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Contribution of Geothermal Approaches to the Study of Thermal Waters in the Region of Agadez (NORTH-EAST of NIGER)

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Abstract

This study aims to estimate the temperatures reached in thermal springs reservoirs in the region of Agadez through the application of the most commonly used geothermal equations (Silica, Na/K, Na-K-Ca, Na-K-Mg) and to compare these values with those calculated from the saturation indices. The equations of these geothermometers were processed with the Excel software. The Aquachem software allowed us to know the state of equilibrium between the rocks and the thermal water and to draw the Giggembach diagram for the estimation of the reservoir temperatures of the different springs. The saturation indices (SI) show that the waters in the study area are under-saturated with respect to Halite (NaCl), Gypsum ($CaSO_4$, $2H_2O$), Fluorite and Anhydrite ($CaSO_4$). The temperature results show that the silica geothermometers (temperature between 42-100°C), the Giggembach ternary diagram (temperature between 40-100°C) and the saturation index (temperature between 60-90°C) give the same 40-100°C estimation intervals. The Agadez thermal springs can be classified among the medium energy geothermal sources, thus the possibility of recovering these sources though the production of electricity, the drying of agricultural products or metal recovery.

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Geothermal energy, Thermal springs, Saturation index, Electricity, Agadez.

Introduction

Geothermal energy is the set of techniques that extract heat from the subsoil and transform it into a source of electricity or heat.

There are four types of geothermal energy: (1) high energy (temperature between 150-400°C) mainly intended for the production of electricity, (2) medium energy (temperature between 90-150°C), used for the production of electricity, drying of agricultural products and recovery of metals [1], (3) low energy (temperature between 30-90°C), mainly used for space heating, greenhouses, fish farming and very low energy geothermal (4) (temperature below 30°C, it is used only for heating with heat pump/room air conditioning after temperature rise [2].

There are three methods for estimating the temperature of a geothermal deposit: geological, geophysical and geochemical methods.

The geological methods are based on aerial photographs and satellite imagery, the purpose of which is to search for tectonic and volcanic zones and structures and hydrothermal alterations [3]. Geophysical methods involve the use of instruments such as gravimeters. The goal is to define the lateral density variation related to the magmatic body at depth, which represents the heat source.

Geochemical methods (chemical geothermometers) are based on the chemical composition of thermal springs. It is the latter method that we will use to estimate the temperature of our geothermal reservoirs, given the lack of adequate technical means to use geophysical and geological methods. Moreover, geochemical methods are the most widely used in geothermal prospecting using chemical geothermometers. These methods are based on the balance of minerals within a geothermal reservoir.

This work is a contribution to the development of the thermal springs of Agadez. The objective is to study the geothermal energy of these springs in order to know the fields of use (electricity production, heating of premises, drying of agricultural products, recovery of metals etc .).

Presentation of the study area

Agadez is a region that covers the northern part of Niger between longitudes 6° and 15° and latitudes 16° and 22° with an area of 667,799 km2 (52.6% of the total area of the country), it is the largest of the seven regions of the country. It is bordered: to the East by Chad, to the North by Libya and Algeria, to the West by the Republic of Mali. In the country, it is bordered by the regions of Tahoua, Maradi, Zinder and Diffa to the South.

The department of Tchirozerine is bordered to the north by the communes of Dannat and Timia, to the south by that of Aderbissanat, to the east by the rural communes of Tabelot and Dabaga and to the west by the rural commune of Ingall. It covers an approximate area of 26,539 km2 with a perimeter of 601 km [4].

Three study areas have been identified (Figure 1):

- Our first study zone is located in the department of Tchirozérine, (village of Tafedek) located 20km from Tchirozerine in the North East of Agadez, at about 189 Km from Agadez, between 17°5'00" North latitude and 7°24'00" East longitude of the commune;
- The second study area is the department of Ingall located 160 km west of Agadez between 16°47'16" North latitude and 6°56'02" East longitude.

