Proceedings World Geothermal Congress 2005
Antalya, Turkey, 24-29 April 2005

Hydrostratigraphical Study, Geochemistry of Thermal Springs, Shallow and Deep Geothermal Exploration in Morocco: Hydrogeothermal Potentialities

Yassine Zarhloule[1], Salem Bouri[2], Abderahim Lahrach[3] , Mimoun Boughriba[1] ,Abdenbi El Mandour[1] and Hamed Ben Dhia[2].

1: Faculty of Sciences, Department of Geology, Laboratory of hydrogeology & environement, Oujda, Morocco.

2: ENISfax, Department of Geology, Laboratory of water, energy & environment, Sfax, Tunisia.

3: Faculty of Sciences, Department of Geology, Fès, Morocco.

yassine@sciences.univ-oujda.ac.ma, Zarhloule@yahoo.fr

Keywords: aquifers, thermal springs, geochemistry, temperatures, oil wells, shallow wells, hydrodynamism, geothermal gradient, thermal anomalies, conceptual model, Morocco.

ABSTRACT

The aim of this paper is to obtain a first reliable evaluation of the geothermal potential of the country. It's caracterised by more than 70 hot springs, several deep hot aquifers, more than 1000 petroleum exploration wells and various existing geological, geophysical and hydrogeological data. So, its was possible to distinguish the mains geothermal features if the country, by evaluating both the underground temperature and the potential reservoirs.

The hydrostratigraphical study of each basin revealed several potentiel reservoir layers in which the carbonate aquifer of Turonian (Tadla basin and Agadir basin) and Liasic (North-western basin of Morocco and North-Eastern basin) are the most important hot water reservoirs in Morocco. this study made it possible to identify the main aquifers, their temperatures, depth and extension.

A shallow geothermal prospecting has been performed in four zones in Morocco for wich few deep thermal data are available (North-western basin of Morocco, North-Eastern basin of Morocco, Tadla basin and Agadir basin). These areas are different geologically and hydrogeologically. The shallow temperature measurements program has been launched to estimate the natural geothermal gradient in these areas, to determine the principal thermal anomalies, to identify the main thermal indices, and to characterize the recharge, discharge and potential mixing limits of the aquifers.The main thermals clues and the principal thermal anomalies that coincide with zone of artesianism of Turonian and Liasic aquifers have been identified, as well as the potential mixing limit of the aquifers systems. Also,for each basin a conceptual model is presented to interpret the relation between temperature, hydrodynamism and topography within the sedimentary basins .

The chimical of several thermal springs, in the north part of Morocco, has been investigated. Measured temperature ranges from 21 to 54°C, discharges rates range from 2.5 to 40l/s and TDS range 132 mg/l to 3g/l. The waters are mainly HCO3-Ca-Mg type, resulting from the great influence of carbonate rocks, and the Na-Cl type, resulting from the interaction of water with marine sediments.The geochimical prospecting using geothermometers(silica, Na/K, Na-K-Ca, Na-K-Ca-Mg, Mg/Li and Na/Li) has been applied and only the silica geothermometrs seem to give plausible values. Alkaline geothermometers used for the thermal springs are not reliable for prospecting, inasmuch as the chemical composition is greatly affected by the enormous dilution with the shallow cold water and probably affected by interaction with the evaporitic rocks that are ubiquitous in the basin.The application of Giggenbach method to springs revealed that the waters result from mixing of deep water with shallow cold water. In this case the reservoir deep temperature is given by the mixing model.

The deep geothermal study is based on the petroleum well data which present 1126 BHT and 78 DST. A statistical method is used to process these temperature indications and gives a geothermal gradient ranging from 16 to 41°C/Km. In order to establish the first geothermal gradient map for the whole of Morocco , the country is subdivided to five hydrogeothermal basins. Each basin is characterized by its geodynamical evolution and its specific reservoirs and hydrodynamism. Also, The data were treated separately and five maps of geothermal gradient were realized. The resulting map of Morocco shows that the geothermal anomalies are related to deeper hydrodynamic, recent tectonic, volcanism or to elevation of the Moho.

1. INTRODUCTION

For Morocco, the oil crises and the decrease in local energy ressources, gave impetus to geothermal energy, for potential assessment, exploration and utilisation. The evaluation of hydrogeothermal resources of Morocco is mainly done by the knowledge of the temperature, the chemical characteristics of water, the hydrodynamics of the reservoirs containing hot water. The research undertaken showed a country with real potentialities either by its important deep aquifers or by the relatively high values of geothermal gradient. It is expected that these efforts of geothermal investigation will continue in the future.

2. GEOLOGICAL SETTING

Morocco is located in a strategic area at the interaction of several plates (Africa, European, Mediterranean and Atlantic). The structural framework is characterized by transition from the African domain in the southern part of Morocco to Alpin foldeed structures (Atlasic domain and Rif troughs). Four main structural units are defined from South to North (Fig. 1): Anti-Atlas and Saharian domain corresponds to the Precambrian basement, Atlas corresponds to an Alpine intracontinental range, Mesetas corresponds to stable Paleozoic-Mesozoic basement, Rif represents the Alpine belt around the Western Mediterranean .

Morocco was subdivided into five hydrogeothermal basins (Fig. 1), distinguished by specific geological and hydrogeological feautres (North-Western basin, North-

Eastern basin, South-Western basin, Tadla basin, Errachidia-Ourzazate-Boudnib basin and Tarfaya. Laayoune-Moroccan Sahara basin).

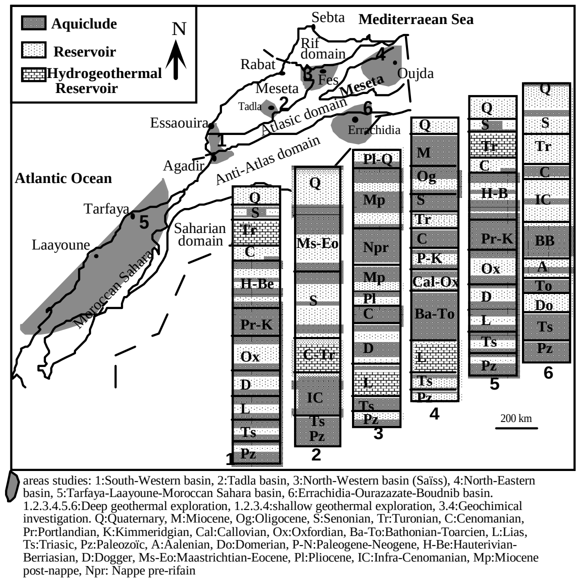

Figure 1: Simplified geological map of Morocco with the study zones and their hydrostratigraphical logs.

3. HYDROSTRATIGRAPHICAL STUDY

The basic data were mainly obtained from final well reports, from both oil and hydrogeologic research. Also some data have been acquired on the land (piezometrical level, chemical analysis of water, measure of temperature). These data proved useful for characterising the hot aquifers of Morocco.

The hydrostratigraphical study (Fig.1) of each basin revealed several potential reservoir layers in which the carbonate aquifer of Turonian (South-Western and Tadla basin) and Liasic (North-Western and North-Eastern basin) are the most important hot water reservoirs in Morocco (Zarhloule, 1999, Zarhloule et al.2001). These areas are different geologically and hydrogeologically.

3.1 Hydrogeological characterstics of the Turonian aquifers

3.1.1 South-Western basin

In the Agadir basin the aquifer is mainly limestone. The outcrops are limited to High-Atlas, Haffaia, Sidi-bourja, Ouled bou Rbia, El Aaricha and Tagtrannat zones. The aquifer thickness ranges from 10m in the East to 120m in the West. The depth of the aquifer varies from the outcrops in the south of the basin to 500 m in the East (Fig. 2a). The hydrodynamic flow is from the Est (outcrops zone) to the West of the basin, where the reservoir is deep and artesien (Ouled Teima, El-Klea and El gouna zones) (Fig. 2b). The aquifer temperature and the salinity varies respectively from 22°C to 32°C and from 330 mg/l to 750 mg/l.

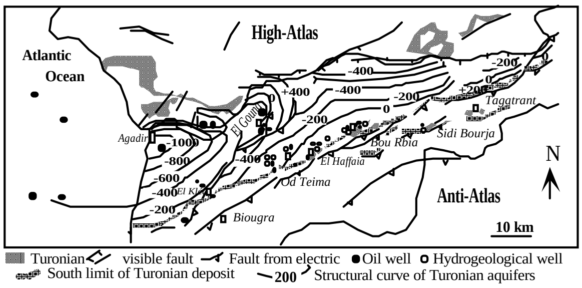

Figure 2a: Structural map of Turonian aquifer.

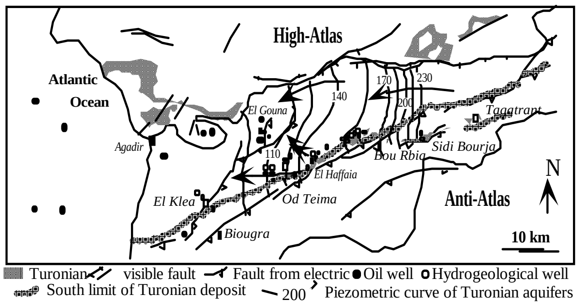

Figure 2b: Piezometric map of Turonian aquifer.

