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Exploitation of a Hydrogeothermal Aquifer by Means of Surface and Subsurface Data, Ksour Essaf basin (Eastern Tunisia)

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ABSTRACT

A multi-disciplinary study was carried out with the aim of assessing thermal potential in water of the Ksour Essaf basin (eastern Tunisia). We analysed the geothermal reservoir and determined the different chemical facies of thermal waters and to understand their origin. The integrated review of all the existing and newly acquired data confirms that the thermal water of the Hammam Ksour Essaf is of meteoric origin. It is deeply infiltrated within the Upper Miocene sands and sandstones (Searravallian-Tortonian) and reaches high temperatures (75°C - 106°C), before emerging as a thermal spring in correspondence with a fracture system related to the Ksour Essaf fault. The high geothermal gradient observed in this region and the presence of Triassic "Dome" showed in the seismic cross-sections confirms the existence of an important exploitable geothermal reservoir.

1. INTRODUCTION

Thermal waters can represent an important resource in the economic development of all countries. The study of hydrothermal systems can have several economic consequences for example crenotherapy.

The resource valuation in thermal waters of a region requires in most cases a good knowledge of the distribution of the temperature, the water chemical characteristics, and the hydrodynamics of the reservoirs and of their petrophysical characteristics.

The geological, geochemical, geophysical and hydrogeological studies re tools which allow identification of potential reservoirs. This allows for better comprehension of the dynamics within the basin as well as possible interactions between the various factors present. In fact, the underground water, by its circulation through the rock and its physicochemical properties plays a role in the temperature and the dissolution of element.

The thermal drilling of Hammam Ksour Essaf (Fig. 1) is located in the centre of the city of Ksour Essaf. This region is characterized by a complex geology which has the potential to be a good natural resource. The important reservoirs of water revealed by oil wells and hydrogeology indicative of a place in this basin to target for thermal waters.

The emergence zone is situated in the intersection of the fault of Ksour Essaf and the secondary faults. Water appears in a temperature in the order of 40°C and salinity 10 g/l. The chemical quality of the thermal waters of this drilling proves to be interesting for its use in the thermal remedies.

The drilling of Hammam Ksour Essaf is still exploited as "popular bath". Regarding to improve its exploitation in thermal station this work offers to evaluate the potential in thermal waters through a hydrogeothermal study with the objective to determine the water origin, its underground journey and its resurgence method to lead to the model of hydrodynamic functioning of the aquifer system of Ksour Essaf.

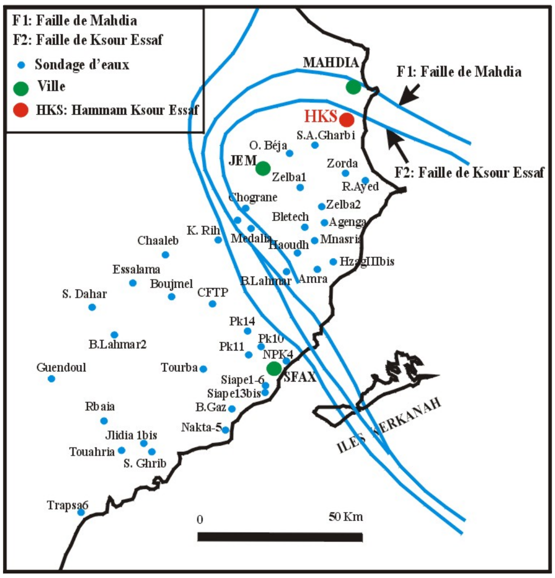

Figure 1: The study zone with location of borehole Hammam Ksour Essaf.

2. OUTLINE GEOLOGICAL AND STRUCTURAL

The region of Ksour Essaf is characterized by the presence of two monocline structures overhanging the plains of the Sahel de Mahdia. They delimit the Sebkha de Moknine in the north and the plain of Mahdia to the south. The monocline of Ksour Essaf constitutes a plateau presenting a weak pendage towards it where series of the upper Miocene (Messinian) and Pliocene are covered by a thick crust of Quaternary limestone.

