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Hydrochemistry and Stable Isotopes ($\delta^{18}O$ and $\delta^{2}H$) tools applied to the study of karst aquifers in Southern Mediterranean basin (Teboursouk area, NW Tunisia)

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Hydro and isotope geochemistry were used in this study:

- to identify the hydrodynamic functioning of the karst aquifer;
- to investigate the water type of groundwater in the semi-arid north-western Tunisia;

Hydrochemistry and Stable Isotopes ($\delta^{18}O$ and $\delta^{2}H$) tools applied to the study of karst aquifers in Southern Mediterranean basin (Teboursouk area, NW Tunisia)

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Abstract

Karst aquifers receive increasing attention in Mediterranean countries as they provide large supplies water used for drinkable and irrigation purposes as well as for electricity production. In Teboursouk basin, Northwestern Tunisia, characterized by a typical karst landscape, the water hosted in the carbonates aquifers provides large parts of water supply for drinkable water and agriculture purposes. Groundwater circulation in karst aquifers is characterized by short residence time and low water-rock interaction caused by high karstification processes in the study area. Ion exchange process, rock dissolution and rainfall infiltration are the principal factors of water mineralization and spatial distribution of groundwater chemistry. The present work attempted to study karstic groundwater in Teboursouk region using hydrochemistry and stable isotopes ($\delta^{18}O$ and $\delta^{2}H$) tools. Karst aquifers have good water quality with low salinity levels expressed by TDS values largely below 1.5 g/l with Ca-SO_4-Cl water type prevailing in the study area. The aquifers have been recharged by rainfall originating from a mixture of Atlantic and Mediterranean vapor masses.

Keywords: karst, aquifers, hydrochemistry, stable isotopes, Teboursouk, Tunisia

1. Introduction

The karst aquifers are characterized by a complex heterogenic and anisotropic hydro-geological system created by groundwater flow which is very different from the other aquifers (Bakalowicz, 2005; Ford and Williams, 2007). This wide variety of functioning and characteristics is due to the complex conditions under which they were formed (Bakalowicz, 2015). Generally, the karstification processes are controlled by various factors such as the mechanical structure, karstic rock chemical composition, soil texture, fracturing, climate, temperature and precipitation (White, 1999; Ford and Williams, 2007; Ayadi et al., 2014).

In Mediterranean countries, the groundwater hosted in karst aquifers constitutes a very important resources for development as they supply about 25% of the total domestic water supply and it is, furthermore, used for irrigation and industrial activities (Bakalowicz and Döfliger, 2005; Bakalowicz, 2015). In many countries, this groundwater type presents a potential and unique water resource (Bakalowicz, 1979, 2015). In Tunisia, located in the southern Mediterranean basin, the karst resources represent over 13 % of the groundwater resources where two carbonate outcrops of Campanian-Maastrichtian (Abiod Formation) and Lower Eocene (Metlaoui Formation) play a role in the karst hydrogeology (Ennabli and Dars, 1981). Teboursouk area, Northwestern Tunisia, is characterized by water resources enclosed in a karst aquifer used for domestic and agricultural activities. It is characterized by a long tectonic history owing to a complex and heterogeneous geological structure. Thus, the understanding of hydro-geological system of the region is particularly difficult. Several methods have been suggested for the study of the structure and functioning of karst aquifers.

Hydrochemistry and stable isotopes ($\delta^{18}O$ and $\delta^{2}H$) methods were applied to the study of karst aquifers. They have been used to identify the water quality, groundwater origin and mechanisms, hydrochemistry evolution, water-rock interaction, recharge sources and residence time, in order to fill in the gap in the knowledge about its functioning. This study aimed to present the major karst aquifer and integrate hydrochemistry and stable isotopes tools to investigate the groundwater quality in the study area.

2. Geography and climatology studies

Tunisia, as a part of the Northeastern African continent, bordered by the Mediterranean Sea from the North and the East and the Sahara platform of North Africa in the South (Fig. 1a). It represents a climatic transition zone influenced by Mediterranean and Atlantic air masses (Rindsberger et al., 1990; Kallel et al., 1997; Hamed, 2011; Hamed et al., 2013, 2014). The Mediterranean precipitations represent 66 % of total rain amount (Hamed et al., 2014). The study area (Teboursouk) situated in Northwestern Tunisia, between X1: 510000, X2:530000 and Y1:4024000; Y2:4038000 (Fig. 1b), is characterized by high mountains structures, and belongs to a semi-arid to sub-humid climate characterized by regular rainfall amount leading to an expansion of agricultural activities and intense karstification process of carbonate formations. Figure 2 shows the mean annual climatic parameters for the period 1997 to 2015. The precipitation ranges from 6.12 in July and 95 mm in January with a mean annual precipitation 613.6 mm. The rainy season lasts from September to May and the dry period lasts from June to August. The mean annual temperature is 19.1 °C with a maximum value of up to 28.4 °C in summer (July and August) and a minimum value of up to 9.8 °C in winter (February). The relative humidity has a maximum in February (87 %) and minimum in July (55.2 %). The evapo-transpiration potential is as low as 861.98 mm/year.

3. Geology and hydrogeology studies

The Northwestern Mediterranean region has complex and complicated geological features resulting from the convergence between Africa and Europe, which started in the late Cretaceous and continued until the present day (Decourt et al., 1986) and contributed to the formation of the Atlas Mountains (Rouvier, 1977; Ben Ayed, 1986). The Northern Tunisian Atlas is characterized by apparent NE-SW trending Triassic evaporitic diapirs since Aptian (Burollet, 1956; Perthuisot, 1975; Zargouni 1975; Turki, 1985; Ben Ayed, 1986; Chikhaoui et al., 2002; Jalouli et al., 2005; Benassi et al., 2006).

Teboursouk basin, as a part of diapir zone (Fig. 1b), is shaped by several Triassic extrusions. The Triassic atypical landforms are the results of intense halokinesis activity. Structurally, the study area is characterized by two major structures of NE-SW direction (Ben Ayed, 1993; Chihi and Philip, 1998; Abbes, 2004; Melki et al., 2010, 2011; Zouaghi et al., 2011), Thibar diapir to the North and J. Cheid to the South. Smaller structures such as Ain Jammala (NE of Teboursouk) and Fej el Adoum (SW of J. Goraa) are reported. The study region shows, furthermore, NE-SW atlasic synclines, most often with geological landforms inversions. This inversion is consisted of perched synclines and anticlines with axes occupying the depressions. The fault system of Teboursouk region shows a NE-SW major alignment. Teboursouk fault constitutes the major tectonic feature of the region and it corresponds to a reverse fault manifested by visible overlaps (Perthuisot and Jauzein, 1972; Perthuisot, 1978; 1979; Hammami 1999; Kadri and Ben Haj Ali, 1999; El Ouardi, 2002; Chikhaoui, 2002; Balti et al., 2014; Hachani et al., 2014; Redhaounia et al., 2015a,b).

In hydro-geological terms, two units make up the most important reservoir aquifers in the region used for agricultural and domestic activities. The first is represented by Metlaoui

Formation (Lower Eocene) and the second is represented by Abiod Formation (Campanian-Maastrichtian).

These aquifers are hosted in Karstic limestone with separate and isolated hydro-geological units related to the complexity of the tectonic features of Tebousrouk area (Bolze, 1955; Zebidi, 1967, 1971; Talbot, 1974; Talbot and Andrieu, 1974; Hachemi and Talbi, 1978; Zebidi, 1980; Ben Gsim, 1984, 1985; Balti, 2004; Balti et al., 2013). Lower Eocene aquifers are hosted in synclines (Aïn Tounga, Chetlou, Teboursouk, Aïn Zitouna and Gorra) (Figs. 3, 4 and 5) with thicknesses between 40 and 150 m (Talbot and Andrieu, 1974; Hachemi and Talbi, 1978; Zebidi, 1980; Ben Gsim, 1984). They have a NE-SW or N-S trending directions. However, the Campanian-Maastrichian aquifer represents anticline structures trending NE-SW (the wadies of Nemcha and Akrout). This aquifer is logged into karstic limestones. These fractured limestones are described as the upper and the lower members of the Campanian-Maastrichian Formation. Their thickness could reach 100 m; the upper member thickness ranges from 30 to 50 m whereas the lower member is about 100 m thick. Furthermore, these structures are considered as very important water reservoirs taking into account their high hydro-geological potential (Bolze, 1955; Zebidi, 1967; Ben Gsim, 1987, 1995; ERI 2009; Redhaounia et al., 2016a).

