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GROUNDWATER HYDROCHEMISTRY AND MASS TRANSFER IN A STRATIFIED AQUIFER SYSTEM (JEFFARA-GABES BASIN, TUNISIA)

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ABSTRACT

The present work exposes the existence of a real mass transfer in the aquifer system of the Jeffara-Gabès basin. The main aquifers (Complexe Terminal) include Mio-Plio-Quaternary and Senonian sequences associated to stratified lower Cretaceous sandstone of the Continental Intercalary aquifer. Geochemical and isotopic data of groundwater aquifers needed to better understand the relationship between different stratified layers and aquifers. It indicates that Senonian aquifer has been recharged to the West of the area of study by the Continental Intercalary via the El Hamma fault network oriented N-S and NW-SE. The major elements analysis shows that water table of the Complex Terminal with low salinity fit to Ca-Na-SO4 type while waters with high total dissolved salts belong to Na-(Mg)-Ca-SO4-Cl type which characterizes the Continental Intercalary hydrochemical facies. Chemical analyses In addition to geological data and thermodynamic calculation attest the existence of an evident lateral communication between Continental Intercalary aquifer and the Jeffara aquifer system through the El Hamma active faults. Isotopic data show that Complex Terminal groundwater has been affected by a paleorecharge and indicate a mixing of Continental Intercalary and Complex Terminal groundwater. Also, the results show an upward leakage from the Senonian aquifer to the uppermost mio-plio-quaternary reservoir via NE-SW and E-W oriented faults.

keywords: Continental Intercalaire, Complexe Terminal, stable isotopes, geochemistry, mixing groundwater, upward leakage

RESUME

Le bassin de Jeffara-Gabès situé au Sud-Est de la Tunisie comporte un système aquifère complexe : le complexe terminal et le continental intercalaire. Les données géochimiques et isotopiques permettent une meilleure compréhension de la relation entre ces deux aquifères. Ils indiquent que le complexe terminal sénonien est rechargé à l'Ouest par les eaux de continental intercalaire par l'intermédiaire du réseau de failles d'El Hamma orientée N-S et NW-SE. Les analyses chimiques montrent que les eaux de la nappe phréatique du complexe terminal a faible salinité sont de type Ca-Na-SO_4 tandis que les eaux a forte salinité du continental intercalaire présentent un faciès hydrochimique de type (Mg)-Ca-SO_4-Cl. En plus des données géologiques et chimiques les calculs thermodynamique attestent de l'existence d'une communication latérale entre les deux aquifères à travers le réseau actif d'El Hamma. Les données isotopiques montrent que les eaux du complexe terminal a été effectuée par une paléorecharge et indiquent aussi le mélange des eaux de ces aquifères comme elles montrent une communication verticale favorisant un flux ascendant des eaux au sein du système du complexe terminal via des failles de direction NE-SW et E-W.

Mots clés: Continental Intercalaire, Complexe Terminal, isotopes stables, géochimie, mélange des eaux souterraines, flux ascendant.

INTRODUCTION

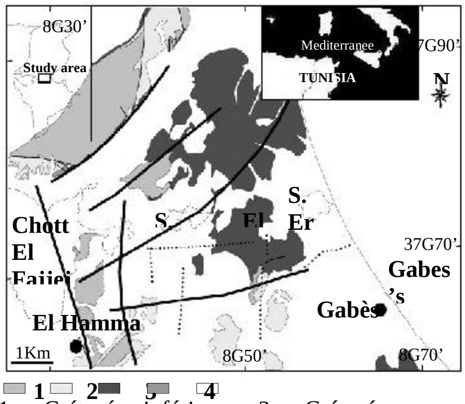
In the central Tunisia, Mesocenozoic sedimentary series host the only groundwater resources of a typically arid, coastal Mediterranean region of the Eastern Chotts. In this area, most of the oasis, agricultural plains, and urban zones as well lie on these sedimentary basins. In addition, land use change and urban extension during the last few decades have deeply altered the hydrological and geochemical regime in the central-east Tunisia. Mechanization of agriculture and land clearing have considerably increased stream flow quantities, and have thus decrease aquifers recharge. Moreover, surface and groundwater pollution by inorganic salts, mostly chlorides and sulphates of Na, Ca and Mg, under arid climate, is the consequence of dryness, salts accumulation in soils after intense evapo-transpiration, mainly in the sebkha area. The solid salts leached down by rainfall or irrigation water, contribute to a continuous deterioration of groundwater quality. Hydrochemical and isotopic methods have been successful in arid and semi arid region as an economical way to determine groundwater type, to identify the source and the flow direction of water table, to research interaction between different water such as deep and shallow groundwater.