3.1.2 Tadla basin

In the Tadla basin the aquifer is represented by the carbonate. The outcrops are limited to the Nord of Kasbat Tadla-El Borouj. The tickness varies from 20m to 100m. The depth of the reservoir ranges from the outcrops to 500m (Fig. 3a). In the north part of Kasbat Tadla-El Borouj, the hydrodynamic flow is from the North to the South of the basin and to South-Ouest, but in the South of this limit the aquifer is deep and the groundwater flow is toward ENE-WSW . The discharge zone is in the South-Ouest of El Brouj (Fig. 3b). The aquifer temperature and the salinity varies respectively from 21°C to 47°C and from 530mg/l to 2530mg/l

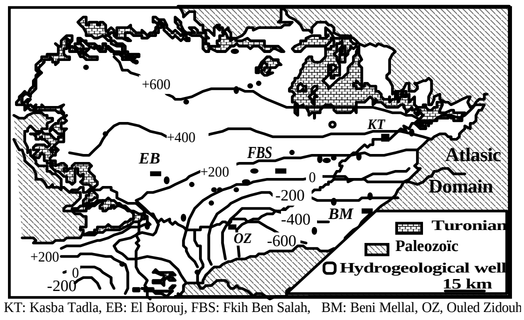

Figure. 3a. Structural map of Turonian aquifer.

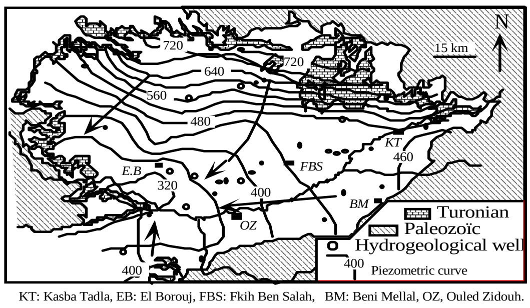

Figure. 3b. Piezometric map of Turonian aquifer.

3.2 Hydrogeological characterstics of the Liasic aquifers

3.2.1 North-Western part of Morocco

In this zone, the aquifer is mainly limestone. The outcrops are limited to the South of the basin. The tickness varies from 14 m to 370m. The deep of the aquifer ranges from outcrops to 1000m (Fig. 4a). The hydrodynamic flow is from the South to the North in the Eastern part of the basin and to the West in the Western zone of the basin (Fig. 4b). The aquifer temperature and the salinity varies respectively from 22°C to 55°C and from 132mg/l to 2334mg/l.

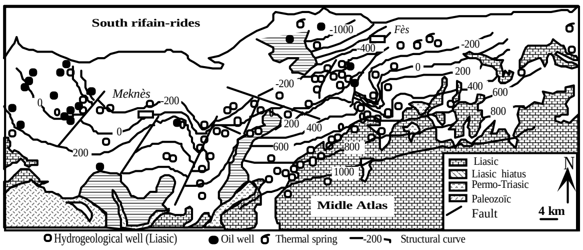

Figure 4a: Structural map of Liasic aquifer.

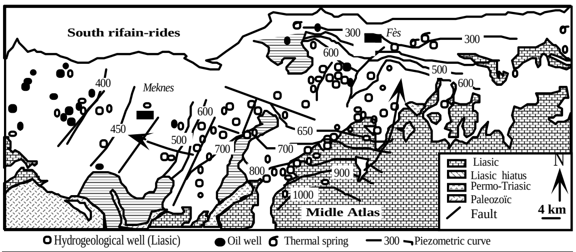

Figure 4b: Piezometric map of Liasic aquifer.

3.2.2 North-Eastern part of Morocco

In this zone, the aquifer is mainly limestone. The outcrops are limited to Beni Snassen, High-Atlas, Midle-Atlas and the South of the basin. The tickness varies from 50 m to 1140m. The deep of the aquifer ranges from outcrops to 1370m. The hydrodynamic flow is from the South to the North of basin (Fig. 5). The aquifer temperature and the salinity varies respectively from 20°C to 52°C and from 130mg/l to 3000mg/l.

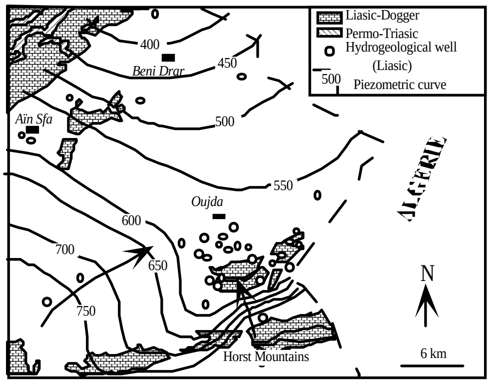

Figure 5b: Piezometric map of Liasic aquifer.

4. SHALLOW GEOTHERMAL PROSPECTION IN MOROCCO

The shallow geothermal methods has ben used in many locations and has met with considerable succes in the past (Leshack and lewis 1983; Smith 1983; Sass et al., 1984; Ben Dhia et al., 1992).The shallow temperature measurements program has been undertaken in four zones in Morocco (Fig. 1) for which few deep thermal data are avaible (North-Western basin, North-Eastern basin, South-Western basin, Tadla basin). It has been launched to estimate the natural geothermal gradient in these areas, to determine the principal thermal anomalies, to identify the main thermal indices, and to characterize the recharge, discharge and potential mixing limits of the turonian and liasic aquifers (Zarhloule et al., 1998, 2001).

The temperature data from depths between 15 and 500m of 250 wells have been analysed. The temperature measurements were made at 5m depth intervals using portable thermistor probe equipment with 0.01°C resolution. The shallow temperature data allowed to establish a thermal profile for each investigated well, assumed to be in thermal equilibrium (Fig. 6).

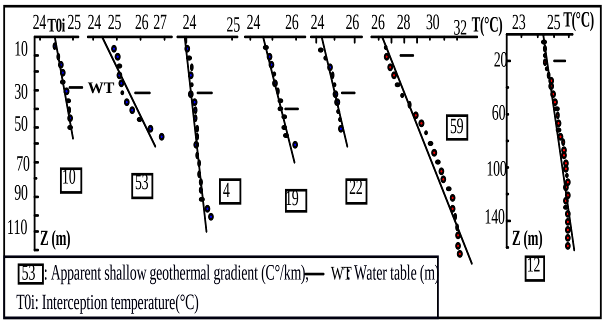

Figure 6: Example of thermal profile.

Thermal behaviour is changing from an area to an another, from a well to another as well as within the same well. These differences in the Lateral and vertical temperature assessment depend on several factors: geological and structural homogeneity within the same region, the lithology and its degree of homogeneity within each well, the depth of water table and its temperature and the well location within the hydrodynamic frame. The temperature values of water range from 18 to 55.5°C.

From a well to another, several main types of profiles have been distinguished depending on whether the evolution V.S depth is increasing (Fig. 7a), steady (Fig. 7c) or decreasing (Fig. 7b). In the same well three main slope breaks in the termal profile have been noticed that are (Fig. 7d): G0 is the thermal gradient between the surface and the limit of influence of surface effects (10m), G1 is the thermal gradient between the groundwater level and he bottom of the limit of influence of surface effects, G2 is the thermal gradient between the groundwater level and the bottom of the well and GGSA is apparent shallow geothermal gradient. Also an another gradient has been defined Gwater that corresponds to the thermal gradient between the groundwater level and the interception temperature (T0i).

The cartography of some parametrizes (water temperatures and GGSA) for each basin show that the recharge outcrops zones of the turonian and lisaic aquifers are characterised by the high topography, high water potential, shallow cold water, low geothermal gradient and negative anomalies (Fig.8a-d). The disharge zones are characterised by low topography, low piezometric level, high geothermal gradient, high water temeprature with hot spring and positive anomalies (Fig. 9a-d).

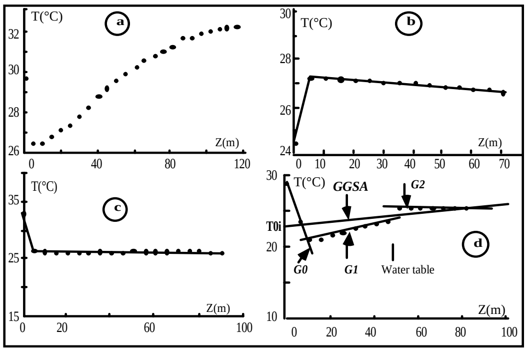

Figure 7: Different types of geothermal gradient: a) positive gradient; b) negative gradient; c) no gradient; d) main slope breaks in the thermal profile.

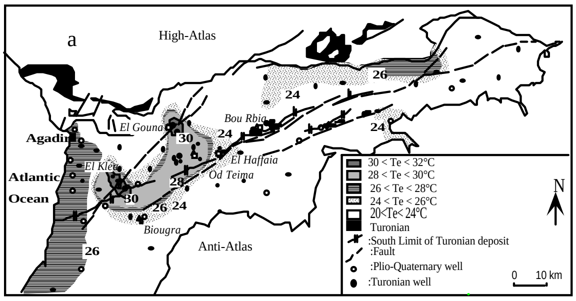

Figure 8a: Temperature distribution map of water of the Turonian and Plio-Quaternary aquifers (Agadir basin).

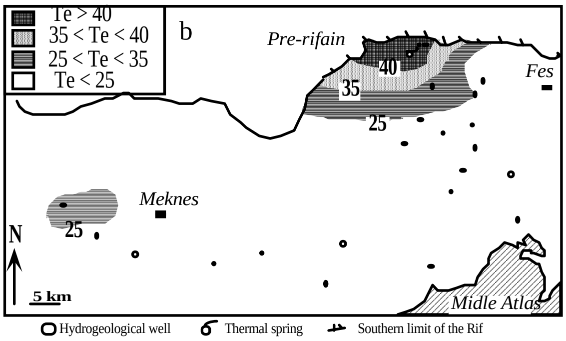

Figure 8b: Temperature distribution map of water of the Liasic aquifer (South-Western basin: Saïss).

