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Journal of Hydrology: Regional Studies 4 (2015) 410–430

Contents lists available at ScienceDirect

Journal of Hydrology: Regional Studies

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

Relationship between tectonic structures and hydrogeochemical compartmentalization in aquifers: Example of the "Jeffara de Medenine" system, south–east Tunisia

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ARTICLE INFO

Article history:
Received 28 April 2015
Received in revised form 5 June 2015
Accepted 14 July 2015

Keywords:
Reservoir
Structure controls
Hydrogeochemical compartmentalization
Facies variation
Jeffara aquifer system
Fault hydraulic properties

ABSTRACT

Study region: "Jeffara de Medenine" aquifer system in south-eastern Tunisia.
Study focus: This study investigates the role of fault structures in the distribution of hydrogeochemical facies and groundwater compartmentalization for the aquifer system.
New hydrological insights for the region: The proposed methodology, including seismic structural study, hierarchical cluster analysis and geostatistical methods, allowed an efficient multi-element characterization of the spatial patterns of the structural elements in the aquifers and of the hydrogeological parameters used in a spatial cross-correlation to explore the dependence of the geochemical properties in each "geochemical population" on the hosting structural compartment to delineate the different geochemical compartments.

The tectonic studies showed that the lateral extent of the aquifers is controlled by normal faults. The multivariate statistical analysis revealed a strong spatial coherence between hydrogeochemical facies clustering and the reservoir compartments at both large and small scales.

The kriged maps of major-ion concentrations and of total dissolved solids in the aquifers were then analyzed and compared with the reservoir facies distribution for each compartment, the geometric characteristics of the aquifer, and the piezometric level trends. This allowed to characterize the hydraulic behavior of the Medenine fault and to understand the underlying physical and chemical processes having led to the spatial distribution of the geochemical properties, and thus, the hydrogeochemical functioning of the aquifers.

1. Introduction

Mediterranean areas of both southern Europe and North Africa are now subject to noticeable climate changes. In North Africa, a particular increase in temperature and a decrease in precipitation is observed, which affect the sustainability,

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http://dx.doi.org/10.1016/j.ejrh.2015.07.004

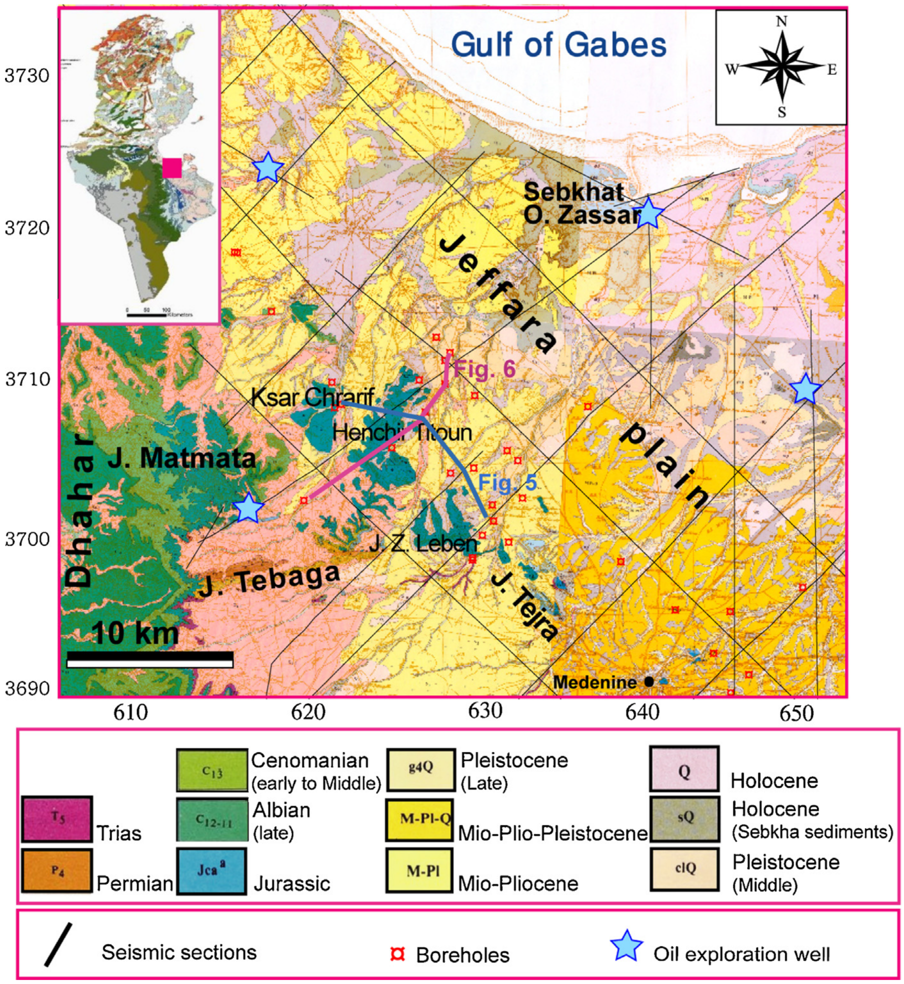

Fig. 1. Map of the studied domain and data location within the Jeffara de Medenine area in Tunisia.

quantity, and quality of water resources (García-Ruiz et al., 2011; Richard and Aureli, 2008). The natural scarcity of water resources is accentuated by increasing water consumption for human needs, and expanded irrigated lands, as well as the growth of urban, industrial, and touristic areas (Mamou and Ould Baba Sy, 2008; Scheumann et al., 2008) These regional conditions enhance the necessity of improving water management in order to ensure water supply and to reduce tensions among regions and countries.

The Jeffara basin hosts complex aquifer systems which extend on three North African countries, Tunisia, Libya and Algeria, that have little apparent natural recharge because of the arid climate, and where significant water level declines have been observed (Chihi, 2014; UNESCO/OSS, 2005; Yahyaoui et al., 2002) whose consequences are a salinization of the groundwater. Consequently, the water quality and water resource management are of great concern.

At the scale of southeastern Tunisia, the Jeffara de Medenine aquifer system hosts a regional aquifer that is part of the primary domestic, agricultural and industrial water supply for numerous communities in the region. In recent years, changes in the groundwater quality have been described in several studies (e.g., Ben Baccar, 1982; Mammou, 1990; Yahyaoui et al., 2002). However, few of them have assessed the spatial variability of chemical components, taking into account geologic environments and, above all, the structural compartmentalization.

The study area is situated in the "Jeffara coastal plain" in southeastern Tunisia (Fig. 1) where intense and repeated tectonic activity (e.g., Castany, 1954; Busson, 1967; Burollet, 1967, 1991; Burollet et al., 1978; Bouaziz et al., 1998; Bodin et al., 2010; Chihi et al., 2013, 2014) has resulted not only in a complex geological framework but also in the existence of numerous brackish and saline water reservoirs.

The potential effects of fault systems on groundwater geochemistry can be divided into two categories:

(i) The "geologic characteristics" of the faults: when faults undergo displacement, they juxtapose different reservoir sub-domains with different lithologies; consequently, the geochemical properties of water may change on each side of the faults.

(ii) The "hydraulic conductivity" of the faults is important in controlling the hydrogeology of the aquifers, and specifically the groundwater flow paths, the water level trends, the recharge and discharge of groundwater within the region. All these parameters are significant in an evaluation of the regional spatial variability of aquifer geochemistry.

This study aimed (i) to investigate the fault structure network and the hydrogeochemical facies distribution to delineate the groundwater compartmentalization in the "Jeffara de Medenine" aquifer system by means of multivariate statistical analyses and geostatistical methods, and (ii) to interpret the spatial variability of groundwater geochemistry in the context of the groundwater flow and the geologic structure. This was accomplished in three steps.

First, we studied the structural framework (Chihi et al., 2013) of the study area and the major spatial trend that has played a key role in the structural compartmentalization of water reservoirs, dividing the area into two major domains.

Second, a multivariate statistical analysis, mainly a hierarchical cluster analysis (HCA), was applied to the geochemical data, grouping the monitoring points into distinct "well populations" with the same hydrochemical facies. A spatial cross-correlation analysis was then applied to explore the spatial relationship between the geochemical properties of each "geochemical population" and the hosting structural compartment in order to identify the different geochemical compartments.

Third, the spatial distribution of each geochemical species (TDS and major-ion concentrations), and the groundwater piezometric head were mapped using geostatistical tools. These maps were analyzed and compared with the reservoir stratigraphic facies for each monitoring point, the geometric characteristics of the aquifer and the piezometric head, to demonstrate the underlying physical and chemical processes that have led to the spatial distribution of the geochemical properties.

Furthermore, an important question will be addressed by (or imposed to) this study: the scarcity of groundwater monitoring data, which remains a common concern in many aquifers, and strongly limits the reliability of water reservoir characterization, particularly in the case of complex environments.

The "Jeffara de Medenine" aquifer system is a typical case with limited data and a complex fault system. We describe, in this paper, an original methodology to combine structural and hydrogeochemical information, in order to face the data scarcity problem by using different types of data, and thus, better characterize the faulted aquifer system.

The broad objective is to analyze and develop an understanding of the system, and thus, predictive capabilities that will contribute to the effective management of the water resources.

2. Geographical setting

The study area, "Jeffara de Medenine", is a part of the Jeffara coastal plain, situated in southeastern Tunisia (Fig. 1). It is located approximately between latitudes 37°10′N and 37°50′N and longitudes 8° 50′E and 9°20′E. The climate is arid. The annual rainfall is around 200 mm, with a maximum (80%) between July and September from the south–east monsoon. The average temperature varies between 12.5 °C in January and 30.4 °C in August. The main drainage is by five Rivers: Zigzaou, Zeuss, Koutine, Oum Zassar and Morra (Fig. 2).

The Jeffara de Medenine includes a multi-aquifer system called the Zeuss Koutine aquifer. It includes four carbonate formations of Jurassic, Albo-Aptian, Turonian and Senonian ages (Figs. 3, 5 and 6). The Zeuss Koutine aquifer is bounded by three aquifers (Fig. 2): the Mareth aquifer in the north–west, the Triassic sandstone aquifer in the south and the Jorf aquifer in the east. It crosses "Sebkhat1 Oum Zassar" before flowing into the Mediterranean Sea in the north. The Zeuss Koutine aquifer is bounded on the northwestern side by the Dhahar plateau represented there by Jebel Matmata, in the south–west by Jebel Tebaga and in the south by Jebel Tejra (Fig. 2).

The lateral and vertical extensions of the aquifer were delimited more precisely in the current study. These limits are defined by the faults that were delineated from the seismic structural study as it will be described in the following paragraphs (Figs. 2 and 11).

The lateral extent of the hydrogeological units, at various depths, is controlled by the structural evolution of the area and its vicinity in Jurassic-Holocene times. The drainage pattern is closely related to the structural configuration, connections between the hydrogeological units are possible either through faults or by vertical leakage (Rouatbi, 1967; Ben Baccar, 1982; Mammou, 1990).

