning of the hydrothermal karst system in Trozza basin (Kairouan region), central Tunisia (Hamed et al., 2014). (a)-bloc diagram, (b)-Trozza cave, (c)-sandy of Oligocene Fm., (d)- mineralization in karst carbonate level.

In addition to the high evaporation (> 1,500 mm/y) which causes the increase of the isotopic desintegration (increase of ^{18}O and ^{2}H) (Fig. 2). The contact evaporitic rock-water, dissolution and alteration of triassic evaporite (gypsum and halite) beds increased the porosity/fractures of the carbonate outcrop (Aptian Formation) which facilitated the upwelling of the hydrothermal fluid and prepared open spaces for the precipitation of ore mineral (Figs. 2 and 3).

We propose the connection of this hydrothermal activity from the Cretaceous deposits probably from the Continental Intercalaire (C.I.) and the ore of Pb-Zn/S deposits in Jebal Trozza. This hypothesis is confirmed by the enrichment of vapor gas water by H_2S and SO_4^{2-}. Due to the tectonic effect (recent and/or ancient) a natural contamination of groundwater and surface water with metals due to the mixing of cold waters (meteoric recent water) with geothermal fluids (fossil deep water) is often associated with a high total dissolved solids content and significant concentrations of Cl, SO_4, Pb, Zn, U, As, B, Fe, Mn, OM etc which increase the salinity of surface and groundwater in the study area. These ore systems are usually generated by water rich magma (tectonic effect: Trozza fault…).