The principal karst units of the study area are:

- J. Goraa consists of a perched syncline over 16 km^2 of surface made by thick limestone series of early Eocene (Talbot and Andrieu, 1974; Chaieb and Hamami, 1986). It presents an axial lowering at the Djebba village. On the edges of these limestones appear numerous springs with variable flows; the most important are the springs of Aïn Nehas and Aïn Brag which can provide a flow rate of 20 l/s and other sources low-rated flow springs;

- The nummulite structure of Ain Zitouna is a small syncline (2 km^2). It consists of an unconfined aquifer emerging through the Aïn Zitouna spring (Bolze, 1955; Zebidi, 1967) with a flow rate of about 10 l/s. This natural spring is mainly fed by the El Faouar wadi. Furthermore, during floods of this wadi the water of Aïn Zitouna becomes cloudy which proves the existence of a superficial karst which regime is influenced by surface water fluctuations. Numbulitic structure of Teboursouk is spreaded over an area of 5 km^2. The fractures of this structure form small, insulated, unconfined aquifers emerging to the surface by several springs with a flow rate of about 1 to 2 l/s (Bolze, 1955; Zebidi, 1967);
- The J. Chetlou structure is a perched but closed syncline, constituted mainly of fractured and karstified nummulitic limestones. The feeding area was estimated of about 10 km2 with an infiltration coefficient of 25% (Ben Gsim, 1984). This syncline contains the cave of Ghar Kriz exploited by a deep well. This cave is characterized by the presence of an underground lake of about 300 m from the entrance and 70 m deep. At 160, 198 and 207 m the bed of an underground river (currently dry) is found. It is formed by dark marls. The high moisture content of these marls and the high moisture at the bottom of the cave show that this river must be active during the rainy periods of the year (Ceteaud, 1955; Ayadi, 2016). The underground lake is characterized by a very large underground river drained by three springs (Aïn Younes, Aïn Chetlou and Aïn Edroua) with low flow (0.5 to 2 l/s). Thus, this perched aquifer is captured by one borehole with a debit of about 1 l/s;
- The structure of J. Tounga is a perched syncline affected in its median part by a serie of accidents that probably contributed to the disappearance of its Southwestern flank (plain of wadi Khalled) (Zebidi, 1971; Hachemi and Talbi, 1978). It has an area of 7 km^2 and an

infiltration coefficient of 18% (Hachemi and Talbi, 1978). The most important springs are located in the lower downstream plain (northern part) at the limit of the underlying limestones and marls such that of Aïn Tounga spring with a flow rate ranging between 2 and 5 l/s;

- The Maastrichtian-Campanian aquifer consists of a confined aquifer forming a continuous structure in contrast to the lower Eocene limestone which is more fractured and fragmented. The Nemcha wadi anticline structure exhibits periclinal terminations with a NE direction at Aïn Milliti spring and SW J. Goraa, affected by NW-SE fault system. Those faults cross the structure causing horizontal misalignment in the limestone bars of the Abiod Formation. The NW flank of the anticline seems to be a very rugged monoclinal. Many springs discharge to Beida wadi and its tributaries (Bolze, 1955; Zebidi, 1967; Ben Gsim 1995; ERI, 2009). The flow rate of these springs, that of Aïn El Ouerda borehole and of Aïn Melliti borehole are 1 l/s, 40 l/s and 7 l/s respectively.

The figures 3, 4 and 5 show that karst areas have a complex permeability such as caves, conduits, fissures, faults and matrix porosity due to the high karstification processes which developed in the region in both superficial and underground forms (caves, lapiaz, dolines…). Additionally, the precipitation is the principal source of recharge to the aquifers. The extensive karst recharge is explained by a coefficient of infiltration ranging from 10 to 25 % (Bolze, 1955; Talbot and Andrieu, 1974; Hachemi and Talbi, 1978; Zebidi, 1980; Ben Gsim, 1984, 1985). The residence time of water in these aquifers is low attributed by the vertical permeability (vertical and opened conduit in unsaturated zone).

Karst aquifers are discharged by many karst springs. The complex structure and the architecture of independent units and the partial knowledge of karst aquifers hydrodynamic and characteristics in Teboursouk basin leads to an exorbitant exploitation of these reservoirs. Thus, the exploitation is limited to natural springs and a few numbers of boreholes catching the Lower Eocene and Campanian-Maastrichtian. The water chemistry of these near surface reservoirs shows a great heterogeneity related to the flow regime, rock water interactions, and different hydro-chemical processes.

4. Materials and methods

In the present study, a total of 30 water samples have been collected during June 2015 across the study area (Fig. 6). They represent both Lower Eocene aquifer with 23 samples and the Campanian-Maastrichtian reservoir with 7 water points (Fig. 1). Total Dissolved Solids (TDS), electrical conductance (EC) and pH were monitored *in situ*. The collected waters were carefully conserved and transported to the laboratory. The geochemical analyses of the major and minor elements were performed in the laboratory of Higher Institute of Sciences and Technologies of Waters of Gabes (ISSTEG- TUNISIA). The correctness of the chemical analysis was verified by calculating the ion balance errors relying on the below formula (Appelo and Postma, 1996):

$$\text{RE}\ (\%) = \frac{\sum \text{Caption} - \sum \text{Anion}}{\sum \text{Caption} + \sum \text{Anion}} \times 100\ (\text{all in meq/l})$$

The environmental isotope analyses were carried out for only 14 samples and they were transferred to the laboratory of the Scottish Universities Environmental Research Centre, Glasgow, Scotland. UK. The measured $^{18}O/^{16}O$ and $^{2}H/^{1}H$ ratios in the samples are expressed as parts per thousand of their deviation relative to the Vienna-Standard Mean Ocean Water (V-

SMOW). The isotopic results were reported as $\delta^{18}O$ (or $\delta^{2}H$) as defined by the following equation (Craig, 1961):

$$\delta^{18}O \text{ (or } \delta^{2}H) = [(R_S/R_{V\text{-}SMOW}) - 1] \times 1000$$

Where R_{sample} represents either the $^{18}O/^{16}O$ or the $^{2}H/^{1}H$ ratio of the sample and $R_{V\text{-}SMOW}$ represents $^{18}O/^{16}O$ or the $^{2}H/^{1}H$ ratio of the SMOW. The typical precisions are ±0.1 % and ±1.0 % for oxygen-18 and deuterium, respectively.

5. Results and discussion

Karst aquifers are hydro-chemically and hydro-geologically different from porous reservoirs. They exhibit a high degree of anisotropy and heterogeneity relative to the complexity of hydraulic aquifer proprieties and a huge challenge for understanding of karst behavior and predictions. The fractured aquifers, in the study area, are attributed predominately to highly mountains relief with carbonate aquifers characterized by intensive karstification function of regular rainfall amount and expanding of limestone and dolomite deposits. The enhanced dissolution and collapse processes create complex networks of preferential flow pathways (Figs. 3, 4 and 5). They are characterized by various types of porosity depending on relative contributions of interplay matrix, fractures percentage, major conduits permeability and recharge characteristics. The spatial distribution of porosity and drainage system requires detailed knowledge and refined description to evaluate the proper karst groundwater potential (Burdon and Papakis, 1963; Atkinson, 1977).

Karst is geomorphologic and hydrogeological system formed by dissolution of soluble rocks, limestone and dolomite and gypsum. Such a dissolution process gives to the development of highly permeable and complex aquifer systems possessing extreme anisotropy and heterogeneity. Karst aquifer includes subterranean drainage networks of fracture and conduit systems that usually discharged at large springs (Bonacci, 2001). The obtained hydro-chemical and isotopic results of the sampled waters are presented in Table 1. The following discussion illustrated the significance of these results in the context of groundwater origin, water types, water-rock interactions, and origin of water chemistry.

5.1. Hydro-chemical analysis

The analyzed samples revealed neutral conditions expressed by pH values ranging from 6.86 to 8.04, thus groundwater is alkaline which is perfect for drinking. The samples TDS values ranging from 0.49 to 1.26 g/l. 90 % allows them to fall in the fresh water category (TDS<1 g/l). Karst groundwater in the study area is generally characterized by low mineralized water indicating regular recharge and rapid groundwater circulation due to the high hydraulic conductivity of the fractured carbonates reservoir (Fig. 7). The highest TDS values are attributed to Eocene water points explained by the contribution of the dissolution of Triassic outcrops and the enhanced dissolution of the hosted water bearing friable carbonate formations (Ayadi et al., 2016, 2017). Correspondingly, 60 % of the sampled waters exhibit EC values above 1500 µs/cm (Table 1).

The karst waters are characterized by pCO_2 varying from 0.24 to 4.62 10^{-2} largely above the pCO_2 of the precipitations ($10^{-3.5}$ atm) suggesting enhanced dissolution of the carbonate outcrops by the acidic rainwater (Edet and Offiong, 2002). The majority of water points reveal the impact of recent rainfall infiltration and the rapid circulation through karst conduits except for two or three samples which were more enriched in CO_2 showing the impact of old water mixing.

Durov (1948) introduced a diagram which provides more information on the hydro-chemical facies by helping to identify the water types. It can display some possible geochemical processes that could help in understanding the groundwater quality and its evaluation. The diagram is a composite plot consisting of two ternary diagrams where the cations of interest are plotted against the anions of interest; the sides form a binary plot of total cation vs. total anion concentrations. The expanded version includes Total Dissolved Solids (TDS) and pH data added to the sides of the binary plot to allow further comparisons. Based on the major cation and anion concentrations of the samples in Teboursouk, Durov diagram (Fig. 8a) show the samples are plotted in the field 5 and the water type is of non dominant anion or cation indicating dissolution or mixing influence. This trend can be attributed to the recent fresh recharge water exhibiting simple dissolution or mixing. Three water points, from Maastricthtian and Eocene reservoirs, fall in Ca-enrichment field indicating an excess of calcium related to intensive chemical weathering and ion exchange process. The pH part of the plot reveals that groundwater in study area is alkaline which is perfect for drinking.