The aim of this study is to determine the main geochemical reactions which control the composition of groundwater in the arid region of the Eastern Chotts and Gabès oasis, to identify the natural induced processes which define there hydrochemical evolution measured in the aquifer system, based on geochemical and isotopic mass balance model.

GEOLOGICAL SETTING

The area of study is underlain by Quaternary, Neogene and Cretaceous rock units of the Northern Jeffara basin sequences, among which the Zemlet el Beiha and Northern Chotts chains Senonian lime and dolostones form the prominent landmarks, Jebel Dissa, Jebel Ragouba and Jebel Moncef. Overlying these rocks are Tertiary Neogene sediments, comprising variegated clays, sands and conglomerates, which show lateral variation of thickness. The Quaternary with 10m average thickness occurs either as flat-lying clayey sand plains, saline sebkha soils.

The Mesocenozoic basinfill and framework were studied by predecessors (Aubert, 1891; Domergue, 1952; Burrolet, 1956; Barnaba, 1965; M'Rabet, 1981; Abdeljaoued, 1983; Abbès et al, 1991; Louhaïchi et al, 1993). At the base, sandstones, dolomites, gypsum and claystones of the Lower Cretaceous include either Purbecko-Wealdian (Continental Intercalaire) series of the chotts anticline dome and the Lower Cretaceous Atlassic marine dolostones and marls of the Northern Chotts mountains. Limestones and dolostones form at least 50% of the lithology of the Upper Cretaceous formations. These were subjected to syndepositional tectonics organized into several epochs from the Upper Cretaceous and have formed twisted blocks delimited by regional master faults directed S-N, E-W, NE-SW and NW-SE which largely cut across the basin and form horsts, grabens and half grabens among which the Ouedhref-Metouia horst and the Chenchou graben are the most prominent (Louhaichi, 1993) (fig.1).



1. Crétacé inférieur, 2. Crétacé supérieur, 3. Néogène, 4. Eocène, 5.

Figure 1 : Location of the study

In the basin, the Upper Cretaceous fractured and folded formations have emerged during the Paleogene and were later prograded over by the Beglia and Ségui Formations encompassing the whole Miocene to Quaternary. The Beglia Formation is coarse-grained sands. The Ségui formation includes molasse and lacustrine facies of clayey sandstones and silts which admit thin alternations of conglomerates. The uppermost beds represent either evaporite-bearing sebkha soils, nebkhas or a veneer of fine sand plains sloping majorly to the East.

HYDRGEOLOGYCAL SETTING

The main system aquifers (complexe terminal: CT) include a sand layers aquifer in the Tertiary sequences and a fractured bedrock aquifer which occurs in the underlying dolomites and limestones of the Senonian sequences. The locally highly fractured dolostones Jeffara-Chenchou reservoir reaches maximum thickness to the West (100m) and diminished toward the East and North-East.
The Miocene-Quaternary upper sandy aquifer are lacustrine clays at the base, grading upwards into continental molasse and alluvial fans highly affected by tectonics. Therefore, this gives rise to important variations in thicknesses and facies heteropies, and in the granulometry of the detrital fraction. The laterally continuous lower impervious lacustrine clays bearing hormites, confine the Jeffara-Chenchou aquifer which is forced under artesian conditions.
The conductivity range between 2.23 and 7 ms/cm in the lower carbonates, and between 4.2 and 11.06 ms/cm in the upper sandy aquifer.
The Southern and Western boundaries of these aquifers are made up of Upper Cretaceous dolomites and marls which are thought to form the impervious substratum of the basin (fig. 2). To the West, groundwater in the Continental Intercalaire aquifer system from the Chotts region, discharges toward the Jeffara-Chenchou aquifer throughout the S-N directed el Hamma master fault system (Mekrazi, 1976; Mamou, 1990; Abidi, 2004). In turn, the groundwater in the lower limestones and dolostones Jeffara-Chenchou fractured aquifer in the studied basin, discharges at least locally toward the Neogene-Quaternary detrital aquifer (Gabes Nord) thus forming the main recharge of this system. To the North and Northwest, these aquifer systems are bounded by the Atlasic sequences of Zemlet el Beidha Northern Chotts chain hosting dolomites, limestones, marls, sandstones and gypsum.