3. Data and methods

Geological, hydrogeological and hydrogeochemical studies were conducted to determine the hydrogeological behavior and the role of tectonic structures in the hydrogeochemical functioning of the aquifers (Fig. 4). The evolution of the groundwater can be identified (i) from multivariate statistical relationships between groundwater geochemical components and the geologic aquifer environment, such as the aquifer stratigraphy and structural framework, (ii) from maps showing the spatial distributions of specific hydrochemical characteristics and signatures related to potential water recharge areas and groundwater flow paths (piezometric map) through the aquifer system.

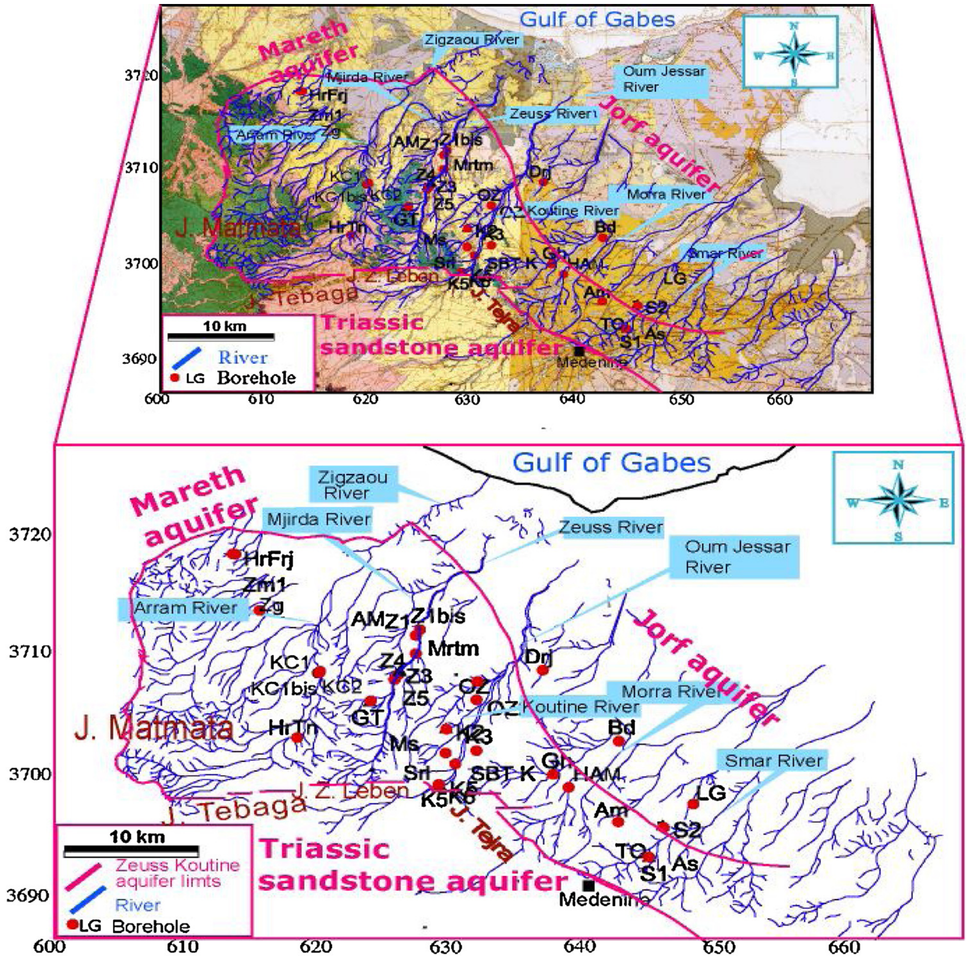

Fig. 2. The Jeffara de Medenine hydrogeological domains: main rivers, outcrops and the boundaries of the Zeuss Koutine aquifer, as specified from the current structural studies.

3.1. Data management

Constructing the database was a first and crucial step before starting the geometrical and hydrochemical characterization of the aquifer system. All available information including geological, well, seismic and hydrochemical data were compiled, harmonized, georeferenced and organized in a common geographic system. They were introduced into a geodatabase connected to a GIS (ArcGIS®) in order to efficiently analyze them in space, while simultaneously integrating and cross-referencing other mapping information such as geologic maps of the study area. In addition, the information produced by the GIS can be exported to other softwares to carry out different geological and hydrogeochemical spatial characterizations.

For the geological, statistical and geostatistical studies, the database was constructed by describing different layers of information: main data (identification, location, name, depth, etc.), lithology (depth intervals of different layers, their age, etc.), hydrogeology (piezometric head, transmissivity, etc.), hydrochemistry (alkalinity, calcium, potassium, magnesium, chloride, sodium, sulfate, Total Dissolved Solids (TDS), pH and temperature) and faults (Name, X and Y location of each vertex).

All wells evaluated in this study were assigned to a formation or group of formations based on available data including drilling logs and cross-sections prepared for this study (Figs. 5 and 6). All wells were grouped by formation. All the available water quality data obtained with the help of the Regional Authority for Agricultural Development of Medenine were used in the study.

Fig. 1 shows the location of all wells with water chemistry data used compiled for this study. Wells with water quality data that did not meet regulatory standards are unfortunately widespread in the study area and were eliminated from the database, as will be explained below.

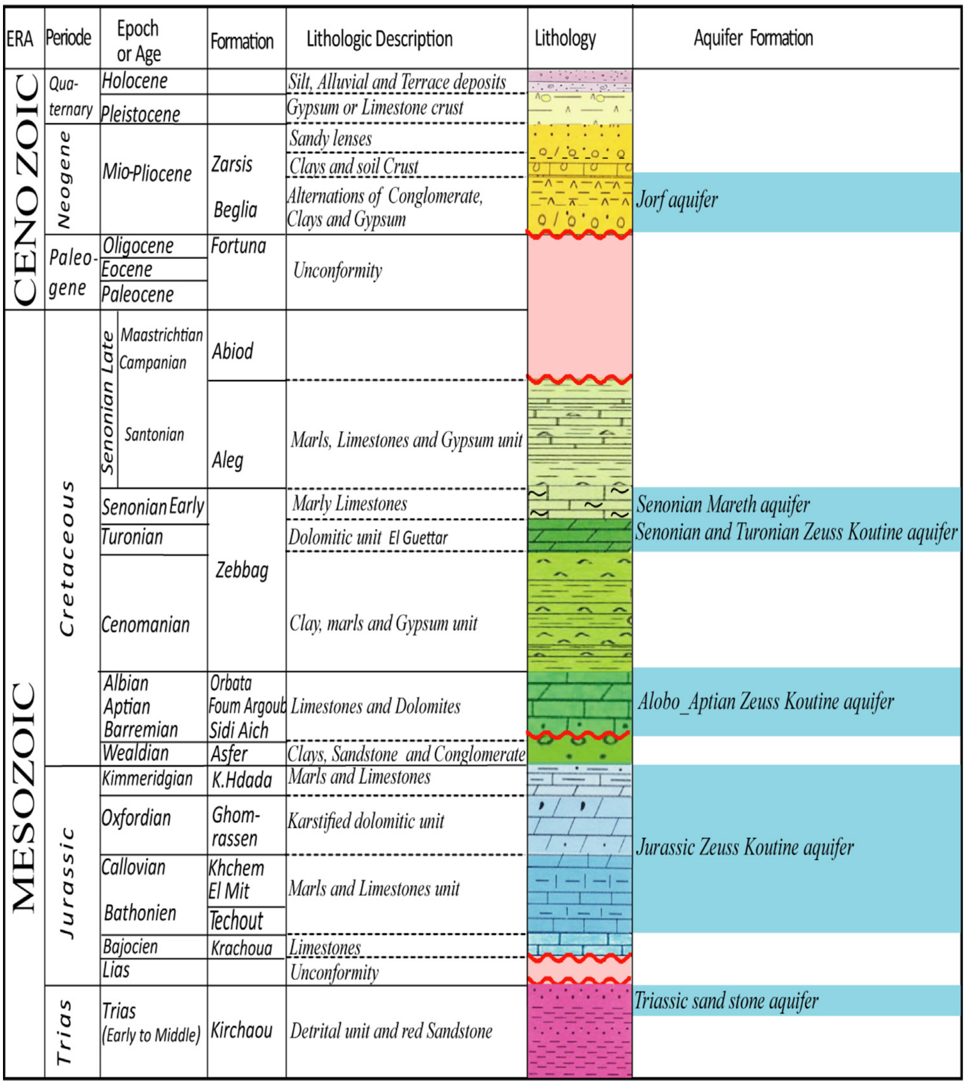

Fig. 3. Stratigraphic section and neighboring formations of the study area.

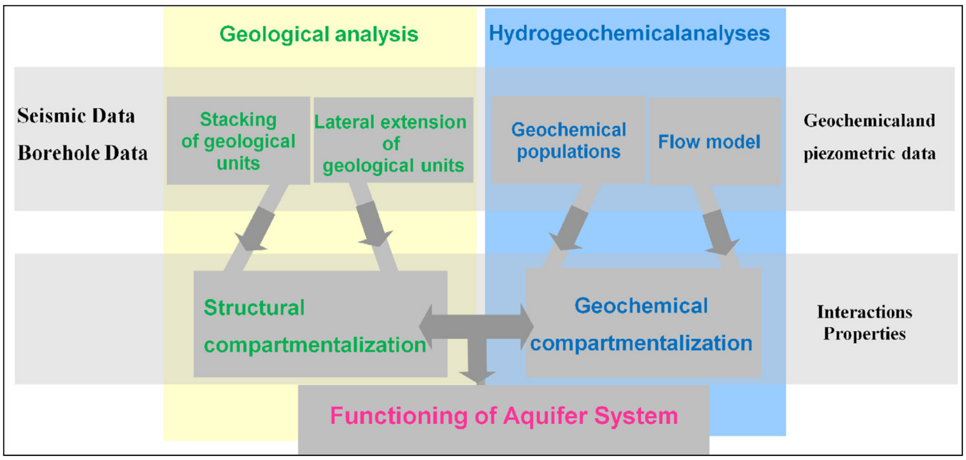

Fig. 4. Workflow showing the methodology used to elaborate the conceptual model of the aquifer system functioning.

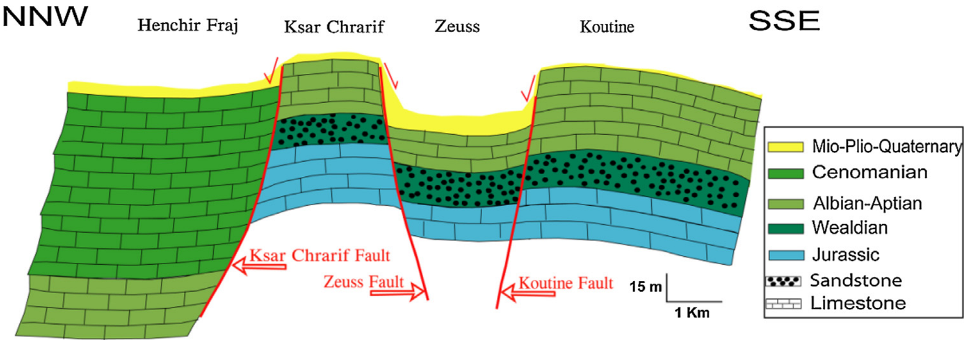

Fig. 5. Geologic cross-section along the NW-SE direction within the study area. (See Fig. 1 for location) (Chihi et al., 2014).