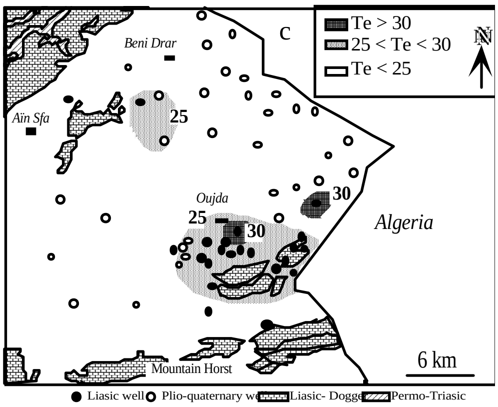

Figure 8c: Temperature distribution map of water of the Liasic aquifer (South-Eastern basin: Oujda).

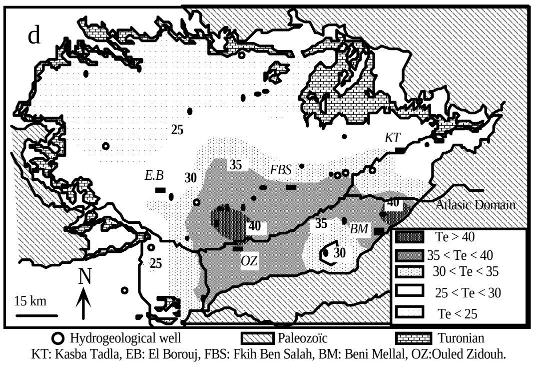

Figure 8d: Temperature distribution map of water of the Turonian aquifer (Tadla basin).

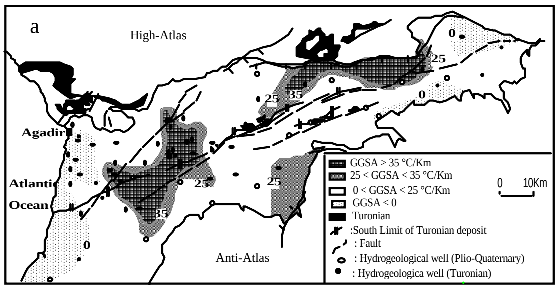

Figure 9a: Isovalue map of apparent shallow geothermal gradient (°C/km) (Agadir basin).

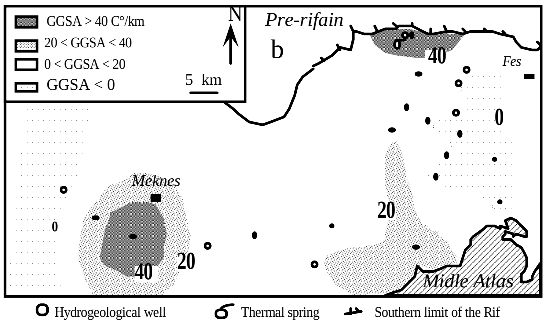

Figure 9b: Isovalue map of apparent shallow geothermal gradient (°C/km) (South-Western basin: Saïss).

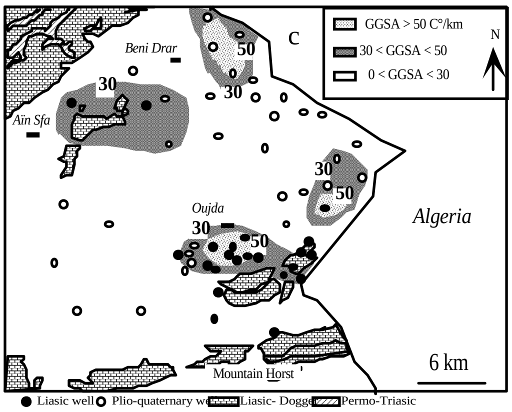

Figure 9c: Isovalue map of apparent shallow geothermal gradient (°C/km) (South-Eastern basin: Oujda).

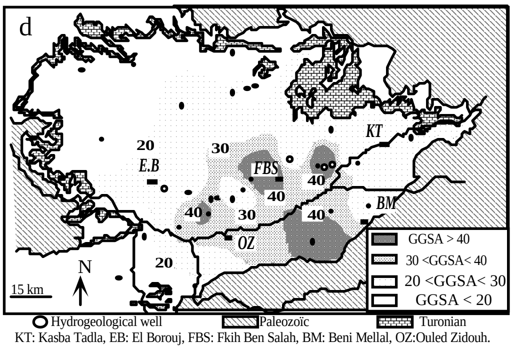

Figure 9d: Isovalue map of apparent shallow geothermal gradient (°C/km) (Tadla basin).

The bottom shallow wells temperatures values are plotted against depth (Fig. 10) showing a rather important disturbed points either for highs or lows. Giving the fact that normal temperature can be considered, at a given depth, as the one in agreement with the regional geothermal gradient, noticible higher and lower values at the same depth, should be considered as anomalous. Negative anomalies correspond to the recharge zone of each aquifer with topographic highs and infiltration meteoric cold water, whereas positive anomalies correspond to the shallow upcoming hot water and to the more or less well defined disharge zones.

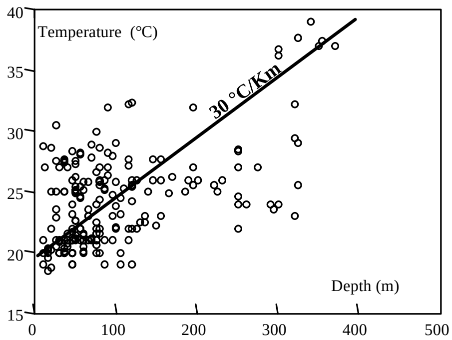

Figure 10: Bottom shallow hydrogeological wells temperture V.S depth

The main thermal indices (Fig. 11) and the principal thermal anomalies coincide with the zones of turonian and Liasic aquifers. Also the water temperatures of the shallow aquifer is higher to the neighborhood of the artesianisme zones of the deep aquifers that in the rest of the basins. What explians the existence of a groundwater flow from deep aquifer to shallow one favoured by an abandant fracturation.

5. GEOCHEMISTRY OF THERMAL SPRINGS IN NORTHERN MOROCCO

The Northern Morocco basin is constituted by a lithological succession from paleozoïc to Quaternary (Fig.1) and only the Liasic limestone aquifer is an importante hydrogeothermic unit. The Numerous hot springs are know in the North part of Morocco (Fig. 12a-b) (Lahrach et al.1998, Zarhloule, 1999).

The outcrops are limited to the Middle-Atlas (Saïss), the Northern and the Southern areas of Oujda. The aquiclude consists of the Cretaceous to Tertiary sediments (schale). The hot springs emanating from the limestone liasic aquifer, have been inventoried and analysed in order to characterize the origin-reservoir, to evaluate undergroud temperature and to determined the mixing shallow cold water with deep hot water.

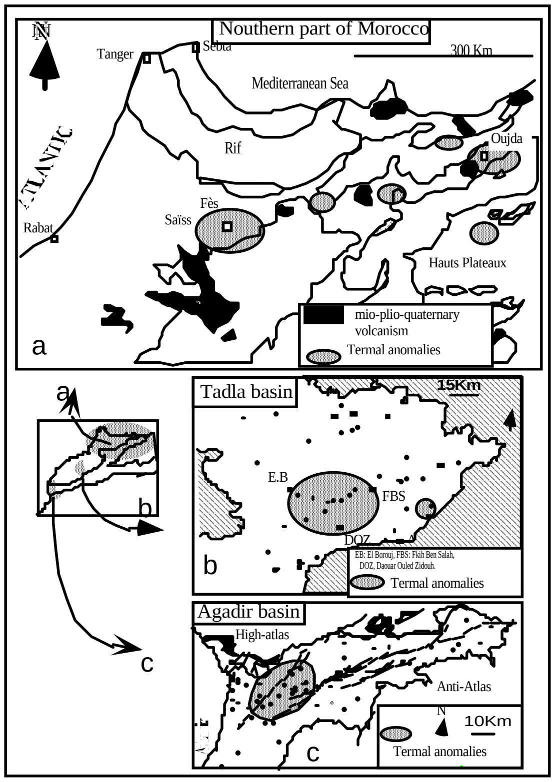

Figure 11: Map of shallow geothermal anomalies in Morocco.

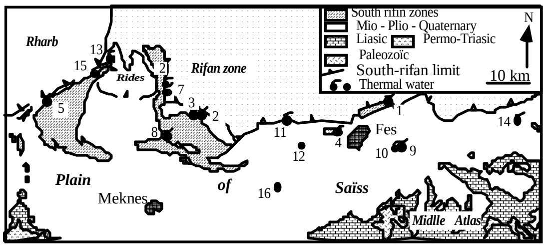

Figure 12a: Geological skech map of the North western of Morocco (Saïs basin) with location of simpling sites.

5.1 Water chemistry

Major (Na, K, Ca, Mg, HCO3, SO4 and CL) and minor (SiO2, Li) components in solution (mg/l) are reporeted in Table 1.

We retained all the analysed springs with good ionic balance. From Table I it can be seen that PH varies from 6.9 to 7.9, temperature ranges from 22 to 54°C, salinity from 0.13 to 27.6 g/l. From the North Western to the North Eastern part of Morocco, there are wide variations in these parametrs because for the same aquifer system there may be heterogeneity within a given reservoir and /or variation in the upflow routes linking the reservoir to the surface (Zarhloule 1999, Lahrach et al.1998).

Based on the relative amount of major ions, The water classification has been made in Figure.13, using the Langelier and Ludwing diagram (1996).