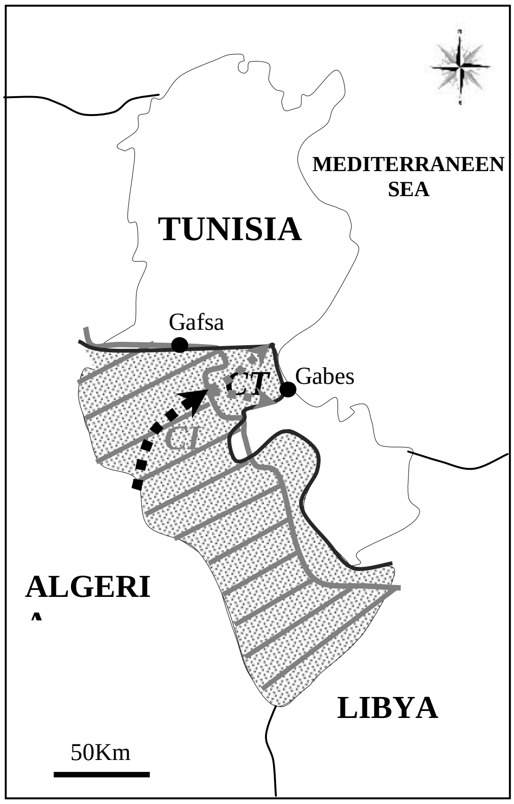


Figure 2 : Extension and groundwater pathway of aquifer system in the south-eastern of Tunisia
- - - - : Direction flow of continental intercalary
- - - - : Direction flow of complex terminal

The system feeding the hot springs at el Hamma consists of a thick carbonate and sandy (Kimmeridgian-Neocomian) aquifer located in the core of the Chott el Fejej anticline. It is confined by the thick gypsum-containing, clayey and impervious Bouhedma Formation (Mamou, 1990; Abidi, 2004; Kamel, 2006). The Eastern periclinal termination of the broad chott el Fejej anticline is deeply cut by master faults directed majorly NW-SE and N-S, among which the el Hamma fault striking to the North, blocks the sandy series of the Continental Intercalaire against the younger Eastern Jeffara basin fill, predominantly limestones and dolostones aquifer sequences.
The flow direction of groundwater is generally to the north-east and the flow system discharges occur mainly in the large el Melah-el Mekhacherma and the Easter Errouhïa sebkha system located near Mediterranean coast, and via wells and boreholes. The depth of the water table in the Quaternary-Neogene sand unconfined aquifers decreases north-eastwards from 35m to the West to 5m

near the Mediterranean coast. The lower Jeffara-Chenchou aquifer is confined, with a water-level virtually above the natural terrain.
The groundwater located beneath the el Hamma city, in the aquifer deeply transacted by the network of master, reactivated and perennial faults, emerges through a line of springs which follows the oued el Hamma, with a salinity of 2500 to 5400 mg/l 1975 (Mekrazi, 1976; Mamou, 1990; Edmunds et al, 2003) and a high temperature gradient (50-70°C). Figure 3 describes in detail the different aquifer dominated springs and observation bores around the Chotts area. It is seemingly that the NW-SE directed el Hamma regional fault acts as a preferential pathway of the Continental Intercalaire groundwater to the surface.
The average transmissivity calculated from pumping tests performed within wells drilled in the Chotts anticline approximates 4.320 m²/d (range: 520-8.640 m²/d) of waters confined under a pressure of 8-10 bar (ERESS, 1969; SASS, 2003). These transmissivities indicate a conductivity of 2-35 m/d for an aquifer average thickness of 250m.

METHODOLOGY AND ANALYSES

Geochemical data for more than 300 samples from wells and boreholes, were donated to us by the DRE (Direction des Ressources en Eaux; Ministry of Agriculture and Gabes's Hydraulic Resources). The data from 30 wells and boreholes which represent the typical hydrological zoning and geochemical types of the aquifers were performed for this study (Fig. 3; Table 1).
In each of all of the wells and boreholes, an acidified (HNO_3, N/10) sample for the cations (Ca^{2+}, Mg^{2+}, K^+ and Na^+), and another unacidified for the anions (F^-, Cl^-, $SO_4^{=}$,…) measurements were collected in 500 ml polyethylene bottles. Temperature, hydrogen potential and electric conductivity in situ of the waters were measured in the field using portable equipments; notably the pH meter was calibrated with common commercial buffer solutions of pH 4.00 and pH 7.00.

