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Identification and characterisation of hydrogeological relays of continental intercalaire aquifer of southern Tunisia

K. Abid · K. Zouari · B. Abidi

Abstract   In southern Tunisia, the major aquifer system is characterised by the superposition of two principal levels; the "complex terminal" (CT) which forms the surface aquifer and the "continental intercalaire" (CI) which constitutes the deep aquifer. The hydrodynamic functioning of this aquifer system is largely influenced by tectonics, lithologic variation and recharge conditions. The tectonics has contributed to the discontinuity of the aquifer levels by creating some barriers which play the role of hydraulic sills. A study of the CI potentiometric map shows three principal flow directions. These flow directions converge at the Sill Zone. The total mineralisation evolution shows an increase from the periphery of the basin to the discharge area. Dissolution of halite, gypsum and/or anhydrite-bearing rocks is the principal source of the salinity of the groundwater. The dissolution of these evaporitic rocks is confirmed by mineral saturation indices, which show an under-saturation of water samples with respect to the mentioned minerals. Moreover, the insulation of certain compartments of the reservoir and intercommunications between the aquifer levels seem to play a principal role in the deterioration of chemical quality of water. In this study, the isotopic tools have been applied to understand the hydrodynamic functioning in the region. These techniques have confirmed the results of the hydrogeologic and hydrochemical studies concerning the interconnection between the different aquifers. They indicate also the recent local recharge of the CI reservoir throughout Cretaceous outcrops, and the older origin of all groundwater in the aquifer system.

Introduction

Southern Tunisia is underlain by two major aquifer systems the continental intercalaire (CI) overlain by the complex terminal (CT). Lateral continuation of the CT in the coastal plain forms the Djeffara aquifer. The CI aquifer is one of the largest confined aquifers in the world. This immense multilayered aquifer is hosted in the continental formations of the Lower Cretaceous (Neocomian, Barremian, Aptian and Albian).

The groundwater reservoir of the CT is contained in the Upper Cretaceous and Tertiary formations. The CT formations are relatively heterogeneous and are composed of two main aquifer horizons separated by semi-permeable to impermeable strata: (1) the early Senonian carbonates (Abiod Formation: main aquifer of the Kebili region), extending over the whole basin and (2) the Tertiary sandy formation (Beglia Formation: in the Tozeur region).

The CI aquifer is shared between Algeria, Tunisia and Libya and covers a surface of more than 1 million km^2 of which 700,000 km^2 are in Algeria, 80,000 km^2 in Tunisia, and 250,000 km^2 in Libya (SASS 2002). The aquifer is, however, hydraulically continuous over the whole basin.

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The Chott's region of southern Tunisia forms the discharge area of the CI and CT aquifers. In this southern region, tectonic activity has been most active. The lithostratigraphic correlations show that the CI aquifer is mainly affected by the major faults which are likely to generate some lateral compartmentalisation in the CI aquifer and the groundwater flow is likely to be complex. Overexploitation of this aquifer, following the excessive request of water, seems to play an important role in the change of groundwater flow conditions, which consequently results in a decline in water quality. This transitory dynamic situation, which is added to structural complexity of the reservoir, makes difficult the comprehension of the hydraulic functioning of hydrogeologic units by the only means of "traditional" hydrogeology. The combination of hydrochemical and isotope data, coupled with the analyses of the stratigraphic setting of the area, in such systems, allows a better understanding of the hydrodynamic properties of this aquifer. These tools are essential for estimating the contribution of different water sources to the overall water balance.

Study area

The study area is located between the longitudes 7°30′–10°30′ east and the latitudes 30°10′–34°10′ north. It is limited in the west by the Algerian frontier and in the east by the hill of Chott El Fedjej and the Dahar upland. It covers all the parts of the territory between the Saharan platform in the south and the Atlas Saharan Mountains in the north (Fig. 1). It is characterised by an arid type climate with a mean annual precipitation of less than 100 mm. The mean annual temperature is 21°C, while potential evapotranspiration exceeds 1,700 mm year^{-1}. Precipitation varies seasonally across the region.

Geological and hydrogeological setting

The CI aquifer is located within a complex succession of clastic sediments of Mesozoic age. The geological succession is composed of several units of detrital sediments separated by clay strata and gypsum intercalations, giving rise to a degree of heterogeneity of this aquifer. At its maximum, the aquifer thickness exceeds 1,500 m. The geological formations forming the CI aquifer show significant lateral variations in facies and thickness beginning from the Saharan platform reaching the Chott area.

In the study area, tectonic processes are important and are at the origin of the genesis of several geological provinces. In the present work only three provinces are analysed (Fig. 1): (1) the Dahar upland which consists of a

N–S-trending, in Tunisia (Zargouni et al. 1985; Bouaziz 1995; Bouaziz et al. 2002; Gabtni et al. 2009), (2) the Draa Djerid Ridge which consist of a NE–SW-trending formed during the Alpine (Late Cretaceous–Early Eocene) tectonic phases (Zargouni et al. 1985) and (3) The Jeffara coastal plain which consists of a NW–SE-trending (Bouaziz 1995; Bouaziz et al. 2002; Gabtni et al. 2009). Within the Dahar monocline there is almost a complete stratigraphic sequence from Late Permian to Upper Cretaceous. This structure contains the oldest outcrops in Tunisia which are of Permian age (Castany 1954; Busson 1967; Bouaziz 1995; Bouaziz et al. 2002). The Dahar upland is bounded in the eastern part by a set of faults, which contributed to the subsidence of the Djeffara basin (Bouaziz 1995; Yahyaoui 1996). These faults are part of a complex called the South Tunisian Accident (Castany 1954). The effect of several tectonic phases on the Jeffara area seems to have controlled the production of a large sedimentary basin (Gabtni et al. 2009). Within this coastal plain, geologic formation consists of a sedimentary succession extending from Lower Cretaceous to Quaternary, with a sedimentary gap from Palaeocene to Eocene. In the Djerid region, the major tectonic feature was the Draa Djerid Ridge, a horst separating the subsiding Chott el Gharsa to the North-West from Chott el Djerid to the South-East. This anticline constitutes the prolongation towards the West of the Northern chain of Chotts (Fig. 1). The southern edge of this structure is affected by E–W striking faults showing the importance of the tectonic activity in this area (Mamou 1990).

The main groundwater flow directions are those coming from Algeria (W–E and SW–NE) as well as those from the Dahar region of Tunisia. Groundwater flow in the CI and CT aquifers reach a single discharge zone in the Gulf of Gabes and the Chott El Fedjej region (ERESS 1972; Trabelsi et al. 2008; Abid et al. 2009). In general, secondary cementation and clays decrease the porosity. Furthermore, the fault systems diminish water movement in some compartments as a result of the fault displacement which induces a placing of clay beds in vertical contact with limestones and sands.

