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Chemical (Cl) and isotopic (^{18}O, ^{2}H, ^{3}H) study of the unsaturated zone in the arid region of Nefta (South Tunisia)

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Abstract. A chemical and isotopic study of the unsaturated zone in Nefta, southwestern Tunisia was initiated to gain an improved understanding of the recharge and evaporation processes in the shallow "*Continental Terminal*" (CT) sandy aquifer outcropping in the region of Nefta, which constitutes the most important water resource for agriculture and domestic uses in the region. A single 13.5-m core was extracted and subsampled from the unsaturated zone at the end of the "rainy season" (23-24 April 1998) using a hand auger to avoid fluid contamination. Estimated recharge rates based on isotope and chemical profiles, uncertainties, and recommendations for future research are discussed.

Introduction

The "*Continental Terminal*" (CT) sandy aquifer outcropping in the region of Nefta constitutes the most important water resource for agriculture and domestic uses. However, this aquifer has been undergoing, especially since the years 88, a drastic decrease in of its water table. Many little springs, which used to discharge about 800 l/s in the years fifties, and provide water for the whole oasis, have completely been drought during the last decade, due to the constant increase in of the water-well exploitation for agricultural purposes in the region.

Consequently, in order to assess the issue of sustainable water resources in the region, a comprehensive hydrogeological investigation program has been launched by the "*Commissariat Régional au Développement Agricole*" and developed in collaboration with the "Isotopic Laboratory at the Sfax National School of Engineering.

The chemical and isotopic study of the unsaturated zone in Nefta - part of the IAEA's RCP on "*Isotope based assessment of groundwater renewal and related anthropogenic effects in water scare areas*" - has been carried out within this general framework with the specific aim of getting a better understanding of the recharge and evaporation processes at the outcrop of the CT shallow aquifer.

1. General features

1.1. Location and climatology

The Nefta / Tozeur region (Djerid) is located in the South - Western part of Tunisia, on the northern side of the interior dry salty lake "Chott El Djerid" (fig.1). This region belongs to the arid zone of the country with an average mean precipitation of less than 100 mm.y^{-1}. As a consequence of this arid climate, there are no perennial rivers, and occasional superficial flows occur only during and after intense storms in the rainy winter season.

The long term pluviometric record registered at the climatologic station of Nefta (fig.2a) illustrates the high variability of the annual precipitation. These values may reach amounts superior to 500 mm in exceptional years (as in 1969), whereas dry periods are characterised by precipitation inferior to 30mm (only 23 mm in 70-71 “rainy season”!). The monthly distribution (fig.2b) shows that the main rain events may occur at any time, at the beginning or at the end, during the rainy season; between October and April (Moumni et Horriche, 1998).

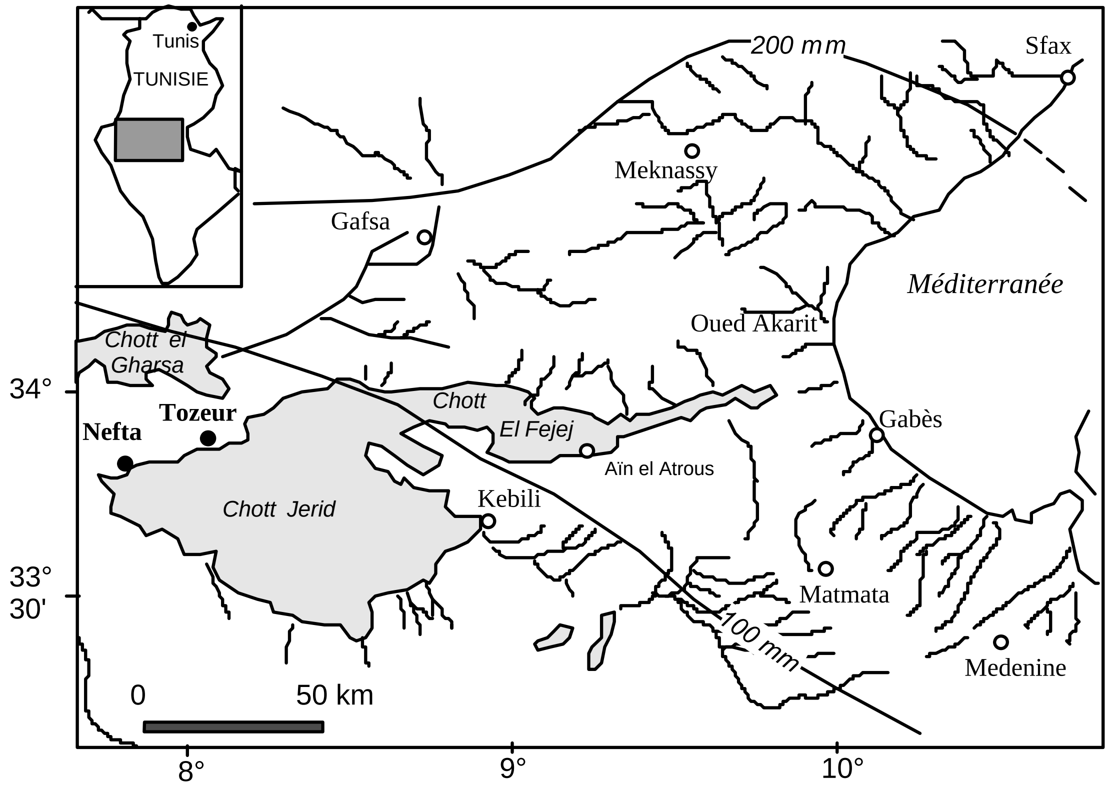
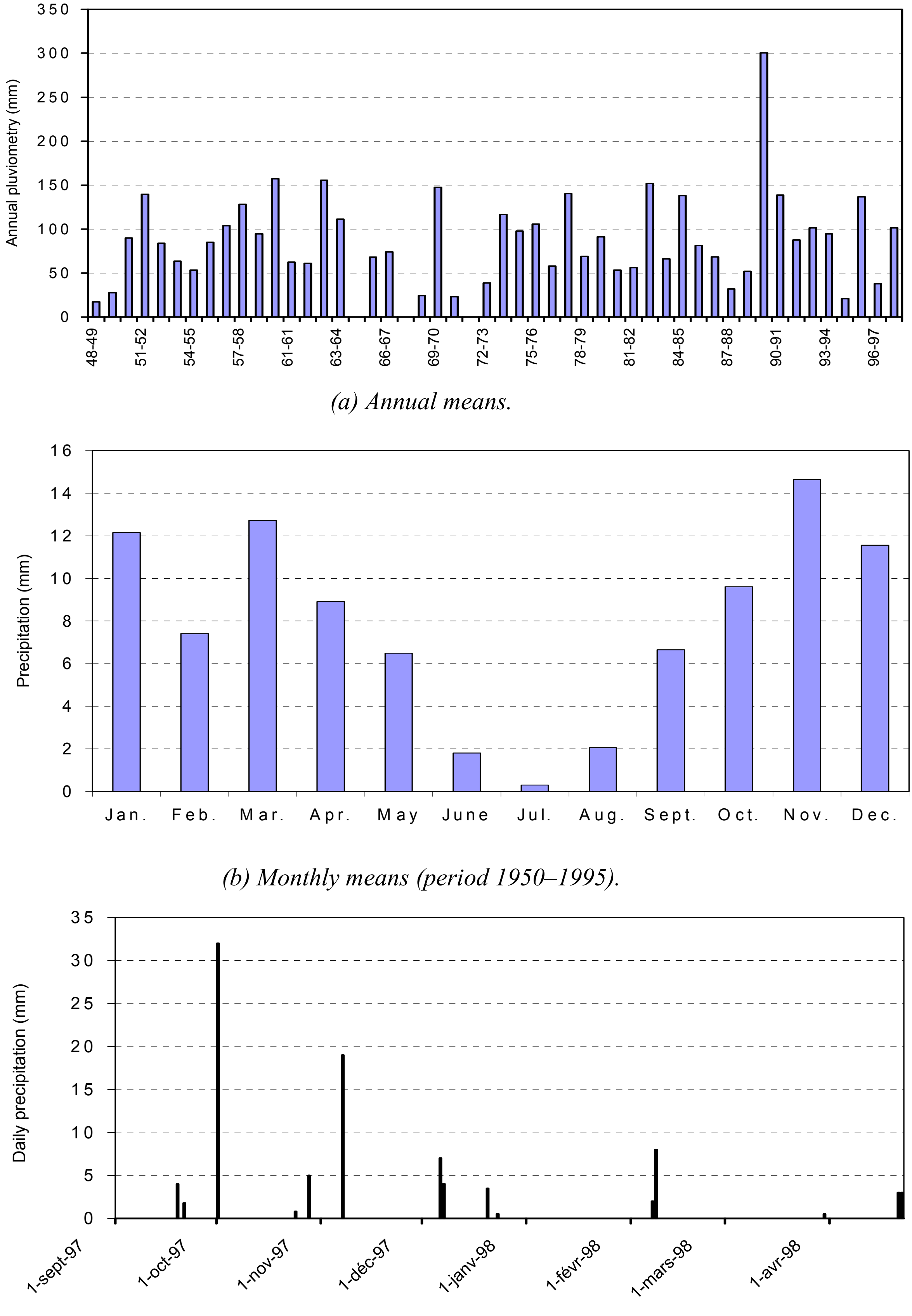