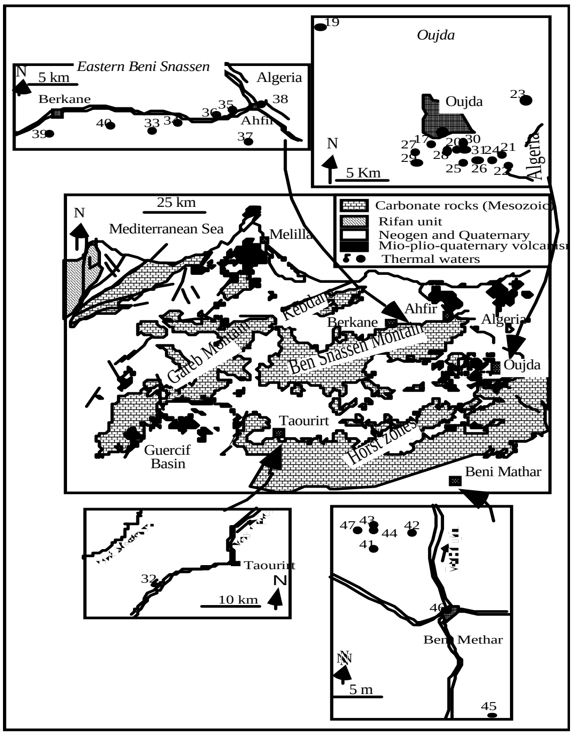

Figure 12b: Geological skech map of the North Eastern of Morocco with location of simpling sites.

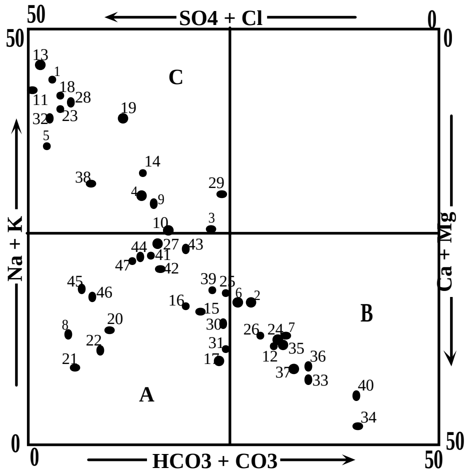

Figure 13: Langelier-Ludwing diagram for the water samples investigated.

The hot waters can be grouped into Ca (Mg)-SO4 (Cl) (A) type waters with moderate salinity (<3g/l), Ca(Mg)-HCO3 (B) type waters with low salinity (<700mg), and Na-Cl (C) type waters with a salinity that varied from 0.61mg/l to 27.6g/l. The C type waters showed a chemical composition nearby to the Ca-Mg with the exception of springs N° 5,11,13 and 32 who have a high salinity. This can be due to the interaction of water with the different rocks principally evaporitic one.

Table 1: Chemical composition of thermal waters from northern Morocco

N°	Name	T (°C)	pH	TDS mg/l	K^+ mg/l	Na^+ mg/l	Ca^{2+}	Mg^{2+}	Cl^-	HCO_3^-	SO_4^{2-}	SIO_2	Li
1	A.H.du Zalagh	35.5	7.1	3850	32	1325	88	42	2066.1	244	184.3	17.1	5
2	A. Anseur	24	7.3	510	9	70	68	21	78.1	280.6	111.9	10.3	1.2
3	A.Maaser	25	7	610	2	125	73	18	177.5	256.2	62.5		
4	A. S. Trhat	**26**	6.9	840	4.6	198	34	28	277.2	305	139.9	15.4	1.7
5	M. Y. Outita	39	7.4	6230	37.8	1704.7	349.2	122.4	3735.9	292.8	1139	24.8	7
6	A. El Beida	22	7.6	460	8.5	65	84	18	92.3	219.6	64.2		
7	A. Es-Skhoun	25	7.5	440	1.9	51.1	74.8	24.8	87.3	283.6	34.5	18	
8	A. H. My. Idriss	31	7.2	2850	6.2	282.2	465	106.1	476.4	283.6	1379	12.8	5.2
9	A. Skhinat	33	7.1	1020	6	244	66	38	440.2	292.8	59	11.1	1.3
10	S. Harazem	35	7.3	710	3.8	150	62	36	312.4	256.2	14	9.4	1.7
11	My. Yacoub Fès	54	7.2	23430	320	7900	1150	260	13668	219.6	28	30.8	60
12	A. Allah	45	7	450	1.3	50	50	48	71	335	67	11.1	0.4
13	M. Y. Tiouka	24	7.8	27610	143	10230	775	400	15365	756	328	16.3	5.3
14	A. S. Metmata	31	7.6	1120	3	300	50	36	525.4	317.2	36.2	10	
15	A. H .Bou Draa	22.5	7.3	540	3.1	75	87.4	29.9	120	271.4	89.7	13	
16	2527/15	38	7	390	2	57	41	22	149.1	170.8	37.8	11.1	0.4
17	Camp. Rose	28	7.6	1005	2.6	37	**60**	66	152	329	62	13.2	
18	Ben Kachour	51	7.2	2680	14	899	70	51	1391	311	181	26.4	0.1
19	1225 / 12	26	7.4	1040	13	335	14	34	362	133	102.8	13	0.1
20	2843 / 12	28	7.6	1010	2.3	53	61	55	220	154	90.5	10.2	
21	**2899 / 12**	25.5	7.6	620	2.7	80	60	52	230	135	57.6	11.2	
22	2933 / 12	27	7.6	650	3.3	55	85	53	230	130	117.7	14.3	
23	2952/ 12	46.5	7.1	2960	18	920	114	52	1508	**372**	192	25.7	0.2
24	2431 / 12	30	6.9	695	1.8	72	70	59	181	**353**	48	15	
25	2364 / 12	26.5	7.4	615	1.6	117	72	58	106	**378**	172	13.8	
26	2363 / 12	28	7.4	700	2.1	69	76	58	135	**402**	52	12.3	
27	Oued Nachef IV	33	7.1	870	3	149	66	60	305	378	**96**	18	0.2
28	Champ de tir	29	7.5	2880	9.8	869	80	50	**1363**	323	96	16	0.2
29	1255 / 12	29	7.2	640	3.2	179	64	**54**	255	323	139	12.8	0.1
30	2311/ 12	28	7.1	580	1.7	74	76	56	142	366	33	12	
31	1125/ 12	28	7.3	715	1.7	71	74	**58**	156	347	67	12.4	
32	S. Gouttitir	49	7.3	9700	24.7	2472	870	169.2	**4110.9**	199		2146.1	34.6
33	Tercha	28	7.3	360	1.5	30	37	38	**35**	268	67.5	12.3	
34	Fezzouane	37	7.9	340	1.1	22	70	36	28	**292**	19.5	15.3	
35	Sidi Rahmoune	29	7.4	500	1.7	43	66	44	106	353	**24.3**	13.2	
36	Aichoun	29	7.8	130	1.7	32	74	33	60	341	33.4	**12.8**	
37	S. Aoulout	20.5	7.4	320	2.6	32	55	49	60	341	55.9	**12.2**	
38	S. Kiss	27	7.1	**780**	45	330	104	52	610	281	176	17.3	
39	1292 / 7	24	7.2	755	1.9	94	60	50	184	341	33	**12**	
40	**1267 / 7**	34.5	7.9	395	0.7	18	60	44	24	378	33	20	0.1
41	**22 / 18**	26	7.1	870	2.3	162	86	49	273	286	124	13.6	
42	62 / 18	**27.5**	7.2	630	2.8	135	56	62	266	274	76	12.6	
43	159 / 18	26.5	7.7	860	2.5	142	56	44	220	268	48	13	
44	170 / 18	27.5	7.1	1020	39.9	135	58	68	248	280	187	12.1	
45	**171 / 18**	25	7.9	1740	5.9	219	170	94	433	225	470	12	
46	188 / 18	26	7.3	1710	4.1	175	160	94	426	237	350	14	
47	**35 / 18**	29	7.3	625	3	144	56	65	266	274	144	15	

Table 2: Chemical geothermometry. Application in Northern of Morocco.