The study aquifer indicates similar deposits able to ensure the possible communications between the various formations. To illustrate the lithostratigraphic relays of the aquifers two profiles were established:

Saharan platform: Chott El Fedjej

As shown in Fig. 2, the hydrogeology of the study area obtained by the existing boreholes reveals a rather complex setting bounded in the eastern part by a vertical fault, which contributed to the subsidence of the Cretaceous formations. This section shows that the groundwater flow
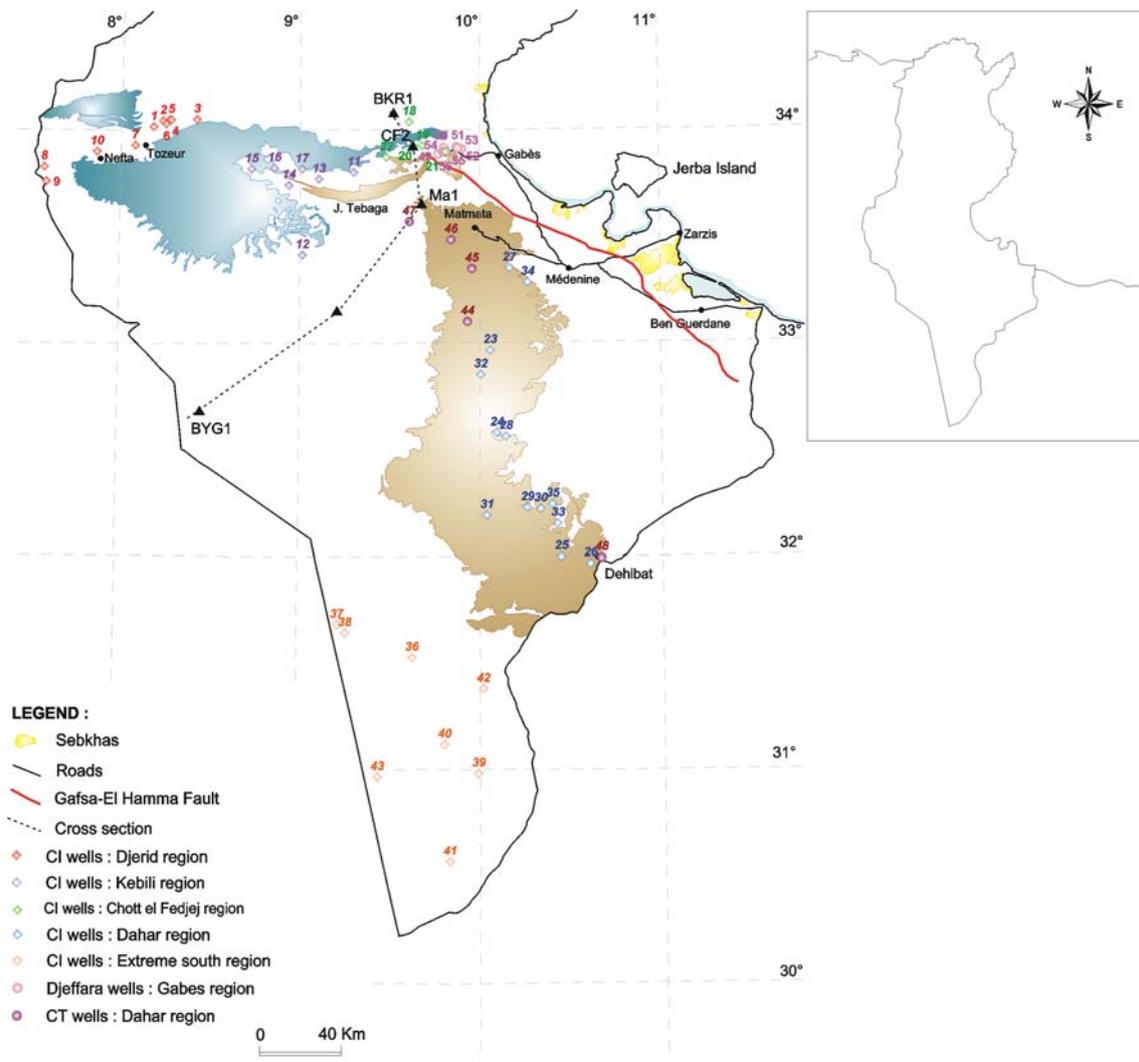
Fig. 1 Sampling wells network