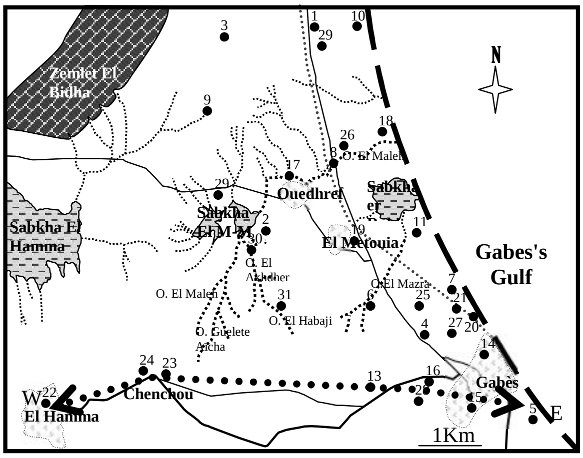


Figure 3 : samples geographical location in the study area

The pH measurements were in three replicates and the pH error on calibration was checked to lie in the commonly accepted range (± 0.5 units).
The analytical determinations by the DRES were carried out in the Direction des Ressources en Eaux Laboratory in Tunisia. In all cases, the bicarbonate HCO_3^- was determined as the total alkalinity by the classic titration with HCl (N/10) in the presence of methyl orange as the indicator of pH 7.00. Analyses of alkalinity and the cations, in particular Ca^{2+} were checked to be performed in the 24h of sampling. The gravimetric barium sulphate method was used to analyse $SO_4^=$; whereas direct potentiometry using coupled specific electrodes measured Cl^- and F^-. Analytical results for each of all the samples considered in this study yielded an ionic balance of less than 5%.
Samples for stable isotope analysis were analysed by gas source mass spectrometry. These analyses have been done for different studies projects which concern the south Tunisian aquifer system (ERESS 1969; RAF/8/007 1985; INT/05/844 1999 and RAF/8/35 2003) (Table 2).

RESULTS AND DISCUTIONS

In the Chotts region, groundwater salinity in the Continental Intercalaire (CI) aquifer is in the range 2500 to 5400mg/l TDS (Mekrazi, 1967; Mamou, 1990), They are neutral to slightly alkaline with pH 7-8.2 and have a high temperature gradient (50°C- 70°C). Most of the CI groundwater are of the SO_4-Cl type, with Na the dominant cation, together with Ca and Mg.
The geochemical data for groundwater used in this study is reported in Table 1.The sampled groundwater from the Jeffara-Chenchou aquifer exhibit broadly similar features to those sampled in the Continental Intercalaire and described by Mamou, 1990. Indeed, groundwater salinity in Jeffara-Chenchou aquifer is in the range 3200 to 5400mg/l with pH values which fall in the range 6.7-8 but show little significant trends with water type or salinity. The less saline waters of this aquifer tend to be dominated by Ca-Na-SO_4; the more saline ones by Na-(Mg)-Ca-SO_4-Cl. There is however a significant variation in water type as it may be noticed from data in Table 1. The temperature measured in-situ in groundwater in the lower Jeffara-Chenchou aquifer diminishes from 63°C in bores in the vicinity of el Hamma master fault, to 30°C in bores of the South-eastern area of the basin between Jebel el Hamma and jebel Dissa. An abrupt diminution in temperature (range: 22-22.5) occurs North to a straight line directed E-W which borders the central Chenchou-el Melah Complex endorheic basin (Fig. 4).

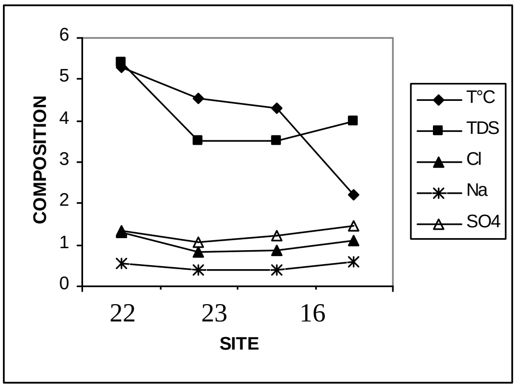


Figure 4 : Concentration evolution of temperature, salinity and major elements in W-E flow direction of groundwater between El Hamma asn the coast