N°	Name	T (°C)	Qz Rof	Qz Arn	Cal Rof	Cal Arn	Na/Li L S	Na/Li H S	Na/K Arn1	Na/K Arn2	Na/K Tr	Na/K Mi	Na/K Rof	Na-K-Ca	Na-K-Ca Mg	Mg/Li
1	A.H.du Zalagh	35.5	58	44	25	29	164	220	84	119	73	119	119	133	34	72
2	A. Anseur	24	40	26	7	12	341	347	222	298	216	298	239.5	167.5	47	55.5
3	A.Maaser	25							61	91	49	91	98	88	67	
4	A. S. Trhat	26	54	40	21.5	25	245	282	82	116	70	115.9	117	112		57
5	M. Y. Outita	39	72	59	40	43	171	226	79	113	68	113	115	123	44	56
6	A. El Beida	22							224	300	218	300	241	165	67	
7	A. Es-Skhoun	25	59.5	46	27	31			114	155.5	103	155.5	146	108	47	
8	A. H. My. Idriss	31	48	34	15	19	353	254	79	112	67	112	115	98	67.5	52
9	A. Skhinat	33	43	29	10	15	195	244	85	120	73	120	120	112	26	45
10	S. Harazem	35	37	23	4.5	9	280	306	87	122	76	122	122	108	27	51.5
11	My. Yacoub Fès	54	80.5	68	49	52	538	272	118	161	107	161	150	165	69	88
12	A. Allah	45	43	28	10	15	237	276	89	124	77	124	123.5	96		19
13	M. Y. Tiouka	24	56	42	23	27.5	456	242	54.5	82	42	82	91.5	123	29	74.5
14	A. S. Metmata	31	39	25	6.5	11			39	63	26	63	76	84		
15	A. H .Bou Draa	22.5	48	34	15	20			120	163	109	163	152	116	45	
16	2527/15	38	42	29	10	15	223	265	108	148	97	148	141	110	28	33
17	Camp. Rose	28	49	35	16	20			162	189	152	217	188	310	27.5	
18	Ben Kachour	51	74	61.5	43	46	7	41	60	103	48	89	97	270	27	28
19	1225 / 12	**26**	48	34	16	20	45	81	115	151	104	157	147	346	36	32
20	2843 / 12	28	40	26	7	12			123	158	112	167	155	279	22	
21	2899 / 12	25.5	43	29	10	15			105	143	94	145	139	270	20	
22	2933 / 12	27	51	38	19	23			148	178	**138**	199	177	302	39	
23	2952/ 12	46.5	73	60	41	45	31	67	72	114	60	104	108	283	49	41
24	2431 / 12	30	53	39	21	25			86	126	75	121	121	243	15	
25	2364 / 12	26.5	50	36	17	22			53	97	41	81	90	214	11.5	
26	2363 / 12	28	46	32	14	18			99	137	87	136	133	255	20	
27	Oued Nachef IV	33	60	46	27	31	128	166	74	115	62	106	110	246	14	39
28	Champ de tir	29	55	42	23	27	34	69	44	89	32	70	82	244	25	41
29	1255 / 12	29	47	34	15	19	75	112	67	109.5	55	98	103	242	15	28
30	2311/ 12	28	45	31.5	13	17			81	122	70	115	117	237	17	
31	1125/ 12	28	46	33	14	18			84	124	72	118	119	239	16	
32	S. Gouttitir	49	85	73	54	57	59	95	39	83	26	63	76	232	84	62
33	Tercha	28	46	32	14	18			134	166.5	123	181	164	281.5	20	
34	Fezzouane	37	54	40	21	25			134	166.5	123	181	164	265	35	
35	Sidi Rahmoune	29	49	35	16	20			116	152	105	159	148.5	265	26	
36	Aichoun	29	48	34	15	19			138	170	128	187	168	279	45	
37	S. Aoulout	20.5	46	32	13	18			175	200	166	234	200	320	35	
38	S. Kiss	27	58	45	26	30			229	241	223.5	307	245	455	131	
39	1292 / 7	24	45	31.5	13	13			74	116	62	106	110	207	10	
40	1267 / 7	34.5	63	50	31	35	260	294	115	151	104	157	147.5	243	18	29
41	22 / 18	26	50	36	17	21			55	99	43	83	92	221	22	
42	62 / 18	27.5	47	33	14	19			75	117	64	108	111	247	12	
43	159 / 18	26.5	48	34	15	20			66	109	54	97	103	237	16	
44	170 / 18	27.5	46	32	13	17			340	319	344	465	332	545	147	
45	171 / 18	25	45	31.5	13	17			90.9	130	79	127	125.5	265	32	
46	188 / 18	26	51	37	18	22			82.5	123	71	116.5	118	250	26	
47	35 / 18	29	53	39	21	25			75.7	117	64	108	111	249	11	

The application of the IIRG diagram (D'Amore et al.1983) (Fig.14), show the same results gotten by the Langelier and Ludwing diagram.

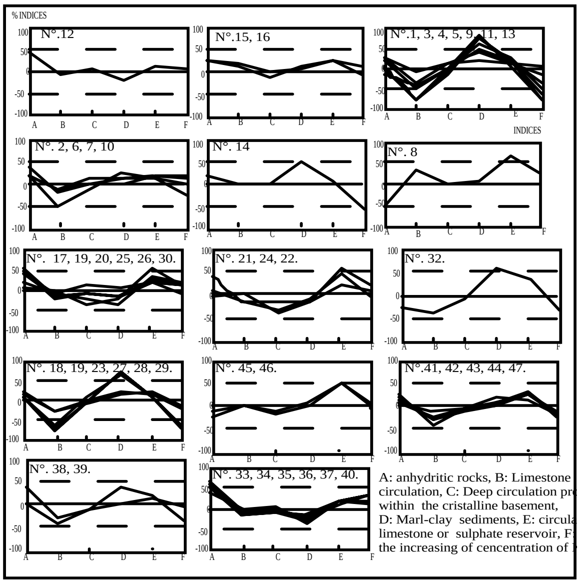

Figure 14: IIRG diagram for the water samples investigated.

The thermal waters are mainly Cl or HCO3-Ca and Mg. The parameterize calculated (A, B, C, D, E, F) are reported in Figure and Table . That shows that the thermal springs (1, 3, 4, 5, 9, 10, 11, 13, 14, 18, 19, 23, 27, 28, 29, 38, 41 and 42) have a deep circulation in detrital layers , what shows the influence of the evaporitic rock of the Triasic on the chemical composition of the water. The springs and a borholes (2, 6, 7, 12, 15, 16, 17, 20, 24, 25, 26, 30, 31, 33, 33, 34, 35, 36, 37, 39, 40 and 43) have a limestone origin also revelead by the local geology near of the emergence zones (36, 37 and 2). The points (21, 22, 44, 45, 46 and 47) show that the waters circulated in the limestone resrvoir in contact with a evaporitic rock of the Triasic. The thermal springs N°32 and 8 have a deep circulation with influence of gypseous layers.

5.2 Geothermometry

The following geothermometers were applied to estimate subsurface temperatures and the depth of the thermal aquifers by using the geothermal gradient (Zarhloule, 1999, Lahlou Mimi et al 1999): silica (Fournier et Rowe, 1966, Arnorson et al., 1983), Na/K (Fournier, 1979, Truesdell, 1976, Michard, 1979, Arnorson et al., 1983, Arnorson, 1983), Na-K-Ca (Fournier and Truesdell, 1973), Na-K-Ca-Mg (Fournier and Potter, 1979), Mg/Li (Kharaka and Mariner, 1986) and Na/Li (Fouillac and Michard, 1981). Table 2, shows the temperature estimates from the above geothermometers. Extreme values revealed by each are: 37

to 85°C (QzRof), 23° to 73°C (Qz Arn), 7 to 54°C (cal Rof) and from 12 to 57°C (cal Arn). The mesaured températures are ranges from 20°C to 54°C.

In order to evaluate the applicability of those geothermometers (Lahrach et al.1998, Zarhloule, 1999), the estimated values are plotted against the measured values(Tm). Figures 15a-i, show the plots of Tm versus alkaline geothermometers (TNa/K-Arn2, TNa/K-Tr, TNa/K-Mi, TNa/K-Rof, TNa-K-Ca, TNa-K-Ca-Mg, TMg/Li, TNa/Li high salinity and TNa/K low salinity).

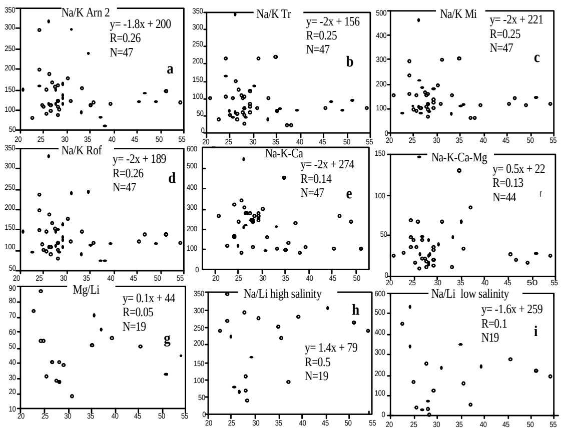

Figure 15a-i: Plot of Tm Vs alkaline geothermometers.

The wide spread of the geothermometer values reveal that these temperatures can not be considered reliable. This could be explained by a strong possibility of a mixing between fresh and deep waters during upflow from the reservoir to surface such mixing could greatly affect all the geothermometry. Also the water composition is greatly affected by the interaction with the evaporitic rocks that are ubiquitous in the region.

The silica geothermometers have been applied: quartz Rof (TQRof), quartz Arnorsson (TQArn), chalcedony-Rof (Tcal-Rof) and chalcedony-Arnorsson (Tcal-Arn). Figure 16a-d, shows the plot of TQRof, TQArn, Tcal-Rof and Tcal-Arn against Tm, with the correlation coefficients of 67%.

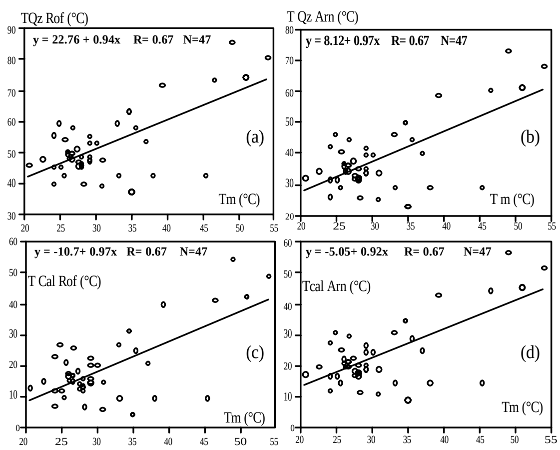

Figure 16a-d: Plot of Tm Vs silica geothermometers.

Temperature estimated by QRof are systematically higher than for the other three. It ranges from 37 to 85°C for Qrof, 23 to 73°C for QArn, 7 to 54°C for Cal-Rof, 12 to 57°C for Qcal-Arn. The mesured temperatures ranges from 20 to 54°C. Also the gap between the measured and estimated temperatures (TQRof) are all positive (except N°12) and it ranges from 2.4°C (n°10) to 36.4°C (n°32). On the other hand, several Tcal-Rof and Tcal-Arn are lower than Tm, for which silica equilibrium seems to be in correspondence with Quartz (Fig. 17).