The region of Ksour Essaf corresponds to plain covered by recent alluvium. Along the coastal zone flushes deposits of (upper Pleistocene) Tyrrhenian deposits composed of:

- The cord of quartz sands of paleothyrrenian age allocated in training Douira
- The cord of sands oolitic of the formation Rejiche of age Tyrrhenian;

- The conglomerates in Strombus bubonius of the formation Cheba of age Tyrrhenian.

The reliefs of Ksour Essaf show at the bottom of the clay-sandy alternations of age tortonian overcome by limestones oolites and bioclastires of messinian age above Pliocene. The Pleistocene, resting on Pliocene, is composed by white and red sands overcome by a massive crust that go with the morphology of the relief.

The zone of Salakta presents a relief of direction NW-SE which introduces the same stratigraphy units like Ksour Essaf. Alongside the quotation line are situated the cords Rejiche, Douira and conglomerates of Cheba.

The structuring of the zone of Mahdia-Ksour Essaf corresponds to a succession of horst and graben. This structure is made up of a paleo-high bottom of the Cretaceous in Eocene, overcome with its top by a pleated graben miocene Bedir (1995). This domain is bordered by two deep faults of direction E-W affecting quaternary formations.

Deep structures of the region are analysed by Bedir (1995) from interpretation of the seismic data which show that the north and south borders of this structure constitute the limits of the basins of Moknine to the north and the one of Jebeniana to the south. In these borders, we can distinctly observe the angular conflicts of series Paleogene, truncated to their roof by series of the upper Oligocene. The upper intra-cretaceous conflicts are well marked by the variations of thicknesses in both compartments of faults showing the importance of these conflicts since Aptien. The domain of Mahdia-Ksour Essaf introduces a rather dense fracturation.

The north fault F1 (fault of Mahdia) is synthetic accident synsedimentary in Miocene. It introduces a big vertical rejection responsible for 2700 m of miocene deposits. The south fault F 2 (fault of Ksour Essaf) is accompanied by an important network of antithetical faults of parallel and oblique directions. This accident, of direction E-W, shows a vertical rejection not exceeding 500 m at the level of miocenes series. It shows synsedimentary activity marked well in cenomano-maastrichtiennes series and seals by horizons oligo-miocenes that cuts later. On the other hand, structures of tectonic lenses of hundreds metre high, follow south accident.

3. HYDROGEOLOGICAL FRAME

The borehole of Ksour Essaf in the south of the fault F2 picks up the deep aquifer of Sfax living in the sandy levels of Miocene (Serravalian-Tortonian). In the basin of the Sahel de Sfax, this sandy sequence cover a medium thickness of 200 m with a thickening along the costal that attains thickness 300 m, which then thins to 200 m off islands Kerkennah. At the level of the borehole of Ksour Essaf, the thickness of these levels is 180 m.

The mapping in subsurface seismic sequence bottom serravalian (Fig. 2a) and bottom tortonian (Fig. 2b), defined by Amri (2000) and which correspond to the reservoir of the deep aquifer of Sfax, show the role marking faults of Mahdia and Ksour Essaf in the configuration geometric of the reservoir. The maximum of thickness of series is in the zone of the graben between both faults. Next to the borehole of Ksour Essaf, the thickness of levels of structure is reduced.

It is necessary to note that for Zébidi (1989), the localization of the borehole of Ksour Essaf coincides emotionally with the north border of the aquifer. In effect, this border should be brought forward lightly in the north of site of the fault of Ksour Essaf which seems to play the same role as the fault F1 of Mahdia for the aquifer of Zeramdine Béni Hassen.

The deep aquifer of Sfax is picked up at a depth between 200 m and 600 m. Waters from the aquifer are exploited via an artesian borehole, that has been used in the South of the city of Sfax for a long time. However, a new use may be in order and a new exploitation borehole or hydrogeological recognition in the Sahel of Sfax plain. Numerous boreholes, in the order of 40, allow specifying the sprawl and the main hydrodynamic characteristics of the aquifer.

The aquifer waters converge on the Mediterranean Sea. Piezometer levels vary from 17 to 35 m.