from Algeria to Tunisia is transgressive and passes from the highest to the lowest stratigraphic units. This flow component is accompanied by changes in pressure, water temperature and chemistry (Edmunds et al. 1997).
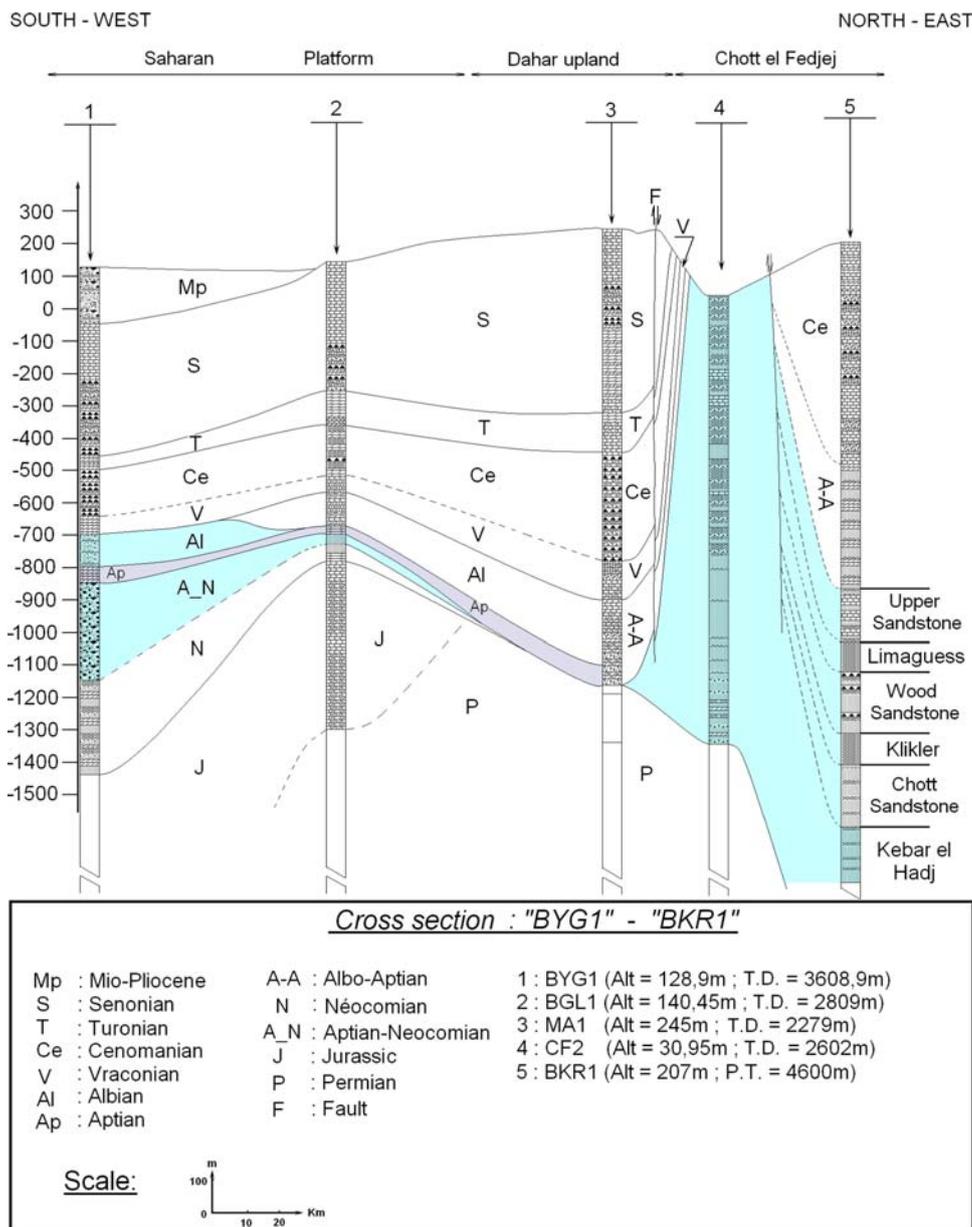
Extreme south: Kebili

The geological formation forming the CI aquifer changes in facies and thickness from Saharan platform to the northern Chott chain (Fig. 3). In the Nefzaoua region, the CI aquifer is principally found in the sandstones of the Kebar El Hadj series at depths exceeding 1,500 m. Towards the east, these formations become shallower and have confining depths between 500 and 900 m (Edmunds et al. 1997). The water discharge temperature is from 38 to 74°C (Table 1). In the Djerid, the CI aquifer is composed of three formations: the sandstone of the Boudinar

formation (Hauterrvanian–Barremian), the sands and sandstone of the Sidi Aïch formation (Aptian) and the sandstone, limestone and marl of the Orbata formation (Aptian–Albian). The main confined horizon is the Sidi Aïch formation found at the depth of 1,300 and 2,200 m (Mamou 1990).

Groundwater sampling and analyses

Samples of groundwater from sites in the study area were collected during high-flow conditions in January–April 2004. Sampling locations are shown in Fig. 1. In situ parameters, such as pH, electrical conductivity (EC), temperature and alkalinity (HCO_3) were measured in the field. Samples for major chemical analyses were filtered (0.45 mm filter paper) and collected in plastic bottles.

Fig. 2 Structure and extension of the continental intercalaire aquifer in Southern Tunisia

Cross section : "BYG1" - "BKR1"

Mp : Mio-Pliocene	A-A : Albo-Aptian	1 : BYG1 (Alt = 128,9m ; T.D. = 3608,9m)
S : Senonian	N : Néocomian	2 : BGL1 (Alt = 140,45m ; T.D. = 2809m)
T : Turonian	A_N : Aptian-Neocomian	3 : MA1 (Alt = 245m ; T.D. = 2279m)
Ce : Cenomanian	J : Jurassic	4 : CF2 (Alt = 30,95m ; T.D. = 2602m)
V : Vraconian	P : Permian	5 : BKR1 (Alt = 207m ; P.T. = 4600m)
Al : Albian	F : Fault	
Ap : Aptian		

Scale:

Unfiltered groundwater samples were collected in 30 ml polyethylene bottles with poly-seal caps for stable isotope analysis. Chemical analyses were done at the Laboratory of Radio-Analyses and Environment of the National Engineering School of Sfax (ENIS: Tunisia). Stable Isotope ratio ($^{18}O/^{16}O$ and $^{2}H/^{1}H$) analyses (Table 1) were performed at the laboratory of the International Agency of Atomic Energy (IAEA) in Vienna using CO_2 equilibration technique for $\delta^{18}O$ (Epstein and Mayeda 1953) and isotopic exchange with H_2 gas for $\delta^{2}H$ (Colpen et al. 1991), followed by mass-spectrometry measurement. Analyses are reported in the standard δ notation representing per mil deviations from the VSMOW standard (Vienna-Standard Mean Oceanic Water), and reproducibility is ±0.1‰ for the $\delta^{18}O$ analyses and ±1.0‰ for the $\delta^{2}H$ analyses.
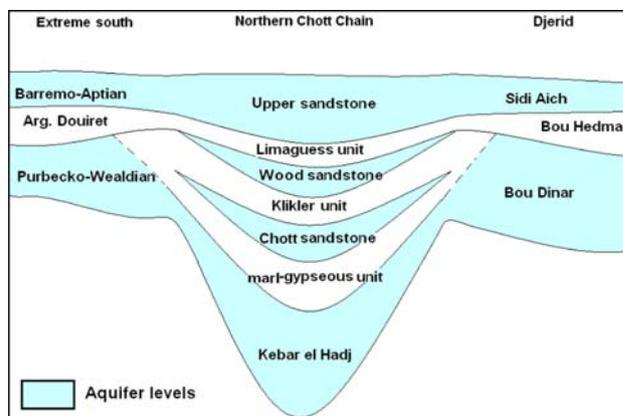