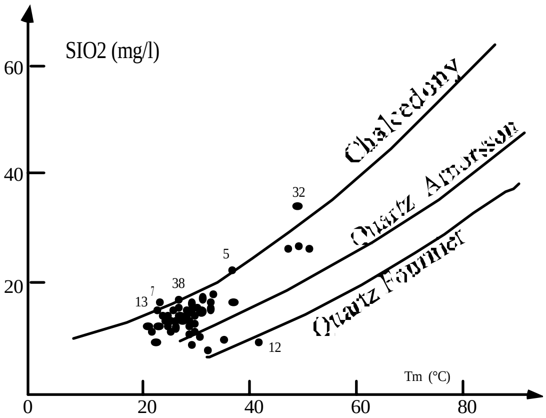

Figure 17: Application of the silica gheothermometer.

While the other springs especially for n°5, 7, 13, 32 and 38 show a good tendency to ward the chalcedony curve. The deep reservoir temperatures cannot be lower than the spring discharge temperatures, so the chalcedony temperatures appear to be in error for the other springs. So, only the silica geothermometers quartz Rof and quartz Arnorsson seem to give plausible values, except for the springs n° n°5, 7, 13, 32 and 38 whose temperature is estimated better by chalcedony. The silica geothermometer used for the thermal waters in North part of Morocco gave 81°C as a maximum value (n°11). Similar estimates have also been obtained through application of the K-Na-Mg technique (Giggenbach, 1988) summarized in the K/100-Na/1000-$Mg^{1/2}$ ternary diagram of Figure 18. where the most of thermal springs are aligned towards the Mg corner, suggesting very low K^2/Mg deep temperatures that varying between 60 and 100°C, what could be to explaine by the enormous dilution with the waters of shallow aquifers in the

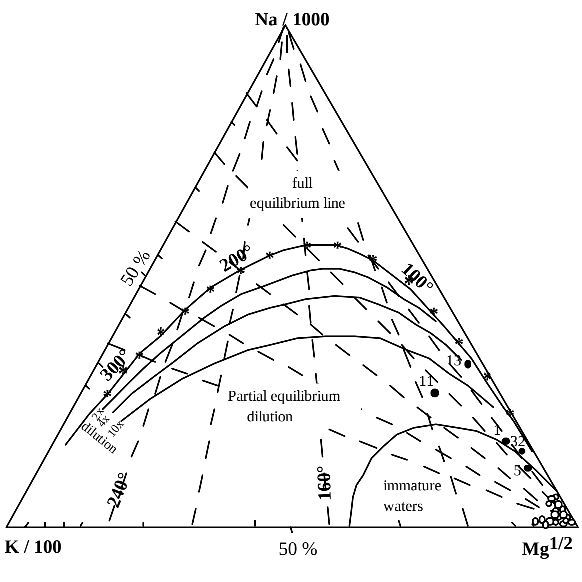

Figure 18: Application of ternary diagram (Giggenbach, 1988) showing relative cation concentrations for thermal springs.

The depth of the thermal aquifers in the North part of Morocco is gotten by the use of the deep geothermal gradient calculated from the petroleum well that ranges from 19 to 42°C/km (Zarhloule, 1999) and the deep temperatures estimated from the geothermometers. The depth of thermal aquifers ranges from 524m to 1700m.

5.3 Schematic and idealized hydrogeological model of thermal waters in Northern Morocco.

As shown in Figure 19, the outcropings zones of the Liasic aquifer are characterized by shallow cold water and both from cold spring and hydrogeological wells are mainly Ca(Mg)-HCO3 type, resulting from great influence of carbonate rocks. The discharge zones are characterized by shallow hot water. The hot springs are generaly Ca(Mg)-SO4(Cl) or Na-Cl, resulting from infleunce of evaporitic rocks. The midle of the basin shows a communication between the deep and the shallow aquifers and the waters are Ca(Mg)-SO4(Cl) or Ca(Mg)-HCO3. In this zone there is a high dilution of thermal water by the shallow aquifers.

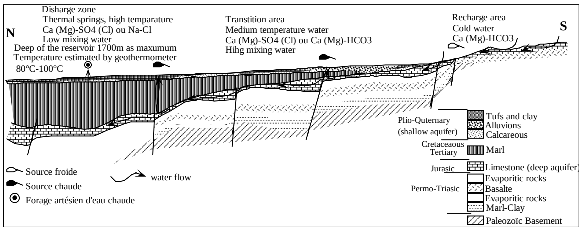

Figure 19: Conceptuel model: relation between topography, temperature, geochemistry and hydrodynamics.

6. DEEP GEOTHERMAL GRADIENT OF MOROCCO: PETROLEUM DATA

The aim of this study is to establish a geothermal gradient map for the whole of Morocco, by using thermal data obtained from petroleum exploration wells. Both the corrected bottom-hole temperatures (BHT) and the drill-stem test temperature (DST) were used to elaborate the geothermal gradient map. A total of 410 wells provided 1204 temperature values (1126 BHT and 78 DST) (Fig. 20).

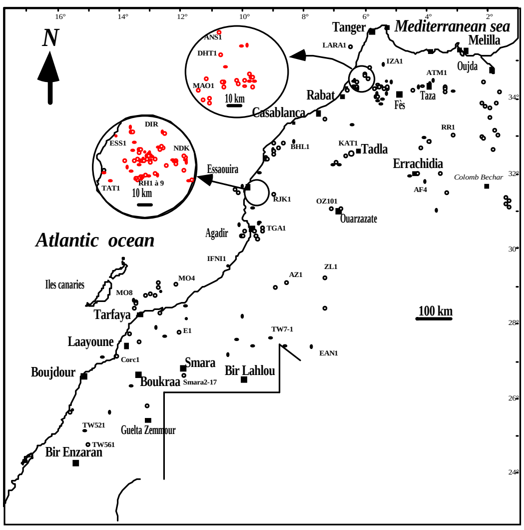

Figure 20: Location of petroleum wells used.

BHT were systematically corrected for mud circulation cooling effects either by Horner technique when several temperature records are available at a given depth or by the comparison of all BHT with test temperatures (DST) that are representive of the actual formation temperatures. In order to establish the geothermal gradient of Morocco , the area was subdivided into five hydrogeothermal basins (Fig. 1): north-eastern basin, north-western basin, Errachidia-Boudnib basin, south-western basin and the tarfaya-laayoune-sahara basin. Each basin presents the same geodynamical evolution and is characterised by its specific reservoirs and hydrodynamism. For each basin the petroleum well data have been processed. The objective was to set a regional geothermal gradient map, and then to compile a geothermal gradient map of Morocco.

6.1 Processing of temperature values

Temperature behaviour with depth is studied both for the rough BHT (Fig. 21a-g) and DST (Fig.22)..

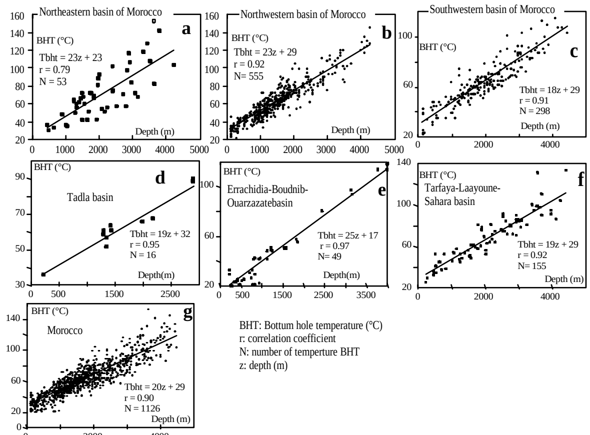

Figure 21: BHT vs depth for each basin

The least squares fitted straight line gave: For BHT(Fig. 21), T= az+Ts, where a is the slope of the straight line and the average geothermal gradient measured in the mud, Ts is the BHT at the surface and T is the BHT (°C) at any given depth z(m). For Morocco the average geothermal gradient is 20°C/km. For the DST (Fig. 22), T=az+Ts, where a is the averge geothermal gradient of DST, which could be the value nearest the true geothermal gradient, and Ts is the surface temperature, representing the mean annual temperature as indicated by climatic surveys. For Morocco the geothermal gradient from DST is 24°C/km

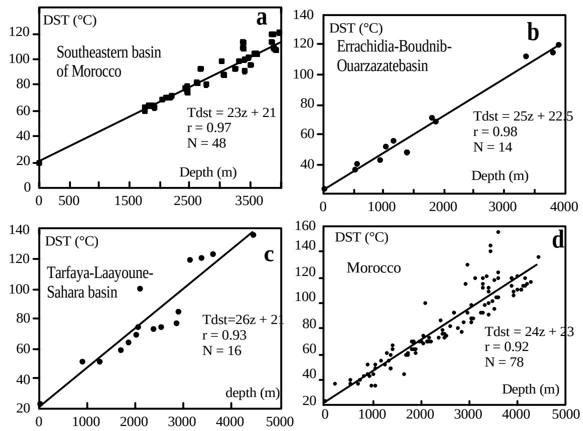

Figure 22: DST vs depth for each basin

With DST values as references, it was possible to calculate the difference (ΔT) beween DST and BHT at the same depth for each value. Plotting the ΔT values with depth (Fig. 23a) gave a curve wich is used a correction abacus. Also, for the Northern part of Morocco, there is no DST values, the application of the Horner plot method's allowed us to correct the BHT tempertures in this area (Fig. 23b).