In the centre and north of the plain, flow makes Miocene outcrops of the structures of Kordj-BouThadia-Chorbane, towards with a medium hydraulic gradient in the order of 0.2 %. These anticline structures border the Sfax plain and separate it from that of Kairouan.

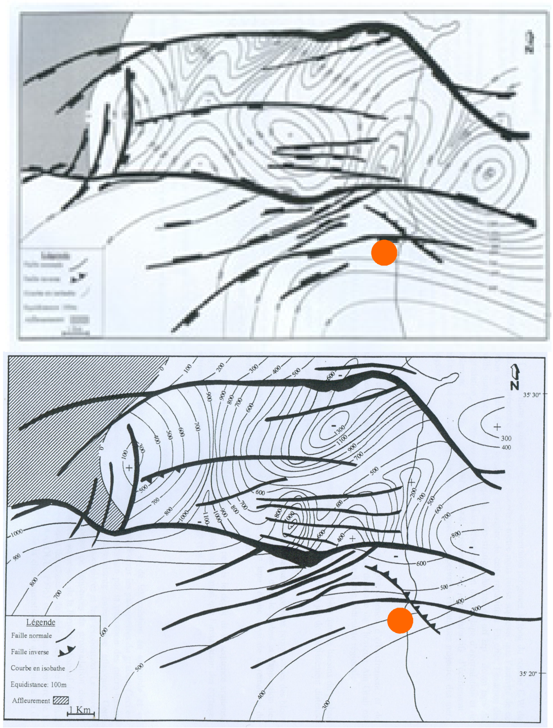

Figure 2: Isobath map of the bottom of sequence Serravallian (a) and Torotonian (b) with location of borehole Hammam Ksour Essaf.

4. HYDROCHEMICAL CHARACTERIZATION

Thermal waters often constitute a memory which brings in surface of chemical indications on the subsurface. Their geochemical study represents a complete tool of recognition which allows to determine better their origin, borrowed underground circuit and possible superficial cold waters.

Figure 3 also shows borehole taken a sample in order to following the variations of the physicochemical characteristics of the main aquifers of the hydrogeological system of the area of study.

The Table 1 shows chemical and physical characteristics useful to specify the origin of the mineralization of waters and the nature of levels reservoirs.

Table 1: Physicochemical data of deep waters of the basin of Ksour Essaf – Sfax.