Fig. 1. location of the study area.

The influence of the frequent dry winds coming from the Southern Saharian regions, together with the high temperature all over the year (cf. table 1) result in a very high potential evaporation rate, much higher than the amount of precipitation during the same period (at the monthly scale).

In fact, the only possibilities of vertical infiltration of the rain events and actual recharge of the unconfined aquifers must be looked at the daily scale (rapid infiltration of the rain in very permeable sandy formations). The most favourable conditions to facilitate the infiltration consist in a sequence of a slight rain - to increase the permeability of the soil[1] - followed by heavier precipitation, possibly of several tens of millimetres in some days (a too high intensity is not favourable to the infiltration but concentrate the superficial flows).

[1] A dry sand has a very low permeability and favours run-off



(a) Annual means.

(b) Monthly means (period 1950–1995).

(c) Daily precipitation during the 1997-1998 rainy season

Fig. 2 (a–c). Pluviometric records at the station of Nefta.

Table 1. Monthly mean values of the precipitation and the potential evaporation at the station of Nefta

(Temp.: period 1950-1995 ; Precip.: period 1950-1995 ; ETP: period 1984-1991)

	Jan.	**Feb.**	**Mar.**	**Apr.**	**May**	**June**	**Jul.**	**Aug.**	**Sept.**	**Oct.**	**Nov.**	**Dec.**	**Total**
Temp	11.2	13.4	16.4	19.9	21.6	29.5	32	32.1	28.5	22.6	16.4	12	-
Prec.	12.15	7.41	12.72	8.91	6.49	1.8	0.3	2.06	6.65	9.61	14.65	11.56	**94.3**
ETP	50.28	65.17	101.1	142.3	188.9	227.4	258.2	227.9	163.8	133.3	67.2	49.2	**1675**

Daily measurements of the last rainy season concerned by the study (1997-1998) show (fig.2c) that some slight precipitation occurred late September (5.8 mm); these were followed by heavier rain beginning October (32 mm), which gave the possibility of effective infiltration during that month. The precipitation in November (19 mm) and December (15 mm) could also have, partially infiltrated. No infiltration may be expected from the following months, taking into account the low precipitation during the period January-April.

1.2. Geological setting and regional hydrogeology

The geological setting is constituted by a very thick sedimentary sequence starting from the Lower Cretaceous (Neocomian) to the Plio-quaternary deposits, with a stratigraphic gap between the Maastritchian and the Miocene (Mamou, 1990).

The study area corresponds to the outcrop of the "*Continental Terminal*" formation which appears in the centre of the East-West anticline uplift structure at the Northern side of the Chott El-Djerid along the Nefta - Tozeur axis (fig.3 ; fig.4).

The *Continental Terminal* aquifer is hosted in the Upper Cretaceous and Tertiary formations. According to the local structure and lithological characteristics, the main productive level are located either in the carbonated levels of the Turonian and upper Senonian in the carbonated levels of the upper Cenomanien, Turonnian and lower Senonian or in the Tertiary sandy formation (Pontian).

The South-West Tunisian region constitutes one of the natural outlet of the SSE-NNW regional flow which discharges mainly in the Chott Jerid (through the Mio-Plio-Quaternary sequence) and in the Chott El-Rhasa, on the other side of the Tozeur uplift.

