Investigation of uranium geochemistry along groundwater flow path in the Continental Intercalaire aquifer (Southern Tunisia)

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ABSTRACT

Environmental tracers (2H, 18O, isotopes of Uranium) and geochemical processes occurring within groundwaters from the Continental Intercalaire (CI) in Southern Tunisia were used to understand the hydrodynamics and the recharge conditions of this aquifer. This study investigates the chemical and isotopic compositions of the CI groundwater. The water types are dominated by Na+, SO42−, Cl− throughout most of the basin with a general increase in total dissolved solids from the Saharan Platform margins towards the Chotts region. Large scale groundwater flow paths are toward the Chotts region. The stable isotopes composition of the analyzed groundwater ranges from −8.8 to −6‰ vs V-SMOW for δ18O and from −67 to −40% vs V-SMOW for δ2H. The relatively enriched stable isotopes contents suggest the contribution of the Dahar sandstones outcrops in the current recharge of the CI aquifer in an arid context. However, the most depleted values in heavy isotopes indicate a paleorecharge of the aquifer under wetter conditions revealing a long residence time of groundwaters. The results from water samples using alpha spectrometry method indicate a range in 238U concentrations and 234U/238U activity ratios (AR) of 0.044–1.285 µg kg⁻¹ and 1.2 to 8.84 respectively. The geochemistry of uranium isotopes in groundwater is controlled by many factors, essentially, the influence of water rock interaction, the preferential dissolution of 234U relative to 238U due to alpha recoil and the mixing processes between different waters with distinct AR as well as 234U concentrations.

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1. Introduction

The deep Continental Intercalaire (CI) aquifer is one of the world largest groundwater reservoirs extending from the Moroccan borders to Libya from West to East. In Southern Tunisia the CI is one of the most important natural groundwater resources for water demand supply. It may be considered as a type area for large artesian basins (Edmunds et al., 2003). Over exploitation of this aquifer has occurred due to the excessive increase of water request of the different economic sectors (agriculture, tourism, industry …) with preponderance of the agricultural needs. Hence, it seems fundamental for these groundwater resources management to better understand the hydrodynamics and the recharge conditions. The CI aquifer has been the subject of numerous studies whose synthesis was conducted as part of a project supported by UNESCO (ERESS, 1972). It has been established during this project that the Chott region forms the discharge area of the CI aquifer (ERESS, 1972). It was also shown that the CI aquifer consists of several horizons with strong artesian pressure (5–25 bars) and with temperatures from 65 to 75 °C (ERESS, 1972 in Edmunds et al., 2003). ERESS study has been pursued by several authors and over different projects, for instance Gonfiantini et al. (1974), Mamou (1990), Guendouz (1985), Yahyaoui (1996), OSS 2003, Abid et al., 2010. It has been shown that the δ18O and δ2H values indicate a cooler recharge regime with rainfall having lower primary evaporation than today (Edmunds et al., 2003). The combined evidence shows that the recharge coincides with cooler humid periods during the late Pleistocene which exists across the whole of Saharan Africa (Guendouz et al., 1997). The main objective of this paper is to provide a further understanding of the groundwater flow pattern and the induced geochemical processes occurring in the CI aquifer system. The mechanisms controlling the groundwater geochemistry and the
transport processes in the CI water rock system were investigated using different environmental tracers (\(^{18}\)O, \(^{2}H\), isotopes of Uranium). The radionuclides of uranium constitute the novelty of the present approach relative to previous related contributions.

2. Study area

The study area is located at the Southern boundary of the Atlas Saharan mountains and at the Northern boundary of the Saharan Platform. It is limited in the East by the Golf of Gabes and Libyan frontier and in the West by the Algerian frontier (Fig. 1). From South to North, it represents the geographic space that extends from the extreme South to the Northern chain of Chotts. The mean annual temperature is 21°C with a potential evapotranspiration of 1700 mm/year. The mean annual precipitation is less than 100 mm indicating therefore an arid type climate.