			Physical parameters			Majeurs element (mg/l)						
N°	Drilling	Niveau D	T (°C)	pH	RS (g/l)	Ca	Mg	Na	K	Cl	SO4	HCO3
1	Agenga	226-274	28,3	7,26	3,66	204	93,3	891	21	1290	885	181,9
2	Akerma	262-325	32	7,38		141	97,3	920	8,5	1430	479	170,7
3	Amra	297-430	27,7	7,67	3,84	173	92	849	18,6	1420	719	191,4
4	Bir Lahmar	430-535	27,8	7,42	3,15	169	84,4	664	16	1140	675	184,1
5	Bir Lahmar 2	360-430	23,2	7,34	3,1	185	99	769	18	1140	755	193,9
6	Bletech	360-430	32	6,79	3,37	133	73,7	852	45,5	1170	782	69,5
7	Boujmel	305-397	29,3	7,16	3,86	144	84,8	613	16	914	593	183
8	Britich gaz	530-612	27,1	7,25	3,51	219	112	796	17,9	1150	952	147,5
9	CFTP	452-536	28,2	7,29	2,8	212	81,7	653	18,3	910	596	220,7
10	Chaaleb	275-323	28,5	7,28	3,1	197	95,4	696	19,7	1120	621	262,3
11	Chograne	553-645	27,9	7,44	3,36	195	94,1	789	20,6	1250	727	204,8
12	Essalama	551-606	35	8,59	2	101	154	627	23,5	880	224	47,6
13	Guendoul	521-589	32,5	8	10,9	654	257	2310	88	4000	2180	36,6
14	Haoudh	410-479	26,5	7,52	3,54	226	97,9	848	18,4	1190	953	162,2
15	HKE		39,5	7,52	10,13	300	150	2370	28,75	3728	2396	231,8
16	Hzag III bis	251-356	33,1	7,29	3,92	205	84,3	824	18,4	1330	813	172
17	Jlidia 1bis	414-550	27,5	7,25	4,26	283	139	889	22,6	1490	1050	147,5
18	Ksar Rih	437-522	28,1	7,64	3,1	165	77,5	655	16,9	1110	584	201,2
19	Meddalia	630-704	28,1	7,45	3,61	210	105	793	21,4	1330	718	208,5
20	Melita	588-643	27,6	7,4	3,34	153	80,5	821	15,6	1220	717	171,9
21	Mnasria	287-363	24,9	7,92	2,97	216	103	952	20,5	1480	781	165
22	Nakta-5	290-346	36,1	7,16	3,81	235	119	859	17,8	1250	1000	179,2
23	NPK-4	510-588	26,8	7,38	3,81	197	91,6	894	19	1280	913	214,3
24	PK-10	511-590	27,8	7,25	3,17	175	82,3	739	16,9	1040	786	204,8
25	PK-11	393-471	27,7	7,5	3,04	173	89,2	738	16,7	1100	696	159,7
26	PK-14	440-513	27,7	7,2	3,08	175	87,8	748	17,7	1040	724	203,6
27	Ramla 3	395-477	27,9	7,42	3,6	167	87,6	930	15,3	1350	780	164,7
28	Rebaia	290-382	26	9,64	4,28	176	78	1180	254	1640	854	54,9
29	Remla-1	265-343	26,7	7,31	3,6	160	82,5	828	16,4	1200	757	159,2
30	Remla-2	283-361	26,9	7,41	3,6	175	92,2	963	16,8	1410	824	152,4
31	Siape 13 bis	290-354	27,7	7,18	3,61	204	95,4	827	18,6	1180	903	156,1
32	Siape II-1	476-554	28,3	7,3	9,85	730	331	1990	40,9	3440	2270	149,9
33	Siape II-3	198-240	28,1	7,4	9,4	691	281	1890	41,6	3240	2040	156,1
34	Siape II-6	214-255	25,2	7,16		812	341	1990	36,8	3530	2510	155
35	Siape II-6	220-262	28,5	7,21	10,5	822	358	2060	42,8	3540	2550	151,2
36	Sidi Daher	432-530	26,9	7,67	2,63	119	64,6	679	11	970	533	191,6
37	Sidi Ghrib	475-456	32,5	9,36	4,26	232	121	909	23,5	1380	954	126,8
38	Touahria	401-480	32,4	8,3	4,62	230	115	1060	29	1620	927	120,4
39	Tourba-1	238-297	28,8	7,27	3,58	161	83,2	616	15,1	940	706	163,4
40	Trapsa-6	193-240	24,3	7,15	9,9	710	304	1870	33,2	3280	2270	143,8

Table 2: The Temporal Evolution of the physicochemical characteristics of thermal waters of Hammam Ksour Essaf.

Prelevement	RS (g/L)	PH	Ca	Mg	Na	K	Cl	SO_4	HCO_3	Halite	Anhydrite
juil-57	9.28	7.3	312	165.6	2622	23.4	3150	2976	193	2.5	30.98
juin-63	9.39	7.1	340	134	2820	33	3372	2544	152.4	2.68	26.48
vrl-94	9.37	7	308	170	2810	30	3372	2460	219.6	2.68	25.61
janv-07	10.13	7	300	150	2370	28.7	3727	2396	231.8	2.65	26.30

The picture 2 introduces the temporal evolution of the physicochemical characteristics of thermal waters of Hammam Ksour Essaf. Hydrochemical approach revealed that waters of the basin sense variable saltiness and are characterized on the whole by a dominance of sulphates of sodium and calcium.

To determine the chemical facies of analysed waters, we put the results of analyses in the diagram of Piper. Figure 3 show that all samples have a big chemical homogeneity. Waters are of chlorinated type sodium.

In effect, thermal waters of Hammam Ksour Essaf (T = 39.5°C) and those of borehole Nakta-5 (T = 36.1°C) have very close temperatures show the same chemical facies and could be attached to the same reservoir. To confirm this hypothesis and prove the chemical consanguinity of analysed waters, we used the diagram of Schoeller-Berkaloff (Fig. 4). Such acquired chemical contours confirm the presence of the single chemical family characterizing the lithological level of the aquifer.