More precisely, the area under study corresponds to the outcrop of the sandy Pontian formation where the natural outlet of the general deep CT groundwater circulation used to sustain a permanent discharge through the numerous springs located in topographic depression called "*Corbeille de Nefta*" (fig.4).

The chemical composition of the *Complexe Terminal* water, determined under the "*Corbeille de Nefta*" in the deep well "*Ras El Aïn*" is given on table 2.

Table 2. Chemical composition of the water in the Ras El Aïn deep well (N° IRH 20 786/5)

Ca	**Mg**	**Na**	**K**	**SO_4**	**Cl**	**HCO_3**	**Salinity**	**pH**
252	50	370	-	837	560	240	2520	8

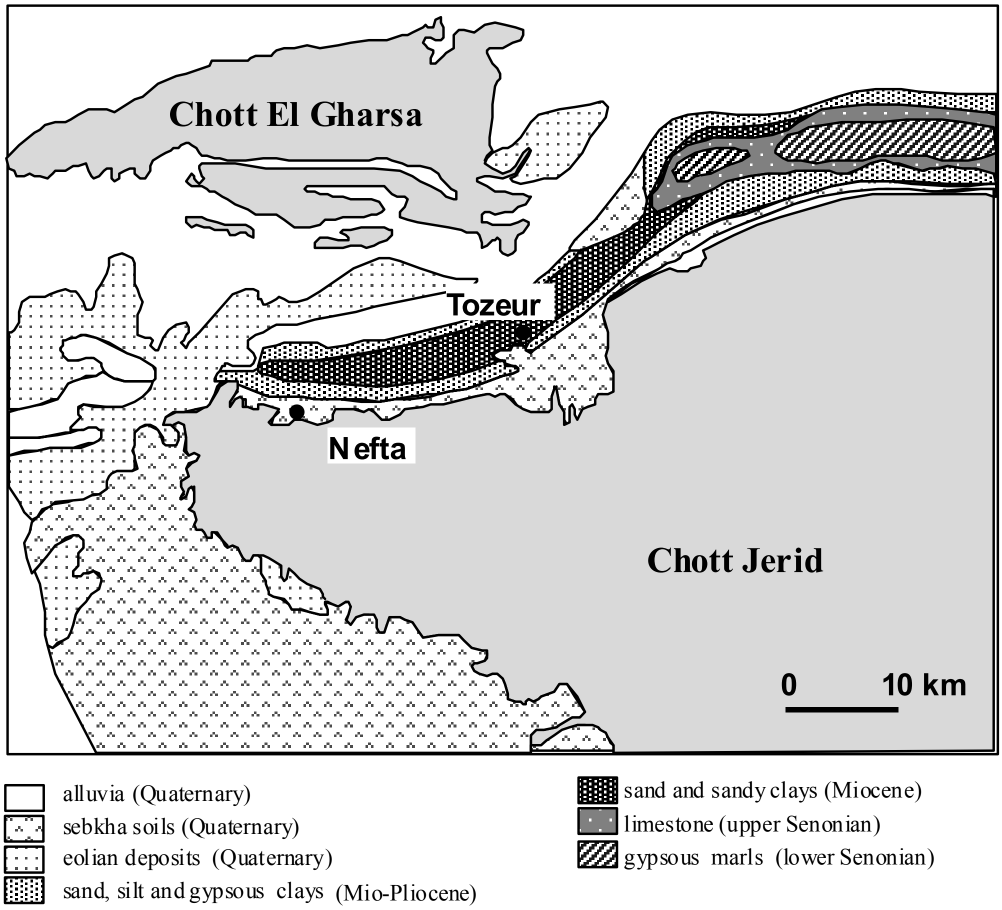


Fig. 3. Simplified geological map.
(Extracted from the geological map of Tunisia 1/500 000)

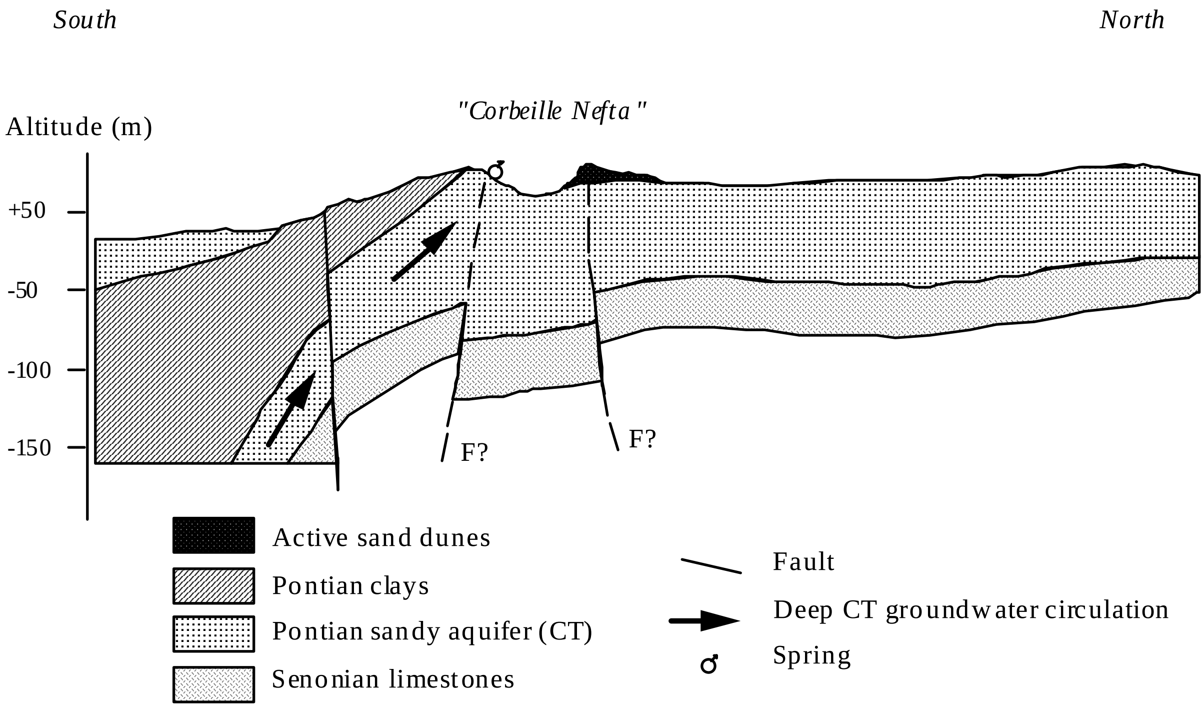


Fig. 4. Schematic geological cross section.