Chadha diagram (Chadha, 1999) is a common representation used in the identification of the hydro-chemical facies based on major elements concentrations. It helps to identify spatial water composition behavior and classify groundwater samples based on the effect of different chemical processes, regarding the different factors and interactions between hosted aquifers and groundwater (Chadha, 1999). According to figure 8b, strong acidic and alkaline earths are in excess over weak acidic and alkali-metals respectively. The sampled waters are mostly of Ca-SO_4-HCO_3 water type in consistence with carbonate dominance. An Eocene water point, in

Southwestern part of the study area, and three water samples fall in Na-Cl and Na-HCO_3 fields respectively indicating the impact of the weathering of quaternary formations on karst water chemistry while exhibit Na-HCO_3 water type indicating .

Ca, HCO_3 and SO_4 are the dominant elements in water samples in the study area. The high Ca and HCO_3 content is due to the enhanced dissolution of the hosted carbonates formations while the increasing SO_4 concentrations are explained by the leaching of evaporate outcrops from Triassic extrusions. The analyzed water samples show the dominance of Ca-SO_4-Cl water type referring to Karstification processes (vertical permeability) and fracturing of lime stones outcrops allow a low water-rock interaction. Two samples from Lower Eocene aquifer fall in Ca-Mg-HCO_3 field showing the dominance of the dissolution of the hosted carbonates units. A sample from Lower Eocene and another from Campanian-Maastrichtian aquifers were attributed to Na-Cl water type revealing the contribution of evaporates formation leaching in major elements concentrations.

The water in dolomite and limestone aquifers is dominated by Ca, Mg and HCO_3. The geogenic origin of the carbonate minerals reveals a hydrochemical evolution of karst groundwater indicative of rock-water interaction and intensive chemical weathering of the hosted formations (Bonacci, 2001; Omo-Irabor et al., 2008). The relationships between the major elements have been evaluated in figure 8. According to the Ca+Mg *vs.* HCO_3 scatter diagram given in figure 9a, the analyzed samples show a linear relationship which suggests that these elements originated from calcite and dolomite dissolution.

The addition of SO_4 to HCO_3 in figure 9b, illustrated the majority of water points were around the1:1-line showing that evaporates, mainly gypsum influence the groundwater chemistry. Moreover, the study of SO_4 *vs* Ca plot (Fig. 9c) shows a good correlation (R^2 =

0.7266) and reveals that most of the groundwater samples were close to gypsum and anhydrite dissolution. However, the chemical data of samples plot in Na *vs* Cl plot (Fig. 9d) provided a good correlation between Na and Cl ($R^2 = 0.8012$) and this explained that the mineralization of waters was attributed to the halite dissolution.

The Ca/Mg molar ratio exceeding one indicates a calcite dissolution. However, when the ratio equals one, it is a sign of a dolomite rock dissolution. A ratio surpassing 2 is a clear evidence of silicate minerals dissolution into the groundwater (Katz et al., 1997). The majority of samples (Fig. 9d) show a Ca^{2+}/Mg^{2+} ratio between 1 and 2 which indicated that the dissolution of calcite. In fact according to Ca *vs* HCO_3 plot, the analyzed samples are governed by calcite-dolomite dissolution (Fig. 9e).

5.2. Isotopic analysis

The isotopes environment of oxygen-18 ($\delta^{18}O$) and hydrogen (δ^2H) (Tab. 1) contents of Lower Eocene and Campanian-Maastrichtian aquifers ranged from -6.8 to -5.3‰ (vs. SMOW) and from -42 to -34 ‰ (vs. SMOW), respectively. The obtained ^2H-^{18}O isotopic data has been plotted on $\delta^{18}O/\delta^2H$ diagram (Fig. 10a) with the Global Meteoric Water Line (GMWL: $\delta^2H= 8\ \delta^{18}O+10$) (Craig, 1961) and the Local Meteoric Water Line of the Tunis-Carthage (LMWL: $\delta^2H= 8\ \delta^{18}O+12.4$) illustrating two different groups.

The First group (G1) lies between the local and global meteoric line showing depletion in $\delta^{18}O$ confirming that they are not affected by evaporation and testifying for the rapid infiltration of these waters which is in consistence with high hydraulic connectively in the karst (vertical permeability due to vertical conduits) (Ford et Williams, 2007). However, the second group (G2) shows an enrichment of $\delta^{18}O$ confirming these waters have undergone the influence of evaporation during their route to rainfall site. The variability in water isotopic composition suggests different recharge events, runoff conditions, sampling period salinity and altitude effect.

This diagram shows the isotopic composition of meteoric water collected from Beja area in 2015 with -5.4‰ (vs. SMOW) for δ^{18}O and -33‰ (vs. SMOW) for δ^2H plot between GMWL and LMWL. This signifies that the origin of the recharge in the Teboursouk area is from the mixture of the Atlantic and Mediterranean vapor masses (Hamed et al., 2013, 2014; Ayadi et al., 2016). In addition, the cave sample plot in δ^{18}O/δ^2H diagram with -5.5 ‰ (vs. SMOW) for δ^{18}O and -33 ‰ (vs. SMOW) for δ^2H, shows the rapid recharge of the precipitation due to vertical conduits and suggests that groundwater is of a meteoric origin (Fahdi et al., 2015; Ayadi et al., 2016).

In this connection, the Cl vs. δ^{18}O diagram (Fig. 9b) illustrates the two separate groups. The progressive enrichment of Cl with the increase in δ^{18}O refers to the contribution of evaporate deposits and evaporation process while the majority of the water points show a significant arrangement with increasing δ^{18}O values and low Cl) confirming the recent rainfall infiltration (freshwater). Additionally, D excess vs. ^{18}O scatter diagram shown in figure 9c illustrates the contribution of the evaporation process in the groundwater composition (increase of D excess with increase of δ^{18}O).

Figure 9d shows a good arrangement of δ^{18}O vs, the altitude which is of about -0.3‰ per 100 m for the majority of the water points indicating the rapid groundwater recharge through carbonated karstic structures for all the samples regardless of their source (plain or mountain). The average calculated altitude of recharge of the sampled waters was determined based on karst water isotopic composition. The obtained recharge elevation varies between 800 and 950 m.a.s.l in consistence with the altitude of the mountains in Teboursouk basin (J. Gorra). The karst system is principally fed by rainwater infiltration.

6. Conclusions

Teboursouk basin reveals a great potential of near-surface groundwater resources hosted in karst system revealing good water quality with low salinity levels expressed by TDS values largely below 1.5 g/l. Height karstification processes (open conduit, vertical permeability) proved short residence time and low water-rock interaction. Ca-SO_4-Cl water type is dominant in the study area. Evaporate and carbonate formations weathering seem to be the dominant factor controlling groundwater chemistry. Similarly, the isotope analyses confirm the recent recharge of these reservoirs as all water samples are plotted around the Local and Global Meteoric Lines.

However, groundwater recharge estimation in the karst system considering the great heterogeneities seems to be difficult especially for the study area characterized by a hydro-geological system partially known to consist of independent karst units. The assessment of the aquifer behavior and the vulnerability predictions remains incomplete. This situation defines a huge challenge for groundwater management in the study area as karst groundwater is a vital resource for drinkable water and agriculture activities, and therefore special attention needs to be paid to the two following points:

First, the groundwater resources are intensively exploited in agriculture, which may lead to quality degradation correspondingly with the excessive utilization of groundwater fertilizers and poor land management. Second, the inadequate proper management of these groundwater exclusively related to rainfall amount may lead to water scarcity issues, taking in account the unpredictable climate variability and the increasing droughty trend in arid and semi-arid regions as Tunisia.