The perfect similarity of the chemical characteristics of thermal waters of Hammam ksour Essaf and those of borehole Nakta-5 confirm more the hypothesis of the same reservoir of origin.

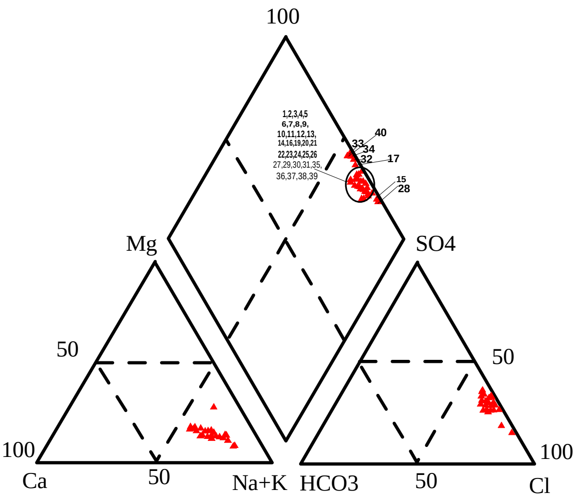

Figure 3: Piper diagram (1944) applied to waters of the basin of Ksour Essaf-Sfax.

It is necessary to signal that the physiochemical characteristics of the water of Hammam Ksour Essaf remained comparatively stable over the course of time (Table 2). This can be explained by the passage of thermal waters across a regulating deep circuit. The strong content of chlorides and sodium recorded especially at the level of thermal waters of Hammam Ksour Essaf and in borehole Nakta-5, can be explained by the passage of thermal waters in the contact of the salinity fields, in the west mass grave zone of graben of Mahdia, or by basic exchange with loam, drawn away by depths, by the tectonic affecting all region of Ksour Essaf.

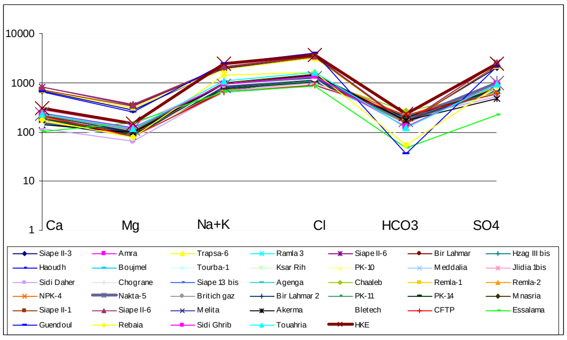

Figure 4: Geochemical contours of analyzed waters.

The natural lithology of the reservoir containing thermal waters was determined by the method developed by Amore and al (1983). This method applied to waters of Hammam Ksour Essaf and borehole Nekta-5 (Fig. 5) shows a rectangular configuration which is typical of a deep circulation. Structural context showed the important role played by deep accidents. Seismic contours revealed the existence of Trias punctuated by these accidents. This leads us to allocate the strong salinity of the water of the borehole of Ksour Essaf in a provision of deep salt water.

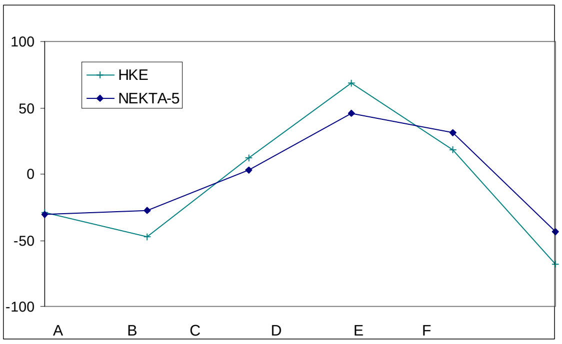

Figure 5: Application of method IIRG (Amore et al, 1983) in thermal waters of Hammam Ksour Essaf and borehole Nakta-5.