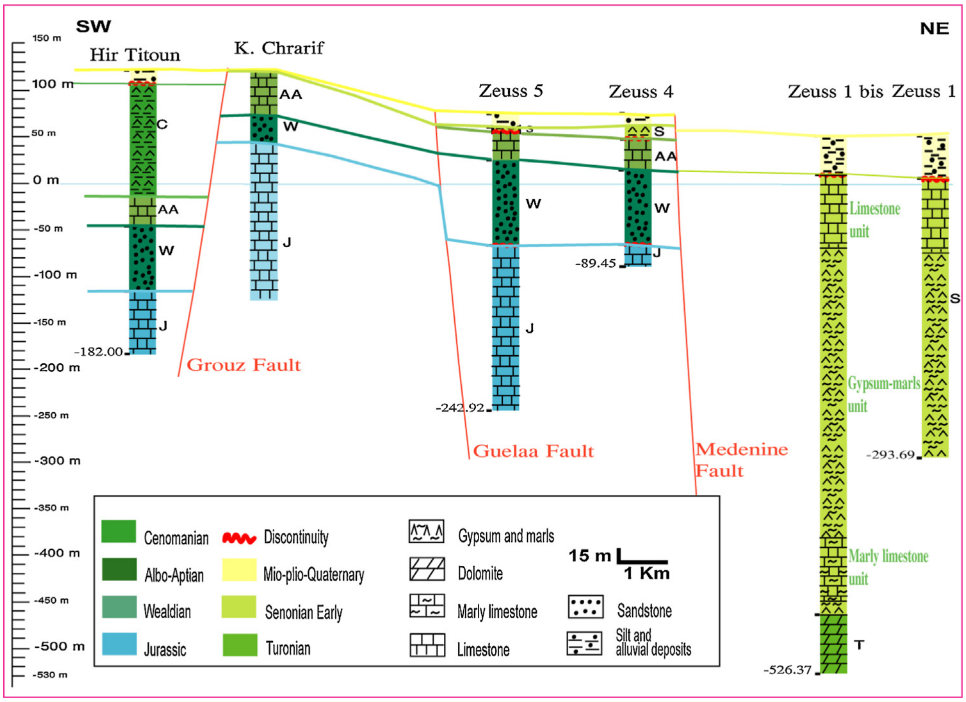

Fig. 6. Geologic cross-section along the SW-NE direction within the study area. (See Fig. 1 for location).

3.2. Geological and structural analysis

A geological and a structural analysis were first performed. The main focus was to represent the fault system which affects the different lithological reservoir units. This was attempted mainly because faults are known to drastically affect water reservoir homogeneity, by creating lateral cuts and hence a change in the hydraulic reservoir properties.

Twelve seismic sections and four petroleum exploration wells were acquired for a seismic structural study of the area (Chihi et al., 2013). Locations and lineaments of the faults interpreted from seismic data were drawn on the geological map to build the fault network at a large scale. 49 boreholes were also used for lithostratigraphic correlation to construct geological cross-sections (Figs. 5 and 6) and interpret the small-scale faults (Chihi et al., 2014).

3.3. Groundwater geochemistry

Groundwater geochemistry studies were carried out by using a combination of multivariate exploratory data analysis and geostatistical mapping to interpret the observed spatial distributions of the geochemical properties, to determine the controlling factors and to understand the influence of aquifer flow and structure on the geochemistry.

The hydrogeochemical data used in this study consisted of about 350 groundwater analyses, collected irregularly from 1974 to 2012 from 23 sampling sites.

Table 1
Preliminary statistical characteristics of the data set.

Variable(mg/L)	Minimum	Maximum	Mean	Standard deviation	Variance
Ca^{++}	128	339	237.81	72.30	5226.78
Cl^{-}	334	1420	817.44	366.48	134307.25
HCO_3^{-}	121	233	176.63	27.13	736.23
K^{+}	9	28	17.44	5.20	27.00
Mg^{++}	75	249	133.88	54.87	3010.98
Na^{+}	216	727	471.25	171.97	29573.94
SO_4^{--}	528	1728	934.88	342.00	116962.98
TDS	1570	4220	2900.50	926.91	859164.25

The groundwater samples were all assessed in the geochemical study, but were not all included in the statistical analysis (HCA), as several input parameters were not measured. Water sampling was not made every year and does not take into account all sampling sites at once. However, for some years and at some locations, more than one sampling event was made and their chemical constituents were analyzed.

A selection of data was made according to:

(i) The calculated ion-charge balance which had to be less than ± 5 percent, which is considered an acceptable level of accuracy for use in statistical analyses.
(ii) Outliers: several detailed, preliminary descriptive (minimum, maximum, mean and variance), geochemical plotting tools (Piper and Stiff diagrams) and multivariate statistical analyses (HCA) were used to identify 'outliers', with chemistries dissimilar to the other samples. Outliers show Stiff diagrams with extended apex and form a separate group from all other samples populations on dendrograms. Based on this assessment, three data points with only one sample value were excluded so as not to bias the subsequent assessment.
(iii) The HCA: two different approaches were tested to cluster the data. The first consisted in integrating results from multiple sampling events into a single HCA assessment; the second involved for each sampling event (occurring during one given year and at the same season) a separate HCA. We tried this alternative approach, separately, for each year whenever we had enough sampled points, i.e., at least 12–16 observations from repeatedly sampled locations.
(iv) The spatial distribution of the samples; they must cover the entire study area, every compartment must be represented by at least one sample.
(v) Moreover, for some compartments, some of the data points are too close. Thus, some samples were eliminated to avoid redundancy problems when making interpolations.

Accordingly, the selected sixteen boreholes are:

- Koutine wells: **K2** and **K3**,
- Zeuss wells: **Z1, Z1bis, Z3, Z4** and **Z5**,
- Ksar Chrarif wells: **KC1** and **KC2**,
- Henchir Fraj wells: **HF1** and **HF2**,
- and the remaining wells: Henchir Titoun: **HT**, Hassi Abdel Mlak: **HAM**, Amra: **Am**, Martoum: **Mrtm**, and Drouj: **Drj**.

Hierarchical cluster analysis of chemical elements (focuing on Ca^{++}, HCO_3^{-}, Mg^{++}, Cl^{-}, Na^{+}, SO_4^{--}, K^{+} and TDS) (Tables 1 and 2) was used to determine if the samples could be grouped into statistically distinct hydrochemical clusters that might be significant in the geologic context of interest. A number of studies have used this technique to successfully classify water samples to investigate the chemical evolution of groundwater along the flow path. Swanson et al. (2001) proposed a two-way cluster analysis of the geochemical and apparent ages of sampled groundwaters to determine which of the considered regionally extensive bedrock aquifers, is a more likely source of water discharging to the springs in a watershed in south central Dane County, Wisconsin. Güler and Thyne (2004) employed a Q-mode HCA for partitioning spring, surface, and well water samples, in southeastern California, in order to evaluate water quality and to determine processes that control water chemistry. Valdes et al. (2007) performed a spatial correlation between the geochemical and the geometrical properties, on a chalk karstic aquifer in northern France. Having insight information regarding the directional structure of the data, the authors gave evidence of directional relations between geochemical and geometrical properties. GWMA (2009) used geochemical signatures, such as the cation ratio (Na + K)/(Na + K + Ca + Mg), plus HCA and principal components analysis in combination with spatial mapping, to delineate regional hydrochemical patterns that reflect the relative residence times of groundwater and reveal regional flow patterns within aquifers in the Washington State. Bushman et al. (2010) combined HCA with several techniques, such as mass balance modeling, isotopic constraints, and structural arguments, to define the possible sources of water at Ash Meadows, Nevada. Belkhiri et al. (2010) applied multivariate statistical techniques, cluster and principal component analysis to groundwater quality data in Algeria, to extract principal factors corresponding to the

Table 2
Ranges and parameter values of the four principal water clusters determined by HCA.

Clusters			Monitoring		Cl (mg/L)	Na (mg/L)	SO_4 (mg/L)	Ca (mg/L)	K (mg/L)	Mg (mg/L)	HCO_3 (mg/L)	TDS (mg/L)
A	A1	A1-1	K2, K3, KC1, KC2	Min	334	216	528	128	19	75	194	1570
				Max	425	271	608	181	9	86	233	1794
		A1-2	HF1, HF2, HAM	Min	493	325	928	188	12	106	136	2478
				Max	555	422	1070	265	13	119	191	2610
	A2		Z1bis, Z2, Z3, Z4, Z5, HT	Min	845	433	645	152	19	118	121	2490
				Max	1272	689	955	332	28	135	195	3880
B			Am, Dj, Mrtm	Min	887	575	1440	220	12	235	156	4050
				Max	1420	727	1728	339	22	249	170	4220

different sources of variation in the hydrochemistry, with the objective of defining the main controls on the hydrochemistry at the plain scale.

In this paper, we used hierarchical cluster analysis to give relevant information about the relations or differences between the waters in the tectonic compartments and the permeability of the faults and flow paths. A classification scheme using Euclidean distances (straight-line distance between two points in c-dimensional space defined by c variables) for similarity measurements, together with Ward's method of linkage, produced the most distinctive groups where each member of the group resembles its fellow members more closely than any other member outside the group (Güler et al., 2002; Belkhiri et al., 2010). Hydrochemical results of all samples were analyzed statistically with the software STATISTICA (1998).

Geostatistical methods have been useful, especially for analyzing hydrochemical data at a regional scale (Goovaerts, 1997) by producing maps showing the spatial distributions of specific hydrochemical characteristics and piezometric-level maps (representing the groundwater flow). The data were mapped by ordinary kriging (Chilès and Delfiner, 2012) with the ISATIS software (Geovariances, 2012) using an omnidirectional variogram, which represents the variance between two samples with increasing lag space without taking the direction between the samples into account (Edward and Srivastava, 1989). Experimental variograms of hydrochemical parameters show in general convex curves, with a linear portion at the origin that can be described by means of spherical models (Figs. 12 B, 14 B, 15 B and 16 B).

We have to emphasize here that the available data were collected with a higher well density along the general directions of the regional groundwater flow and do not cover the entire study area, particularly in the NE compartments where the data are too sparse. To account for this lack of hydrogeochemical data, we looked for a rigorous and computationally efficient technique to produce the most appropriate maps of the different parameters being estimated. Clearly, there is no "unique" nor "best" way to generate a map based on limited data. Various interpolation procedures were tried and compared, including inverse distance, spline, classical kriging and kriging with a "fault constraint". The performance of each method was evaluated through a comparison of descriptive statistics (minimum, maximum, mean and variance) of the known sampled values and the estimated ones, and the hydrogeochemical realism of the generated maps.