The third study area is the department of Timia, located 224 km south-east of Arlit, (Uranium extraction city) and capital of the department, and 220 km north-east of Agadez, capital of the region. It covers an area of 32,000 km2, 70% of which is occupied by mounts. Timia is located in the central part of the Aïr between 17°50' and 18°15' North latitude and 8°30' and 9°00' East longitude. With a surface area of about 267.5 km2, it is bounded by three mounts: Egalah to the north, Aroyan to the east and Iskou to the south, peaking at 1855 m, 1134 m and 1708 m respectively [5].

Geology and hydrogeology of the area

Geology

The geology of the region of Agadez is subdivided into three (3) major groups:

- The extreme Northeast by the Bilma and Djado basins;
- The central part by the Aïr characterized essentially by metamorphic and granitic rocks.
- The southwestern part of the region represents the sedimentary rock domain.

The Aïr mount is a set of high crystalline and volcanic mounts emerging from an ancient basement. It is in fact an anticlinorium, made up of isoclinal folds leaning slightly to the east. The Precambrian basement zone of the Aïr is composed of deposits of folded and metamorphosed sedimentary rocks (gneiss, shales) and volcanic rocks dating from the Lower Proterozoic. These deposits, several kilometres thick, are intersected by granitoids dating from the Suggarian and by eruptive rocks put in place during the Pan-African orogeny 600 million years ago (or in the Paleozoic for the most recent).

In the Jurassic, annular faults in the crystalline basement, located at an altitude of 500 to 1,000 m, allowed the surrection of granite peaks: Adrar Bous, Greboun (1,944 m), Mount Tamgak (1,988 m), Mount Agalak, Mount Bagzane (2,000 m) and Tarouadji. These summits are sometimes surmounted by volcanic cones or domes of various types and ages (some date from the end of the Cenozoic) [6].

Hydrogeology

Significant groundwater resources remain in the study area [6], mainly the Agadez sandstone table, the Precambrian basement table, the continental infill table, the Namurian table and alluvial aquifers:

Aquifers of Agadez sandstones: It is a multilayered reservoir made of solidified wood, sandstone. It is made up of two large groups: the Teloua sandstones (which contain the Teloua 1, 2 and 3 aquifers) and the Tchirozerine sandstones (made up of the Tchirozerine 1 and 2 aquifers) which is an alternation of clayey sandstones with analcimes glomerules and coarse conglomerate vacuolar sandstones.

Infill continental aquifer: This is a general captive aquifer with areas of open water near outcrops. It consists of lower Cretaceous sandstone and sandy-clayey continental deposits.

Namibian Aquifer: This is a multilayered series of sandstone and clayey silt with a depth often exceeding 300 m. This Namurian aquifer is made up of the Tara aquifer at the top with a thickness of 25 to 50 m and the Guezouman aquifer at the base between 50 and 60m.

Aquifer of the Precambrian basement: The basement of the basin is a foliated diorite with amphibole enclaves to which quartz veins and pegmatites are associated.

Alluvial aquifers: these are shallow aquifers buried under permeable soils with coarse sands; their renewal is ensured by rainwater.

Material and Methods

In this study, a sampling campaign was carried out in August 2019. The physico-chemical analyzes were carried out on the thermal waters of Tafadek, Ingall, Tassinik, Ingiténe, Akakara, Teghazer, Agassara, Tozayate, Awlizdig, Taganjir, Tighraya, Tekarkar, Tiffadakéne, capturing the layers of Agadez sandstone, the Precambrian basement, the intercalary and alluvial continent, The choice of the aforementioned sources is dictated by the fact that these sources are the best known and used by the population. Water samples were collected in one liter capacity polyethylene bottles. The samples were taken until overflowing in vials previously rinsed with water from the slick, then capped and labeled. They were then stored at 4 ° C in a cooler and brought to the laboratory for analysis within 24 hours. The physical parameters, namely pH, temperature, conductivity and turbidity were measured in situ using a multi-parameter device from the cyber scan PC 300 brand. The analyzes focused on the following parameters: pH (hydrogen potential), EC (electrical conductivity); temperature (T); calcium (Ca^{2+}), magnesium (Mg^{2+}), potassium (K^+), bicarbonate (HCO_3^-), nitrate (NO_3^-), nitrite (NO_2^-), fluoride (F^-), chloride (Cl^-), sulfate (SO_4^{2-}), sodium (Na^+).