$$A = 100[(HCO_3 - SO_4)/\Sigma(-)]$$

$$B = 100[(SO_4 / \Sigma(-)) - (Na/ \Sigma(+))]$$

$$C = 100[(Na/ \Sigma(+)) - (Cl/ \Sigma(-))]$$

$$D = 100[(Na - Mg)/\Sigma(+)]$$

$$E = 100[((Ca + Mg)/\Sigma(+)) - (HCO_3/ \Sigma(-))]$$

$$F = 100[(Ca - Na - K)/ \Sigma(+)]$$

$\Sigma(-)$ = sum of cations

$\Sigma(-)$ = sum of anions

Put in the diagram of Durov, the almost points representative of different analysed waters is in the rack n°9 (Fig. 6). The strong mineralization of waters is principally linked to the dissolution of the halite.

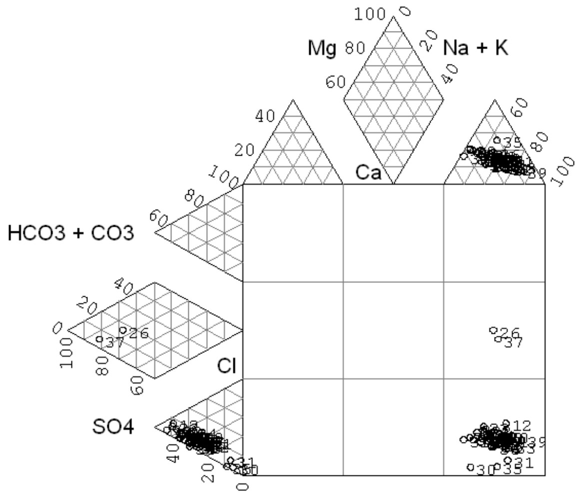

Figure 6: Durov diagram of waters of south Sfax.

5. GEOTHERMOMETRY

Geothermometry allows the temperatures of the last chemical or isotopic equilibrium to be estimated from the composition of the measured one. This chemical technology gives supplementary information to geological and geophysical information. Deep waters arrive at the surface and bring their deep history in general with them. Nevertheless, during its ascent, hot water can be subjected to a mixture with superficial cold water that can complicate the use of the chemical geothermometry, they will be dealing either with an ovestimation or an underestimation of temperatures. The rise of thermal waters since their reservoirs of origin, is accompanied in general by a reduction of the temperature and a change of complete mineralization (Bouri and al., 1998). However, the concentration of certain constituents of geothermal fluid varies according to the temperature, so reports between these elements can play the role of quantitative geothermometres application of which must satisfy particular conditions (Founier, on 1973; Arnorsson and al ., on 1983; Giggenbach, on 1991).

This geothermometer assumes that there is not significant chemical change some water in the course of the rise, in spite of different often remarkable and possible coolings. Because of this the geothermometer approach is principally going to interest the boring of Hammam Ksour Essaf and seen boring Nakta-5 that their hot waters could be attached to the same hydrothermal system.

The application of the chemical geothermometry in thermal waters of Hammam Ksour Essaf and borehole Nakta-5 showed that the geothermometry of Na-K is the best adapting in these waters in comparison with other geothermometry. Temperatures estimated by some waters at origin is about 48 and 106°C for Hammam Ksour Essaf is 53 and 117°C for borehole Nakta-5 (Table 3). For Hammam Ksour Essaf the most appropriate geothermometers are those of Nieva and Nieva, 87 giving a temperature estimated of 75°C while for the borehole of most appropriate Nekta-5 is that of Arnorsson, 83 with a temperature of 75°C.

Put in the triangular diagram Na-K-Mg1 / 2 (Giggenbach, on 1988), thermal waters of Hammam Ksour Essaf and borehole Nakta-5, (Fig. 7) show a tendency towards equilibrium thermodynamics. By the curve of tendency they note a temperature estimated by about of 75°C. It coincides well with estimate by the geothermometrie.

Nevertheless, it is necessary to signal that waters of the source of Hammam Ksour Essaf prove to be less influenced by superficial waters than those of borehole. The representative points of thermal waters of these two water points are located in the domain of mature waters (Fig. 8), this testifies a rate of comparatively weak mixture to impose its chemical on thermal resolution.