Farther to the East, the Jeffara-Gabès aquifer displays a wide range of hydrochemical types. Outflows of the Oasis Miocene-Quaternary upper aquifer belong to the Ca-Mg-Cl-SO4 type with values of TDS which vary in a wide range: 4200-9000 mg/l.
The prominent outflows of groundwater with a high temperature (range: 54-56°C) in the lower Continental Intercalaire are those hot spots of the Western el Hamma. These waters belong to the Ca-Mg-Cl-SO_4 type with total dissolved salts which approximate 4500 mg/l. This hydrochemical facies is characteristic of ground water flow in a deep confined Pubercko-Wealdian, clay- and gypsum-bearing formations (Mamou, 1990; Edmunds, 2003).
The relationship between salinity and conductivity (Fig. 5), which is a measure of the total mineralisation, is linear for the three aquifers of the mio-pliocene, phreatique aquifer and the tow deep ones Gabès Nord and continental intercalaire. This correlation shows that shallow and deep aquifers have the same chemical source and evolution (Kamel, 2007).

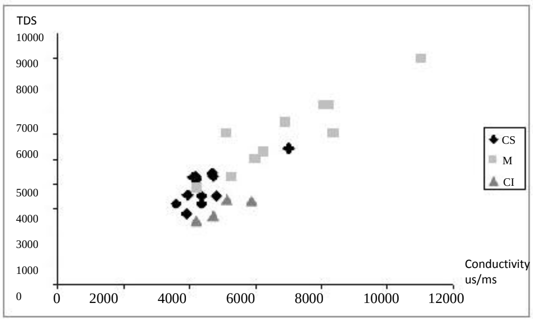


Fig. 5: Relationship between salinity and conductivity in groundwater of aquifer system

Figure 5 : relationship between salinity and conductivity in groundwater of aquifer

Major elements evolution

Chlorides and sulfates increase proportionately in groundwater thus suggesting that they are relatively conservative species which indicate dissolution of gypsum/halite paleoevaporites, and possibly evapotranspiration and concentration of surface recharge waters (fig. 6a).
Sodium, chloride and sulphate all exhibit higher concentrations in bores located to the East and may result from a slow groundwater flow and its progressive hydrochemical maturity (Fig. 4).
Representing concentration value for several major elements, temperature and salinity in different pathway between El Hamma and the Mediterranean coast show a mixing of diverse types of groundwater. In fact, temperature decreases from El Hamma city to the coast, which means firstly combination between CI groundwater and Jeffara-Chenchou groundwater beneath El Hamma fault, secondly temperature decreases in flow direction. Salinity is higher in the west and the East of the Jeffara aquifer which means before mixing and after impact of mixing. Calcium, sodium, sulphate and chloride have the same comportment as salinity.
Groundwater are nearly saturated or even supersaturated with respect to aragonite, calcite and dolomite (Fig. 7 a, b, c and d). There is also a neat to increase in calcite saturation with increasing chloride concentration. In contrast, calcium, magnesium and alkalinity HCO_3^- show no significant variations vs salinity (Fig. 6 a, b, c and d) thus suggesting that aragonite, calcite and dolomite saturation and precipitation are the limiting factors for the accumulation of these components in groundwater.

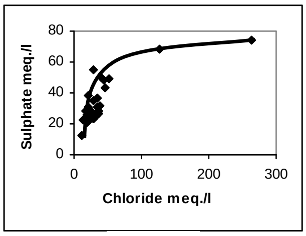


Fig. 6a

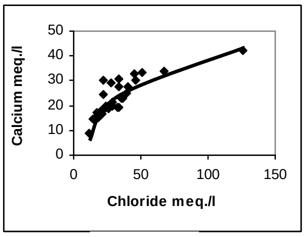


Fig. 6b

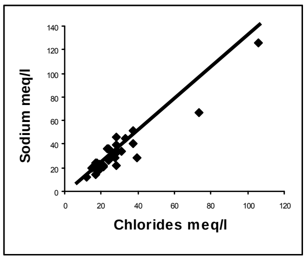


Fig.6c

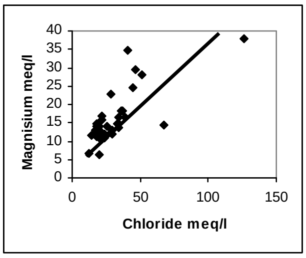


Fig. 6d

Figure 6 (a, b, c and d) : Relationship of SO_4, Mg, Ca, Na and Cl for groundwater collected from the CT aquifer

Gypsum remains generally undersaturated, but approaches saturation with SI> -0.5 in proportionality with Cl^- salinities, thus indicating $SO_4^=$ accumulation in the groundwaters (Fig. 7 d).