3. Geological and hydrogeological settings

In Southern Tunisia, a large extension of sedimentary deposits of Mesozoic age was highlighted from the Chotts area in the North to the Libyan frontier in the South (Bouaziz, 1995). The Cretaceous, main resource of water wells in Southern Tunisia is largely outcropping along the northern chains of Chotts as well as in the Dahar upland. The Lower Cretaceous is characterized by significant variations in facies and thickness from the Saharan Platform to the Chott area. This period corresponds to an episode of continental sedimentation continued until the Vraco-Cenomanian (Mamou, 1990). Therefore, it is also known as Continental Intercalaire presenting a succession of detrital sediments separated by clay-rich strata and gypsum intercalations leading to an extent of heterogeneity within this aquifer. In Southern Tunisia, tectonic processes have generated several geological provinces with different stratigraphic and structural particularities from one province to another. The Dahar upland which consists of a N–S trending (Zargouni et al., 1985; Bouaziz, 1995; Bouaziz et al., 2002; Gabtni et al., 2009), is located between the plain of Djeffara in the East and the Saharan Platform in the West. The Chotts depression constitutes its Northern boundary (Fig. 1). The overthrow faults consist of a NW–SE trending in relay from the northern chain of chotts up to El Hamma region. This set of faults extends towards the SE across the faults of Ben Gerdane and Djerba-Zarzis constituting therefore the continuity of the NW–SE trending faults of El Hamma region whose role in the communication between the CI aquifer and the Djeffara aquifer of Gabes is determining (ERESS, 1972; Trabelsi et al., 2009; Abid et al., 2009; OSS, 2003). These faults are responsible for the subsidence of the Eastern flank of the Djeffara dome under the Mediterranean Sea (Mamou, 1990) and are part of a complex called the South Tunisian accident (Castany, 1954). In Southern Tunisia, the consequent structure of these sets of faults corresponds to successive outcrops of compartments with some local complications leading to the individualization of horsts and grabens. This structure is of a great interest on the hydrogeological scheme and obviously in the hydraulic communications between aquifers (Mamou, 1990). Groundwater flows in the CI aquifer converge towards the Chotts region (Fig. 1). The principal W–E groundwater flow line in the Continental Intercalaire aquifer comes from the Algerian frontier towards the discharge zone in the Gulf of Gabes. It has been shown that the hydraulic gradient increases at El Hamma region, which explains the discharge effect through vertical leakage (drainage) of waters from the Kebeur El Hadj series of the CI. The fault of El Hamma is responsible of this configuration which makes of the Chott region the single discharge zone of the CI aquifer in Southern Tunisia (ERESS, 1972; Trabelsi et al., 2009; Abid et al., 2009; OSS, 2003). The S–N flow direction highlights the flow line coming from the Lower Cretaceous outcrops located on the Dahar reliefs. The piezometric lines indicate that these outcrops represent a local recharge area of the CI aquifer through water runoff. The SSW-NNE direction comes from the Algerian-Libyan frontier towards the discharge area of the aquifer. Lithostratigraphic correlation along a SE–NW cross section (Fig. 2) has been established to study the geometry and the lateral extension of the aquifer system and to show the main aquifer levels.

As shown in Fig. 2, the multilayer CI aquifer is characterized by i)
its heterogeneity due to the succession of different detrital sediments separated by clayey levels ii) increasingly depth and thickness of the layers towards Nefzaoua and the chotts regions.

4. Material and methods

25 samples collected during May 2010 and November 2010 from the Cl aquifer in Southern Tunisia were analyzed for major elements and stable isotopes (Fig. 3).

In order to enhance the representation of the data, a total of 25 samples were collected for chemical and isotopic analyses (18O, 2H) from different aquifer horizons in different areas (Nefzaoua, Djerid, Dahar outcrops) across southern Tunisia (Table 1).

In Nefzaoua region, 11 samples were collected with 9 ones from Kebeur El Hadj aquifer, 1 sample from the upper sandstones and 1 sample from the Albian aquifer.