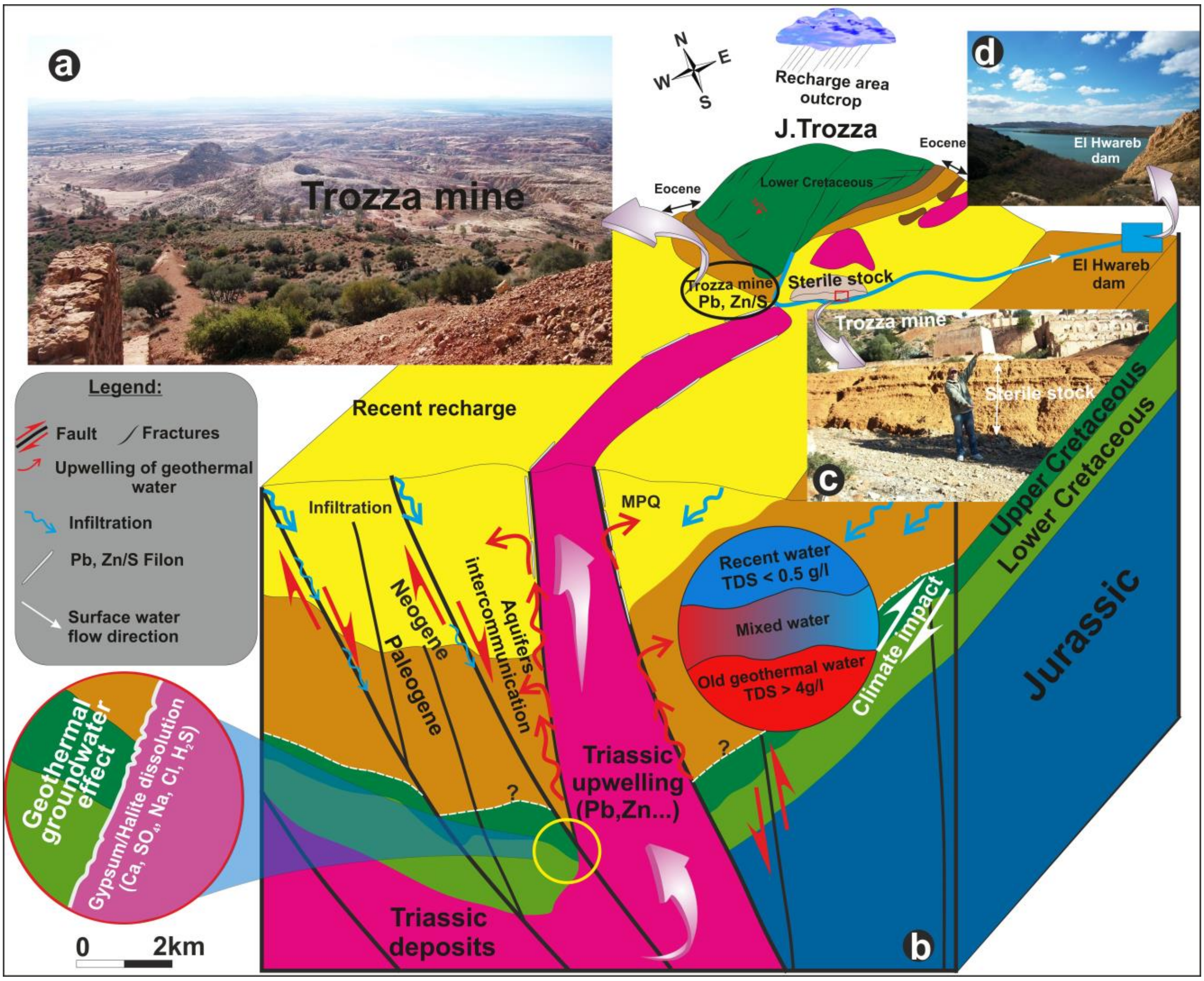

Figure 3) Conceptual model showing the intercommunication between the reservoirs and the functioning of the hydrothermal karst system in Trozza basin (Kairouan region), central Tunisia (modified by Hamed et al., 2014 - After Zouaghi et al., 2011). (a)- panoramic observation of the study area, (b)- boc diagram, (c)- sterile stock of Trozza mine, (d)- El Hwareb dam.

The solubility of sulphides/sulphates/carbonates and silicates decreases as temperature decreases this phenomenon engender the precipitation of minerals. Hydrothermal mineral phases that develop in epithermal systems in the study area are a function of temperature, pressure, rock type, nature of the circulating fluids (such as pH, activities of CO_2, H_2S, H_2O) and water/rock ratios. As the hydrothermal system becomes more active, high temperature fluids ascend through permeable fractures/faults towards the discharge area.

The geochemical and hydrologic processes responsible for the various water types in the study area are discussed in the following sections:

- $2CaSO_{4(\text{Triasic deposits})} + CaMg(CO_3)_{2(\text{Carbonate aquifer})} + H_2O_{(\text{C.I. thermal})}$ -----> $Ca^{2+} + Mg^{2+} + SO_4^{2-} + 2H_2S_{(gaz)} + 2H_2O_{(vapor)} + CO_{2(gas)}$ (Equation 1),
- Yypresian deposits$_{(\text{Organic matter})}$ + $H_2O_{(\text{C.I. thermal})}$ -----> $Ca^{2+} + Mg^{2+} + SO_4^{2-} + 2H_2S_{(gaz)} + 2H_2O_{(vapor)} + CO_{2(gas)}$ (Equation 2),
- $2FeSiO_4 + 4H_2O_{(\text{C.I. thermal})}$ -----> $2Fe^{2+} + 4OH^- + 2H_2SiO_4$ (Equation 3),
- $FeS_{2(pyrite)} + 7/2\ O_2 + H_2O_{(\text{C.I. thermal})}$ -----> $2Fe^{2+} + SO_4^{2-} + 2H^+$ (Equation 4).

The hydrothermal veins in the Trozza anticline are the best indicators of hydrothermal fluid flow and as such can also be considered an expression of the conduits or fractures through which fluids circulate. Textural variations and morphology of vein crystals (usually quartz and carbonates) provide valuable information on the nature of the hydrothermal system from which the veins were sourced (Fig. 3).

The mixing of H_2S with the fluid metallic elements (Fe, Zn, Pb…) would cause sulphides deposition due to this intercommunication. The groundwater contains bicarbonates, sulphates, chlorides and alkali metals, with their amount depending on the composition of the surrounding rocks and the length of time that the water has been in contact with them. Extensive fluid circulation would have taken place along fractures and faults (NW-SE, N-S and NE-SW) (Ouali and Mercier, 1997). This upwelling ore in Tunisia was the subject of geological and geochemical investigations by several authors (Burollet, 1956; Rouvier, 1967, 1977; Gharbi, 1977; Bouhlel, 1985; Ben Jemia, 1986; Ben Dhia, 1987, 1990; Slim-Shimi, 1992; Slim-Shimi and Tlig, 1993; Jellouli, 2000; Tlig *et al*., 2011; Hamed *et al*., 2013).

Other geophysical explorations mentioned the presence of these geophysical faults extending longitudinally in the study area (Zouaghi, 2009), which caused the intercommunication between the different aquifers (fresh water and fossil hydrothermal water) (Figs. 2 and 3).