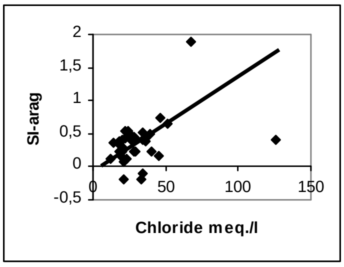


Fig. 7a

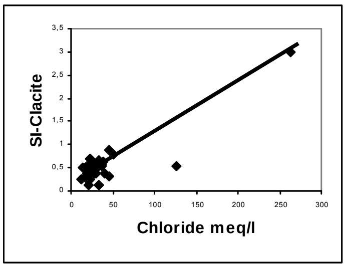


Fig. 7b

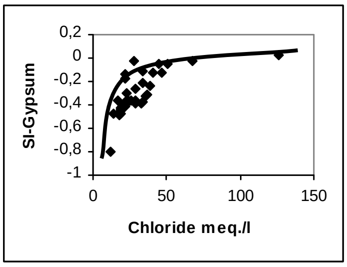


Fig. 7d

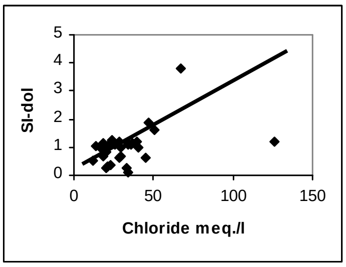


Fig. 7c

Figure 7 : Evolution of CI calcite, SI argonite, SI dolomite and SI gypsum in groundwater of the aquifer system

Stable isotopes

During the past three decades, a great variety of isotopic methods has been developed and tested with the aim of defining the different aspects of water of the water cycle, providing fundamentals information on the recharge and groundwater flow condition. In general, stables isotopes for the water molecule are related to isotopic composition of precipitation from which they derive (Oueld Baba Sy, 2005). Most precipitation throughout the world originates from the evaporation of sea water (Moulla, 2005). In fact, stables isotopes ratios ($\delta^{18}O$, $\delta^{2}H$, $\delta^{3}H$ and $\delta^{14}C$) provide information on rain fall source, mode and condition of recharge of groundwater and help to indicate there resident time and their origins (Barbecot, 1999; Maliki, 2000).
Isotopic composition of CT aquifers had not changed for the last four decades (Fig.8a and b) (Abidi, 2004). This stationary state of the deep and the shallow aquifer has been caused by the long time of residence of groundwater and the slow infiltration process (Abidi, 2004).

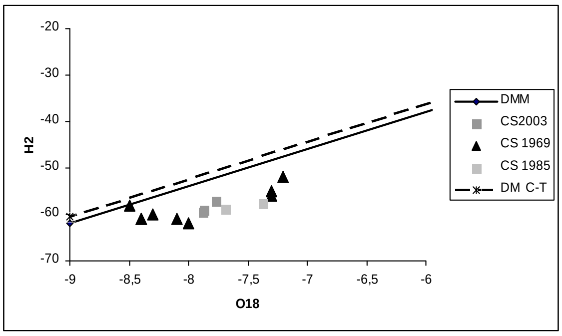


Fig. 8a : Isotopic composition of Jeffara groundwater between 1969 and 2003

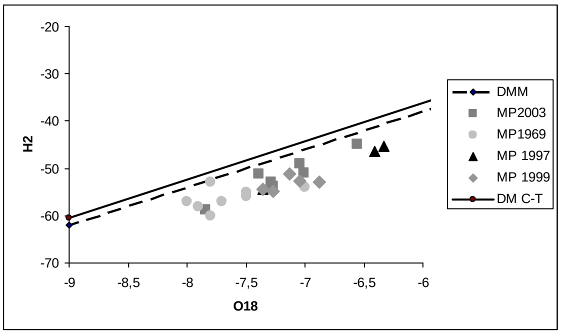


Fig.8b: Isotopic composition of Neogen-Quaternaire shallow aquifer between 1969 and 2003