Accordingly, we decided to adopt an interpolation method merging quantitative numerical data provided by well information (piezometric head, TDS and major ion concentrations), and qualitative information based on intuition and an underlying hydrogeochemical conceptual model (i.e., geologic studies and preliminary hydrogeochemical statistical investigations). This method allowed for geological constraints (faults) to be enforced within a geostatistical framework.

The question of the specific geologic constraints, deduced from the structural and geochemical compartmentalization described above, was addressed by integrating fault discontinuities (that were digitized, classified and attached to the ISATIS data file) in the interpolation procedure. For each target point to be estimated by kriging in a given compartment, the search neighborhood was defined so that the neighboring samples, used for estimation, were all located within the considered compartment, between fault boundaries (Delhomme, 1976; Chihi et al., 2013). For each such local estimation, we used a unique neighborhood method because of the scarcity of data points. This procedure helped to respect local variability and to improve the prediction accuracy of the geochemical and piezometric variables that were then mapped on a grid of 6500 cells (500 m × 500 m).

Despite the fact that the calculated maps are not very precise in the less informed zones, and mainly within the NE compartment, where extrapolation was often based on a single data point, the adopted interpolation method takes into account the specificities of the hydrogeological parameters being estimated. The generated maps reflect the specified constraints, leading to conclusions that are consistent with the underlying conceptual model and the structural and geochemical compartmentalization; the local spatial distributions within each compartment was considered, as well as the regional trend toward the NE within the entire study area.

Synthetic analysis: the results of the statistical clustering of the hydrochemical data combined with the spatial distribution of the clusters were analyzed and interpreted to understand the spatial coherence and coincidence with major hydrogeological parameters and geological features (Fig. 4).

This process (Valdes et al., 2007; Ayraud et al., 2008) tests the choice of clustering methods and can be iterated using knowledge of the geologic information (lithostratigraphy and structural compartmentalization) to explain particular local geochemical behaviors and to refine the statistical clusters to make them as geologically meaningful as possible.

4. Results

4.1. Geological and structural analyses

This section details the structural geometry of the study area by emphasizing the geometry of sedimentary layering and major faults. This has been implemented (i) by carrying out lateral lithostratigraphic correlations in order to locate the uplifted or down-shifted compartments and then (ii) mapping the fault system that affects the different reservoir units.

4.1.1. Seismic data analysis

The seismic profiles interpretation carried out in our previous studies in the NE Jeffara basin (Chihi et al., 2013) has already assessed the structural framework at a large scale. It particularly showed that the study area is down-tilted in the north and the northeast directions as a result of normal faulting. The most prominent faults trend in the NW–SE directions, with throws toward either the NE or SW (Fig. 7). These faults are, from SW to NE: the faults of Tejra_Medenine, Medenine, Zarat, Lella Gamoudia, Oum Zassar, and Jorf.

4.1.2. Lithostratigraphic correlation

All wells evaluated in this study were, in a first step, validated (Chihi et al., 2014) and assigned to a formation or group of formations, based on the available data including drilling logs and cross-sections (Figs. 5 and 6).

The second step consisted of a lithostratigraphic correlation of the previously validated borehole logs completed by a fieldwork study carried out in order to check whether the fault system assessed in the seismic study is actually expressed in the field, and to check the position of the studied wells in relation to the faults. The wells drilled along the Medenine fault are used here as examples: Smar, Amra, Hassi Abdel Mlak, Oum Zassar, Zeuss3, Zeuss 1bis and Martoum. Fig. 7 shows the new structural map of the Jeffara de Medenine area with updated fault lines.

Figs. 5 and 7 show that the sedimentary sequences in the Jeffara de Medenine area are strongly controlled by tectonic deformation, especially NW–SE and NE–SW normal faults, which induce significant thickness and facies variations (Figs. 5 and 6).

4.1.3. Structural compartmentalization

The mapped NW–SE major and NE–SW minor faults allowed us to compartmentalize the study area and to build a system of uplifted and down-shifted structures within a generally down-tilted domain.

(i) The Tebaga_Tejra_Medenine fault separating the “Triassic sandstone aquifer” from the “Zeuss Koutine aquifer” (Figs. 7 and 11).
(ii) The Medenine fault separating the Jeffara de Medenine area into two NW–SE domains: the SW uplifted domain and the NE down-shifted domain (Figs. 7 and 11). The major potential water reservoir systems considered in this study are situated in the SW uplifted domain.

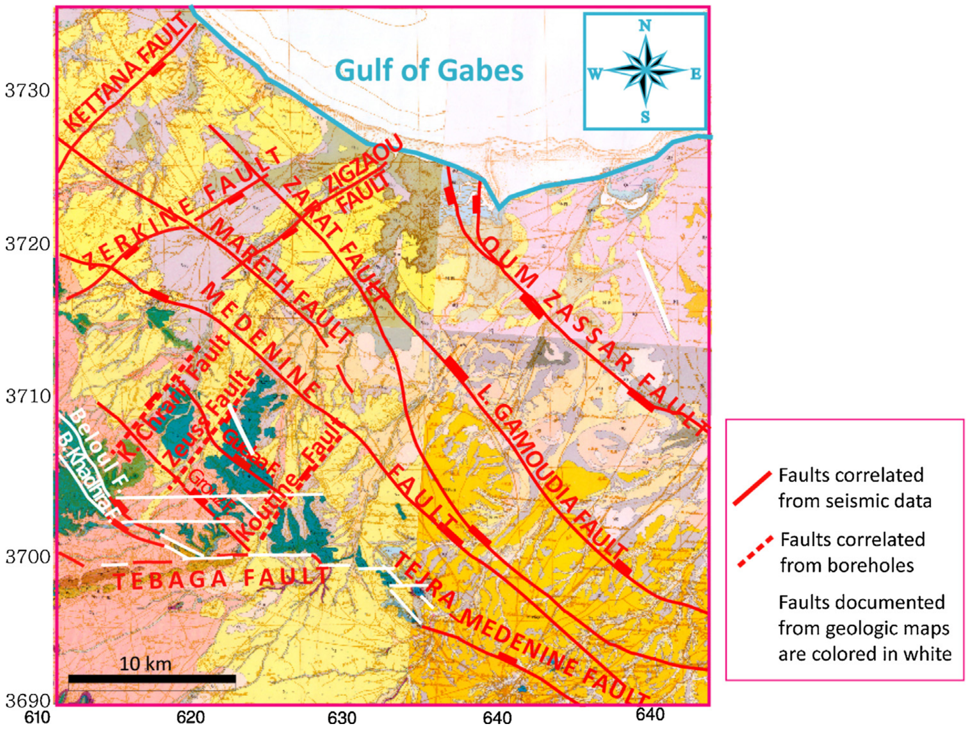

Fig. 7. Fault network correlated from seismic and geological data (Chihi et al., 2014, modified).

(iii) At a smaller scale, the NE–SW faults divide the SW uplifted domain into three compartments: that of Koutine, Zeuss and Ksar Chrarif (Figs. 7 and 11).

Accordingly, the study area is characterized by two geological sets or compartments. The SW uplifted compartment containing Jurassic and Early Cretaceous formations composed mainly of carbonate and sands (Figs. 3, 5 and 6) and the NE down-shifted compartment filled with the Late Cretaceous formations composed mainly of carbonate, clay and gypsum (Figs. 3, 5 and 6). A thick alluvial Mio-Plio-Quaternary formation covers the major part of the study area.

The Koutine sub-compartment is bounded by the Medenine fault in the north, the Tejra_Medenine fault in the south, and the Koutine fault in the west. Its structure is illustrated by the cross-section shown in Fig. 5 and the structural map (Fig. 7). It is an uplifted compartment consisting mainly of Jurassic carbonates. The Albo–Aptian sediments are encountered locally and composed of dolomite and limestone (Figs. 3 and 5).

The Zeuss sub-compartment is bounded by the Medenine fault in the north, the Tejra_Medenine fault in the south, the Koutine fault in the east and the Zeuss fault in the west. It is a collapsed compartment which includes a thick sedimentary sequence composed of carbonate and sandy formations of the Jurassic, the Wealdian, and the Albo–Aptian intervals. This sedimentary sequence is covered by thick Mio–Plio–Quaternary sediments.

The Ksar Chrarif sub-compartment is bounded by the Medenine fault in the north, the Tebaga fault in the south, and the Zeuss fault in the east. Its structure is illustrated by the cross-sections shown in Figs. 5 and 6 and the structural map (Fig. 7). It is an uplifted compartment consisting mainly of carbonate and sandy formations of the Jurassic, the Wealdian and the Albo–Aptian intervals. Cenomanian sediments are encountered locally.

4.2. *Groundwater geochemistry analyses*

The continuity and degree of connection of the groundwater flow within and between the defined structural compartments depend on the internal stratigraphy and structure of the compartments and on the physical properties of their bounding faults, as well as on the sources and locations of recharge and outflow (Caine et al., 1996; Ashland et al., 2001). In this section, we study the role of tectonic structures in the hydrogeological and geochemical functioning of the aquifers in the area using multivariate statistics and geostatistical methods.

4.2.1. *Preliminary statistical analysis*

A preliminary statistical analysis was made to identify the general characteristics of the groundwater geochemistry in the study area. It shows that the overall groundwater quality in the Jeffara de Medenine area is impaired by high total dissolved solids (TDS) concentrations, all samples commonly exceeded 1000 mg/L. Based on World Health Organization standards

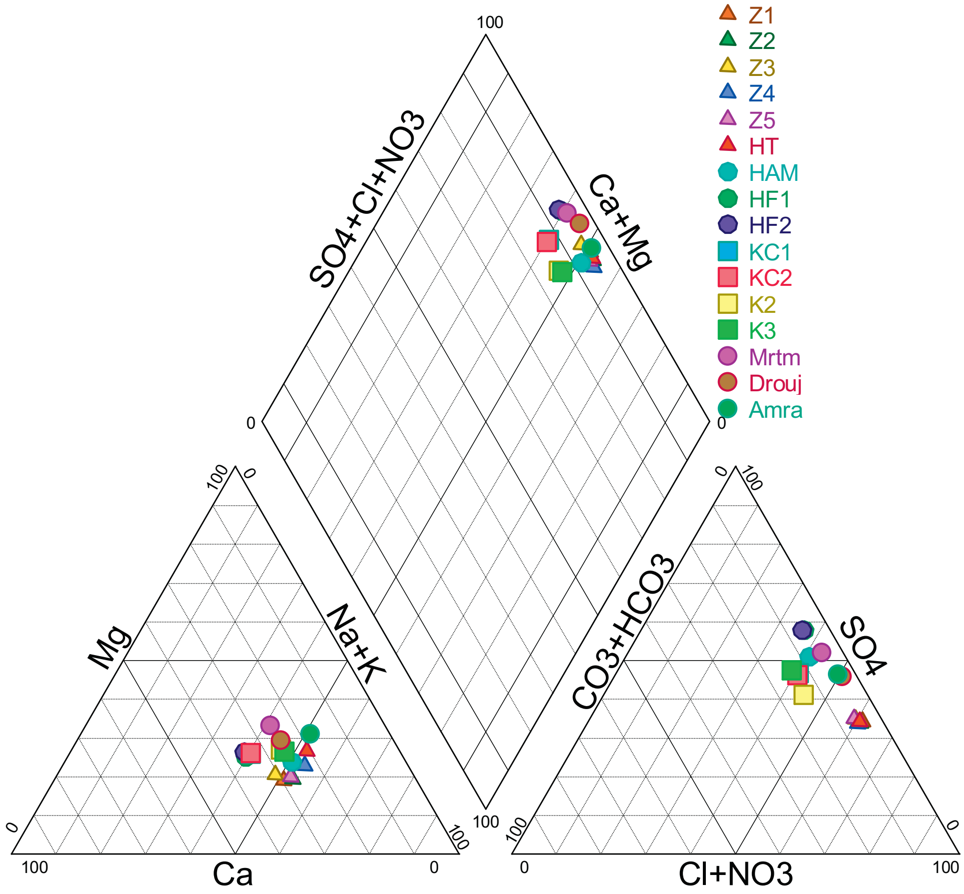

Fig. 8. Piper diagram showing groundwater classification (Piper, 1994).