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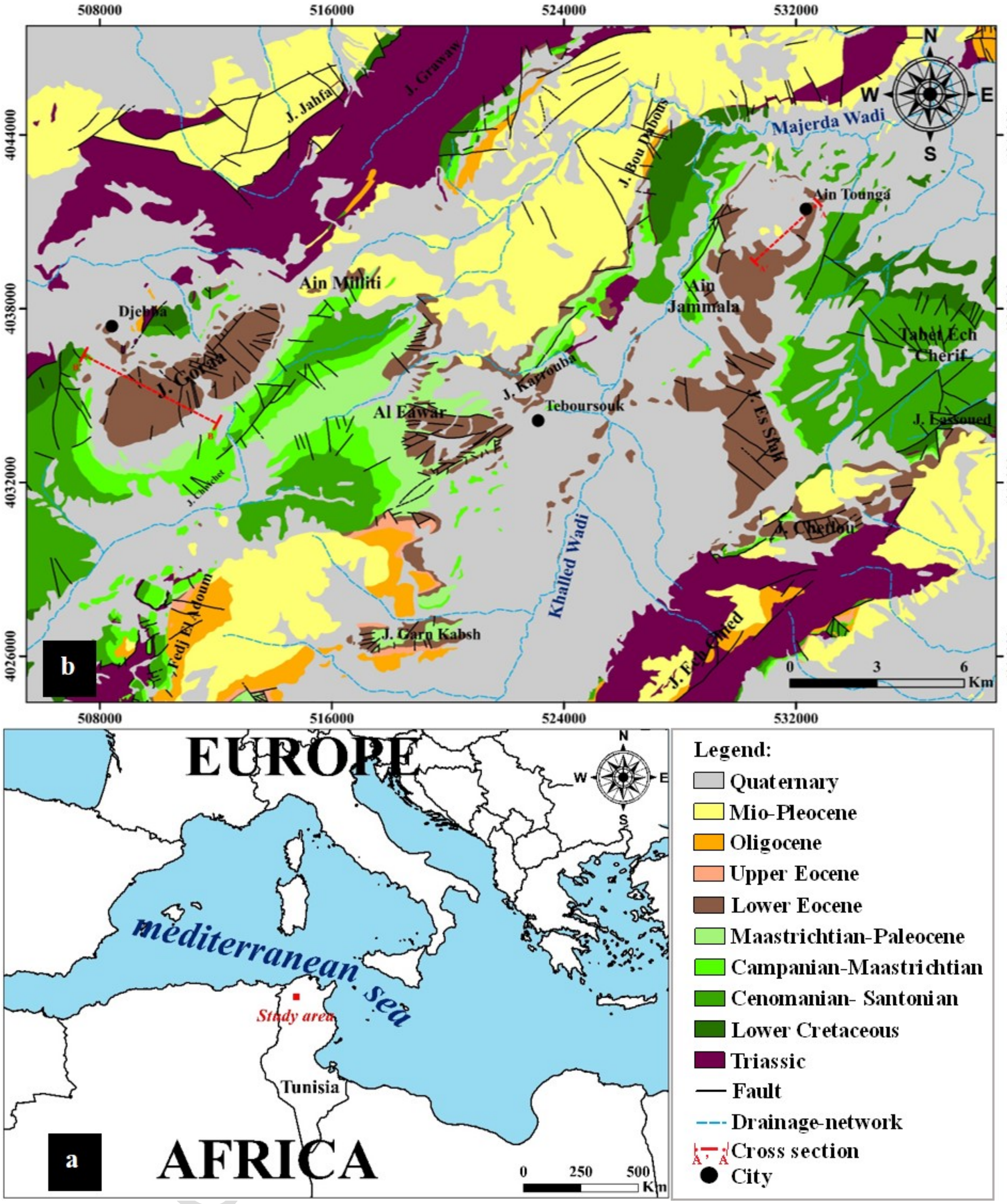
List of figures

List of tables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516000
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N
W
E
S
J. Grawan
J. Jahfa
J. Bou Dabous
Majerda Wadi
Ain Tounga
Ain Milliti
Djebba
J. Goraa
Ain Jammala
Tahet Ech Cherif
J. Karrouba
Teboursouk
Al Fawar
J. Es Sfuk
J. Lassoued
J. Chehet
J. Cheltou
Khalled Wadi
J. Garn Kabsh
Fedj El Adoum
J. Ech Cheid
b
0
3
6
Km
EUROPE
mediterranean sea
Study area
Tunisia
AFRICA
a
0
250
500
Km
Legend:
Quaternary
Mio-Pleocene
Oligocene
Upper Eocene
Lower Eocene
Maastrichtian-Paleocene
Campanian-Maastrichtian
Cenomanian- Santonian
Lower Cretaceous
Triassic
Fault
Drainage-network
Cross section
A
A'
City

Fig. 1

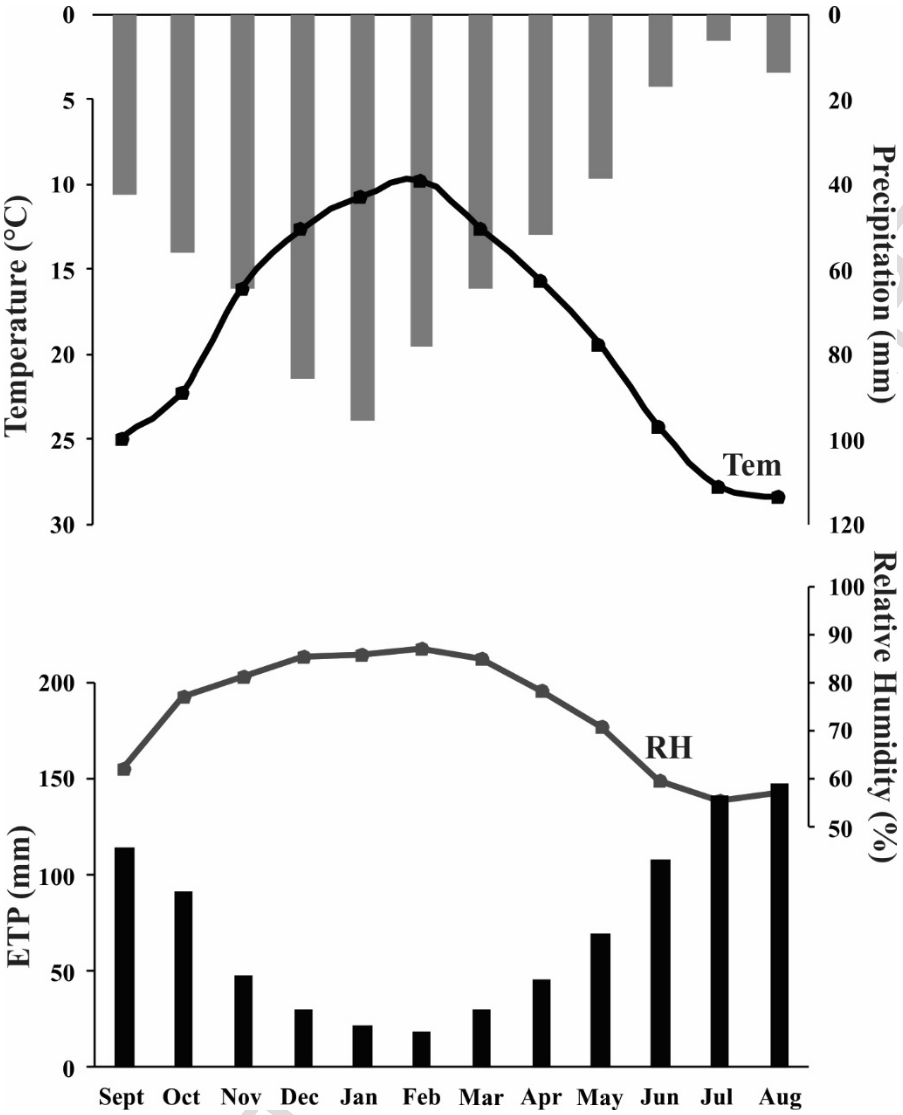

0
5
10
15
20
25
30
Temperature (°C)
0
20
40
60
80
100
120
Precipitation (mm)
Tem
200
150
100
50
0
ETP (mm)
100
90
80
70
60
50
Relative Humidity (%)
RH
Sept
Oct
Nov
Dec
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug

Fig. 2

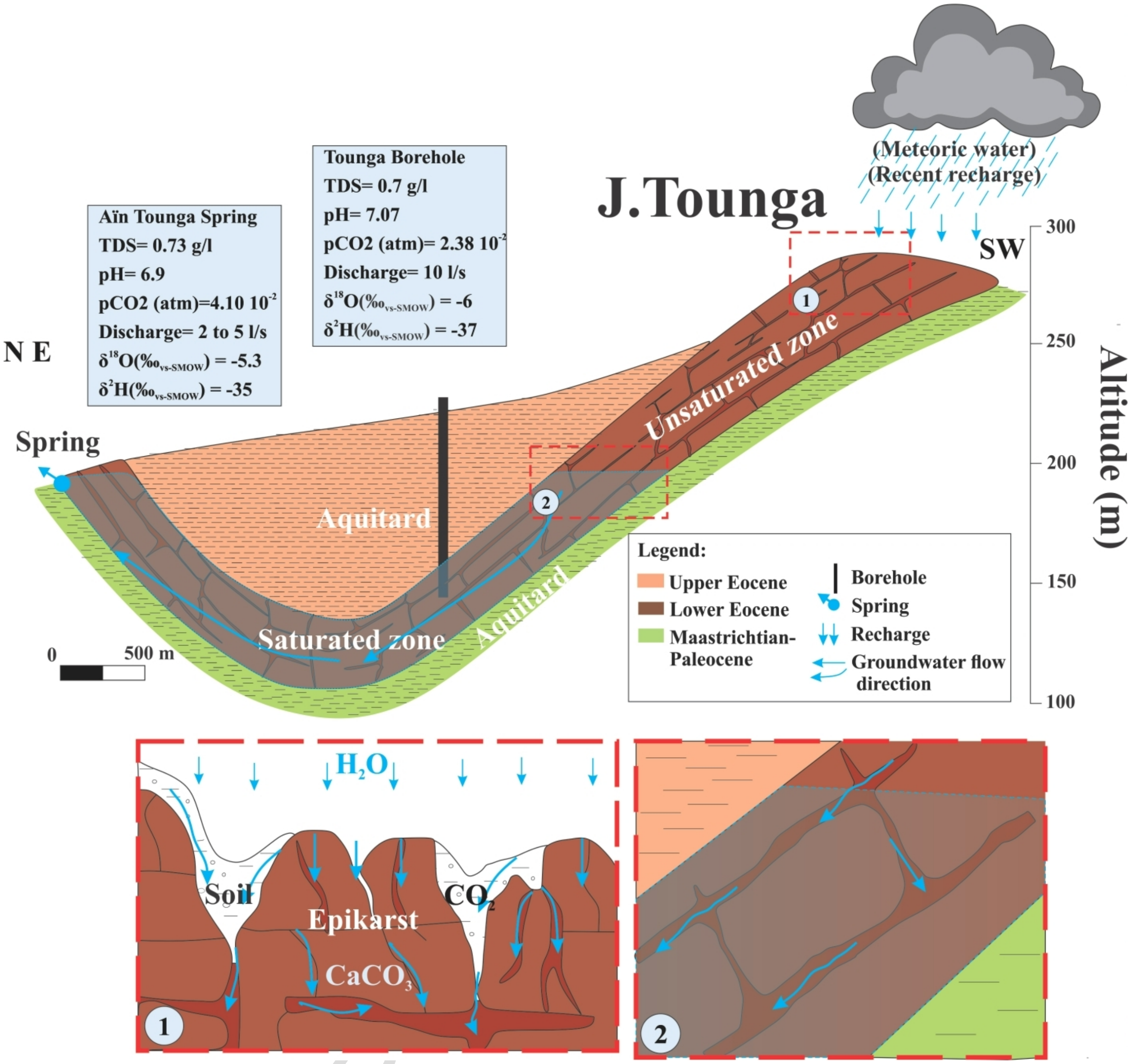

Aïn Tounga Spring
TDS= 0.73 g/l
pH= 6.9
pCO2 (atm)=4.10 10^{-2}
Discharge= 2 to 5 l/s
$\delta^{18}O(‰_{vs-SMOW}) = -5.3$
$\delta^{2}H(‰_{vs-SMOW}) = -35$
Tounga Borehole
TDS= 0.7 g/l
pH= 7.07
pCO2 (atm)= 2.38 10^{-2}
Discharge= 10 l/s
$\delta^{18}O(‰_{vs-SMOW}) = -6$
$\delta^{2}H(‰_{vs-SMOW}) = -37$
J.Tounga
(Meteoric water)
(Recent recharge)
N E
SW
Spring
Aquitard
Unsaturated zone
Saturated zone
Aquitard
1
2
0
500 m
300
250
200
150
100
Altitude (m)
Legend:
Upper Eocene
Lower Eocene
Maastrichtian-Paleocene
Borehole
Spring
Recharge
Groundwater flow direction
H_2O
Soil
CO_2
Epikarst
$CaCO_3$
1
2

Fig. 3

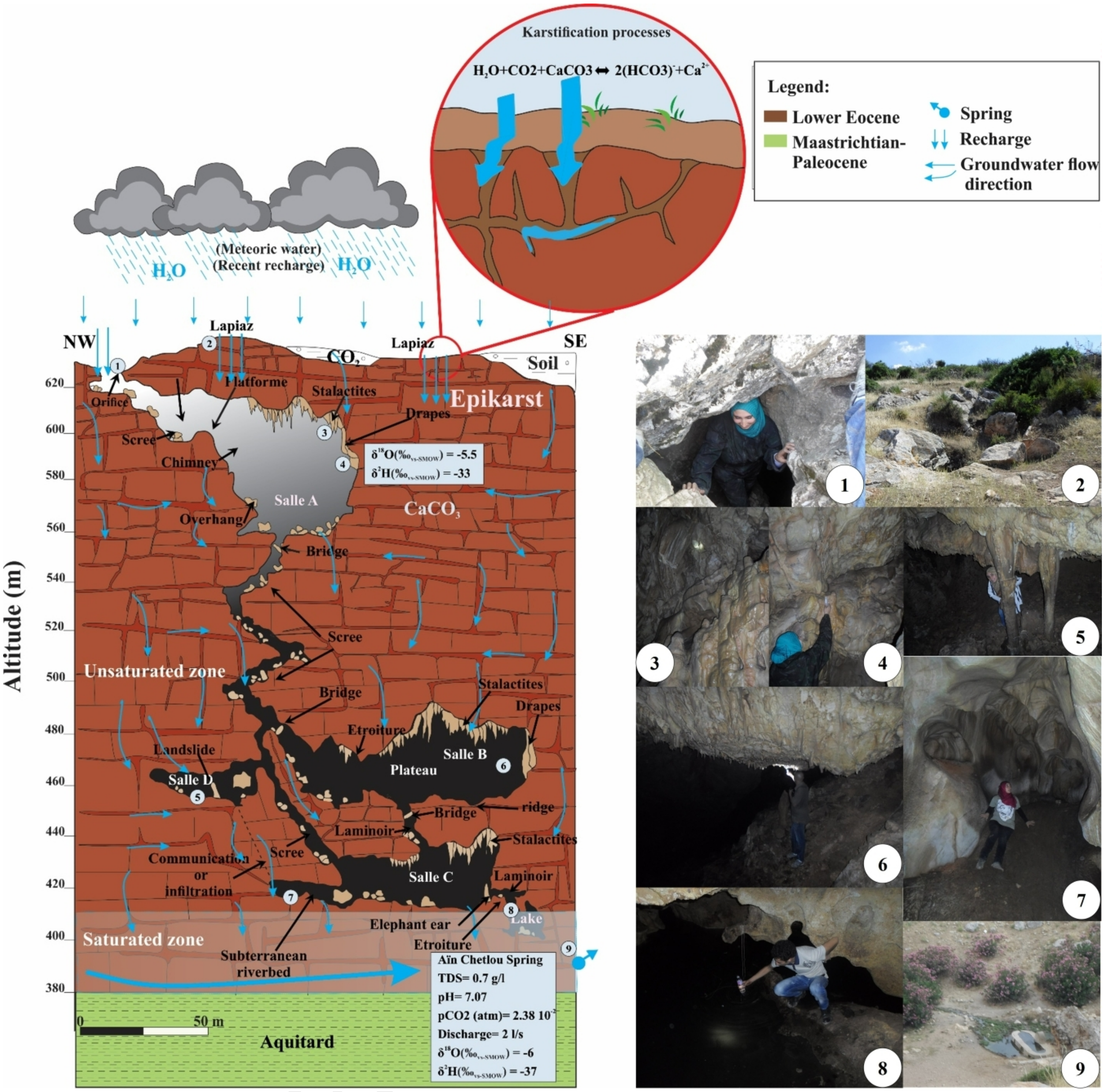

Karstification processes
$H_2O+CO2+CaCO3 \leftrightarrow 2(HCO3)^-+Ca^{2+}$
Legend:
Lower Eocene
Maastrichtian-Paleocene
Spring
Recharge
Groundwater flow direction
(Meteoric water)
(Recent recharge)
H_2O
H_2O
NW
SE
Lapiaz
Lapiaz
CO_2
Soil
Epikarst
Orifice
Platforme
Stalactites
Drapes
Scree
Chimney
Salle A
$\delta^{18}O(‰_{vs\text{-}SMOW}) = -5.5$
$\delta^{2}H(‰_{vs\text{-}SMOW}) = -33$
$CaCO_3$
Overhang
Bridge
Scree
Unsaturated zone
Bridge
Stalactites
Drapes
Etroiture
Salle B
Plateau
Landslide
Salle D
Bridge
ridge
Laminoir
Stalactites
Communication or infiltration
Scree
Salle C
Laminoir
Elephant ear
Etroiture
Lake
Saturated zone
Subterranean riverbed
Aïn Chetlou Spring
TDS= 0.7 g/l
pH= 7.07
pCO2 (atm)= 2.38 10^{-2}
Discharge= 2 l/s
$\delta^{18}O(‰_{vs\text{-}SMOW}) = -6$
$\delta^{2}H(‰_{vs\text{-}SMOW}) = -37$
Aquitard
0
50 m
Altitude (m)
620
600
580
560
540
520
500
480
460
440
420
400
380
1
2
3
4
5
6
7
8
9