Fig. 3 Distribution of the aquifer levels of the CI aquifer in Southern Tunisia

Table 1 Isotopic and geochemical data for CI aquifer

Aquifer	No.	Formation	TD	T (°C)	pH	EC	Na	Ca	Mg	K	Cl	SO₄	HCO₃	CO₃	¹⁸O	²H
CI Djerid	1	1	1,475	69	8.2	3,510	539.6	201.1	23.7	73.4	294.4	1,227.4	103.7	12	−6.99	−48.48
	2		1,438	74	6.7	3,000	316.7	349.9	29.6	66.8	436.7	777.5	231.8	12	−7.09	−48.31
	3		1,430	69.5	6.9	3,160	277.0	355.0	41.0	89.0	371.0	975.0	179.0	0	−7.4	−56.4
	4		1,430		7.6	2,840	255.0	288.0	69.0	75.0	390.0	960.0	175.0	0	−7.46	−51
	5		2,186	71.5	7.3	6,210	897.2	316.8	28.2	99.5	1,643.9	612.4	91.5	30	−7.02	−49.87
	6		2,412	74	7.9	3,200	326.1	308.3	22.2	52.9	437.0	950.6	146.3	6	−6.69	−49.03
	7		1,997	66	7.1	4,200	327.0	390.0	46.3	60.0	356.0	1,320.0	110.0	0	−7.6	−61
	8	2	2,970	73	6.8	2,930	215.9	309.4	56.9	76.3	327.0	788.6	134.2	18	−7.75	−53.59
	9		2,225	60	7.0	2,430	1,465.3	1,007.2	641.2	168.4	3,486.5	4,099.4	67.1	0	−7.30	−52.58
	10		2,122	70	7.3	5,130	529.0	412.0	66.5	69.9	600.0	1,510.0	140.0	0	−7.1	−58
CI Kebili	11	3	1,450	55.6	7.7	3,620	377.4	421.1	46.8	24.3	524.7	1,058.7	231.8	0	−8.52	−60.84
	12		2,020	51.6	7.6	5,900	888.1	446.7	60.2	97.8	1,623.6	913.1	140.3	6	−8.16	−62.6
	13		1,752	69.7	8.0	3,250	338.1	327.0	52.9	30.7	574.6	707.7	97.6	12	−8.38	−60.19
	14		1,904	52	7.6	4,940	562.0	408.0	87.9	38.5	850.0	1,260.0	122.0	0	−8.3	−64
	15		2,290	71	7.1	4,640	306.0	271.0	72.2	44.9	592.0	734.0	128.0	0	−8.1	−58
	16		2,250	68	7.4	2,830	281.0	201.0	61.3	42.3	464.0	645.0	110.0	0	−8.2	−59
	17		1,786	72.5	7.5	3,250	341.0	271.0	78.6	47.3	652.0	710.0	140.0	0	−8.4	−59
CI	18	3	1,292	67.6	7.0	3,040	290.6	327.5	49.4	45.1	592.3	729.5	97.6	24.0	−8.18	−59.60
	19		860	52		3,670	361.7	387.1	52.7	36.4	620.1	877.3	97.6	12.0	−8.34	−59.48
Chott	20					3,700	369.0	362.0	68.2	43.8	638.0	1,010.0	121.0	0.0	−8.4	−59
	21		1,310	50		5,250	586.4	511.0	60.9	28.1	974.8	1,339.5	97.6	12.0	−7.87	−58.98
Fedjej	22	4	350	32	7.2	7,260	274.0	981.3	124.2	21.6	831.3	2,025.6	85.4	18.0	−8.38	−60.4
CI Dahar	23	5	160	20	8.0	3,100	394.1	217.6	29.7	0.0	431.9	712.1	91.5	12.0	−7.23	−49.6
	24		125	23.6	7.6	2,650	292.7	174.3	40.9	18.8	414.8	552.9	140.3	6.0	−7.04	−47.2
	25		441	27	7.5	2,380	263.0	195.0	61.4	33.0	500.0	397.0	171.0	0.0	−8.3	−66
	26		168	26.4	7.5	2,210	138.0	267.0	88.5	18.5	190.0	854.0	129.0	0.0	−7.4	−43
	27		223	26.2	8.1	3,300	175.9	398.2	60.3	0.0	187.9	1,279.3	97.6	12.0	−6.16	−36.2
	28	6	126	25.2	7.0	2,520	345.5	142.6	50.7	13.3	396.7	591.0	140.3	12.0	−6.91	−45.7
	29		142	26.6	7.4	1,820	249.0	101.0	61.1	8.4	255.0	458.0	169.0	0.0	−8.4	−57
	30		150	26	7.9	2,850	258.1	245.4	42.8	41.8	652.5	477.7	122.0	12.0	−7.99	−64
	31		260	26.4	6.9	3,810	377.5	346.0	69.5	35.6	897.7	721.7	158.6	0.0	−8.41	−67.2
	32			20.6	8.1	5,660	693.6	394.4	163	0	1,236.5	1,356.8	140.3	18.0	−7.02	−46.9
	33		162		7.6	8,770	1,150.0	472.0	321.0	33.0	2,385.0	1,680.0	51.0		−6.43	−51.1
	34		175		7.9	2,380	349.0	119.0	44.0	12.0	383.0	686.0	58.0		−6.4	−38.3
	35		37		7.8	1,990	193.0	135.0	80.0	16.0	426.0	336.0	217.0		−6.32	−48.2
CI extreme south	36	6		26.8	7.4	7,550	1,145	549	138	0	2,047	1,133.7	91.5	0.0	−8.56	−66.1
	37			33.6	7.8	4,800	1,181	293.4	74	0	1,492	1,070.6	91.5	30.0	−8.92	−68.2
	38			34.8	7.5	6,870	1,097	307.6	70.2	0	1,566	999.2	115.9	0.0	−8.78	−66.8
	39				7.2	1,280	415.9	382.0	114.1	0.0	1,276.6	475.7	79.3	0.0	−8.62	−72.7
	40		414	30.3	7.5	4,770	603.5	359.0	115.5	0.0	974.6	1,286.8	103.7	0.0	−9.16	−70.5
	41		900	51	8.1	2,570	370	134	40	43	554	437.0	198		−7.94	−61.1
	42			31.5	7.4	8,570	1,104	688	185	0	2,516	1,009.6	109.8	6.0	−8.43	−64.3
	43					7,900	614.3	812.1	267	0	1,910	1,510.0	73.2	12.0	−8.80	−69.7

Formation: Sidi Aîch sandstone (1), Sidi Aîch-Bou Dinar sandstone (2), Kebar el Hadj sandstone (3), Upper sandstone (4), Wealdian sandstone (5), Albian sandstone (6)

Geochemical data (mg l⁻¹)

Stable isotope: ‰ versus VSMOW

EC electrical conductivity (μS cm⁻¹)