(World Health Organization (WHO), 2006), water with TDS above 600 mg/L is not recommended for use as drinking water (Table 1).

The TDS ranged from 1570 to 4220 mg/L (Table 1). All samples exceeded the WHO recommended limits for drinking water (Table 1): Ca^{++} (75 mg/L), Mg^{++} (50 mg/L), Na^{+} (200 mg/L), Cl^{-} (200 mg/L) and SO_4^{--} (500 mg/L). The order of abundance of major cations was $Na^{+} > Ca^{++} > Mg^{++} > K^{+}$ and the abundance of major anions was: (i) $Cl^{-} > SO_4^{--} > HCO_3^{-}$ for Z1, Z1bis, Z3, Z4, Z5 and HT, and (ii) $SO_4^{--} > Cl^{-} > HCO_3^{-}$ for HAM, HF1, HF2, KC1, KC2, K2, K3, Mrtm, Am and Drj.

A detailed statistical exploration (Figs. 8 and 9, Table 2) of the data shows that the groundwater quality is locally impacted by specific constituents:

- Drj, Am and Mrtm samples generally have high sulfate, chloride and sodium concentrations, the order of abundance is $SO_4^{--} > Cl^{-}$.
- Z1, Z1bis, Z3, Z4, Z5 and HT samples generally have high chloride, sulfate and sodium concentrations, the order of abundance is $Cl^{-} > SO_4^{--}$.
- HAM, HF1 and HF2 samples generally have particularly high sulfate concentrations compared to the other components.
- However, KC1, KC2, K1 and K2 waters are characterized by a lower variability of the different chemical constituents. This is confirmed by the Piper diagram (Fig. 8) that shows no dominant ions for this group.

The relative composition of groundwater signatures found in this preliminary statistical analysis reflects a diversity of hydrogeochemical facies and suggests a relatively complex groundwater-geochemical system that may be explained by the heterogeneous geological conditions, in particular the structural and hydrostratigraphic specificities of the area.

4.2.2. Cluster analysis of the hydrochemical data

While the use of summary statistics resulted in four groups of monitoring points with similar geochemical characteristics (that will be discussed in the following sections), cluster analysis offers a secondary, objective test to confirm and refine the statistical clustering.

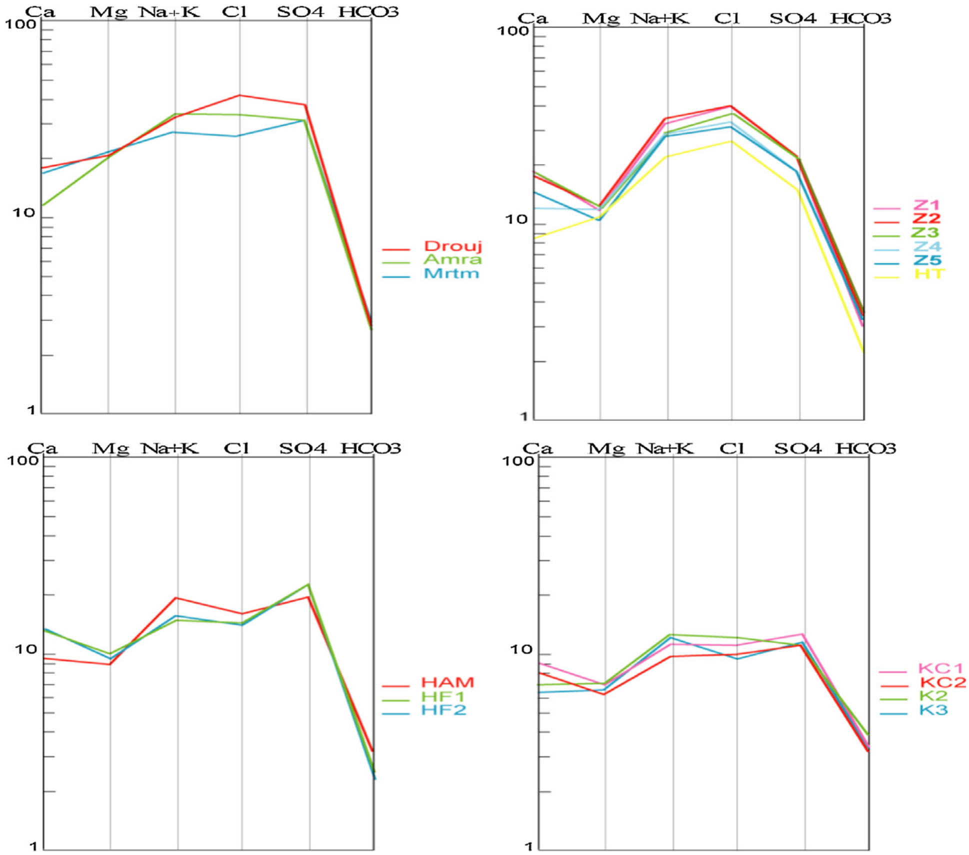

Fig. 9. Schöeller-Berkaloff diagram showing groundwater classification (Schoeller, 1962).

The dendrogram generated by Hierarchical Cluster Analysis for the 16 samples is shown in Fig. 10. Four preliminary groups were selected based on visual examination of the dendrogram; clusters were examined at three levels (linkage distances of 500, 400, and 280) to evaluate common chemical characteristics and differences between the sample groups. Table 2 summarizes ranges and mean values for every variable in the generated clusters, each representing a hydrochemical facies.

In Fig. 10, two major branches are visible in the dendrogram at the 500 linkage distance level. These two branches represent two major cluster groups, labeled A and B.

Cluster A consists of 13 monitoring wells: KC1, KC2, K1, K2, HAM, HF1, HF2, Z1, Z1bis, Z3, Z4, Z5 and HT. The waters have lower TDS than in cluster B (Table 2); the concentrations of HCO_3^{--} ions are higher than those of Mg^{++} ions.

Cluster B consists of the 3 remaining monitoring wells Drj, Mrtm and Am. The water samples have higher TDS than cluster A (Table 2), the highest concentrations of SO_4^{--} and Mg^{++}, and the lowest concentrations of HCO_3^{--}.

Cluster A is further subdivided at the 400 and 280 levels into smaller groups (A1–1, A1–2 and A2) of samples characterized by differences in relative proportions of Cl^-, Na^+, Ca^{++}, and Mg^{++}, further discussed in the following.

4.3. Geochemical versus structural compartmentalization

The possible significance of the hydrochemical grouping (presented above in Fig. 10 and Table 2) was indicated by the geographic, stratigraphic and structural distributions, the spatial evolution of TDS and the piezometric map analysis taking into account outcrop proximity, river and recharge zone location.

In fact, the geochemical grouping derived from the well-water data in the Jeffara de Medenine area indicates that the zone is hydrogeologically compartmentalized, in part because of faults that function as “structural discontinuities” influencing the flow path and the down-dip flow of recharge water. The chemical composition of the water can change along flow paths from one compartment to another due to various processes or to contact with different minerals.

In order to investigate the potential hydrogeochemical compartmentalization of the hard-rock aquifers, we used the geological context of each “structural compartment” to determine the location of each of its wells: first at the large-scale, i.e., the SW uplifted or the NE down-shifted compartments; second, at the small scale, i.e., the Koutine, the Zeuss or the Ksar Chrarif sub-compartments. Their properties are presented in Table 3 and Fig.11.

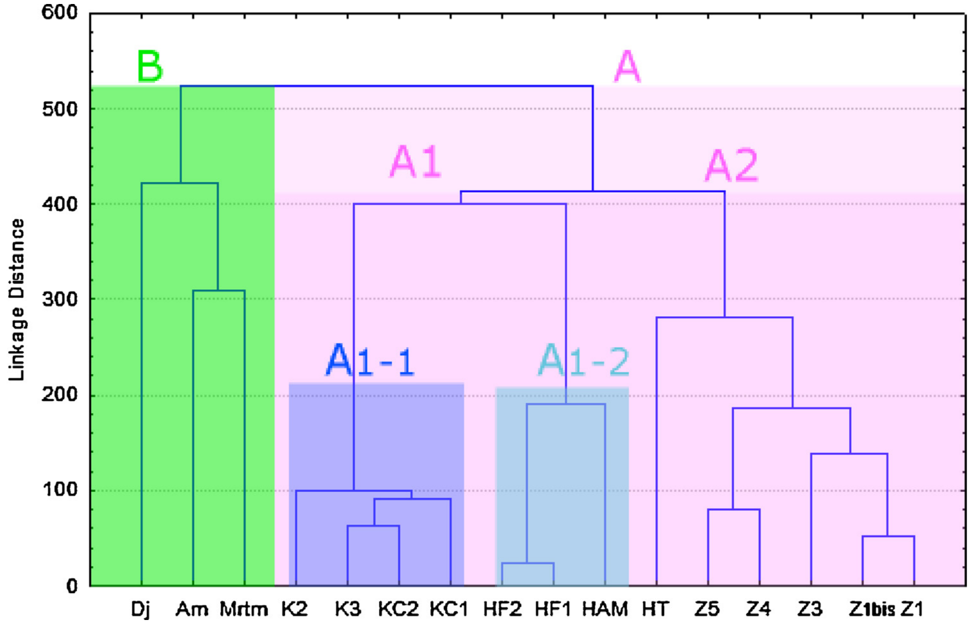

Fig. 10. Cluster dendrogram of the groundwater samples generated by hierarchical cluster analysis.