Nevertheless, the recent increase of global demand for alternative renewable energy resources has stimulated the development of new research projects focused on the evaluation of the potential for low enthalpy energy production from the hydrothermal system of the Kairouan basin particularly. There are other similare projects installed in the southern Tunisia (Gabes, Kebili and Tozeur) and even in the Algerian and Tunisian Sahara Platform (Grand Erg Oriental).

Hot springs can also result from regions of anomalous heat flow due to high concentration of radioactive elements in the crust or in high-heat producing. Hot springs and associated hydrothermal systems that can be related to high heat flow due to radioactivity have been called amagmatic. In the central Tunisia, the hydrothermal veins are the best indicators of hydrothermal fluid flow and as such can also be considered an expression of the conduits or fractures and/or permeable faults through which fluids circulate. Textural variations and morphology of vein crystals (usually quartz and carbonates) and other silica precipitates provide valuable information on the nature of the hydrothermal system from which the veins were sourced (Hamed, 2015a,b).

In this study area, the reservoir is characterized by fractured limestone locally suffering dissolution and grading to karstic system, which is frequent in central Tunisia (Rouvier, 1967, 1977; Ouali and Mercier, 1997; Hamed, 2013, 2015b). Karst aquifers are known to be highly heterogeneous, formed by a complex conduit system that is generally impossible to locate. Moreover, the resources are very hard to exploit view the circulation in the karst reservoir, but the vapor is exploited after upwelling in the Trozza caves (traditional public bath) (Figs. 2 and 3).

Generally, TDS of surface and groundwater's (0.8 - 6 g.l-1) increases from the mountainous regions (the piedmont area in the western of the study area, which characterize the recharge areas) towards the discharge area (eastern part), as a result of the scarcity of recharge in these regions, the relatively residence time of water/rock interaction (Amri *et al.*, 2016) (Fig. 4).