Table 2 Isotopic and geochemical data for CT aquifer

Aquifer	No.	Formation	TD	T (°C)	pH	EC	Na	Ca	Mg	K	Cl	SO$_4$	HCO$_3$	CO$_3$	^{18}O	^{2}H
CT Dahar	44	7		22.7	8.09	2,300	640.1	221.8	111	0	639.6	1,108	170.8	0	−6.81	−46.93
	45			27.2	7.45	700	234.9	99.4	44.1	0	204	402.2	225.7	0	−6.70	−39.06
	46		298	27.6	7.75	1,200	240.7	222.5	66	0	271.9	684.2	164.7	0	−6.66	−41.09
	47		280	24	6.7	3,890	390.1	337.6	87.6	0.0	527.8	1,025.2	140.3	0.0	−6.89	−51.9
	48		13	21.8	8.1	3,680	237.9	245.9	102.3	19.3	330.9	763.1	183.0	30.0	−7.57	−54.4
Djeffara of Gabes	49	7	264	30.5	7.5	4,320	449	403.1	59.4	37	748.5	1,039	140.3	0	−8.31	−58.6
	50			49.5	32.5	7,170	834	686.6	102	57.2	1,444	1,455	170.8	6	−8.2	−57.4
	51		66	41.6	7.7	4,250	459	420.6	68.2	51.5	731.6	1,105	116	12	−6.9	−54.5
	52		90	34	7.7	5,180	747.6	432.9	111.0	0.0	940.0	1,789.2	61.0	12.0	−7.75	−62.73
	53		68	41	7.9	4,700	511.0	405.5	105.2	0.0	814.0	1,316.0	61.0	ND	−7.17	−60.73
	54			44	7.4	4,600	316.0	360.2	58.9	0.0	706.8	857.3	85.4	ND	−8.25	−61.05
	55			45.6	7.7	4,460	566.5	507.3	66.7	0.0	1,084.0	1,139.2	61.0	ND	−8.29	−62.67
	56			46.2	7.5	4,180	479.4	416.0	86.1	0.0	797.6	1,318.4	79.3	ND	−8.29	−61.08

Formation: Upper Cretaceous carbonates (7)

EC electrical conductivity (µS cm^{-1})

Geochemical data (mg l^{-1})

Stable isotope: ‰ versus VSMOW

Groundwater chemistry

All the analytical data are reported in Tables 1 and 2. Well depths are between 13 m (in the recharge area) and over 2,970 m, in the deepest part of the basin. Groundwater well-head temperatures increase from 20°C in the recharge area to 74°C at depth. Values of water temperature and depth of boreholes are not well correlated probably due to the influence of atmospheric temperature on the shallow wells and the leakage of water from overlying formations.

The conductivity values, which are a measure of the total mineralisation, range from 700 to 7,170 µS cm^{-1}. The spatial distributions of the major ions, the EC and TDS over the study area are somewhat similar. They show an increase from the mountainous regions (recharge areas) towards the discharge area (Abid et al. 2009; Trabelsi et al. 2008).

A preliminary characterisation, carried out using the Trilinear diagram, shown in Fig. 4, shows the different geochemistry of the sampled waters. Cation contents in the samples were not similar. Generally, the CI water was enriched in calcium and sodium. In terms of anion content, the CI water was typically characterised by sulphate and chloride. The sum of cations and anions shows two main groundwater types: Na-Cl and Ca-SO$_4$.

In order to highlight the contribution of the infiltrated rain water in the local recharge of the limestone aquifers of the Dahar upland (Gonfiantini et al. 1974; Abid et al. 2009), the major ions concentration of wells located in this upland have been compared to the major ions concentration
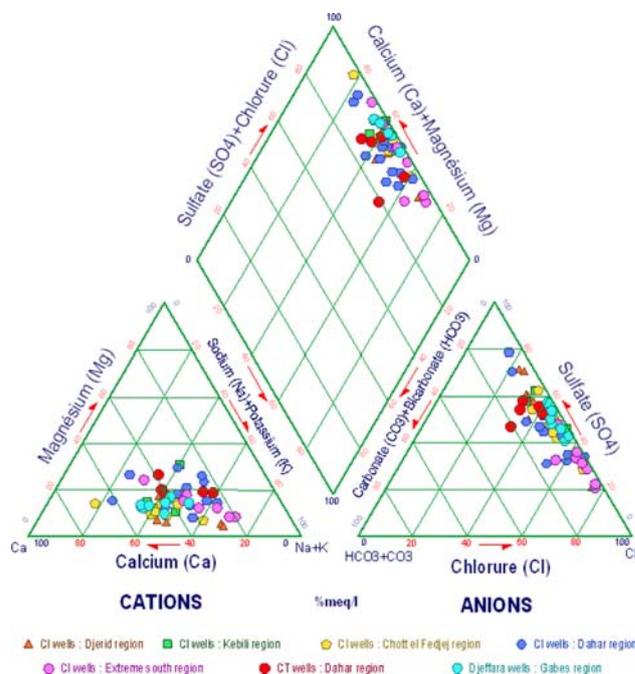

Fig. 4 Trilinear diagram showing some major chemical compositions of continental intercalaire groundwater from southern Tunisia

of boreholes situated in the Chott el Fedjej region (Fig. 5). This profile reveals a systematic increase in the EC and the major elements contents along the flow direction. The observed pattern can be explained by mineral dissolution which occurs along the flow direction. The lowest values of salinity are measured in the CI aquifer of the Dahar region.