In Djerid, 4 samples were collected from the sandstones of Sidi Aich aquifer.

In Dahar outcrops, 7 samples were collected from the Albian aquifer and 3 samples from the Upper Jurassic-Lower Cretaceous aquifer.

Parameters such as temperature (T) and pH were measured in the field. The major elements (Na\(^+\), Ca\(^{2+}\), Mg\(^{2+}\), K\(^+\), Cl\(^-\) and SO\(_4\)\(^{2-}\)) were analyzed by the liquid chromatography at the laboratory of Radio-analysis and Environment of the national school engineers of Sfax. The CO\(_3\)\(^{2-}\) and HCO\(_3\)\(^-\) concentrations were analyzed by titration using 0.1 N HCl acid. Stable isotopes were analyzed using laser absorption spectrometry (LGR DLT 100) (Penna et al., 2010). Analyses are reported in per mil (‰) versus Vienna-Standard Mean Oceanic Water (VSMOW).

4.1. Uranium radiochemical procedure

The analysis of uranium isotopes by alpha spectrometry requires
a volume of at least 10 L of water sample (IAEA, 2013). In southern Tunisia, the CI groundwaters are known by very low uranium contents (Causse et al., 1988; Chkir and Zouari, 2007; Chkir et al., 2009), therefore high volumes of samples are required for uranium estimation procedure in order to avoid the detection limit of alpha spectrometry. The analytical detection limit of uranium concentrations by alpha spectrometry measurements is of 10^{-3} (Gellermann and Fröhlich, 1984). The largest variation ranges of both uranium and 234U/238U activity ratio (AR) are shown in groundwaters. Uranium concentrations range from 10^{-3}–10^{0} ppb and may be lower than 10^{-3} depending on the sampled water volume. Activity ratios range from 0.5 to 30. Values of AR superior than 5 reflect very low uranium concentrations and depend on the type of the host rock (Gellermann and Fröhlich, 1984; Bondarenko, 1981).

The applied radiochemical technique for water samples in this study was based on Galindo et al. (2004). Samples of 20 L from CI groundwaters were collected and seemed optimal owing to alpha spectrometric low detection limit. Samples were filtered through 0.45 μm membranes to remove suspended solids and colloids and

Table 1
The chemical data, δ^{18}O, δ^{2}H, for groundwater sampled from the CI aquifer.

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<th>T (°C)</th>
<th>TDS (mg/L)</th>
<th>pH</th>
<th>Cl^{-} (mg/L)</th>
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<th>CO_{3}^{2-}</th>
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TDS: Total dissolved solids.
then concentrated by evaporation in order to reduce the initial volume of each sample to 500–600 ml. This evaporation was performed in a nitric acidic medium to decrease the pH of samples water to approximately 2; this was to dissolve the salt precipitate that could be settled. Samples were spiked with 0.028Bq of 232U tracer for radiochemical yield. 6 ml of FeCl3 was added and then V-SMOW for residue in some samples. Uranium was coprecipitated with Fe(OH)3 as carrier at pH 8 using ammoniac solution then the precipitate was retrieved by centrifugation. This step was done twice in order to recover the chemical yield. A first separation and purification of U-Th was carried out using anion exchange resin column DOWEX AG-1X8 in HCl (8 N) environment. Uranium was adsorbed onto the resin and then washed with 0.1 M HCl. The resulting solution containing uranium and Fe was evaporated and taken back in 5 ml of 3 M HNO3. Then the solution was passed through a second UTEVA resin ion exchange (Eichrom, 1995). Uranium was electroplated onto a stainless steel disk to allow alpha counting (Talvitie, 1972). The disk was washed with distilled water and acetone before being counted by alpha spectrometry. U activities were counted as much time as necessary to reach a statistical error below 10% (Chkir et al., 2008). The good quality of the precipitation on the disks has to be ensured before the counting; this is to avoid significant error in uranium activities calculation. During counting, the resolution of each alpha radiation, each “peak” of the spectrum is represented by the width at half peak height. The spectrum analysis consists in determining the surface of each peak (Sánchez and Tomé, 1992). In this study, uranium analyses have been applied for 8 samples located in the discharge area (Table 2). We have focused on the individual radionuclide concentration in water as it can be affected by several factors relative to the defined flow paths. In order to advance the interpretation, 3 samples (Nos. 7, 8 and 11) were taken from previous contributions. The recovered chemical yield was about 60–80%.