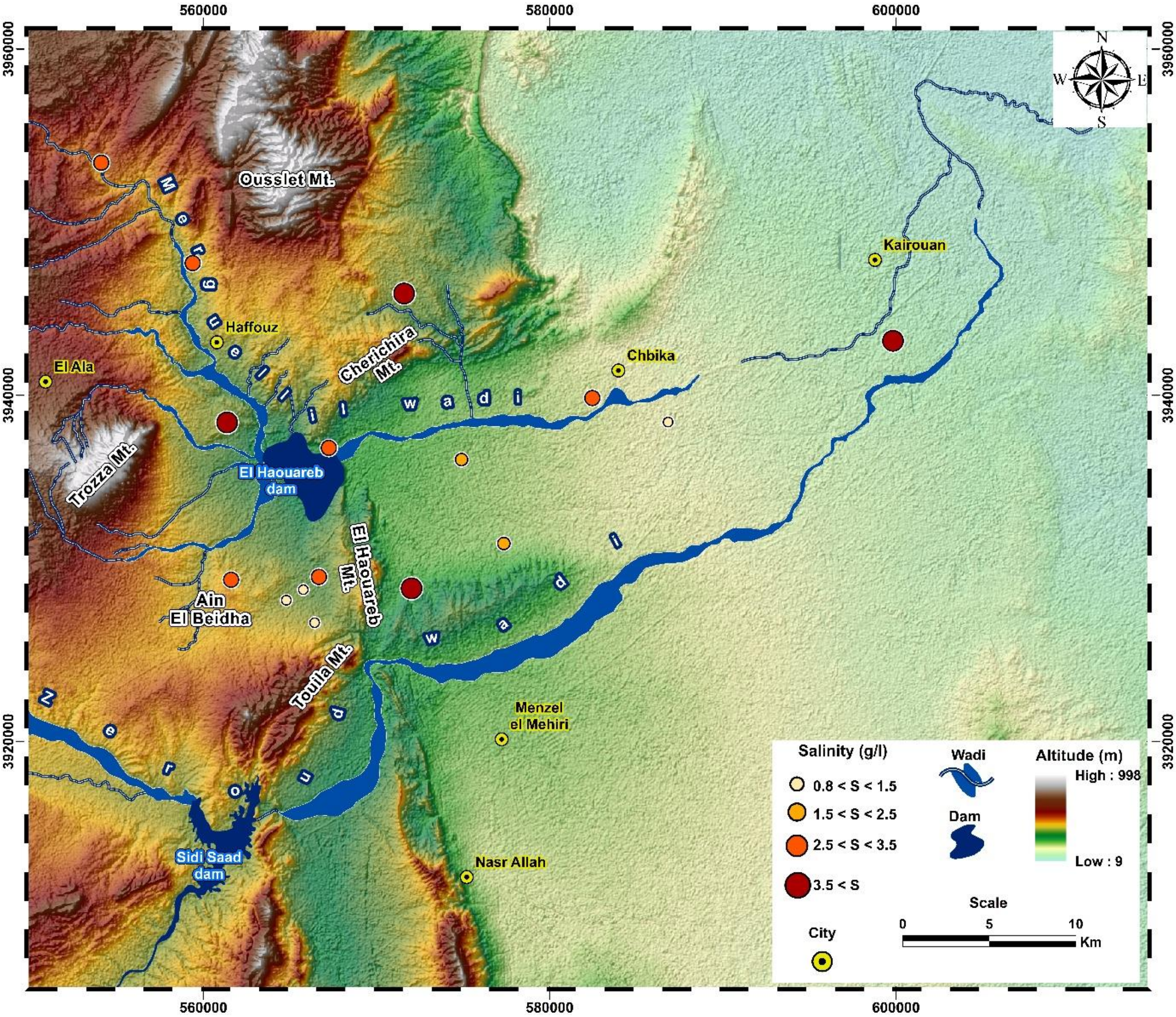

Figure 4) TDS map of groundwater and surface water in the study area (Amri et al., 2016).

In the conceptual model (Fig. 5), we would like to mention the principal characteristics (fracturation, porosity, interconnectivity, temperature, pressure, etc.) of this hydrothermal karst of Trozza area (central Tunisia) and their relation with the tectonic setting (permeable faults to drain the meteoric, fossil and the juvenile water).

The intensive tectonic processes will produce extensive joint systems that provide access to water that can migrate into deeper sections of the thick rock mass. Fragmentation of masses, resulting from tectonic processes, represents the most important factor in karstification, which operates both horizontally and vertically in the study area. Water movement within all these joints is caused by gravity. The velocity and quantity of the flowing water depend upon the size of the channels and fractures and their degree of interconnection.

It is evident from this Fig. that, the karstification process decreases with depth according to an exponential law, then ($\varepsilon = a.e^{-bH}$), Where ε is the index of karstification, H is the depth in meters, e is the natural logarithm, (a) and (b) are coefficients.