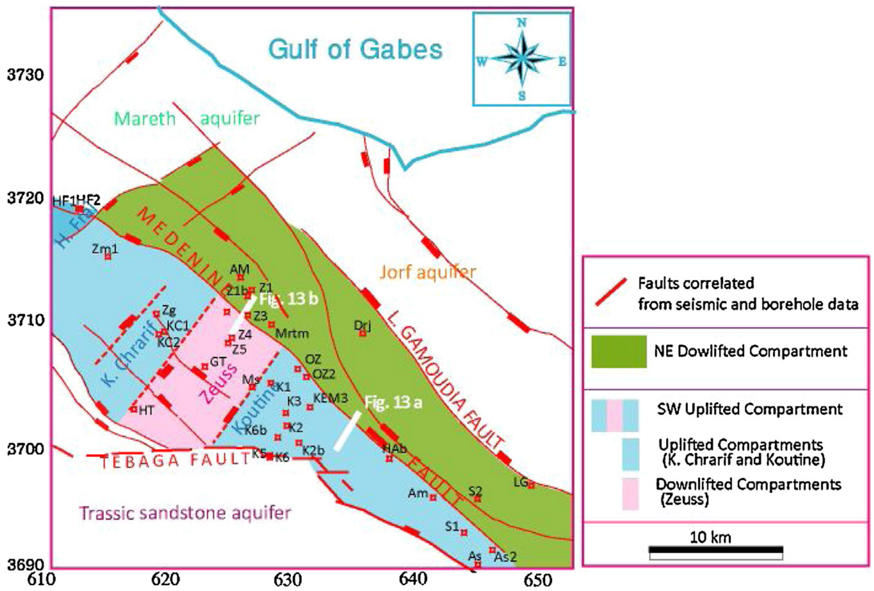

Fig. 11. Geochemical versus structural compartmentalization.

A general grouping of geochemical data by formation and/or by compartment assumes little mixing of the waters from different lithological units. However, the geochemical facies signature is based mainly on the magnitude of the deep water contribution.

In this context, we observe particular geochemical behaviors, within the groups defined above in the cluster analysis section, for the wells HAM, Am, Z1, Z1bis and Z3.

(i) The monitoring well Amra is screened in the Late Jurassic interval at a depth of 150 m. It is located on the west side of the SW uplifted compartment (Koutine sub-compartment) at a distance of about 1 km from the Medenine fault. However, the sampling results from this well are very similar to those of Cluster B (Fig. 10). The water from this well has higher sulfate, sodium and dissolved-solids concentrations than those detected for Cluster A1–1 in the Koutine subsystem. This suggests a mixing with waters of higher sulfate and sodium content. In fact, Amra is located northwest of a perennial surface flow near the Morra River, where groundwater emerges from the "Triassic sandstone" aquifer and is exposed to

Table 3
General grouping of geochemical data by formation and/or by compartment.

<table>
<tr><th colspan="3">Structural Compartment</th><th>Reservoirs</th><th>Monitoring Wells</th></tr>
<tr><td rowspan="4">SW Uplifted Compartment</td><td rowspan="3">Uplifted Sub-compartment</td><td>Koutine</td><td rowspan="3">Jurassic and Lower Cretaceous (Albo-Aptian/Wealdian)</td><td>K2, K3, HAM, Am</td></tr>
<tr><td>Ksar Chrarif</td><td>KC1, KC2</td></tr>
<tr><td>Henchir Fraj</td><td>HF1, HF2</td></tr>
<tr><td>Down-shifted Sub-compartment</td><td>Zeuss</td><td>Jurassic</td><td>HT, Z5, Z4, Z3,</td></tr>
<tr><td colspan="2">NE Down-shifted Compartment</td><td></td><td>Upper Cretaceous (Senonian/Turonian)</td><td>Z1, Z1bis, Dj, Mrtm</td></tr>
</table>

Table 4
Some examples of case-studies with limited data providing satisfactory results.

Case study	Data size	Cluster number
Baig et al. (2009)	25 Ground water samples	3
	23 Surface water samples	3
Belkhiri et al., (2010)	18 data points sampled in June, September and December.	3
Swanson et al., (2001)	22 data points 18 well samples and 4 spring samples	4

evaporation. Thus, it is quite likely that the area around the Amra monitoring well is contaminated by the infiltration of this evaporated water which is characterized by high concentrations of chlorides and sulfates.

(ii) The monitoring well HAM is also located in the Koutine sub-compartment at a distance of 1 km from the Medenine fault. The groundwater shows some characteristics consistent with Cluster A1–2 representing the Henchir Fraj area situated on the east side of the Ksar Chrarif sub-compartment. However, the water discharging from this well has higher sulfate and sodium concentrations than those detected for Cluster A1–1 representing the Koutine sub-compartment, which suggests a mixing with waters with higher sulfate and sodium content. However, the grouping of geochemical data by compartment assumes some mixing of groundwaters between lithologic units (or water reservoirs) belonging to the same structural compartment. Actually, the Jurassic reservoir in the HAM site overlays unconformably the Lower Triassic reservoir. Thus, the Jurassic reservoir may receive water from the Lower Triassic one by upward leakage. The water pumped from the HAM well may be a mixture of the two groups. Therefore, it is not surprising that the water shows some characteristics that are consistent with Cluster A1–2 representing the Ksar Chrarif compartment.

(iii) The monitoring wells Zeuss 3, Zeuss 1 and Zeuss 1bis are located in the NE down-shifted compartment. Their water comes from the Senonian and the Turonian reservoirs at a depth of several hundred meters. But it shows some characteristics that are consistent with Cluster A2 representing the Zeuss sub-compartment. This suggests that the NE down-shifted compartment of the aquifer system is fed directly by groundwater from the neighboring SW uplifted compartment, i.e., from the deep Jurassic reservoir at the Zeuss 4 and Zeuss 5 well sites. Consequently, the spatial association between the water from the Upper Cretaceous (Senonian and Turonian) reservoirs in the NE down-shifted compartment with water from the Jurassic formations in the SW uplifted compartment suggests that the Medenine fault acts as a preferential flow path in the Zeuss area.

While there are limited data available, the results obtained with these limited data have provided satisfactory results. Cluster analysis is usually an efficient tool to use when the data are limited. Here are some examples of case-studies with limited data (Table 4).

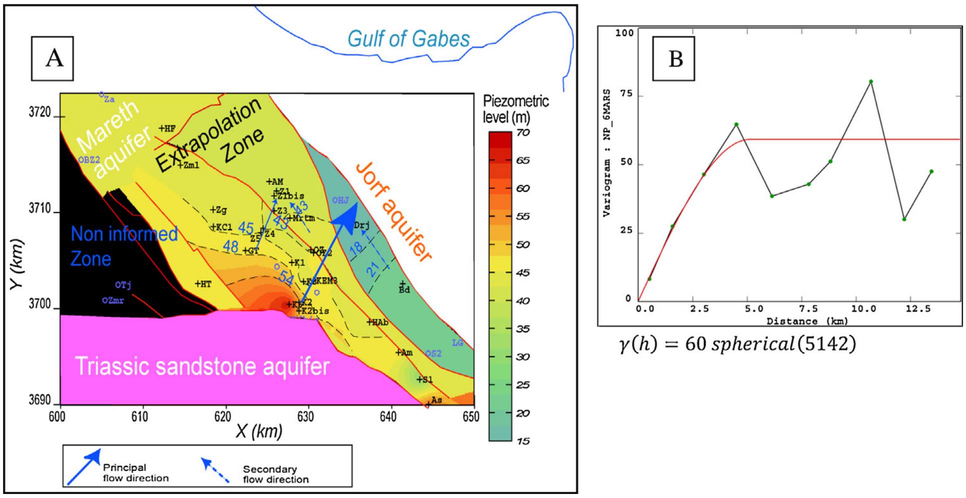

Fig. 12. (A) Piezometric map, main normal faults and groundwater flow in the Jeffara de Medenine aquifers. (B) Experimental (/) and modeled (/) omnidirectional variograms for piezometric levels.

Concerning the cluster analysis presented in our study, the full dendrogram represents a hierarchy that displays the progressive clustering of objects (well populations and structural compartments, Fig. 10). It is then possible to choose a partition that, with a specified number of clusters, is derived by truncating the dendrogram at different levels. The level and the partitioning depend upon constraints that we have defined objectively according to structural and hydogeochemical relevant criteria. For various numbers of clusters of homogeneous well populations, we have to evaluate the consistency with the number and the scale of the structural compartment.

Most likely, the obtained clusters are very meaningful for both the large clusters and the smaller ones. Even breaking a "true" cluster (A, Fig. 10) into two parts (A_1 and A_2 which could be considered as too uncertain) given the data size (16 data points), provides meaningful results: these clusters are consistent with the multiscale structural compartmentalization and lead to a meaningful spatial distribution of hydrochemical data at the local and regional scales.

So we can say that *the best number of clusters is the value which works best for a particular task*. In our opinion, it is not possible to define an "optimal" number of clusters. It is the consistency of *different possible clusters with the data that provides guidance on the number of clusters to select*.

4.3.1. Groundwater flow: The recharge zone piezometric map analysis

The groundwater flow of the study domain is based on the estimated piezometric map (Delhomme, 1976; Marsily de, 1986; Besbes, 2010) obtained by kriging (Fig. 12) and on the "hydrogeological domains" map (Fig. 2).

The Jeffara de Medenine aquifer system receives two types of water. The first one is the direct surface recharge by rainwater, runoff and river flow from different reliefs surrounding the depression, mainly Jebel Dhahar in the west and Jebel Tejra Kbira and Jebel Tejra Sghira in the south-east (Fig. 2). At a local scale, the groundwater is preferentially recharged from the high-elevation areas within the uplifted compartments Koutine and Ksar Chrarif.

The second water origin is the lateral deep groundwater flow from neighboring aquifers. The combination of surface and deep water gives the Jeffara de Medenine aquifer its specific chemical facies. The geochemical facies signature is determined by the preponderance of one or the other contribution.

The piezometric map (Fig. 12) shows significant water level changes across the different zones of the study area. But it indicates that the regional groundwater flow in the aquifer is in general from southwest to northeast. A thorough examination of the piezometric map reveals that the tectonic structures exert considerable control over the groundwater flow and the hydraulic head in the study area.

(i) The regional ground-water flow follows the down-dip direction and is parallel to the topographic slope. This implies that, in general, the groundwater is recharged from the higher elevation, mainly in the south–west "Dhahar", and flows toward a common, hydrographically low, discharge area, the Sebkhat Oum Zassar and the Mediterranean Sea (Figs. 2 and 12).
(ii) Furthermore, the NW–SE normal faults appear to function as "structural discontinuities" that influence the flow path and the down-dip flow of recharge water between the different compartments. The Medenine fault is the main structure that conditions the hydraulic connection between the two major compartments, the SW uplifted one and the NE down-shifted one (Figs. 7, 11 and 2). It acts as a conduit or a preferential flow path in the center and on the western side of the study area, the "Zeuss and Oum Zassar" region; it functions as a barrier to the groundwater flow in the eastern domain, the "Smar and Hassi Abdel Mlak" area.