Fig. 5 Hydrogeochemical cross-section through CI aquifer (from Dahar upland to Chott el Fedjej region) with EC, Cl, Ca, SO_4 and Na
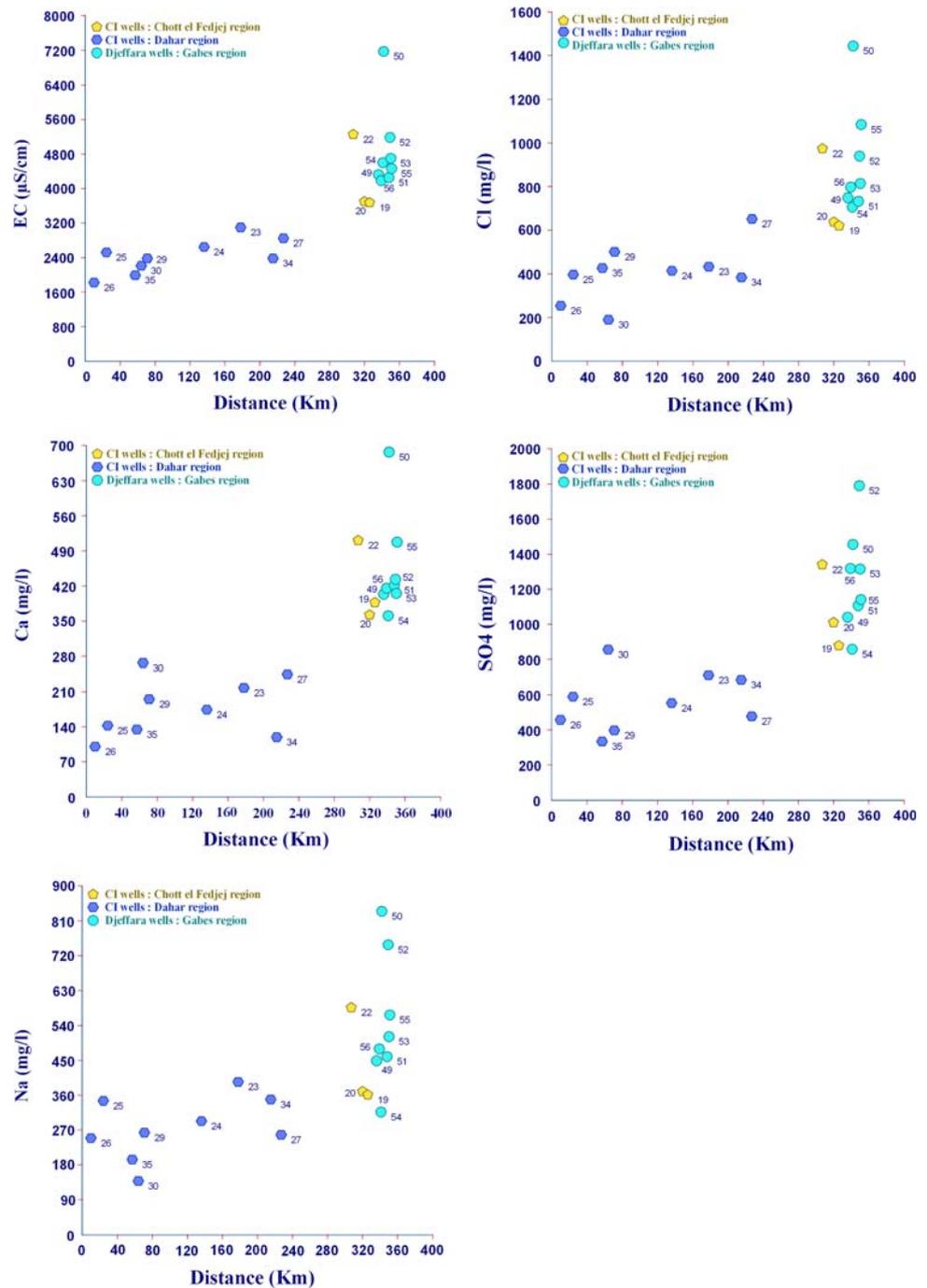
These low conductivities show the importance of this structure in the local recharge of the CI aquifer. The leaching of salts during water–rock interaction, in combination with the evaporation losses, increases the concentration of the major elements in groundwater. The positive correlation between Cl^-/Na^+ (Fig. 6a), and SO_4^{2-}/Ca^{2+} (Fig. 6b) suggests that any increase in these ions across most of the aquifer is probably from a uniform source of gypsum/anhydrite with some halite within water-bearing

formations. However, the depletion in Ca^{2+} contents relative to SO_4^{2-} concentrations as shown in Fig. 6b is probably due to (1) calcite precipitation and (2) cation exchange reactions which absorb Ca^{2+} on the clay fraction as Na^+ is released (Abid et al. 2009). The dissolution of evaporites and the precipitation of calcite are also confirmed by the saturation indices calculated with the aid of WATEQ-F program (Plummer et al. 1976). They show that water is undersaturated with respect to halite (Fig. 7a), saturated to

Fig. 6 Relationships between major elements in the analysed groundwater samples: Na/Cl (**a**), Ca/SO$_4$ (**b**)
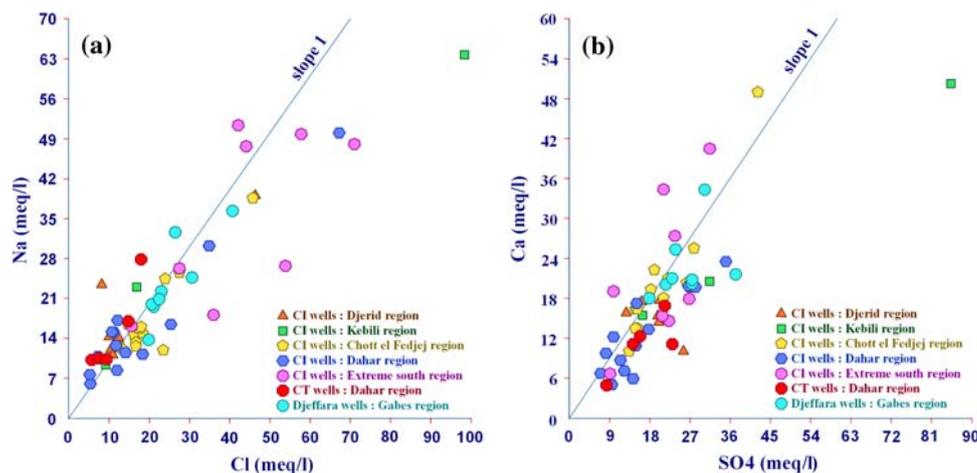
undersaturated with respect to gypsum (Fig. 7b) and anhydrite (Fig. 7c), and supersaturated with respect to calcite (Fig. 7d).

The hydraulic continuity between the CI and Djeffara aquifers has been demonstrated by the study of in situ parameters and the analytical results of major ions. The mixing process is mainly through vertical leakage of the deep Lower Cretaceaous groundwater replenishing the shallow Djeffara aquifers. Thus, the similarities in the geochemical signatures between the CI aquifer of Chott el Fedjej region and the shallow aquifers of Djeffara of Gabes (Fig. 4) and the high-temperature recorded in the Upper Cretaceous aquifers of El Hamma region (Table 2) suggest a recharge of the coastal plain of Djeffara from the CI aquifer through deep faults. The hydraulic head differences in these aquifers at the El Hamma sill zone (SASS 2002), and most importantly tectonic activity (Bouaziz et al. 2002; Gabtni et al. 2009) seem to be the main causes of this upward leakage of the deep groundwater to the shallow aquifers of Djeffara basin.