Fig. 4

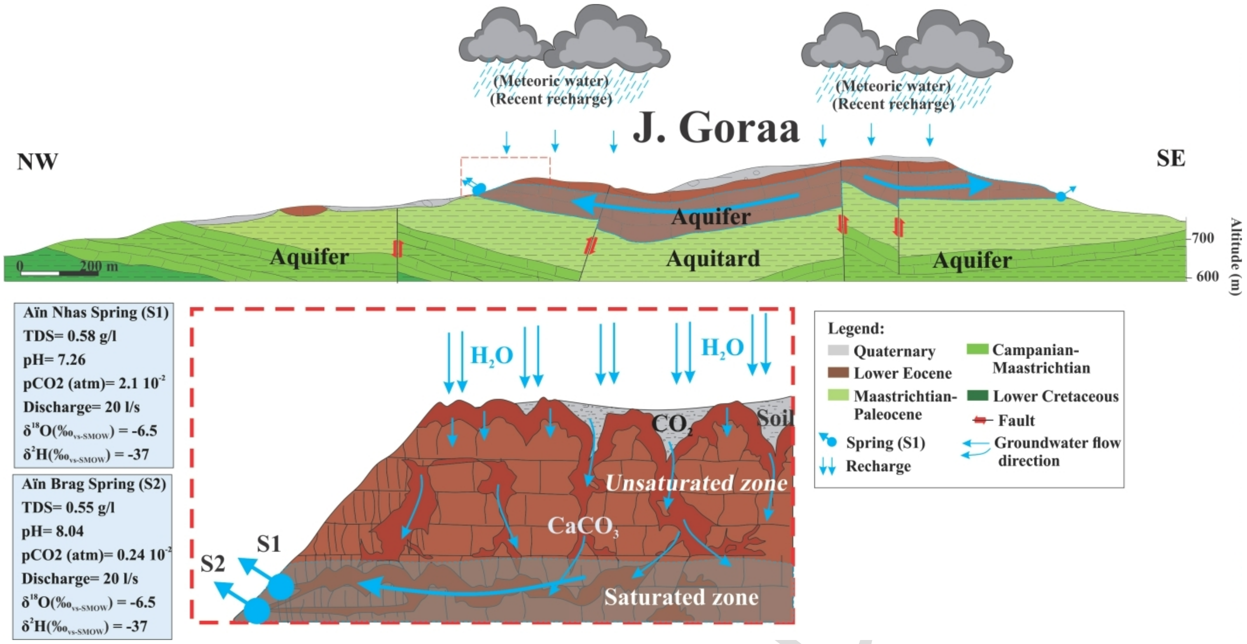
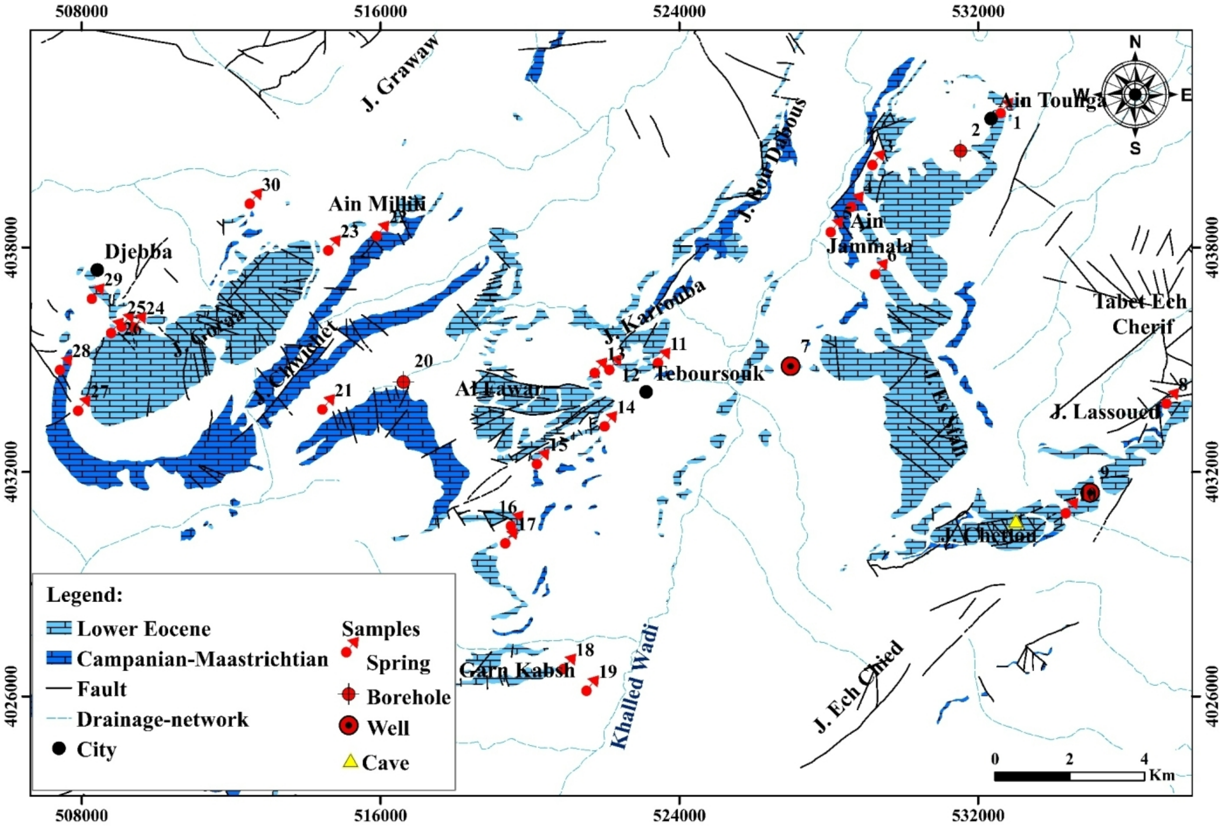

(Meteoric water)
(Recent recharge)
(Meteoric water)
(Recent recharge)
J. Goraa
NW
SE
Aquifer
Aquifer
Aquitard
Aquifer
0
200 m
700
600
Altitude (m)
Aïn Nhas Spring (S1)
TDS= 0.58 g/l
pH= 7.26
pCO2 (atm)= 2.1 10^{-2}
Discharge= 20 l/s
$\delta^{18}O(‰_{vs\text{-}SMOW})$ = -6.5
$\delta^{2}H(‰_{vs\text{-}SMOW})$ = -37
Aïn Brag Spring (S2)
TDS= 0.55 g/l
pH= 8.04
pCO2 (atm)= 0.24 10^{-2}
Discharge= 20 l/s
$\delta^{18}O(‰_{vs\text{-}SMOW})$ = -6.5
$\delta^{2}H(‰_{vs\text{-}SMOW})$ = -37
H_2O
H_2O
CO_2
Soil
Unsaturated zone
$CaCO_3$
Saturated zone
S1
S2
Legend:
Quaternary
Lower Eocene
Maastrichtian-Paleocene
Campanian-Maastrichtian
Lower Cretaceous
Fault
Spring (S1)
Recharge
Groundwater flow direction

Fig. 5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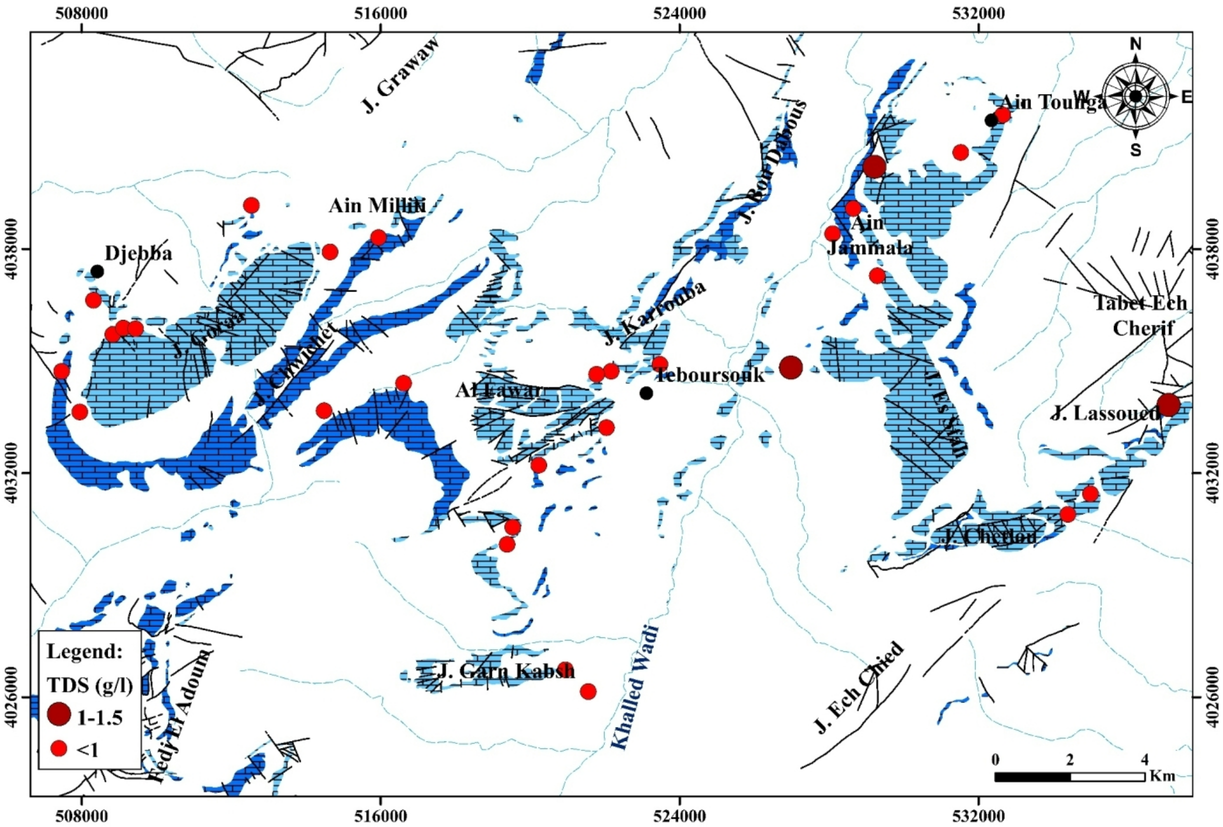
516000
524000
532000
4038000
4032000
4026000
J. Grawaw
Ain Tounga
Ain Millin
Djebba
J. Gorraa
J. Chahier
J. Bou Dabous
Ain Jammala
Tabet Ech Cherif
J. Karrouba
Teboursouk
Al Lawar
J. Es Mabl
J. Lassoued
J. Cheffou
Garn Kabsh
Khalled Wadi
J. Ech Chied
N
S
E
W
0
2
4
Km
Legend:
Lower Eocene
Campanian-Maastrichtian
Fault
Drainage-network
City
Samples
Spring
Borehole
Well
Cave
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
30