The isotopic content of the *Complexe Terminal* water varies with the position within the formation. In depth, its values range around –7‰ in ^{18}O (Jeribi, 1997). Concerning the aquifer in the Djerid study area, a compilation of analyses from waters sampled in the more shallow Pontian sands (Aranyossy & Mamou, 1985) has provided values in ^{18}O between -3.9 to -4.36 ‰ indicating a clear mixing with evaporated waters.

These isotopic characteristics, together with the carbon-14 activities of the dissolved carbonates have been interpreted by Mamou (1990) as an indication of present aquifer recharge on the outcropping Pontian aquifer in the Dräa Djerid. This present recharge is supposed to occur through two processes: one part from the "lateral infiltration" during the surface floods in the wadis ; the other part from the direct rain water infiltration into the permeable sandy formation. The ratio between these two parts is still unknown.

2. Sampling and analytical results

2.1. Sampling

The profile has been carried out at the end of the "rainy season" (23-24 April 1998) near the dry wadis in the small depression of Nefta ("Corbeille de Nefta"; fig.5). The coring was achieved using a hand auger (in order to avoid any risk of contamination by the fluid with a drilling machine). Samples were integrated between intervals of 15 cm from the topsoil to 60 cm depth; of 20 cm up to 5 m depth and 25 cm further down. Drilling was stopped at the depth of 13.5 m due to technical reasons.

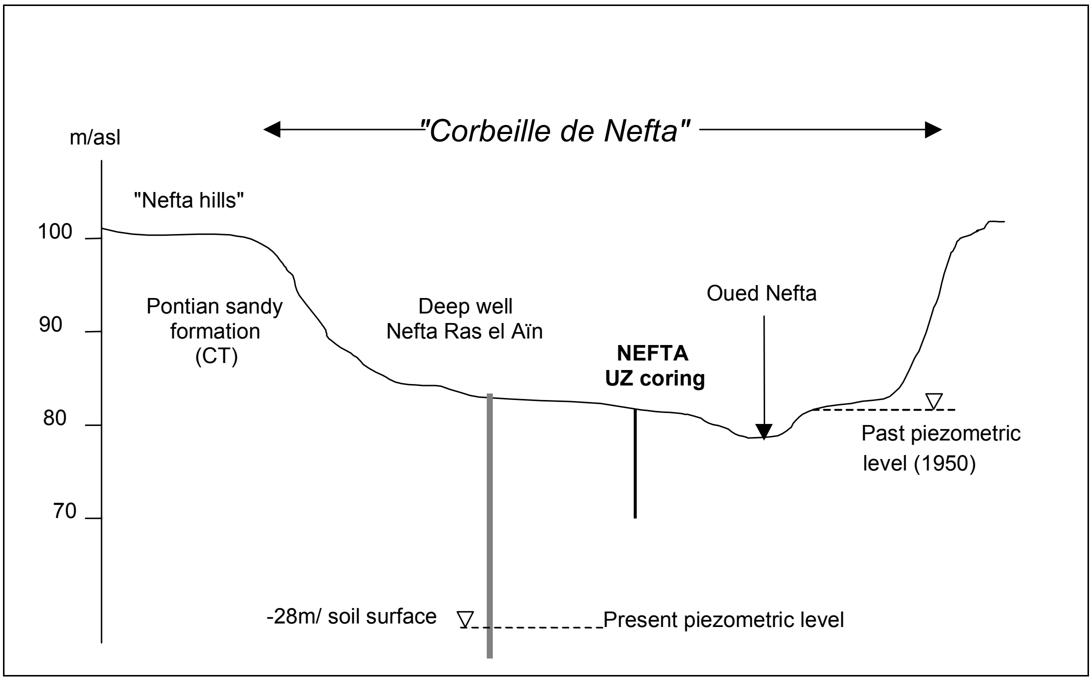


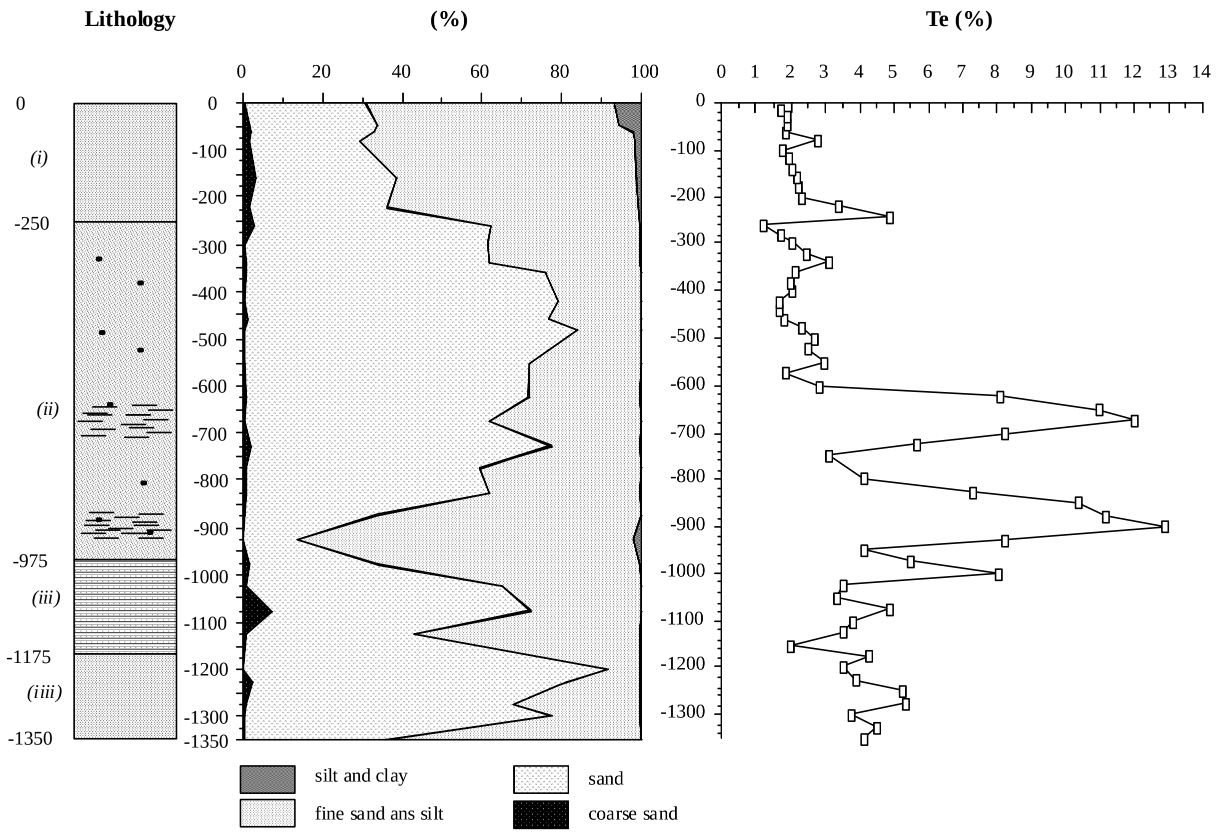
Fig. 5. Location of the coring in the depression of Nefta.