Table 3: Application of the different geothermometres in Hammam Ksour Essaf and Borehole Nakta-5 thermal waters

Name	Truesdell, 76 Na-K	Tonami, 80 Na-K	Arnorsson, 83 Na-K	Arnorsson, 83 Na-K	Fournier, 83 Na-K	Nieva & 87 Na-K	Giggenbach, 88 Na-K	Giggenbach, 88 k-Mg
H. k E	36	36	48	92	85	75	106	61
Nakta-5	64	65	75	117	111	100	53	63

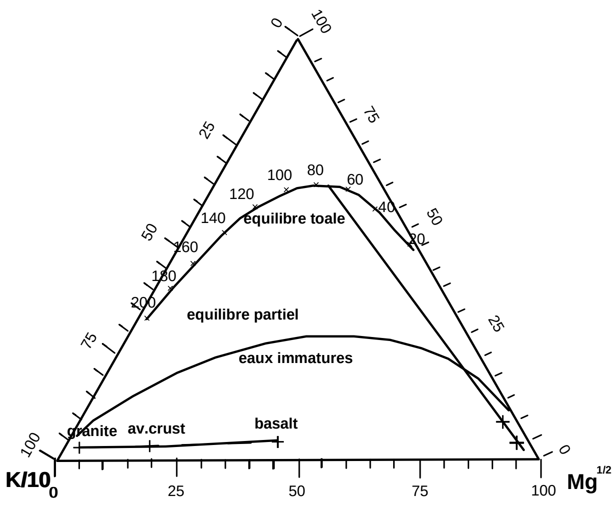

Figure 7: Triangular Diagram Na-K-Mg1/2 (Giggenbach, 1988), applied to thermal waters of the source of Ksour Essaf and borehole Nakta-5.

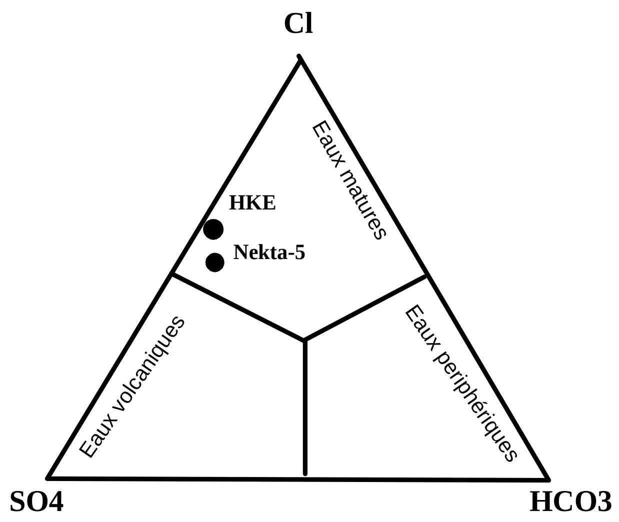

Figure 8: Triangular Diagram Cl-SO4-HCO3 (Giggenbach, 1988), applied to thermal waters of the source of Ksour Essaf and borehole Nakta-5.

Moreover hydrogeothermal studies, led in Tunisia oriental (Chulli, 2000 and 2002), (Fig. 11) reveals a certain correlation between geothermal data and structural data. In effect, the map of the geothermal gradient of oriental Tunisia shows one in the region of Ksour Essaf general tendencies of curves iso-gradients are parallel in major accidents Mahdia-Ksour Essaf, affecting the region.

The positive geothermal anomaly characterizing the study area (Fig. 9) is linked to major tectonic events who favours the heat transfer.