Fig. 6


508000
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532000
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4032000
4026000
N
S
W
E
J. Grawaw
J. Bou Dabous
Ain Tounga
Ain Millin
Djebba
Ain
Jammala
J. Gorraa
J. Chweher
J. Karrouba
Teboursouk
Tabet Ech
Cherif
Al Lawar
J. Es Stah
J. Lassoued
J. Chelou
J. Garn Kabsh
Khalled Wadi
J. Ech Chied
Hedj El Adoum
Legend:
TDS (g/l)
1-1.5
<1
0
2
4
Km

Fig. 7

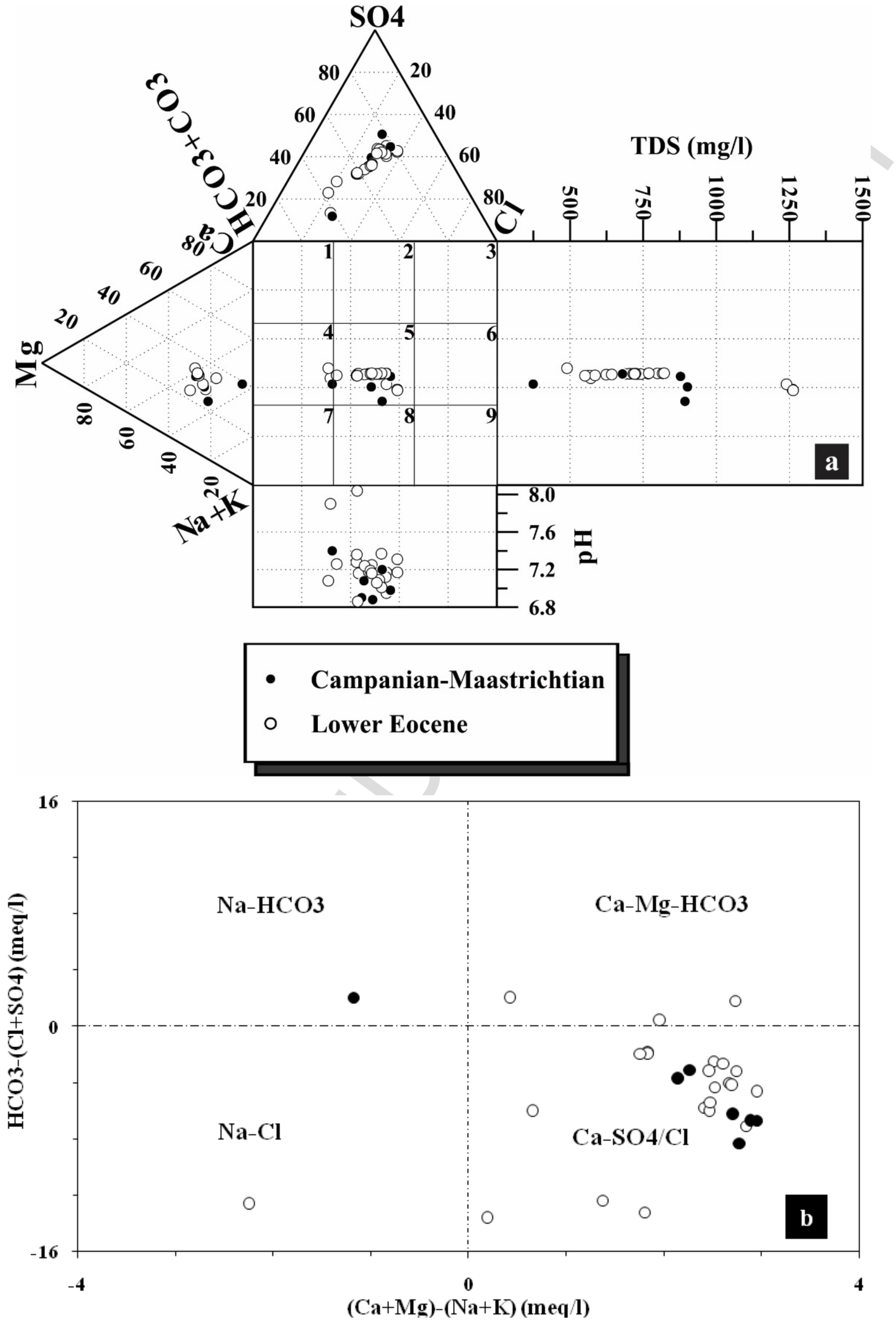
SO4
80
60
40
20
20
40
60
80
HCO3+CO3
Cl
Ca
80
60
40
20
Mg
80
60
40
20
Na+K
1
2
3
4
5
6
7
8
9
TDS (mg/l)
500
750
1000
1250
1500
a
8.0
7.6
7.2
6.8
pH
● Campanian-Maastrichtian
○ Lower Eocene
16
0
-16
HCO3-(Cl+SO4) (meq/l)
-4
0
4
(Ca+Mg)-(Na+K) (meq/l)
Na-HCO3
Ca-Mg-HCO3
Na-Cl
Ca-SO4/Cl
b

Fig. 8

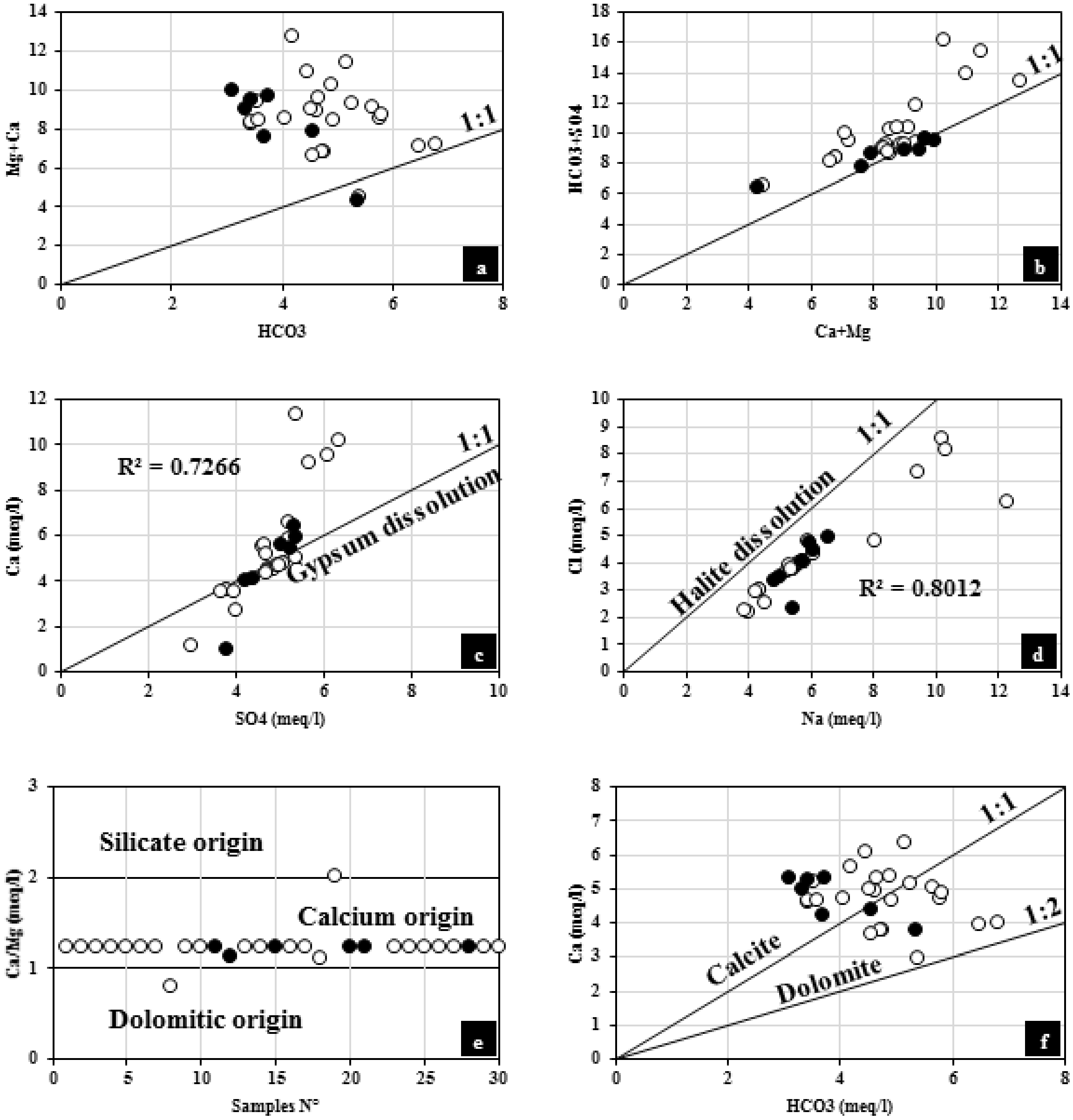
Mg+Ca
HCO3
1:1
a
HCO3+SO4
Ca+Mg
1:1
b
Ca (meq/l)
SO4 (meq/l)
R² = 0.7266
1:1
Gypsum dissolution
c
Cl (meq/l)
Na (meq/l)
1:1
Halite dissolution
R² = 0.8012
d
Ca/Mg (meq/l)
Samples N°
Silicate origin
Calcium origin
Dolomitic origin
e
Ca (meq/l)
HCO3 (meq/l)
1:1
1:2
Calcite
Dolomite
f