In the western part of the basin (Djerid region), the salinity of waters is dominated by Na$^+$ and Ca^{2+} for the cations and Cl$^-$ and SO$_4^{2-}$ for anions, whereas the groundwater is of the Na$^+$-Cl$^-$ to SO$_4^{2-}$ mixed water type. In this area, EC in the groundwater CI samples ranges from 2,430 to 6,210 μS cm^{-1}. These large variations in chemical compositions may imply discontinuities in the hydrogeology (change of lithology, faults and variations in the flow patterns). Two principal solute sources are needed to account for the observed variations in salinity of the CI groundwater of Djerid region. At first, the initial composition may be modified by mixing of different groundwater masses. This process is exclusively dependent from cross formational flow (i.e. Boudinar and Sidi Aïch formations) and the tectonic activities which play an important role in the observed variations in salinity. Indeed, the normal faults affecting the Draa Djerid Ridge have introduced

some lateral compartmentalisation in the CI aquifer (Kamel et al. 2006) and the variation of flow routes. Moreover, this part of the basin receives one of the main flow lines which continue from Algeria. The mixing of the different water masses has largely contributed to the geochemical evolution of CI groundwater. The second source for groundwater salinization is the different geochemical processes produced in the aquifer such as cation exchange between solution and clay minerals and the dissolution of evaporite minerals (gypsum/anhydrite and halite). These reactions, mainly dependent from the lithology of strata forming the reservoir, are indicated by high Na$^+$ relative to Cl (Fig. 6a) suggesting cation exchange reaction releasing Na$^+$ at the expense of other cations. This relative increase in Na concentrations is restricted to waters in the Djerid region and some wells of extreme south (Fig. 6a). Calcium concentrations are controlled by dissolution/precipitation of carbonate minerals (calcite (Fig. 7d), aragonite (Fig. 7e) and dolomite (Fig. 7f). Groundwater is at or above saturation with respect to these minerals. Gypsum and anhydrite dissolution in these waters, suggested by Ca^{2+} and SO$_4^{2-}$ in one-to-one equivalent ratio (Fig. 6b) and the saturation indices of these minerals (Fig. 7b, c), should tend to maintain saturation or oversaturation with respect to carbonate minerals. Moreover, the decrease of 0.5 pH units due to loss of CO$_2$ would bring values closer to saturation (Edmunds et al. 2003).

Stable isotopes

In the Djerid region, variations in stable isotope composition of the CI groundwater are great (Fig. 8), suggesting differences in origin as well as in groundwater evolution. These significant differences in the isotopic signatures are considered likely to indicate separate flow paths and recharge areas. Oxygen-18 and deuterium values in this area range,

Fig. 7 Relationships between saturation indices and major elements in the analysed groundwater samples: IsHalite/(Na + Cl) (**a**), IsGypsum/(Ca + SO$_4$) (**b**), IsAnhydrite/(Ca + SO$_4$) (**c**), IsCalcite/(Ca + HCO$_3$) (**d**), IsDolomite/(Ca + HCO$_3$ + Mg) (**e**) and IsAragonite/(Ca + HCO$_3$) (**f**)
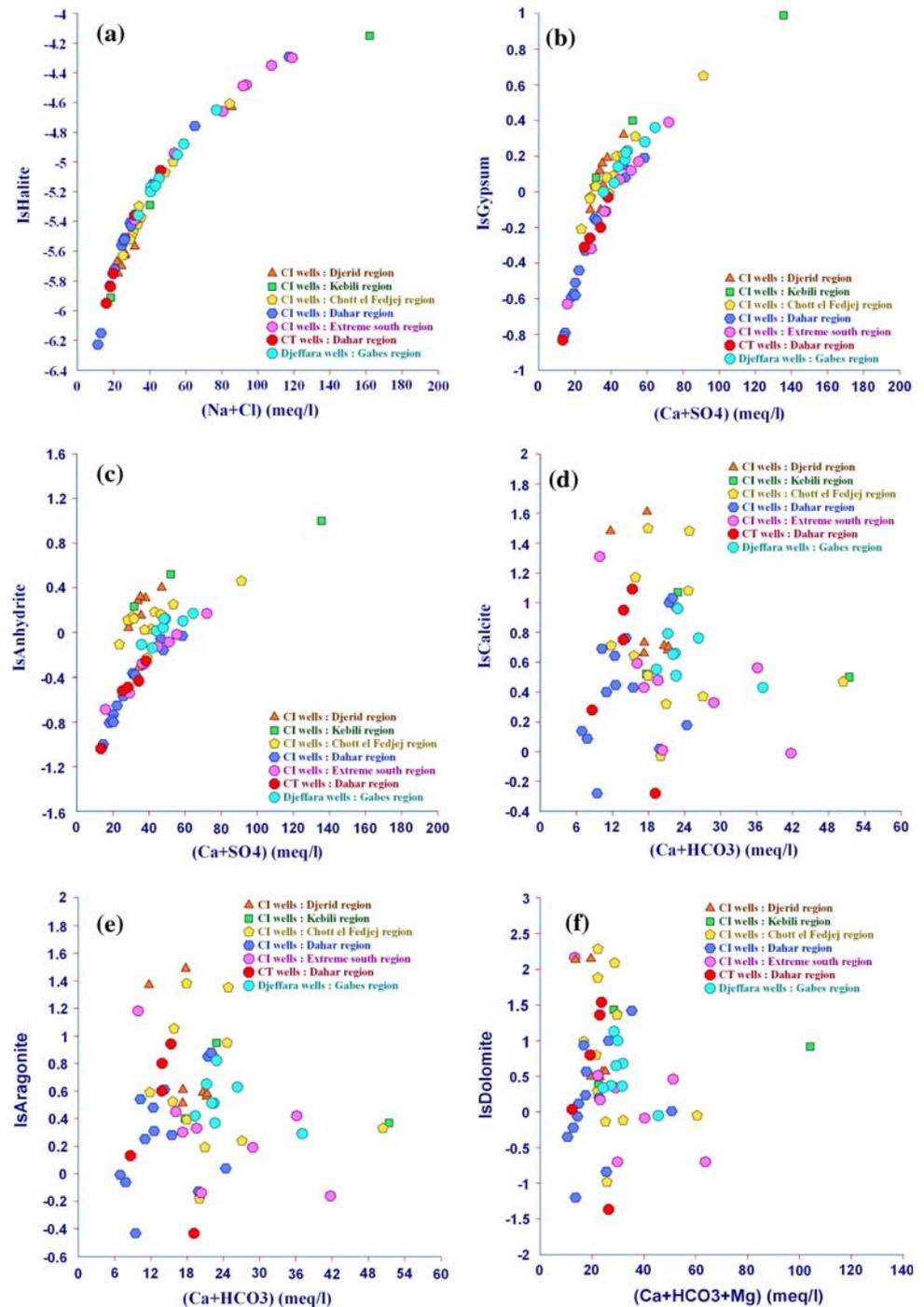
respectively, from −7.75 to −6.69‰ with a mean of −7.24‰ versus V-SMOW and from −61 to −48.31‰ with a mean of −52.83‰ versus V-SMOW. The deeper groundwater in the CI aquifer of the extreme south region has typical compositions of $\delta^{18}O$ −7.9 to −9.2‰ versus V-SMOW and δ^2H −61 to −73‰ versus V-SMOW. These depleted isotopic signatures, typical of old water, are probably related to humid periods of Late Pleistocene and the Early Holocene

recharge (Gonfiantini et al. 1974; Fontes et al. 1983; Zouari 1988; Zouari et al. 2003; Abid et al. 2009).