The soil samples were immediately conditioned in hermetic metallic boxes, to avoid any further evaporation to the sampling, and proceeded to the laboratories where the different operations and analyses have been carried out:

- at the ENIS; granulometry, water extraction by vacuum distillation, lixiviation, chlorine analysis (classical titrimetry, and HPLC for analysis of precipitation[2]) ;
- in the British Geological Survey (BGS) ; ^{18}O, ^{2}H analyses on the extracted water samples ;
- in the IAEA laboratories in Vienna ; tritium measurements (by direct counting).

- **lithological profile** (fig.6a) **and granulometry** (fig.6b)

The core is formed by a succession of sandy strata with small intercalation of more silty layers.
Two more permeable strata, corresponding to the more sandy parts in the profile correspond to the sectors ; 2.5 to 8 m and 11 to 13 m. An intercalation of more silty layers appears around 9 m and 11 m depth.



(i): fine sand with small roots
(ii): coarse to medium size sand with quartz and some silty clayey levels
(iii): sand with small clay layers
(iiii): coarse to medium size sand

Fig. 6. NEFTA UZ profile: physical characteristics.

2.2. Analytical results

All the results are presented on table 3, together with the corresponding analytical uncertainties, when available. Precision on ^{18}O and ^{2}H measurement are of 0.1 and 1‰ respectively.

[2] HPLC: High Performance Liquid Chromatography

Table 3. Analytical results

Z1 *(cm)*	Z2 *(cm)*	Hp %	Hv	Cumul *(mm)*	Cl *(mg/l)*	Cl cumul *(g/m²)*	Cl th. Age *(years)*	O-18 *(‰)*	Deut. *(‰)*
0	-15	1,70	0,023	3	2723	9	14	0,8	-19
-15	-30	1,90	0,026	7	3050	21	31	0,1	-27
-30	-45	1,91	0,026	11	1498	27	40	-0,5	-22
-45	-60	1,87	0,025	15	2696	37	55	-2,6	-37
-60	-80	2,78	0,038	22	3054	60	89	-4,4	-40
-80	-100	1,77	0,024	27	1850	69	102	-4,5	-47
-100	-120	1,97	0,027	33	830	73	109	-4,7	-49
-120	-140	2,08	0,028	38	432	76	112	-4,9	-53
-140	-160	2,14	0,029	44	2036	87	130	-4,3	-48
-160	-180	2,21	0,030	50	6819	128	190	-3,4	-46
-180	-200	2,29	0,031	56	2275	142	211	-3,5	-43
-200	-220	3,38	0,046	65	2620	166	246	-5,6	-51
-220	-240	4,90	0,066	78	3888	218	322	-6,1	-50
-240	-260	1,19	0,016	82	5687	236	349	-0,5	-30
-260	-280	1,70	0,023	86	5545	261	387	-3,2	-41
-280	-300	2,07	0,028	92	2957	278	412	-2,5	-32
-300	-320	2,44	0,033	98	2066	291	432	-3,8	-37
-320	-340	3,07	0,041	107	1829	307	454	-4	-39
-340	-360	2,10	0,028	112	2714	322	477	-4,2	-39
-360	-380	2,01	0,027	118	3422	341	505	-2,8	-34
-380	-400	2,04	0,028	123	2001	352	521	-5,1	-40
-400	-420	1,66	0,022	128	3043	365	541	0,9	-20
-420	-440	1,66	0,022	132	1481	372	551	0,7	-21
-440	-460	1,80	0,024	137	909	376	557	-2,6	-38
-460	-480	2,30	0,031	143	1062	383	567	-0,9	-31
-480	-500	2,67	0,036	151	1623	395	585	2,3	-12
-500	-525	2,52	0,034	159	762	401	594	-0,6	-22
-525	-550	2,99	0,040	169	889	410	607	-2,5	-37
-550	-575	1,84	0,025	175	959	416	616	-1,6	-27
-575	-600	2,85	0,038	185	426	420	622	-2,9	-42
-600	-625	8,09	0,109	212	426	432	640	-4,6	-41
-625	-650	10,98	0,148	249	405	447	662	-5,5	-52
-650	-675	12,00	0,162	290	735	476	706	-5,2	-48
-675	-700	8,20	0,111	318	575	492	729	-3,8	-39
-700	-725	5,70	0,077	337	737	507	750	-4,5	-46
-725	-750	3,09	0,042	347	1176	519	769	-3,6	-37
-775	-800	4,13	0,056	361	934	532	788	-3,8	-35
-800	-825	7,30	0,099	386	761	551	816	-3,3	-39
-825	-850	10,37	0,140	421	740	577	854	-4,5	-43
-850	-875	11,18	0,151	459	898	610	904	-4,7	-45
-875	-900	12,90	0,174	502	478	631	935	-4,4	-48
-900	-925	8,21	0,111	530	1034	660	978	-4,6	-49
-925	-950	4,12	0,056	544	1395	679	1006	-3	-32
-950	-975	5,49	0,074	562	987	698	1033	-3	-33
-975	-1000	8,03	0,108	589	239	704	1043	-4,2	-37
-1000	-1025	3,50	0,047	601	2408	732	1085	-5,3	-44
-1025	-1050	3,34	0,045	612	640	740	1096	-4,3	-38
-1050	-1075	4,91	0,066	629	730	752	1114	-2	-32
-1075	-1100	3,84	0,052	642	901	763	1131	-3,2	-47
-1100	-1125	3,52	0,048	654	2347	791	1172	-1,1	-31
-1125	-1150	2,00	0,027	661	713	796	1179	-1,9	-39
-1150	-1175	4,25	0,057	675	282	800	1185	-4,9	-46
-1175	-1200	3,50	0,047	687	172	802	1188	-5,4	-51
-1200	-1225	3,91	0,053	700	266	806	1194	-4	-43
-1225	-1250	5,24	0,071	718	263	810	1201	-6,5	-58
-1250	-1275	5,36	0,072	736	514	820	1214	-5,8	-47
-1275	-1300	3,78	0,051	748	654	828	1227	-6,1	-48
-1300	-1325	4,50	0,061	764	245	832	1232	-5,3	-46
-1325	-1350	4,10	0,055	777	292	836	1238	-3,3	-37