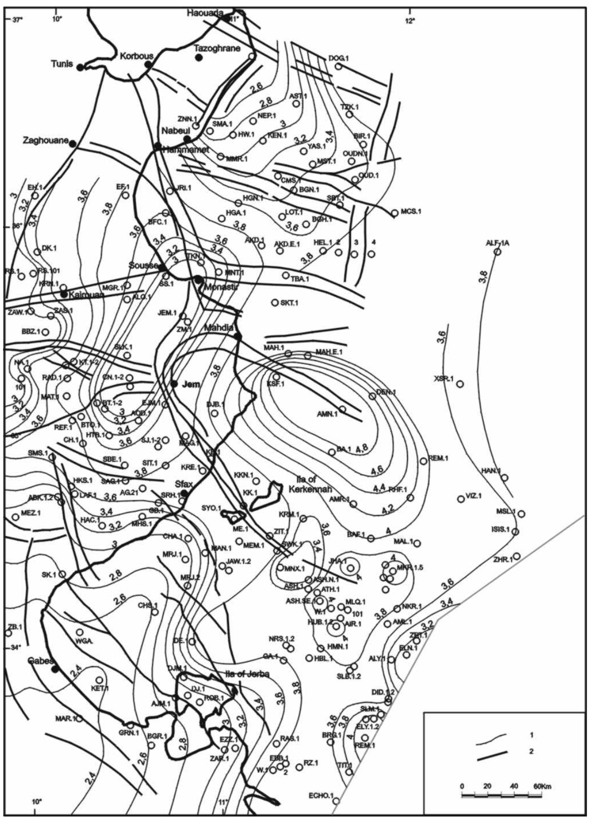

Figure 9: Geothermal gradient map of oriental Tunisia (Chulli, on 2000). 1, isogradient curve. 2, Fault.

We can consider that the underground temperature variation is closely linked, in the variation of geothermal gradient which is principally controlled by deep events, orientated E-W and NW-SE (fault of Mahdia and fault of Ksour Essaf). So, the use of geothermal gradient of the region (3.5°C / 100 m) and temperatures estimated by the geothermometer allowed us to deduce the depth of the reservoir of origin.

The geothermometer approach allowed us to estimate the temperature at the origin of waters of the Hammam Ksour Essaf which is in the order of 75°C. From this temperature we can determine the depth of the reservoir of origin by applying following equation:

$$P\ (km) = Tcal - Ta / G \qquad (1)$$

where *Tcal*, *Ta*, *G* are temperature estimated by the appropriate geothermometer (75°C), the annual median temperature of the surface of the region (20°C), median geothermal gradient of the region (3,5°C / 100 m) respectively.

The application of this equation has allowed us to deduce the depth of reservoir of origin for Hammam Ksour Essaf to be 1570 m.

6. SYNTHESIS AND CONCLUSION

The integrated treatment of surface and of subsurface data allowed us to better understand the structural outline of the basin of Ksour Essaf. This region is characterized by several thermal indices placing this basin as a promising target in thermal water.

The potential of this system was identified as a result of geological, geophysical and hydrogeological studies. In fact, the geology of surface and the geophysics allowed us to identify physical limits and the basin extension that generally corresponds to the corridor of fault Kssou Essaf above which exists the drilling of Hammam Kssour Essaf that is lodged in the sandy series of the upper Miocène (Serravalien - Tortonien).

The outcrops of the upper Miocene, to this place, constitute recharge zone. Thus, one can suppose that the flow is usually in the North West to the South East direction.

The study of the isotopic geochemistry conducted by Maliky (2000) showed the recent weak recharge of waters of the upper Miocene, integrated treatment of all newly acquired or existing data confirm the thermal water of Hammam Ksour Essaf is of meteoric origin. water seeps in through the aquifer to the north at the level of the Jebel Meloussi. These waters are introduced at depth, where they reheat according to the geothermal gradient of the region, then go back up along the deep faults, that constitute the preferential way of resurgence for thermal waters of Hammam Ksour Essaf.

The hydrochemical approach applied to waters of the basin of Ksour Essaf-Sfax revealed that the mineralization of these waters is acquired in most cases by the dissolution of the halite as well as by basic exchange with clays seen the dominance of sulphates, chlorides, sodium and calcium. It shows that these waters come from reservoirs of origins homogeneous different where dominate the facies of chlorinated type sodium (for waters of Cretaceous lower) and sulphate - calcium (for waters of Cenomano-Turonien).

We note a perfect similarity between the chemical characteristics of waters of Hamam Ksour Essaf and the one of drilling Nakta-5.

The monitoring of its physicochemical composition reveals a certain consistency during the time indicating thus the circulation of thermal water through a regulating deep circuit.

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