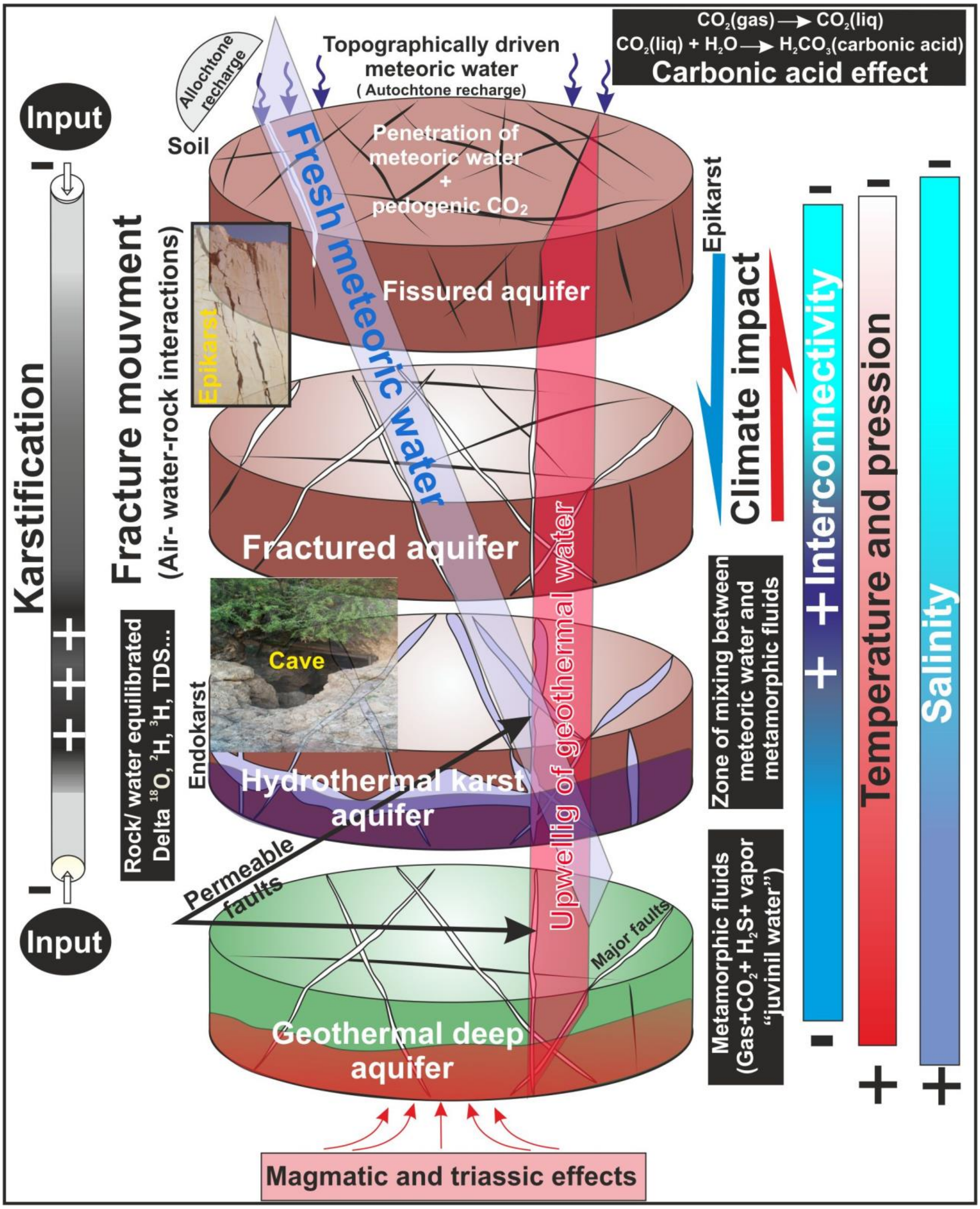

Figure 5) The characteristics of the Trozza hydrothermal karst aquifer.

The zone of greatest karstification, and at the same time the highest porosity, is at the depth ranging from surface to 15 to 30 m (epikarst zone). The hydrodynamic water (surface and groundwater) is related to the climate impact (precipitation, CO_2, Temperature, humidity…). The climate effect plays a key role in karstification in Tunisia (Hamed, 2009, 2015a; Hamed and Dhahri, 2013; Ayadi *et al*., 2014; Redhaounia *et al*., 2015a and b, 2016a; Hamed *et al*., 2012, 2017).

In Tunisia, karst aquifers develop in response to dynamic phenomena that operate in time and space. Their geometry changes very rapidly, which in turn changes hydrodynamic regimes of the aquifers. All of these changes represent a uniform process: the evolution of karst aquifers. Karst aquifer evolution is based on the tendency of karsts to adjust their water level to the zone of discharge in reference to the base of erosion (Milojević, 1967).

Geothermal exploitation thus requires deep boreholes representing a sizeable investment, and therefore a particular socio-economic environment for the development of geothermal projects. In Tunisia, the temperature of geothermal water discharge does not exceed 90°C and C.I. geothermal groundwater is classified as a low enthalpy resource with a Geothermal Gradient (GG) ranging from 30 to 35 °C/km (Ben Dhia, 1988, 1989; Kamel, 2012; Hamed *et al*., 2013, 2014).

In the study area, the use of the low-enthalpy resource is limited to primarily direct use, including swimming, bathing, washing, and greenhouses heating (Kharoubi *et al*., 2012; Hamed *et al*., 2013, 2014). In the southern Tunisia, approximately 10,000 l/s is exploited from geothermal resources of the C.I., for industrial sector (Ghanouch area in Gabés basin), agricultural (oases, greenhouses and aquiculture: however, whatever collective heating system is used in agriculture “geothermal or not”, the economic results are only modest and the reasons for this are not only technical), traditional bathing and swimming, tourism (hotels and swimming pools in Tozeur, Kebili, Mednine regions), district heating (geothermal energy systems have only been developed in a few urban centers), and for human utilization.

Finally, it is worth mentioning that the quality improvement of this moderate interpretation, probably when we adopt a model analysis on fracturation with combination with several studies like the geophysical, geochemical, Scanning Electron Microscopy (SEM) analyses. Moreover, like several scientific authors in the word, I hope that application of these methods and modelling by GIS (geo-risk) to improve and facilate the interpretations of the climate impact on water resources in the central Tunisia.

Acknowledgements

Special thanks to the colleagues from Tunisia and Algeria for their collaboration. The authors are thankful to the Editor and the reviewers for their valuable suggestions. This paper was written during the period of the field school students of Earth Sciences (LFST2- Gabes and LFST3/RES-Gafsa). We would like to thank our colleagues of Gabes and Gafsa universities particularly my colleagues Dhahri, Jamali and Ben Assi of their helps during the field school in the Kairouan basin.

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