5. Results and discussions

The isotopic analyses of the CI aquifer in Southern Tunisia indicate that this one is exclusively logged into old water particularly in the regions of Djerid and Nefzaoua with homogeneous isotopic signatures. The corresponding ionotope content sources represent the most depleted values varying from −8.8 to −8.1‰ vs V-SMOW for δ18O and from −67 to −60‰ vs V-SMOW for δ2H. This is explained by the long residence time of water in the aquifer and its paleorecharge under a wetter climate corresponding to the Pleistocene period (Guendouz et al., 1997). However, the measured stable isotopes of the CI groundwater on Dahar outcrops are relatively more enriched (values varying from −6 to −6.5‰ vs V-SMOW and from −48 to −40‰ vs V-SMOW respectively for δ18O and δ2H) (Fig. 4). This suggests the contribution of these outcrops in the local recharge of this aquifer system.

Groundwater sampled from the CI aquifer was determined to have low U-content (from 0.044 to 1.285 ppb) with high 234U/238U activity ratios that ranged from 1.2 to 8.84 (Fig. 5). To distinguish aquifer types in terms of U contents, classification mainly refers to 1 ppb and 10 ppb as uranium content limits; values between 1 and 10 ppb indicate oxidized aquifer on normal uranium strata; values higher than 10 ppb indicate oxidized aquifer on enhanced uranium content strata and values lower than 1 ppb correspond to reduced aquifer on low uranium content strata (Cowart and Osmond, 1980).

In our case, uranium contents are less than 1 ppb for most of the water sampled from the CI aquifer indicating therefore a reducing natural environment. In general, U is soluble in oxidizing natural waters, occurring as the uranyl cations and trends to form stable carbonate complexes (Langmuir, 1978; Klinkhammer and Palmer, 1991).

Table 2

<table>
<thead>
<tr>
<th>No</th>
<th>U (ppb)</th>
<th>±</th>
<th>234U/238U</th>
<th>±</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.938</td>
<td>0.02</td>
<td>1.835</td>
<td>0.2</td>
</tr>
<tr>
<td>4</td>
<td>1.285</td>
<td>0.01</td>
<td>1.924</td>
<td>0.3</td>
</tr>
<tr>
<td>6</td>
<td>0.483</td>
<td>0.01</td>
<td>3.570</td>
<td>0.2</td>
</tr>
<tr>
<td>7</td>
<td>0.568</td>
<td>0.1</td>
<td>3.190</td>
<td>0.3</td>
</tr>
<tr>
<td>2</td>
<td>0.170</td>
<td>0.01</td>
<td>2.358</td>
<td>0.2</td>
</tr>
<tr>
<td>8</td>
<td>0.259</td>
<td>0.02</td>
<td>4.890</td>
<td>0.2</td>
</tr>
<tr>
<td>3</td>
<td>0.118</td>
<td>0.02</td>
<td>1.206</td>
<td>0.1</td>
</tr>
<tr>
<td>5</td>
<td>0.163</td>
<td>0.1</td>
<td>1.803</td>
<td>0.2</td>
</tr>
<tr>
<td>9</td>
<td>0.054</td>
<td>0.01</td>
<td>8.840</td>
<td>0.9</td>
</tr>
<tr>
<td>10</td>
<td>0.044</td>
<td>0.03</td>
<td>7.940</td>
<td>0.6</td>
</tr>
<tr>
<td>11a</td>
<td>0.056</td>
<td>0.1</td>
<td>7.840</td>
<td>0.1</td>
</tr>
</tbody>
</table>

* From Chkir and Zouari (2007).
It has been demonstrated also that U behaves conservatively in the oxygenated groundwaters (Osmond and Cowart, 1982) such as found in the Southern Great basin in USA (Winograd and Robertson, 1982). In reducing waters like in our case, U is insoluble and exists as U(IV) (Langmuir, 1978; Klinkhammer and Palmer, 1991; Drever, 1988).