Z1-Z2: interval of sampling ; Hv: volumetric humidity ; Cl th Age: Cl theoritical age (years) ;
Hp: weighted humidity ; Cumul: cumulative water content

Due to the low humidity, the tritium counting has been made on grouped soil samples representing wider intervals than the other measurements (table 4)

- **Water content** (fig.6c)

The water content has been obtained on the same samples extracted by vacuum distillation and further checked by over desiccation at 110°C (during 12 hours).

The superficial level, formed by loamy sands about 2.5 m in thickness, shows a slight progressive increase of the water content from 1.7 % in weight (corresponding to about 2.3 % volumetric[3]) to 2.2 % (~2.9 % volumetric). The only point above the general trend in this superficial stratum (2.8 % at 70 cm depth) corresponds to a level marked by the presence of organic matters (presence of small roots).

The first sharp increase in water content is located at the bottom of the superficial sandy formation, just before the interface with the underlying layer. This increase in humidity may correspond to the change of permeability between the two layers (the "yellow sands" below being more permeable than the upper superficial formation).

Below that transition, the increase in water content does continue regularly up to 6 m in depth where two very sharp peaks (maximum at 6.8 m and 8.8 m) are marking the presence of two clayey layers at the same depth.

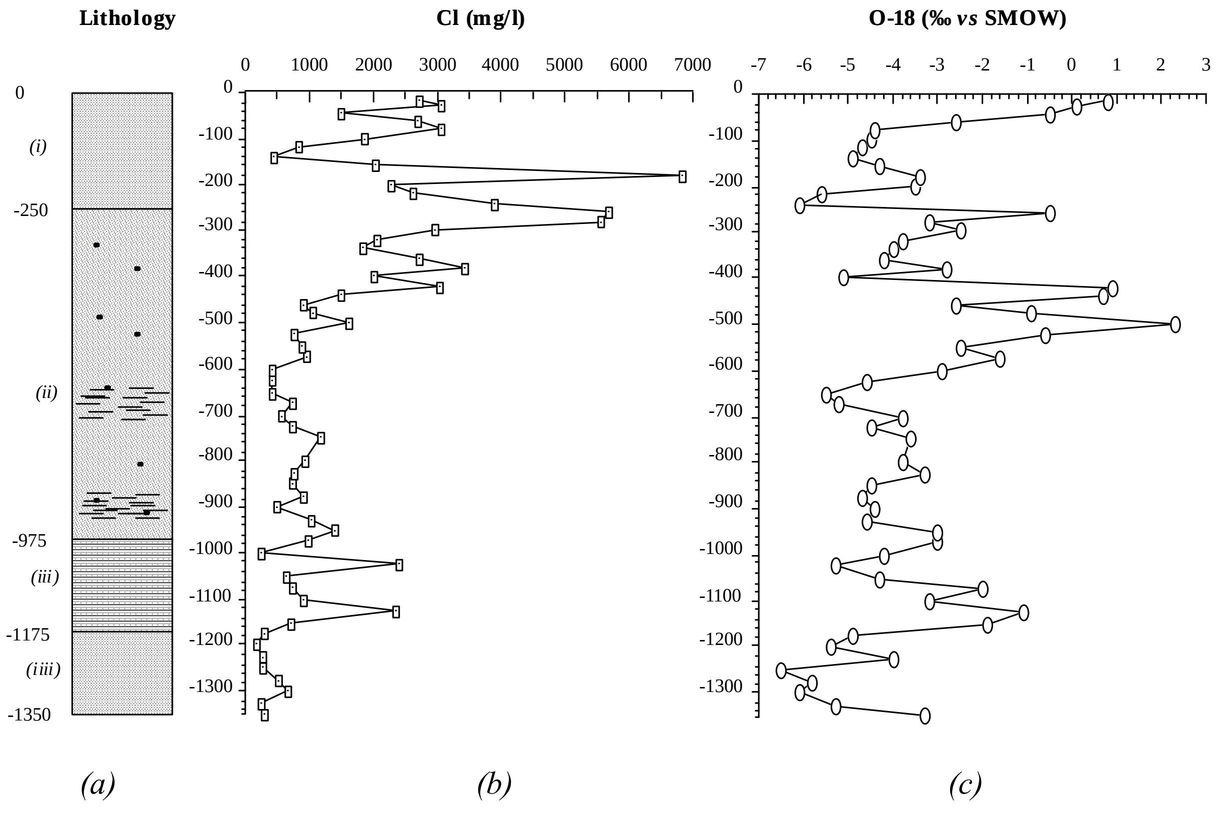


Fig. 7. NEFTA UZ profile: Chemical and isotopic results.

[3] *The humid bulk density is estimated, by comparison with measurements made on other sites, to be between 1.20 and 1.4.*

- **Chlorine profile** (fig.7a)

The chlorine profile is mainly characterised by two different sections:

- The upper part, from the surface to 1.5 m in depth, with a global decrease in the concentration, ranging from 3000 ppm at the top to less than 500 ppm at the bottom;
- The lower part, starting with an important chorine peak located at 2 m in depth (of about 7000 ppm), shows a progressive decrease in the concentration with depth to reach a quasi "steady state" of some hundreds ppm (300 to 500) below 12 m.