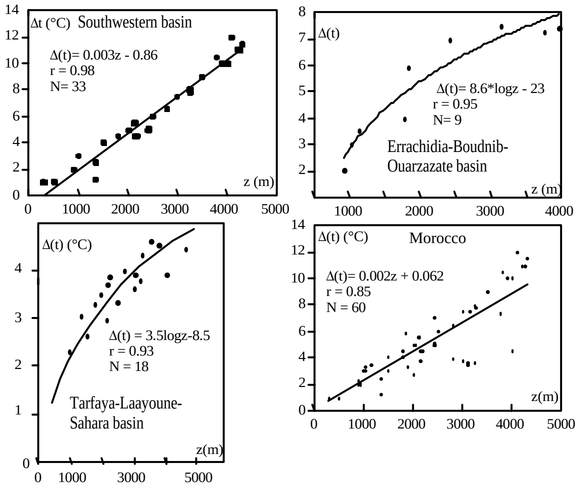

Figure 23a: ΔT vs depth

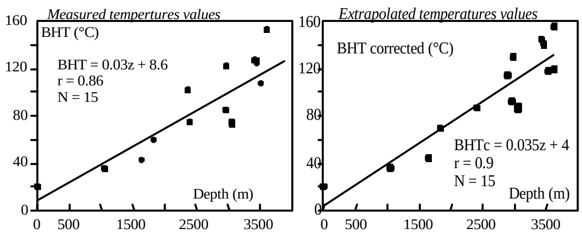

Figure 23b: Application of Horner plot method's.

Thus, after correcting all the BHT values, we plotted coorected BHT and DST with depth (Fig. 24a-g). The least squares fitted straight line gave: T= az + Ts, where T is the undergroud temperature at any given depth z, a is the slope, representing the average geothermal gradient in the region (28°C/k for north-eastern basin, 27°C/km for north-western basin, 28°C/km for Errachidia-ouarzazat-Boudnib basin, 21°C/km for the south-western basin, 21°C/km for the tarfaya-laayoune-sahara basin, 22°C/km for Tadla basin and 23°C/km for the whole of Morocco) and Ts is the surface temperture.

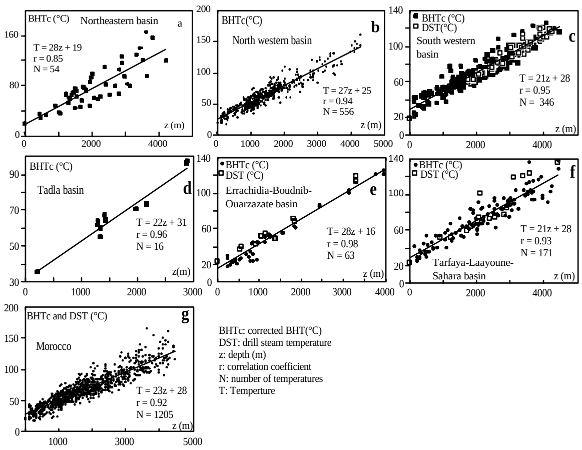

Figure 24: Corrected temperature vs de

6.2 Geothermal gradient map of each basin

Corrected BHT and DST values for each well will be used to estimate theaverge geothermal grdaient to selected wells and thus to construct the geothermal gradient map for each hydrogeothermal basin and the compilation of the regional maps allowed us to establish he geothermal gradient for the whole of Morocco.

In the North-Western part of Morocco (Fig. 24a) the deep geothermal gradient ranges from 26°C/km to 35°C/km . Zones of relatively high geothermal gradient seem to correspond to zones proved or supposed faults. Also the anomalies are related to deep hydrodynamic activities (Zarhloule, 1999).

The spatial distribution of geothermal gradients in the North-Eastern Morocco (Fig. 24b) could be related to the hydrodynamic effects and the neotectonic associated to the recent volcanim. It ragnes from 15 to 42°C/km (Zarhloule, 1999).

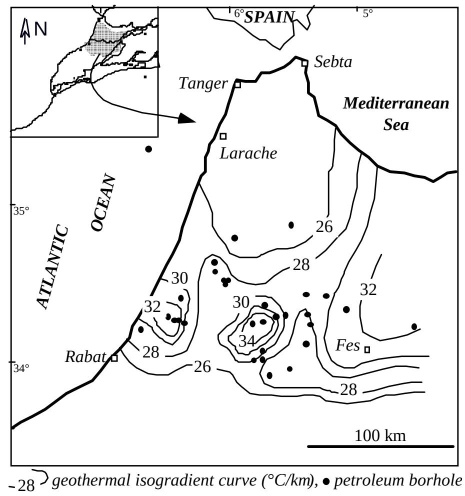

Figure 24a: Geothermal gradient map of the North-western basin of Morocco.

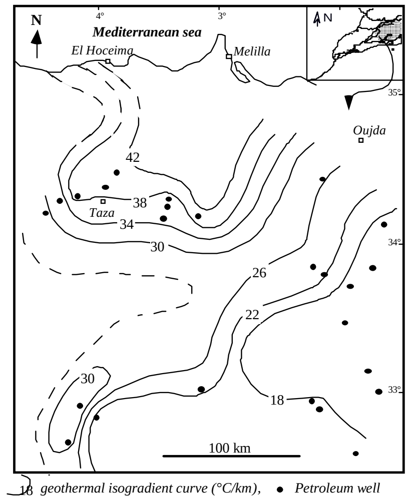

Figure 24b: Geothermal gradient map of the North-Eastern basin of Morocco.

In the South-Western basin (Fig. 24c), the higher geothermal gradient observed in the center could be the consequence of proximity to the Tidsi diapir, given the high thermal conductivity of evaporitic rocks (Zarhloule et al., 1998). Also the anormal geothermal gradient is related to the deep hydodynamic effects (oxfordian reservoirs) (Zarhloule, 1994). In the South of the basin, the geothermal gradient is related to the basement faulting.

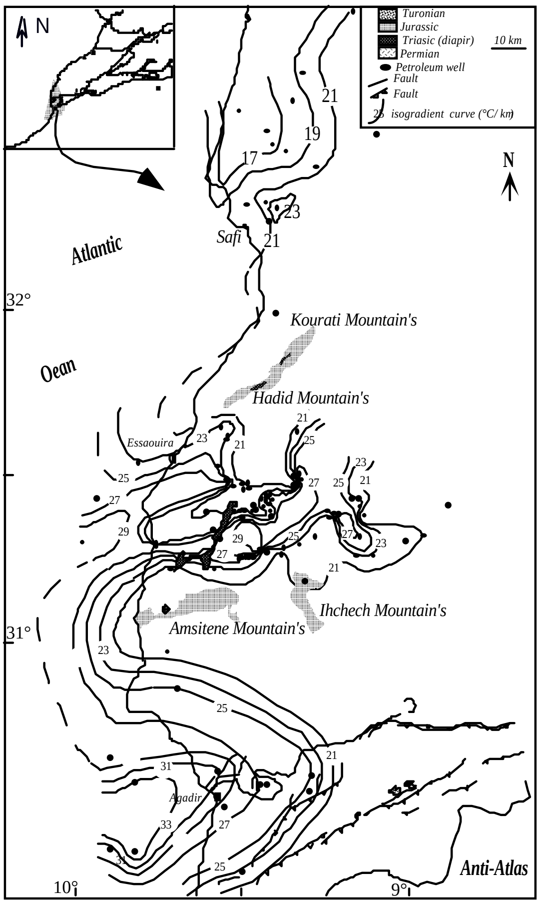

Figure 24c: Geothermal gradient map of the South-Western basin of Morocco.

The Tarfaya-Laayoune-Sahara basin (Fig. 24d) presents two domains with a relative high geothermal gradient: the on-shore domain characterized by a great fault basement of N65 to N70 direction revealed by geophysics, and the off shore domain where the Miocene volcanoes of the Canary Islands contribute to increased geothermal gradients (Zarhloule, 1999).

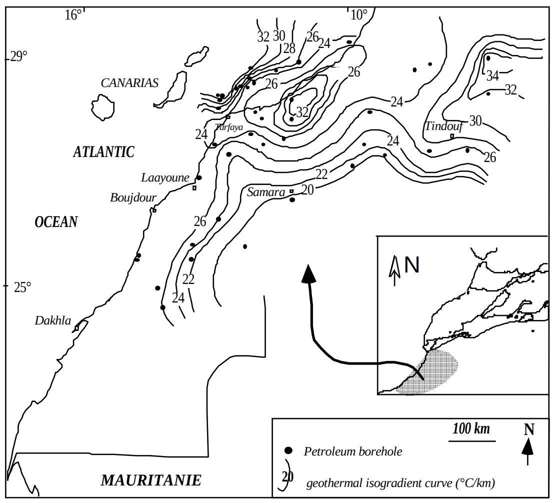

Figure 24d: Geothermal gradient map of Tarfaya-Laayoune-Sahara basin.

The regional distribution of geothermal gradients in the Errachidia-Ouarzazate-Boudenib basin (Fig. 24e) shows that the relatively high geothermal gradients could be related to subsidence and the basement proximity, respectively, in the south-eastern and southern sectors in the basin (Zarhloule, 1999).

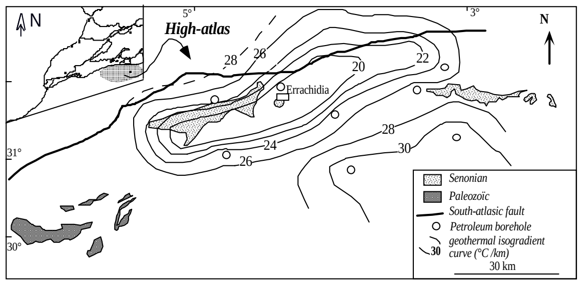

Figure 24e: Geothermal gradient map of the Errachidia-Ouarzazate-Boudnibe basin.

For the whole of Morocco (Fig. 25) the geothermal gradient varies from 15 to 42°C/km. A distinction can easily be made between zones of high geothermal gradient (>30°C/km) and others of low geothermal gradient (<30°C/km). The major part of the region is characterized by low gradient ranging from 20 to 30°C/km. The areas of high gradient marked in the regional maps (Fig. 24a-e) are in the geothermal gradient map of Morocco (Fig. 25). The isogradient curves dispaly several main directions where the geothermal anomalies are related to deeper hydrodynamic, recent tectonic, volcanism or to elevation of the Moho (Zarhloule, 1999, 2003).