The high value of activity ratio is a recognized characteristic of groundwater having long been in contact with the matrix (Chkir et al., 2009). To interpret these data, theoretical knowledge and previous case studies (Osmond and Cowart, 1992; 2000; Dabous and Osmond, 2001; Chkir and Zouari, 2007; Chkir et al., 2009, Hadi Ammar et al., 2010) were used. A preliminary characterization using the diagram of $^{234}$U/$^{238}$U AR versus reciprocal U content ($1/^{238}$U) was carried out in order to highlight the geochemical processes taking place in the aquifer (Osmond and Cowart, 1992) (Fig. 6). This diagram allows the recognition of mixing processes (conservative systems) and water–rock interactions (non-conservative systems) according to lines on which data are plotted. $^{234}$U/$^{238}$U plotted against reciprocal uranium concentrations typically exhibit a linear trend extending from the lower left (Low AR with high U concentrations) to the upper right (high AR with low U content). This can be interpreted as mixing lines. At the upper right end member, the aquifer is considered very dilute having experienced little leaching of uranium, while the other end member (lower left) corresponds to the concentrated leachate of the host rock (Chkir and Zouari, 2007; Osmond et al., 1971; Osmond and Cowart, 1992). The dispersion of points between these two end members indicates water with various mixture ratios (Chkir and Zouari, 2007). Two parameters define the trend line: the Y-intercept which is the $^{234}$U/$^{238}$U AR of the U being leached from the host rock, and the slope of the trend line which is the $^{234}$U excess per kilogram (U-equivalent ppb) characterizing the pre-leach water. 

$^{234}$U unit excess is U equivalent parts per billion which is the

![Fig. 6. The $^{234}$U/$^{238}$U AR versus Reciprocal of U-content (kg/mg) for the CI groundwaters in Nefzaoua area (based on Osmond and Cowart, 1992).](image)

![Fig. 7. Relationship between major elements and $^{238}$U concentrations of CI groundwaters.](image)
concentration in micrograms per kilogram of an equilibrated amount of \( \text{U}^{238} \) (\( \text{U}^{234} \) activity per mass of water) (Dabous and Osmond, 2001). 8 points represent this aquifer, therefore the interpretation is supported by data obtained in previous works (Chkir and Zouari, 2007) (samples Nos. 7, 3 and 11). These samples were collected along a local South-North flow path of the aquifer (Mamou, 1990). In the Nefzaoua region, samples were collected from the Kebeur El Hadj formation which consists of Lower Cretaceous sandstones, except for well No. 1 which consists of the Albian sandstones and limestones intercalations. Variations in concentrations and activity ratios among groundwater samples are consistent with the complexity of the system (Chkir and Zouari, 2007) and reveal three groups of points in the \( \text{U}^{234} \)/\( \text{U}^{238} \) vs reciprocal \( \text{U} \) (1/\( \text{U}^{238} \)) diagram (Fig. 6). The borehole No. 2 has been removed from the following interpretation because of a technical error during chemical testing uranium although its \( \text{U} \) content and AR behave conventionally compared to other samples.

The first group (Group 1) made by samples (Nos. 1, 4, 6 and 7) display a linear pattern from the lower left to the upper right. Along this straight line, \( \text{U}^{234} \)/\( \text{U}^{238} \) ARs increase while \( \text{U} \)-contents decrease. It is a first evolution line combining leaching and mixing process. Preferential \( \text{U}^{234} \) dissolution is enhanced by a weak hydraulic gradient that facilitates the water rock interaction (Chkir and Zouari, 2007). The upper right end member which is characterized by a low uranium content with a high activity ratio is expected to be dilute aquifer water that has experienced very little leaching of uranium. It corresponds in this area to water sampled from the oldest formation as observed by Dabous and Osmond (2001) for Nubian aquifer (Egypt). Such process is supported by high temperature environment and indicates that \( \text{U}^{234} \) nuclides are preferentially leached from the mineral structures than \( \text{U}^{238} \) nuclides.