Fig. 9

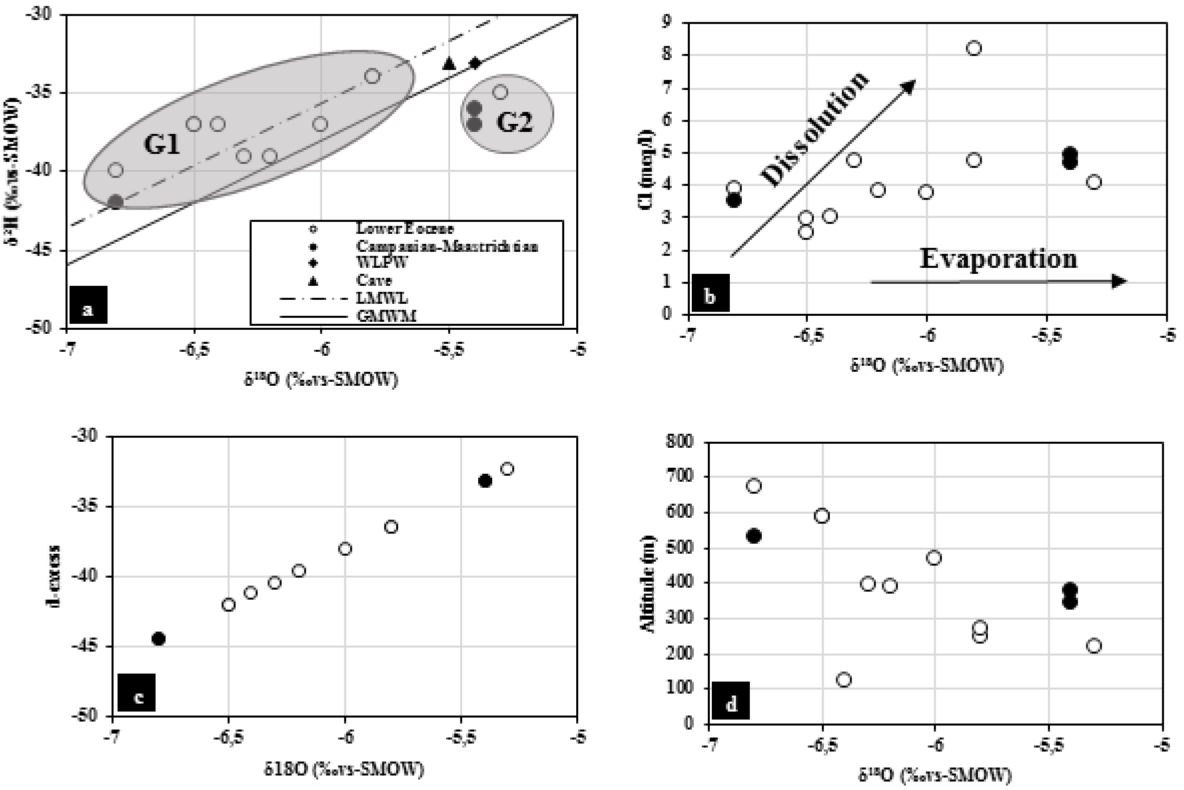
a
δ²H (‰vs-SMOW)
δ¹⁸O (‰vs-SMOW)
G1
G2
Lower Eocene
Campanian-Maastrichtian
WLPW
Cave
LMWL
GMWM
-30
-35
-40
-45
-50
-7
-6,5
-6
-5,5
-5
b
Cl (meq/l)
δ¹⁸O (‰vs-SMOW)
Dissolution
Evaporation
0
1
2
3
4
5
6
7
8
9
c
d-excess
δ18O (‰vs-SMOW)
d
Altitude (m)
δ¹⁸O (‰vs-SMOW)
0
100
200
300
400
500
600
700
800

Fig. 10

Table. 1

N	pH	TDS	CE	Ca	Mg	Na	K	HCO_3	SO_4	Cl	NO_3	E	pCO_2	$\delta^{18}O$	δ^2H	d-excess
		(g/l)	(µS/cm)	(meq/l)								(%)	(10^{-2}atm)	(‰$_{vs-SMOW}$)		
1	6.9	0.73	1769	5.05	4.06	5.76	0.61	5.64	4.76	4.06	0.45	1	4.10	-5.3	-35	-32.4
2	7.28	0.56	865	3.77	3.03	4.35	0.61	4.76	3.63	3.03	0.41	-3	1.46	-6.4	-37	-41.2
3	7.31	1.267	2600	6.09	4.90	10.18	0.62	4.46	9.51	8.59	0.48	-4	1.23			
4	7.16	0.90	1808	5.18	4.17	8.08	0.61	5.27	6.55	4.77	0.45	1	2.09	-5.8	-34	-36.4
5	6.88	0.69	1533	4.74	3.81	5.42	0.61	4.05	4.54	3.81	0.44	4	3.10			
6	6.86	0.69	1554	4.72	3.80	5.40	0.61	5.78	4.45	3.80	0.44	-3	4.62	-6.2	-39	-39.6
7	6.95	1.24	2880	6.34	5.10	9.45	0.62	5.17	10.23	7.31	0.48	-5	3.28			
8	7.17	1.26	2660	5.67	7.07	10.32	0.62	4.19	9.21	8.19	0.64	2	1.60	-5.8	-34	-36.4
9	7.16	0.70	1634	4.86	3.91	5.55	0.61	5.82	4.54	3.91	0.44	-2	2.33			
10	7.08	0.68	1581	4.67	3.75	5.34	0.61	4.93	4.39	3.75	0.43	1	2.38			
11	7.17	0.80	1725	5.25	4.22	5.97	0.61	3.44	5.45	4.71	0.45	4	1.34	-5.4	-37	-33.2
12	6.98	0.88	2450	5.32	4.66	6.58	0.62	3.09	6.45	4.93	0.47	5	1.86	-5.4	-36	-33.2
13	7.12	0.82	1925	5.19	4.178	5.91	0.61	3.54	5.83	4.78	0.45	2	1.55	-6.3	-39	-40.4
14	7.17	0.73	1434	4.59	3.69	5.25	0.61	3.44	5.52	3.69	0.43	2	1.35			
15	7.25	0.62	1150	4.23	3.39	4.85	0.61	3.68	4.04	3.39	0.42	3	1.21			
16	7.36	0.57	885	3.78	3.04	4.37	0.61	4.74	3.66	3.04	0.41	-3	1.21			
17	7.18	0.72	1692	4.93	3.97	5.63	0.61	4.64	4.67	3.97	0.44	3	1.78			
18	7.2	0.89	1500	5.39	4.85	12.30	0.20	4.90	11.33	6.26	1.21	-2	1.74			
19	7.9	0.57	1000	2.99	1.48	4.00	0.05	5.39	1.17	2.20	0.11	-2	0.40			

20	7.24	0.64	1198	4.38	3.53	5.03	0.61	4.56	4.14	3.53	0.43	1	1.53	-6.8	-42	-44.4
21	7.37	0.77	1727	5.01	4.03	5.72	0.61	3.37	5.57	4.03	0.44	3	0.82			
22	7.4	0.37	765	3.79	0.49	5.43	0.02	5.36	1.02	2.31	0.42	3	1.27			
23	7.09	0.74	1491	4.64	3.73	5.31	0.61	3.44	5.59	3.90	0.43	1	1.62	-6.8	-40	-44.4
24	7.08	0.49	1008	4.01	3.23	3.90	0.61	6.80	2.69	2.29	0.41	-4	3.31			
25	7.26	0.58	897	3.94	3.17	4.54	0.61	6.49	3.54	2.54	0.40	-5	2.08	-6.5	-37	-42
26	8.04	0.55	879	3.66	2.94	4.23	0.61	4.56	3.57	2.94	0.40	-3	0.24	-6.5	-37	-42
27	7.19	0.72	1753	4.99	4.02	5.70	0.61	4.52	4.71	4.02	0.44	4	1.69			
28	7.01	0.82	1933	5.35	4.31	6.09	0.61	3.73	5.95	4.49	0.45	4	2.10			
29	7.06	0.72	1489	4.68	3.77	5.36	0.61	3.58	5.21	3.78	0.43	3	1.81			
30	7.16	0.77	1918	5.35	4.30	6.08	0.62	4.66	5.02	4.30	0.45	4	1.86			