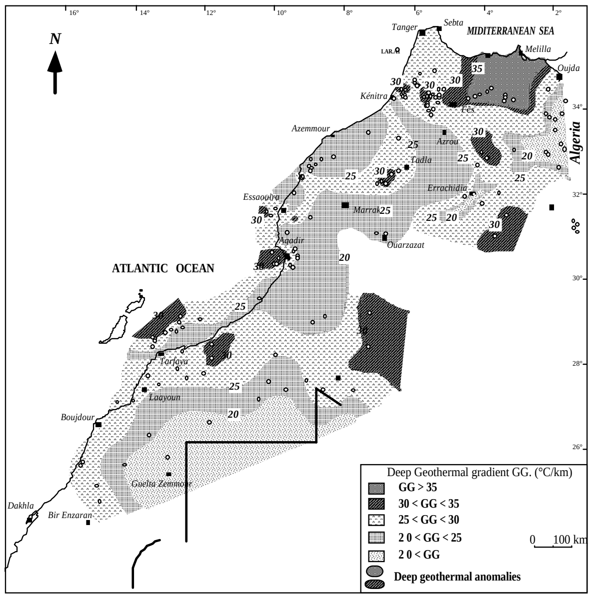

Figure 25: Geothermal gradient map of Morocco.

7. SYNTHETIC GEOTHERMAL APPROACH AND CONCLUSION.

Geothermal studies of sedimentary basin have revealed lateral as well as vertical variations in the temperature fields. These variations are commonly interpreted as resulting from thermal conductivity heterogeneities or local variations in basement heat flow. Variations many also result from groundwater flow systems. The movement of water in deep aquifers can significantly perturb the local underground temperature distribution in sedimentary basins (Zarhloule, 1994).

In sedimentary basins of Morocco, the treatment and the compilation of geological, geophysical and hydro-geothermal data allowed the construction of a conceptual model showing the relationships between topography, hydrodynamism, chemistry and temperature of the all hot aquifers in Morocco (Fig. 26).

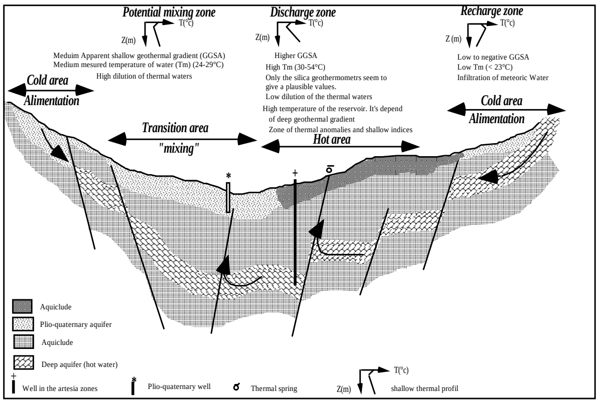

Figure 26. Conceptual model of circulation of hot water of the different aquifers in Morocco: relationship between hydrodynamism, temperature, chemistry and topography (schematic section).

The recharge zones are characterized by shallow cold water, low apparent geothermal gradient, negative anomalies and high topography. The waters are mainly HCO3-Ca-Mg type, resulting from the great influence of carbonate rocks.

The discharge zones are characterized by shallow hot water, high apparent geothermal gradient, positive anomalies and low topography. The hot springs are generaly Ca (Mg)-SO4 (Cl) or Ca (Mg)-HCO3 type, resulting from the main influence of evaporitic rocks.

The middle of the basin shows a low apparent geothermal gradient. However, the communication between the deep and the shallow aquifers found expression in a potentiel mixing zone, with a hot water and a high apparent geothermal gradient.

In general the shallow geothermal gradient is high near hot springs. Hot springs represent discharge from deep reservoir, and upward moving growndwater flow. The upward moving water may come from the centre of the basin and the discharge zone may be related to the hydrologic limit of the aquifer or to the existence of faults or fractures.

REFERENCES

Arnorsson, S.: Chemical equilibria in Icelandic geothermal systems-implication for chemical geothermometry investigations. *Geothermics*, 12, 119-128, 1983.

Arnorsson, S., Gunnlaugsson, E., and Svavarsson, H.: The element of geothermal waters in Iceland III chemical geothermometry in geothermal investigations. *Geochimica. Cosmochimica Acta*, 47, 567-577. 1983.

Ben Dhia, H., Jones, F.W., Meddeb, N., Lucazeau, F., and Bouri, S.: Shallow geothermal studies in Tunisia, comparison with deep subsuraface information. *Geothermics*, 21, 4, 503-517, 1992.

D'Amore, F., Scandifio, G., Panichi, C.: Some observation on the chemical classification of ground waters. *Geothermics*, 12**,** 141-148, 1983.

Fouillac, C., and Michard, G.: Sodium/Lithium ratio in water applied geothermometry of geothermal reservoirs. *Geothermics*, 10, 55-77, 1981.

Fournier, R.O.: A revised equation for the Na/K geothermometer. *Ress.Coun.Tran*, 3, 221-224, 1979.

Fournier, R.O., and Potter, R.W.: Magnesium correction to the chemical geothermometer. *Geochimica Cosmochimica Acta*, 43, 1543-1550, 1979.

Fournier, R.O., and Rowe, J.J.: Estimation of underground temperatures from the silica content of water from hot springs and west steam wells. *American Journal of Sciences*, 264, 685-697, 1966.

Fournier, R.O., and Truesdell, A.H.: An empirical Na-K-Ca geothermometer for naturel waters. *Geochimica Cosmochimica Acta*, 37, 1255-1275, 1973.

Giggenbach, W.F.: Geothermal solute equilibria; derivation of Na-K-Mg-Ca geoindicators. *Geochimica Cosmochimica Acta*, 52, 2749-2765, 1988.

Kharaka, Y.K and Mariner, R.H.: Chemical geothermometers and their application to formation waters from sedimentary basins. *Proceedings*, Thermal History of Sedimetary Basins, Spriga-Verlag, New York, pp. 99-117. (1989).

Lahlou Mimi, A., Zarhloule, Y., Bouri, S., Ouda, B., Lahrach, A., Ben Aabidat, L., and Ben Dhia, H.: Géochimie des eaux chaudes et prospection hydrothermale au Maghreb (NW): Caractérisation du réservoir d'origine et indices thermiques. *Bulletin de Liaison Scientifique Afro-Québécoise, canada*, II, 89-104, 1999.

Lahrach, A., Zarhloule, Y., Ben Aabidat, L., Bouri, S., Ben Dhia, H., Khattach, D., Boughriba, M., El Mandour, A., and Jebrane, R.: Géochimie des eaux chaudes et prospection géothermique de surface au Maroc septentrional: caractérisation du réservoir d'origine et indices thermiques. *Revue Hydrogéologie, BRGM, France*, 3, 7-23, 1998.

Leschak L.A., and Lewis, J.E.: Geothermal prospecting with shallow-temperature surveys. *Geophysics*, 48, 975-996, 1983.

Michard, G.: Geothermomètres chimiques. *Bulletin, BRGM*, Sect. III, 2, 183-189. 1979.

Sass, T.H., Lawyer, L.A., and Munroe, R.J.: Aheat flow reconnaissance of southeastern Alaska. *Can. Jour. Earth Sciences*, 22, 416-421, 1984.

Smith, C.: Thermal hydrology and heat flow of Beowawe geothermal area, Nevada. *Geophysics* 48, 5, 618-626, 1983.

Truesdell, A.H.: Geochimical techniques in exploration. *Proceedings, 2th U.N. Symposium on development and Use of Geothermal Resources, San Francisco 1, Liii-Ixiii, Summary of Section III* (1976).

Zarhloule, Y.: Potentialités hydrogéothermiques du bassin d'Essaouira-Agadir (Maroc). Doctorat de Spécialité. *Ecole Nationale d'Ingénieurs de Sfax sfax, Tunisie.* 240pp. 1994

Zarhloule, Y. : Les Potentialités géothermiques du Maroc: Approche intégrée par les températures profondes et indices de surface. Doctorat d'Etat es sciences. *Faculty of Sciences, Oujda, Maroc*, 153pp, 1999.

Zarhloule, Y. : La carte du gradient Géothermique du Maroc, submitted to *Bulletin de l'Institut scientifique, Section Sciences de la Terre, Rabat Maroc,* 2004.

Zarhloule, Y.: Overview of geothermal activities in Morocco, *Proceedings*, International Geothermal Conference, Mutiple integrated uses of geothermal ressources, Reykjavik 14-17 september, Iceland, 1-8 (2003).

Zarhloule, Y., Lahrach, A., Ben Aabidat, L., Bouri, S., Ben Dhia, H., and Khattach, D.: Anomalies géothermiques de surface et hydrodynamisme dans le bassin d'Agadir (Maroc). *Journal of African Earth Sciences* 27, 71-85, 1998.

Zarhloule, Y., Lahrach, A., Ben Aabidat, L., Khattach, D., Bouri, S., Boukdir, A,. and Ben Dhia, H.: La prospection géothermique de surface au Maroc: hydrodynamisme, anomalies géothermiques et indices de surface. *Journal of African Earth Sciences,* 32, 851-867, 2001.

Zarhloule, Y., Lahrach, A., Khattach, D., Beni Akhy, R., and Ben Dhia, H.: Geothermal Gradient Map of the South Western Morocco Basin. *Bulletin of The Moroccan Association Of Petroleum Geologists.* 3/99 , 10-12, 1999.