All these chemical elements were analyzed at the Niger Water Exploitation Company (SEEN) laboratory in Niamey. These analyzes were carried out using a Hach DR 1900 brand spectrophotometer and the conventional methods recommended by Rodier [7]. The results of these analyzes will make it possible from certain chemical elements to estimate the temperature of the thermal spring reservoirs in the region through the application of geothermometric equations on the one hand and through the calculation of saturation indices

On the other the most commonly used geothermometric equations are Silica, Na / K, Na-K-Ca and Na-K-Mg geothermometers. Different geothermal equations have been established by different autor [8;9;10;11;12;13;14;15;16;17;18;19;20;21]. The values found through the geothermometers will be compared with those found from the saturation indice.

Principles and conditions of use of classic chemical geothermometers

Silica geothermometer

The most widely used chemical silica geothermometers in the literature are chalcedony and quartz geothermometers [7; 8; 10; 11].

They make it possible to calculate, from the silica content observed at emergence, the temperature at which quartz, chalcedony, cristobalite or silica, resulting from hydrolysis of the feldspars of crystalline rocks, have been dissolved, under reserve of verification that the observed silica does not come from dissolution at the level and temperature of the emergence, but it may very well be that part of the silica contained in the deep warm water has precipitated on the deposit of the water temperature [22]. These geothermometers give the temperatures at depth by the following formulas (Table 1).

Geothermometers

The Na/K geothermometer is based on the equilibrium reached between a plagioclase and K feldspath. Na/K should not be applied to estimate the temperature if < 1 because the calculated temperature will be higher than the true water / rock interaction temperature. But it can be used to estimate the temperature of alkaline or near neutral waters, which do not have travertines, and/or waters with low calcium concentration and high [8; 23]. The advantage of this geothermometer is less sensitive to the effects of mixing or dilution. These geothermometers are governed by the following equations (Table 2).

Geothermometer Na-K-Ca

The Na-K-Ca geothermometer is based on the perspective solubility of ions (Na, K and Ca), during reactions that affect minerals in crystallophyllian rocks and especially feldspars [8].

Estimated temperatures are calculated from the following equation:

$$T12 = \frac{1647}{log\ log\ \left(\frac{Na}{K}\right) + \frac{4}{3} log\sqrt{\frac{Ca}{Na}} + 2{,}24} - 273{,}15$$

Na-K-Mg geothermometer

The Na-K-Mg geothermometer is based on the dependence of chemical reactions involving alkaline minerals, it provides two informations on hydrotherapy from the ternary Na-K-Mg diagram proposed by Giggembach (1988): it allows to know the state of equilibrium of the water with the surrounding depth on the one hand, and used to estimate the temperature of the reservoir on the other hand [11]. The equations of these different geothermometers were processed using Excell 2013 sofware. The saturation indices were evaluated by the program PHREEQ of the diagram software. These saturation indices also estimate the temperatures of geothermal reservoirs.

Results and Discussion

The results of the various physicochemical analyzes carried out on the thermal springs of the Agadez region are presented in Table 3.

The application of twelve (12) geothermometers to our sources indicates that the T_3 geothermometer gives reservoir temperatures lower than the emergence temperature (Tem) for all sources, therefore this geothermometer underestimates the temperatures of the reservoirs.