Stables isotopes results of the CI and CT including the dolostone aquifer and the sands one are shown in Fig. 9. Groundwaters plotted together with the Global Meteoric World Line GMWL (Craig, 1961) and the Regional Meteoric World Line (Maliki, 2000). Comparison between each other and in relation with the weighted mean value for modern rain fall in the Sfax region (δ^{18}O-4.6‰, δ^{2}H-23.3‰) (Maliki, 2000; Celle-Jeanton et al, 2001; Edmunds, 2003) shows several observation (Fig. 9). In fact, i) all samples lie as a group below the GMWL showing a mixing for all the three groundwaters in question, this mixing is so clear in Chenchou where we see a superposition of groundwater; ii) impoverishment of CI groundwater compared with actual rain fall, indicate that these waters presumably don't have same origin and CI water had been recharged during a cool regime in the past; iii) samples follow the groundwater fossil line ($\delta^{2}H= 8\ \delta^{18}O + 5$) thus, suggest that these groundwater has been affected by a paleorecharge (Moulla, 2005) and this one has done in a lower temperature, a higher humidity condition then current climatic condition. Groundwater fall into line of GMWL and parallel to it, little or no primary evaporation has been occurred during infiltration process.

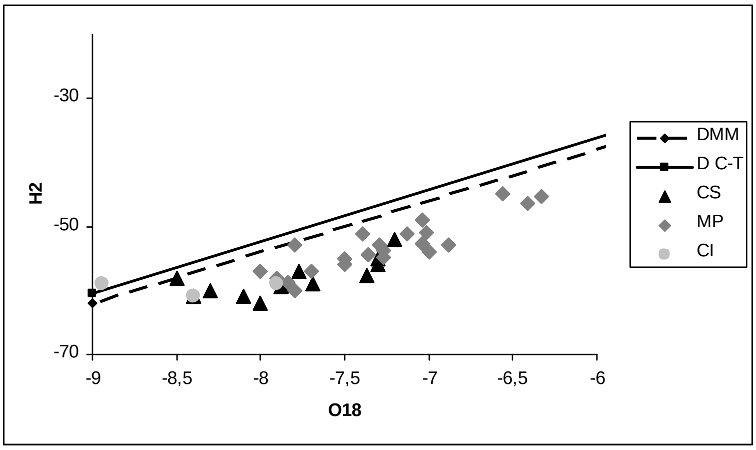


Figure 9 : Comparison between isotopic compositions of different aquifers in Jeffara system

CONCLUSION

Geochemical and isotropic results are used in this paper to give prominence to global and local follow conclusions:

*the CI aquifer from the Chotts region discharges toward the Jeffara system throughout the S-N directed El Hamma master fault system.

*an upward leakage take place to the overlying shallow CT aquifer, this was display by temperature value particularly in Chenchou region (Fig.10).

*stable isotope study indicates that the CT modern water may be recognised up from the main recharge area of the CI aquifer.

The CT aquifer has the risk of highly saline near surface water from the sebkha of El Melah-Mkhacherma which being drawn down and contribute to increase salinity of groundwater besides irrigation water with high salinity will be leached down to the shallow Neogen aquifer.

The groundwater in the CT formation does, however, provide a large reserve of relatively which need to be carefully managed and enhanced in the future by desalination to provide high quality supplies of water.

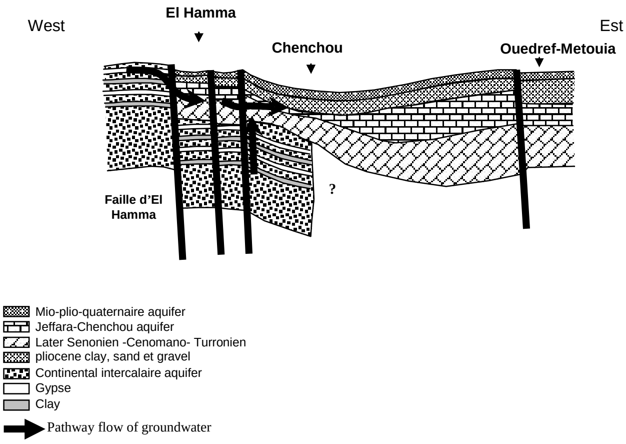


Figure 10 : Synthetic coupe of Jeffara-Gabes North aquifer system and its pathway flow

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