This is usually due to recoil displacement of the daughter product \( \text{Th} \), resulting from alpha decay in the radioactive decay series. Therefore, the oxidation of \( \text{U}^{234} \) from \( \text{U}^{IV} \) to \( \text{U}^{VI} \) may occur and the form \( \text{U}^{234} \) (VI) is preferentially leached to the water (Suski et al., 2001). The lower left end-member with high uranium concentration and low \( \text{U}^{234}/\text{U}^{238} \) AR is expected to be a concentrated leachate of the host rock.

Samples corresponding to this end-member have low temperatures (35° and 55 °C respectively for samples No. 1 and 4) comparing to the upper right end-member samples (65° and 73 °C respectively for wells No. 6 and 7). We note that well No.1 is characterized by a low temperature, low depth and high \( \text{U}^{238} \) content relative to other samples. It is distinct in demonstrating the variation of uranium content with temperature and depth. This well is located in Northern Dahar where the contribution of the Lower Cretaceous outcrops to the local recharge of the CI aquifer has been proven to be significant (Abid et al., 2010). For the Nefzaoua area, \( \text{U}^{234} \)-excess is about 0.9 (\( \text{U} \)-equivalent ppb) and the AR of the host rock is equal to 1 (Fig. 6) indicating that \( \text{U}^{238} \) was in secular equilibrium with its decay product (the radiogenic daughter isotope uranium \( \text{U}^{234} \)) at the origin of the geochemical water rock interaction processes. The mechanism of fractionation taking place in the aquifer could be explained by preferential leaching of \( \text{U}^{234} \) compared with \( \text{U}^{238} \) from solid phase, radiation damage of crystal lattice upon alpha decay of \( \text{U}^{238} \), oxidation of insoluble tetravalent \( \text{U}^{234} \) to soluble hexavalent \( \text{U}^{234} \) during decay, and alpha recoil of \( \text{Th} \) (and its daughter \( \text{U}^{234} \)) into solution phase. Hence, uranium isotopes disequilibrium is highly controlled by water–rock interactions and therefore is enhanced by long residence time of groundwater as recognized for the CI aquifer. Further investigations are currently carried out to verify if this mixing effect could be

![Fig. 8. Piper diagram showing the major chemical compositions of the CI analyzed water samples.](image)
observed for samples located in Southern Dahar uplands.

The second group made by samples (Nos. 8, 3 and 5) display a linear pattern from the upper left to the lower right. Along this line, U-contents slightly decrease while \(^{234}\text{U}/^{238}\text{U}\) activity ratios decrease significantly. A possible interpretative pattern is a precipitation process. Indeed, these samples constitute the E–W flow path component coming from the Algerian boarder towards the Gulf of Gabes. We notice from West to East a decrease in temperature and depth which explains the decrease of uranium contents (Well No.8 with 0.25 ppb, well No. 5 with 0.16 ppb and well No. 3 with 0.13 ppb) along with this flow line tending towards an oxidizing natural environment which is materialized by El-Hamma fault. For the third group formed by samples Nos. 9, 10 and 11, the reciprocal of the uranium concentration increases without affecting the \(^{238}\text{U}/^{238}\text{U}\) activity ratio. This horizontal array of sample points is usual indication of the dilution process (Chkir et al., 2012 chapter). This line might be interpreted as a mixing with water characterized by a low uranium concentration and a high activity ratio which probably comes from the CI aquifer in the Djerid area as it has been established (Chkir and Zouari, 2007) that this water is very depleted in uranium concentrations.