  These values are, although slightly less concentrated, in the order of magnitude than those measured in the aquifer (cf. chap 2)

  However, it should be noticed that the water representative of in the aquifer was sampled at about 40 m in depth, then quite much deeper than the lower part of the profile. In fact, the isotopic and chemical concentration of the profile between these two levels is supposed to be more or less in a "steady states" around theses values. But the verification of this hypothesis could only be made through the realisation of a deeper coring.

- **Stable isotopic profile** (fig.7b and 7c)

The stable isotopes analysis (^{18}O and ^{2}H) of the interstitial water seems - at first glance - to - show a much more variable (or even erratic !) results than the chlorine profile. However, the same global tendency can be evidenced:

- The upper part of the profile (0 - 1.5m) corresponds to a regular decrease in stable isotopic content ; from the enriched value at the surface (+ 1‰ in ^{18}O, obviously due to the evaporation) and the depleted value at the 1.5 m depth (-5‰ in ^{18}O).
- The lower part of the profile (below 1.5 m) shows a succession of enrichment peaks followed by a progressive decrease in stable isotopic content to reach a minimum value around –6.5‰. In more detail, four sections can be distinguished in this part:
  (1) from 1.5 to 6 m, important variations in the isotopic content (-6‰ to +2.5‰ in ^{18}O) corresponding to the succession of well defined enrichment peaks ;
  (2) from 6 to 10 m, a more regular part with concentration ranging between -5 ‰ to -3‰ in ^{18}O ;
  (3) from 10 to 12 m, a small enriched peak (-1‰ in ^{18}O) ;
  (4) below 12 m, very depleted values (up to –6.5‰ in ^{18}O).

The deuterium profile (not represented in the report) shows the same tendencies as the O-18.

Tritium profile (fig.8)

The tritium profile shows variations in tritium concentration between O and 15 TU (table 4). A general trend of decreasing the activity with depth (up to 12 m) can be drawn, before the presence of a little "peak" (10 TU) at 12.5 m. However, it should be already underlined that there is great uncertainty on these values (many of them are under the analytical precision threshold), which reduces the confidence in interpretation.

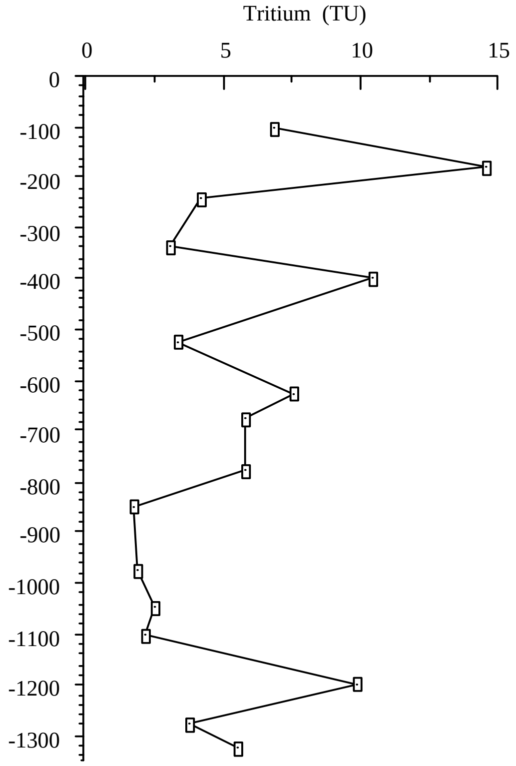


Table 4

P (cm)	TU	Error
80-140	6,91	4,50
140-200	14,59	4,63
220-240	4,3	4,46
320-340	3,14	4,44
360-400	10,48	4,55
480-525	3,43	4,44
525-625	7,63	4,51
650-675	5,89	4,48
725-775	5,89	4,48
825-850	1,84	4,42
950-975	1,98	4,42
1025-1050	2,56	4,43
1075-1100	2,27	4,42
1100-1200	9,95	4,55
1225-1275	3,86	4,45
1275-1325	5,58	4,53

Fig. 8. Tritium profile.

3. Discussion and interpretation

- **Water content**

It is noticeable that, though the profile was made at the end of the rainy season, the water content is very low at the surface of the soil. This feature illustrates the efficiency of the evaporation and also corresponds to the fact that the main rain events occurred at the beginning of the 97-98 rainy season (cf. fig.2b and 2c). The period of several months, elapsed between these rain events and the sampling, was long enough to allow the uptake by evaporation of most of the infiltrated water.

As a matter of fact, the profile seems to be characterised by a general trend - corresponding to a regular and slight increase in the humidity with depth (of about 0.17% per meter) – affected by picks due to changes in the lithology (presence of argillaceous layers, interfaces or presence of organic matter).

This general trend may reflect the establishment of a "*long term evaporative profile*" locally modified by slight infiltration events and lithology influences (presence of “low mobile” interstitial water in more clayey layers).

Compared to the amount of water stored in the profile and the general knowledge of the infiltration under arid conditions (Aranyossy, 1978 ; Zouari, 1983 ; Yousfi, 1984) it can be assumed that the last rainy season 97-98 concerned by the profile has penetrated into the soil up to the minimum depth of about half a meter. That would correspond to a minimal amount of water of 15 mm (*i.e.* about 16 % of the water precipitated in the region). This percentage of rain water remaining in the soil, estimated at the end of the “rainy season”, will of course drastically decrease until the end of the dry season (April to September).

- **Chemical and isotopic tracers**

Both chemical (Cl) and isotopes (^{18}O, ^{2}H) evolution in the upper part of the profile, suggest that the evaporation, starting from the last rainy season (between January and April 98) before sampling**,** affects at least the first metre of the soil.

Between 1.5 and 6 meters depth, the profiles are still marked by longer term evaporation effects which globally correspond to a section enriched both in chlorine and heavy isotopes. This general evaporation profile is perturbed by infiltration events characterised by lower values in chlorinity and stable isotopes, and pushed downwards by successive "piston flow" mechanism.