The composition of water in the CI closest to outcrop (Dahar region) lies on the meteoric water lines [the global meteoric water line (GMWL) and the Sfax meteoric water line (SMWL)] and has values of $\delta^{18}O$ −8.4 to −6.2‰ versus V-SMOW and δ^2H −67 to −36‰ versus V-SMOW. These are the most enriched values of the CI aquifer.
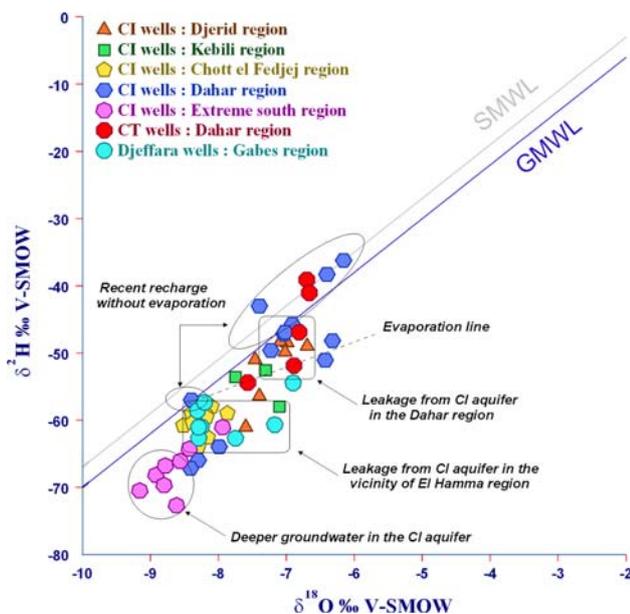
Fig. 8 Stable isotope composition of CI and CT groundwaters

Fig. 9 Cl/δ^2H relationship

However, these signatures are significantly depleted relative to modern rainfall (the weighted mean values of precipitation for Sfax region are δ^{18}O −4.6‰ and δ^2H −23.3‰ vs. V-SMOW; Maliki et al. 2000). This youngest water, showing the contribution of the Dahar upland to the local recharge of the CI aquifer, must also contain a component of older water. Besides this rainwater infiltration, two trends are distinguishable with the CT and CI groundwater data of the Dahar region. The first trend shows a trailing cluster of the groundwater samples along an estimated evaporation line with a slope of 4. The intersection of this evaporation line with the GMWL gives values of −7.3 and −52.6‰ versus V-SMOW for the respective δ^{18}O and δ^2H contents of the recharging precipitation before evaporation. In this area, the stable isotopic values from the CT aquifer decrease gradually towards the major fault, where they become indistinguishable from the observed isotopic composition of the CI groundwater. This trend is likely to represent the mixing process between waters of these aquifers. Some leakage from the CI aquifer in the vicinity of El Hamma region has also been noted since waters in the overlying CT and the shallow Djeffara aquifers contain the same paleowater signature (Fig. 8). The mixing process between these different groundwater masses seems to be controlled by the tectonic activity and the hydraulic head differences in these aquifers.

A plot of chloride content versus deuterium (Fig. 9) shows the different trends of mixing and recent rainwater infiltration responsible for the salinity variation of groundwater in the studied aquifers. In simple two-component mixing, the points representing different proportions of components should form a straight line covering
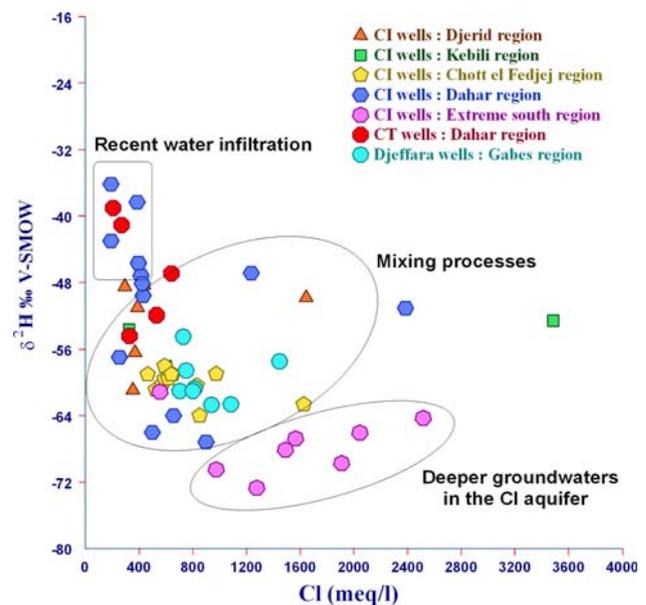
"pure" components. In the presented figure, the situation is slightly different. Three areas demonstrate exponential or hyperbolic dependence. This behaviour can be attributed to the influence of isotopic exchange with molecular waters trapped in gypsum. The first trend indicates the older groundwater pole representative of the deeper part of the CI aquifer. This group includes isotopically depleted waters with higher chloride concentrations in relation to the high residence time of water in the aquifer. The second trend shows the dilute groundwater founded at shallow depths of the Dahar upland. This group is characterised by a mean Cl⁻ concentration of about 309 mg l⁻¹ and relatively enriched δ^2H values with a mean of about −42.3‰. The other samples reflecting mixing processes are characterised by varied Cl⁻ and δ^2H contents (Fig. 9).

Conclusion

The combination of both hydrochemical and environmental isotope methods for the study of the CI aquifer systems of the extreme south of Tunisia has provided basic information about the origin, evaporation processes, migration pathways and mixing between groundwater of the different hydro-stratigraphic units that compose the system. The geochemical evolution of groundwater facies from the recharge area towards the basin outlet is marked by a gradual increase of sodium, calcium, chloride and sulphate as a consequence of evaporitic rocks leaching, mixing and of evaporation processes. In this multilayered system, the evolution of the environmental tracers is quite continuous, showing a relay between the different aquifer levels from

the recharge areas towards the basin outlet (El Hamma sill).

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