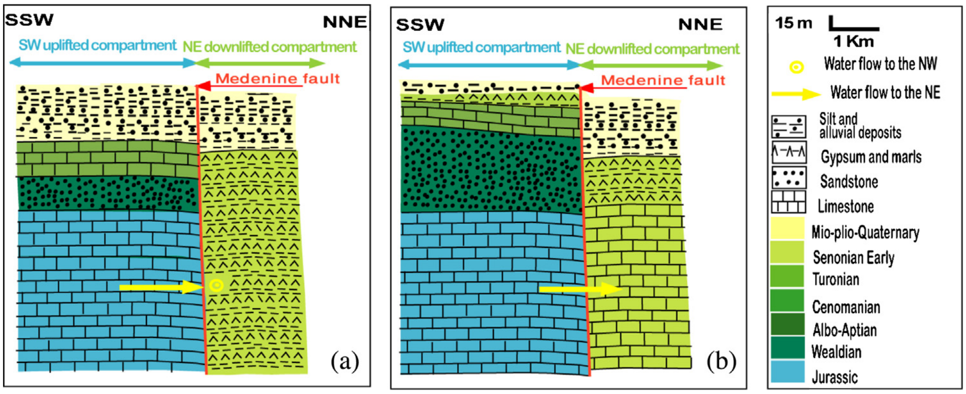

Fig. 13. Influence of the geologic structure on groundwater flow.

(See Fig. 11 for location).

In addition, we can observe that the groundwater level contours cut the Medenine and the Gamoudia faults in the NE down-shifted compartments. This indicates the presence of a secondary groundwater flow path from SE to NW. In fact, the groundwater flow direction is generally from SW to NE in the SW uplifted compartment and turns to the NW in the NE down-shifted compartment closer to the Medenine fault.

In the course of time, the Medenine fault has undergone large displacements with different throw magnitudes. Additionally, Chihi et al. (2013) have shown that the Cretaceous sedimentary units, within the NE down-shifted domain, dip toward the NW. Thus, from the SE to the NW, the fault juxtaposes different flow units with different lithologies. It acts as a combined conduit-barrier system. Consequently, its hydrodynamic properties change depending on whether the fault has placed high permeability units against other high permeability ones or low permeability ones. In the latter case, the flow direction becomes, locally, parallel to the fault.

The SE component of the Medenine fault (Fig. 13a), that forms the northern border of the SW uplifted compartment, may act as a semi-permeable feature with low hydraulic conductivity. In this region, the section north of the Medenine fault is down-shifted. The throw magnitude is very large and causes the displacements of the Jurassic and the Lower Cretaceous sediments by up to several hundred meters. This has resulted in placing the high-permeability carbonate units of the Jurassic interval against low-permeability marls and gypsum units of the Lower Senonian interval and/or against the less permeable marly limestone unit of the lower Senonian.

However, the NW component of the Medenine fault in the Zeuss region (Fig. 13b) acts as a conduit for groundwater flow. The throw of the Medenine fault is very large. The displacement across the faults has caused the juxtaposition of different flow units with high permeability: carbonate units of the Jurassic against carbonate units of the Lower Senonian. This has maintained flow in the NE direction across the fault.

This interpretation of the hydraulic connection between the units is confirmed by a clear evolution of the hydrochemical variables that is observed within the Zeus sub-domain. The water chemical composition of the groundwater samples in the Zeuss domain (wells: Zeuss 5, Zeuss 4, Zeuss 3, Zeuss 1 and Zeuss 1bis) shows a regular increase in the different ion concentrations on the Schoeller-Berkaloff diagram (Fig. 9) and also on the kriged maps (Figs. 15 and 16). Thus the regional groundwater flow described by the piezometric map (Fig. 12) demonstrates that the aquifer system near Zeuss 1 and Zeuss 1bis is located where discharge rates from the deep parts of the aquifer system are relatively high.

4.3.2. Spatial distribution of total dissolved solids

Total Dissolved Solids is a major factor that confirms the difference between the generated geochemical groundwater groups and the structural compartmentalization throughout the study area.

Within the Jeffara de Medenine aquifers, water generally becomes more mineralized along the flow path, from upgradient (south) to downgradient (north), in the direction of the Mediterranean Sea (Figs. 12 and 14). Overall, the TDS increases from cluster A (the SW compartment) to cluster B (the NE compartment) (Fig. 14, Tables 2 and 3). At a smaller scale, the chemical composition of water changes across the SW compartment. From SW to NE, we distinguish:

- cluster A1 corresponding to the uplifted Koutine and Ksar Chrarif compartments, with relatively fresh water and,
- cluster A2 that is attributed to the Zeuss down-shifted compartment with brackish water.

5. Geochemical evolution

In this section, we use a spatial analysis of hydrochemical variables to study the spatial evolution of the groundwater chemical composition. To this end, maps of all hydrochemical variables were constructed by geostatistical methods. For

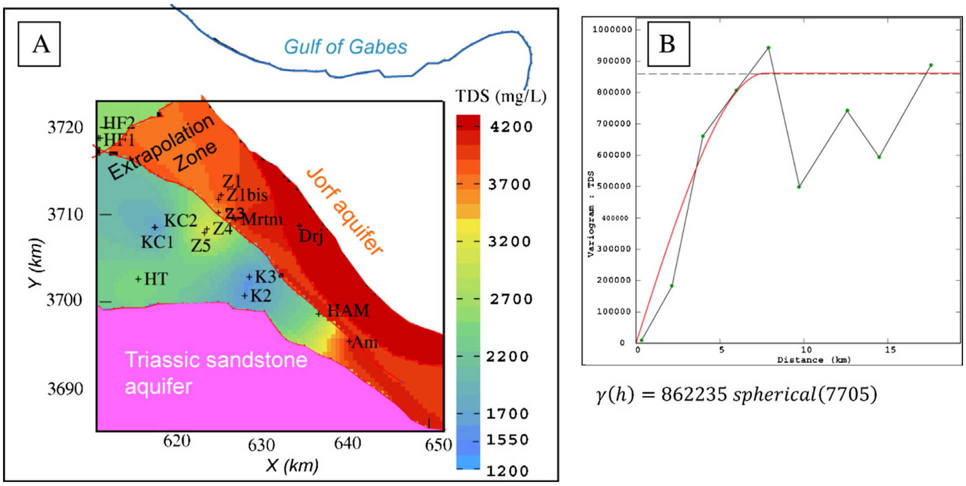

Fig. 14. (A) Spatial distribution of Total Dissolved Solids. (B) Experimental (/) and modeled (/) omnidirectional variograms for TDS concentrations.

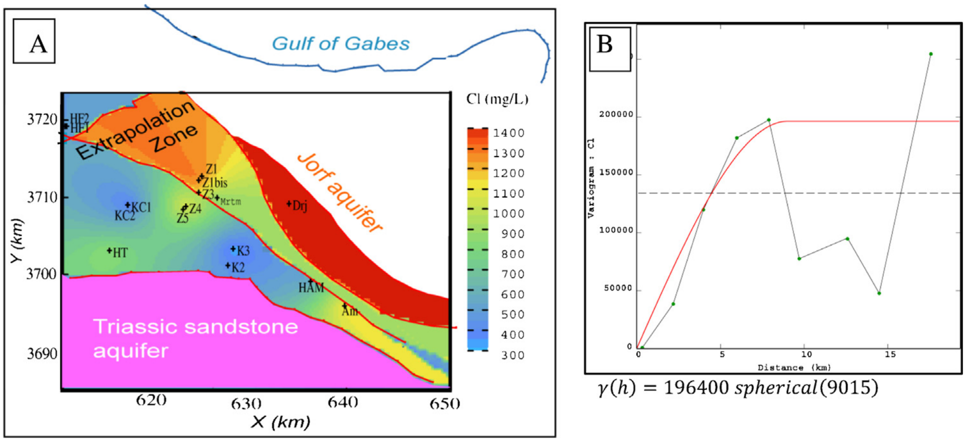

Fig. 15. (A) Spatial distribution of Cl concentrations. (B) Experimental (/) and modeled (/) omnidirectional variograms for Cl concentrations.

the sake of brevity, only SO_4 and Cl concentration maps (Figs. 15 A and 16 A) were selected to illustrate the geochemical evolution in the study area.

5.1. Description of the spatial distribution of major-ion concentrations

The calculated maps of the spatial distribution of major-ion concentrations within the aquifer show that the most prominent feature is their systematic trend in the direction of the Mediterranean Sea (Figs. 15 A and 16 A).

Overall, the hydrochemical concentrations increase from the SW uplifted to the NE down-shifted compartments. They also show that the mineralization of the waters generally increases along the flow path, from up-gradient to down-gradient as shown on the TDS concentrations map (Fig. 14A).

The spatial distribution of each major-ion concentration appears to have a geographic relation to the structural compartmentalization.

Within the SW uplifted compartment, the concentrations show great variability. Concentrations of Ca, Cl, Na, Mg and SO_4 are higher in the down-shifted Zeuss sub-compartment and lower in the uplifted Ksar Chrarif and Koutine sub-compartments. Conversely, HCO_3 concentrations are higher in the uplifted Ksar Chrarif and Koutine sub-compartments, and lower in the down-shifted Zeuss sub-compartment.

In the NE down-shifted compartment, the concentrations excluding bicarbonates HCO_3 would be expected to be similar to those of TDS, which are highest down gradient from the Medenine fault. Furthermore, there is an obvious trend in ion concentrations in the NW direction: concentrations of Ca, HCO_3, Cl and Na increase, whereas those of Mg and SO_4 decrease.

To summarize, we made three important observations: (i) TDS and major ion concentrations differ from one compartment to another; they increase in down-shifted compartments containing evolved waters and decrease in uplifted ones containing

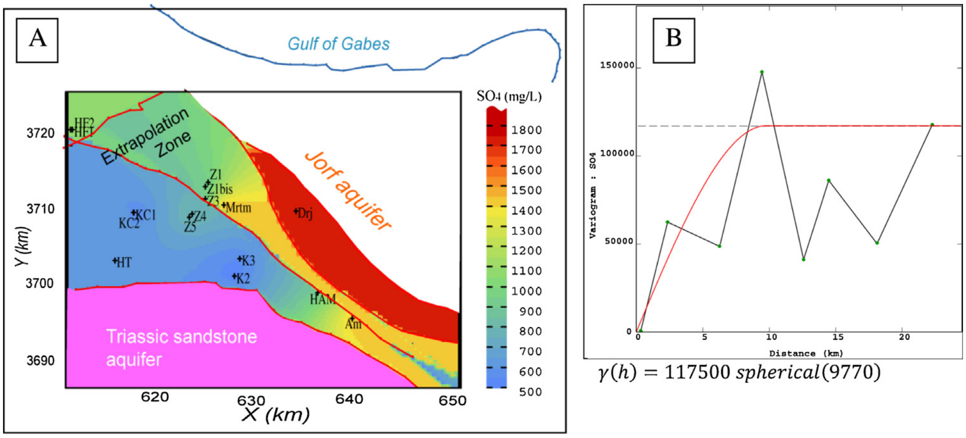

Fig. 16. (A) Spatial distribution of SO_4 concentrations. (B) Experimental (/) and modeled (/) omnidirectional variograms for SO_4 concentrations.

less evolved samples from shallower wells. (ii) Water samples with high TDS concentrations have high Cl^-, SO_4^- and Na^+ concentrations. (iii) All water samples are dominated by Cl^-, SO_4^{--} and Na^+, but have substantially different ionic proportions. Water samples generally show uniform concentration ranges in uplifted domains and variable ones in downshifted ones.