Below this section, the three different parts described in the profile (cf. 2) may be interpreted as follows:

- From 6 to 10 metres; the almost "steady-state" section (both in isotopes and chlorine) corresponds to the bottom of the regular evaporation profile (cf. fig.7). The ^{2}H / ^{18}O plot (fig.9) which shows an evaporation line ($\delta^2H = 4.5 * \delta^{18}O - 24$) defined with a quite good correlation ($r^2 = 0.8$) supports this argument.
- From 10 to 12 meters, the more clayey sandy layer - less permeable than the other layers and significantly marked by higher chlorine and heavy isotopic content - seems to refrain, somehow, the infiltration which occurred occasionally in the superficial layers,
- Below 12 m, the lower part of the profile, with the lowest content in chlorine and the more depleted in heavy isotope, move closer to the local composition of the *Complexe Terminal* water, suggesting a higher contribution of this water coming from the deeper parts of the aquifer.

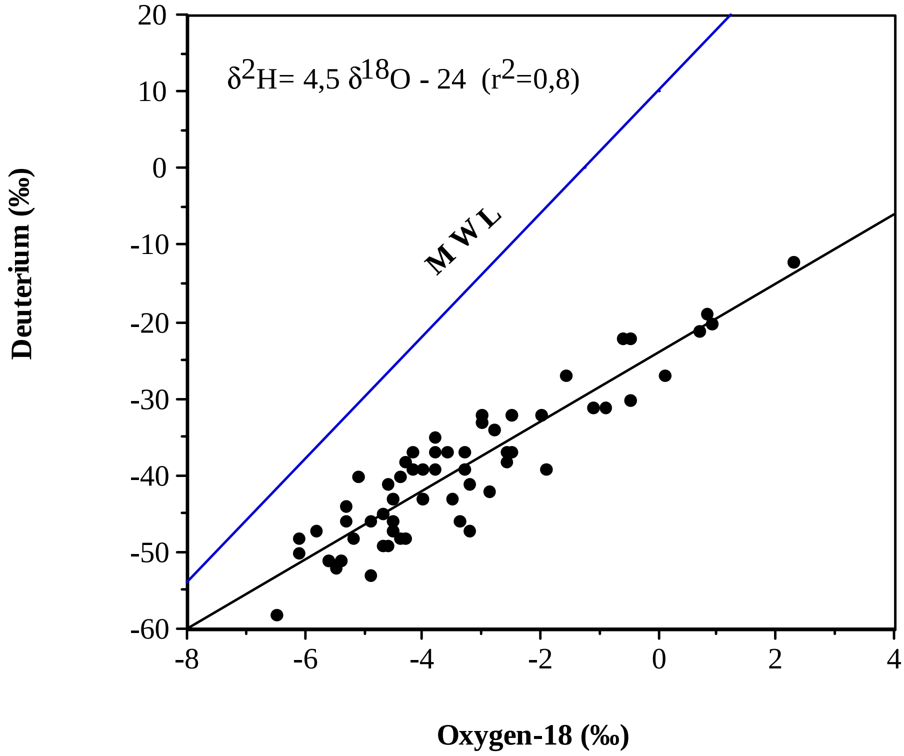


Fig. 9. Deuterium / Oxygen-18 plot for the all set of sample of the Nefta UZ coring.

The alternation of infiltration events and evaporation processes marked by the isotopic and chemical profile seems compatible with the hypothesis of local present aquifer recharge suggested by Mamou (1990). The presence of tritium activity in the profile, although difficult to interpret quantitatively, is also consistent with this hypothesis.

In these conditions, the chlorine concentration profile should theoretically provide a tool for a quantitative estimate of this recharge. Taking into account a local rainfall input of about $7 mg.l^{-1}$, an application can be attempted for different parts of the profile:

- 1 - 1.5m: Ci = 1500 ppm
- 1.5 - 4.5m : Ci = 3500 ppm
- 4.5 - 10 m:Ci = 750 ppm

Ci being the chlorine concentration in the profile.

Applying the classical formulation: R = Cp * P / Ci ; where Cp is the chlorine concentration in precipitation, P the average precipitation, the theoretical recharge rates are respectively:

- 1.0 - 1.5 m: $0.45 mm.y^{-1}$
- 1.5 - 4.5 m : $0.19 mm\ y^{-1}$
- 4.5 - 10 m:$0.9 mm.y^{-1}$

In terms of paleo-recharge, the application of the classical equation (Edmunds et Gaye, 1994):

$$t = \int_{z=0}^{Z=13.5} Cr * \theta * dz \ / (Cp*P)$$

would provide the theoretical residence time of the chlorine given in table 3 (Column "Cl theo. age"). In this calculation, based on the total amount of chlorine stored in the profile and the assumption of a constant value of the term Cp*P, the "Cl age" (which should also correspond to the “age” of the water recharge at the same depth) would be of more than 600 years at 6 meters depth.

In our case, these values seem to be over-estimated because of:

- the under-estimation of the input value of annual chlorine content in the profile. In fact, the area being rounded by several big saline dry lakes (sebkha and Chott El-Jerid, El Gharsa, El-Fedjej…) as important amount of salt is taken out by the winds during the dry season and spread on the soil all over the region ;
- the frequent presence of evaporites (gypsum often associated with NaCl) in the soils themselves, which leads to an over-estimation of the Ci value.

Consequently, great care should be taken in applying the Cl methodology in this region to get reliable quantitative estimate of the infiltration.

In semi-quantitative interpretation of the stable isotopic profile and chlorinity profile it can be attempted assuming a piston flow model pushing downwards the successive infiltrated “trenches“ of partially evaporated water of the successive rainy season. In that case, a sequence of about 10 years could be distinguished in the first 6 meters of the profile. Taking into account the total amount of water in the profile (about 185 mm), that hypothesis would correspond to an infiltration rate of about $18.5 mm.y^{-1}$.

In conclusion, it seems that the simple application of the "chlorinity equation" may lead to an under-estimation of the recharge through the sand dunes. On the other hand, the approach based on the comparison between chlorine and isotopic profile seems to provide an over-estimate of the recharge.

A possible validation of the methodology would certainly consist in the realisation of chronological sequence of several profiles at the same site in order to follow the displacement of the isotopic and chlorinity peaks under the influence of an infiltration event. One efficient sequence could be: one at the end of the dry season (beginning September), one in the middle of the rainy season (January), at the end of the rainy season (April) and another profile at the end of the following dry season.

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