In the present study, the concentrations of uranium are influenced by the geochemical water–rock interaction process which is enhanced by the long residence time of groundwaters being sampled in the discharge area. Long-term monitoring of groundwater for alpha radiation indicates variability that is difficult to reconcile with known hydrogeochemical systems (Oural et al., 1988). Also, the lack of significant correlations between uranium and major chemical parameters (Fig. 7) suggests that water geochemistry has a limited role in governing uranium. This outcome fits with the one being advanced by Hadj Ammar et al. (2010) justifying the conclusion of Hollocher and Yuskaitis (1993) that the presence of uranium in groundwater is not a simple function of a small set of parameters. This relationship could also be attributed to the limited variation range of the hydrochemical conditions of the CI aquifer system in the discharge area.

For the CI aquifer, chemical analysis showed that the water types are dominated by \(^+\text{Na}\), \(^-\text{SO}_4\), \(^-\text{Cl}\) and \(^+\text{Ca}\) relative to \(^+\text{Mg}\) and \(^-\text{HCO}_3\) throughout most of the basin reflecting therefore the abundance of evaporitic lands in this area, as shown by the trilinear piper diagram in Fig. 8.

Thus the mineralization of water is related to a dissolution of evaporitic minerals especially gypsum and halite. This is confirmed by Fig. 9 showing the dissolution of gypsum, anhydrite and halite.

\[\text{Fig. 9. Plots of Saturated Indices (SI) with respect to evaporitic and carbonatic and minerals.}\]
through the parabolic relationships in the plots of water saturation indices versus (Ca + SO₄) and (Na + Cl) with respect to referred minerals (Sacks and Tihansky, 1996).

It demonstrates also the supersaturation of the CI groundwaters with respect to carbonate minerals (calcite, aragonite and dolo-
mite) for most samples. The evaporitic facies reflects the homogeneity of groundwater throughout the study area and could explain the lack of significant correlation between uranium iso-
topes and major chemical elements as uranium concentrations in groundwaters are often associated with carbonate minerals (Oural et al., 1988).

6. Conclusion

This study was carried out in an attempt to identify the geochemical processes of uranium isotopes in the deep continental Intercalaire (CI) aquifer and give an assessment of their comportment relative to groundwater flowpaths. Results of the applied experimental protocol show a range of uranium activities from 0.044 ± 0.03 to 1.285 ± 0.01 ppb associated with 232U/238U activity ratios varying from 1.2 ± 0.1 to 8.84 ± 0.9. Uranium contents in CI groundwater are a result of the interaction with lithologic varia-
tions during water shipment. This is exhibited by the evolution line according to the S–N flow path component. It shows the passage from the secular equilibrium at the origin of the geochemical water rock interaction processes at the recharge area (Dahar uplands) to the disequilibrium between U isotopes caused by water–rock inter-
teractions due to the long residence time of groundwater by the end of the flow path (Chotts region). This evolution was demonstrat-
ed by the composition of the groundwater stables isotopes from Dahar uplands up to the Chotts region. The enriched contents (δ18O from −6 to −6.5% vs V-SMOW) indicate recent recharge on CI outliers while the most depleted values (δ18O from −8.8 to −8.1% vs V-SMOW) are indicators of a paleowaters having long been in contact with the matrix supporting therefore the disequilibrium process between Uranium isotopes. For the E–W flow path component coming from the Algerian boader up to the Chott el Fedjej we delineate a precipitation process along with this flow line tending towards an oxidizing natural environment to the East which is materialized by El-Hamma fault. Uranium concentrations cannot be directly associated with hydrochemistry parameters although they largely depend on the temperature which delineates the oxidation of the natural environment. The insignificant corre-
lation between uranium isotopes and major chemical elements is explained by the predominance of the groundwater evaporitic facies, which are known to reduce the solubility of uranium, as shown by the hydrochemical study of CI groundwaters. The obtained Uranium isotopes data in groundwater from the CI aquifer in Nefzaoua area are in good agreement with data from hydrogeology and with other geochemical and isotopic studies.

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