5.2. Interpretation

The chemical composition of groundwaters and their evolution in the Jeffara de Medenine aquifers are influenced by four major processes when rain water and/or water, percolating from river beds, moves down-gradient along available flow paths, through surrounding outcrops, surface sediments or soil, upper Cretaceous and/or Tertiary sequences overlying the aquifer, to reach the aquifer formations.

(i) Evaporation: constituents dissolved by rainwater, mainly chloride, sodium and sulfate, are concentrated by *evapotranspiration* before the water percolates below the recharge area.
(ii) Water-rock interactions (along flow paths): gypsum/halite evaporites, clays and marls are among the common Mio–Plio–Quaternary materials deposited in the region (Ben Ouezdou., 1983; Ben Youssef and Peybernes, 1986). Sodium, chloride and sulfate are released by the leaching and weathering of sediments. Thus, evaporative salts buried by sedimentation may dissolve as groundwater flows through the sediments. Gypsum is the most likely source of sulfates. Halite may also supply chloride and sodium in the recharge areas. In addition, dissolution of clays such as illite, chlorite, or both, may also be a source of chloride.
(iii) Additional processes such as mixing of groundwater from various neighboring aquifers or aquifer compartments can also be important controls of groundwater chemical concentrations, as described in some studies in domains close to the study area (e.g., Ben Baccar, 1982; Mammou, 1990; Yahyaoui et al., 2002; Kamel et al., 2006; Bouri et al., 2008).
(iv) Groundwater residence time: the three above processes may act together to change the geochemical signature of the groundwater, but the degree of their involvement differs from one compartment to another depending on the hydrogeological and structural characteristics of each compartment. One important fact that impacts the geochemical signature is the *rate at which the carbonate aquifers are recharged*.

What follows is an attempt to present the possible local geochemical and hydrological processes that control the distribution of major ions and TDS over the Jeffara de Medenine area and to infer the geochemical signature of each compartment.

5.2.1. The SW uplifted compartment

5.2.1.1. The SW uplifted sub-compartments of Koutine and Ksar Chrarif. The reservoir formations over most of the uplifted sub-compartments Koutine and Ksar Chrarif are composed of Jurassic carbonates that lie directly under the karstified Albo-Aptian carbonates and the Wealdian sandstones (Fig. 5). The reservoir units are also the closest to the river beds of the Zigzaou and Koutine Rivers and to the land surface in these areas (Figs. 5 and 2).

These geologic characteristics insure (i) a limited exposure to evapotranspiration at the surface and (ii) a fairly short contact time with the reservoir rocks and the overlying karstified and permeable deposits, as the recharge comes directly from runoff; the water rapidly percolates downdip to the aquifer. These conditions may limit water interaction and ion exchange with the sedimentary sequences lying between the ground surface and the aquifer.

Consequently, the water collected in the wells of theses compartments comes from the top of the aquifer, where the salinity is much lower than in the rest of the aquifer; the TDS concentrations are generally between 1500 and 1800 mg/L.

Such a "top-of-aquifer" domain of dilute water is characterized by less variability of the different chemical constituents and shows no dominant ions in this well group (Figs. 8 and 9).

5.2.1.2. The SW down-shifted Zeuss sub-compartment. In the down-shifted Zeuss sub-compartment, TDS concentrations are generally greater than 3000 mg/L and the water types are Cl–SO_4–Na.

As for the Koutine and Ksar Chrarif compartments, the Zeuss wells reach the Jurassic carbonates that lie under the kartstified Albo-Aptian carbonates and the Wealdian sandstone (Fig. 5) and that also lie beneath the river bed of the Zeuss River (Fig. 2). In this area, the reservoir formations are overlain by the upper Mio–Plio–Quaternary unit. As indicated above, sodium, chlorides and sulfates are released by the dissolution and weathering of these sediments and infiltrate into the aquifer. Moreover, the aquifer formation lies at greater depth within the Zeuss compartment, thus the water is recharged less rapidly. Water interaction and ion exchange with the sedimentary sequences may also occur, resulting in higher concentrations than in the Koutine and the Ksar Chrarif compartments.

5.2.2. The NE down-shifted compartment

As water flows through the carbonate aquifers in the SW uplifted compartment and comes into the NE down-shifted one, the mineralization of the groundwater increases significantly and exceeds 4000 mg/L; all ion concentrations increase (Figs. 14 A and 15 A), only bicarbonate ions decrease.

In this collapsed compartment, the Jurassic and the Lower Cretaceous sediments are displaced up to several hundred meters by the Medenine fault (Fig. 6). Groundwater is collected from the upper Cretaceous reservoirs, the Lower Senonian and Upper Turonian carbonates, that lie directly under the Mio–Plio–Quaternary upper unit (Figs. 6 and 13). The reservoir levels are located at very great depths that can reach ~900 m (for the Zeuss 1bis well) inducing long vertical flow paths through the Mio–Plio–Quaternary upper unit and the upper Cretaceous deposits. Moreover, the Senonian carbonate aquifers in the northeastern compartment contain interbedded evaporite deposits that constitute a second possible source, with the Mio–Plio–Quaternary upper unit, of sulfate, chloride, and sodium ions in the groundwater.

The highest mineralization in this compartment, characterized by the presence of several closely-spaced faults, is consequently related to longer residence times. It corresponds to zones of groundwater discharge from the NE uplifted domain and mixing of chemically different waters from deeper formations.

6. Conclusions and recommendations

The complexity of the Jeffara de Medenine aquifer system is such that its thorough characterization required extensive and interdisciplinary methods. We combined tectonic, geophysical, hydrogeological and hydrogeochemical investigations with statistical analysis and geostatistical mapping to provide a comprehensive characterization of the structural compartmentalization and describe its impact on the hydrogeological and geochemical functioning of the aquifer system at the regional and local scales.

A: The methodology illustrated in this paper is an efficient approach in faulted aquifer systems such as this. It takes advantage of two powerful spatial analysis tools:

(i) The geostatistical estimation taking into account the "fault parameter", i.e., the existence of faults which limit the size of the neighborhood from which to use data points (Chilès and Delfiner, 2012; Chihi et al., 2013). This modelling procedure constructs a realistic model of the different parameters (piezometric head, TDS and major ion concentrations).
(ii) The spatial cross-analysis between the significant water groups obtained with the hierarchical cluster analysis method, and the structural aquifer compartments defined by the geological studies, reveals the spatial dependence between the geochemical properties (hydrochemical facies and total mineralization) and the hydrogeological and structural context (recharge area, piezometric level, flow paths, lithology and layering of aquifers, faults). This procedure results in a robust interpretation that helps to understand the hydrochemical functioning at both the regional and local scales, i.e., inside each compartment and from one compartment to another.

B: The results showed that coupling geostatistical techniques with multivariate statistical analysis is an effective approach in hydrogeochemical characterizations of faulted aquifer systems. The major conclusions drawn from the present study are:

(i) The geological and geophysical investigations showed that the study area is characterized by a structural setting that controls the geochemical facies repartition and fluid circulation. The aquifers partitioning into homogeneous groups proved the existence of a geographic relation of these groups with the structural compartmentalization. Thus, we identified five hydrogechemical compartments that are correlated to the five defined structural compartments.
(ii) The above findings reflect the continuous and dependent processes governing the variability in water chemistry in the study area. Kriged maps of piezometric levels, dissolved solids and major-ion concentrations highlightedthe relationship between the different-scale structural groundwater compartments, and helped defining the possible geochemical and hydrological processes that control the distribution of the hydrochemical parameters.

The clear trends observed in major-ion chemistry in the Jeffara de Medenine aquifer system are controlled, in a large part, by *chemical reactions* (mostly dissolution but also most likely precipitation, oxidation, reduction and ion exchange) between groundwater and minerals that compose the aquifer and the overlying units. Two additional major processes, evapotranspiration and mixing of waters from adjacent domains, control the water solute concentrations and their spatial distribution.

The relative importance of these three processes in controlling groundwater chemistry and its spatial distribution is influenced by *groundwater flow paths* (depth and lateral extent) and/or *groundwater residence time*. These two factors are governed by the geological configuration that characterizes the aquifer system: *the structural compartmentalization* by NE–SW and NW–SE normal faults and the sedimentary composition and layering within each aquifer compartment. Moreover, the presence and/or *the thickness of the "upper Mio–Plio–Quaternary unit"*are crucial factors controlling the geochemistry of the groundwater within the different compartments.

C: The methodology used in this study, i.e., the joint spatial analysis of geochemistry and hydrogelogical properties, is of considerable interest, as it can be applied to any aquifer or to other spatial problems.

Mapping "the groundwater geochemistry compartmentalization" in the Jeffara de Medenine aquifer system can provide exceptional insights into:

(i) Delimiting zones of potable water among and within the different aquifer compartments.
(ii) Characterizing the dynamics of the aquifer system both in the past and present, as shown here; combined with other hydrologic information, it provides a basis for developing the conceptual groundwater model of the aquifer system.
(iii) Helping to set up a groundwater artificial recharge system in order to reduce water mineralization and thus provide adequate water quality for human and agricultural use.

Finally, data analyses, result interpretations and discussions as demonstrated in this study provide strong evidence of a high degree of lateral compartmentalization within the Jeffara de Medenine aquifer system. An examination of lithostratigraphic and geochemical correlations, and other information indicates that *the compartmentalization within the aquifer system is smaller in size than the current well spacing*. Well data are collected with a higher well density along the general directions of regional groundwater flow and do not cover the entire study area.

To conclude, to improve the understanding of the functioning of the aquifer system, we need a more detailed characterization of the different heterogeneities within each aquifer compartment, which requires a finer sampling grid with higher resolution. The results presented above could be used *to guide a new sampling program*. New wells could be drilled mainly on the west side of the SW compartment, and in the NE down-shifted compartment in the ESE–WNW directions. The new observations would make it possible to: (i) investigate more precisely the spatial variability of the aquifer geochemistry and to understand the hydrogeochemical functioning of the aquifer system as a whole, and (ii) evaluate the differences in ground–water chemistry in the directions of the regional groundwater flow.

Acknowledgments

The authors thank "Entreprise Tunisienne d'Activités Pétrolières" (ETAP) for providing seismic sections and petroleum exploration well logs, the Regional Authority for Agricultural Development of Medenine (CRDA) for providing borehole data, Prof. M. Besbes (National Higher Engineering School of Tunis), Dr. B. Ben Baccar (General Direction of Water Resources) and two anonymous reviewers for their helpful comments on an earlier draft of this article; and T. Atoui for guiding the field study trip.

Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.ejrh.2015.07.004.

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