The T_1, T_2, T_4, T_5, T_6, T_7 and T_8 silica geothermometers give reservoir temperatures between 43 and 100 ° C (Fig. 2). These values are higher than the emergence temperatures and lower than the quartz precipitation temperatures (160 ° C). The Na-K T_9, T_{10} and T_{11} geothermometers give higher temperatures than those calculated by silica geothermometers where they sometimes triple. These geothermometers are not within the estimated temperature range (25 ° C-250 ° C) given by [16; 17] therefore these geothermometers overestimate the temperatures of the reservoir.

The results of the Na-K-Ca geothermometer divide the hot springs into two groups. The first group shows temperatures below 100 ° C. These are the sources of Tiffadakéne (60.85°C), Tekarkar (42.85°C), Awlizdig (56.85°C), Agassara (58.85 ° C) and Tozayate (58.85°C). The second group shows sources of temperatures above 100°C (Tafadek, Ingall, Ingiténe, Akakara, Tighraya, Taganjir and Teghazer) (Figure 4). This difference could be related to balance problems within the reservoir of these sources (Table 4).

Analysis and interpretation of the ternary diagram Na-k-Mg

On the Giggenbach Na-K-Mg diagram established from the aquachem software, the thermal springs of Tafadek, Ingall, Akakara, Ingiténe, Tozayate, Awlizdig, Agassara are concentrated at the level of the magnesium pole (Figure 3). This indicates that the thermal waters of these areas correspond to immature waters. This may suggest a strong dilution/mixing with cold shallow water. Giggenbach's Na-K-Mg diagram also shows that the thermal waters of Tassinik and Taganjir are partially in equilibrium with the various minerals.

The ternary diagram (Figure 4) shows that the temperature of the tanks of thermal systems varies between 40 and 100°C. These results agree with silica geothermometers (43 to 100°C).

Interpretation of the temperature from the values of the saturation indices

The degree of saturation of water can be estimated by calculating the saturation index, which reaches zero when the solution is in equilibrium with a solid phase. A negative saturation index indicates under saturation and a positive index indicates over-saturation with respect to minerals [24]. Firstly, the saturation indices (SI) were calculated for all the waters sampled from the most complete analysis possible, taking into account the temperature at emergence, the major elements and traces contained in the waters. The saturation indices (SI) thus calculated for the phases present in the rocks, underline the importance of interactions between water and carbonates on the one hand and evaporates on the other.

Thermodynamic interpretation using the simulation of the concentration of major ions (Cl-, SO_4^{2-}, HCO_3^-, Ca^{2+}, Mg^{2+}, Na^+, K^+) under the effect of isothermal evaporation at 25°C, by the thermodynamic software "Phreeq C" in terms of salt/solution equilibrium, shows that the waters of the study area are:

• Undersaturated with a saturation index less than zero compared to Halite (NaCl), which causes its dissolution, leading to an enrichment of the waters of the region in sodium and chlorides (Fig. 5). • under saturated with respect to Gypsum ($CaSO_4$, $2H_2O$), fluorite and anhydrite ($CaSO_4$), which causes precipitation and dissolution leading to enrichment of the water in calcium in SO_4^{2-} and fluoride.

Table.1 Equations of silica geothermometers

Geothermometers	Equations	Authors
Quartz (T_1)	**T(°C) = 1309/ (5.19-log [SiO_2]) -273.15**	**Fournier, 1977**
Quartz (T_2)	**T(°C) = 1522/ (5,75-log [SiO_2]) -273,15**	**Fournier, 1973**
Quartz (T_3)	**T(°C) = -55,3 + 0,3659[SiO_2] – 5,3954x10^{-4}[SiO_2]^2 + 5,5132x10^{-7}[SiO_2]^3 + 74,360log[SiO_2]**	**Arnorsson, 1988**
Calcedoine (T_4)	**T(°C) = 1112/ (4,91-log [SiO2]) -273,15**	**Arnorsson, 1983**
Quartz (T_5)	**12**	**Fournier, 1973**
Quartz (T_6)	**T(°C) = -42,198 + 0,2831[SiO2] –3,6686 -4[SiO2]2 + 3,1665x10-7[SiO2]3 + 77,364log[SiO2]**	**Fournier et Potter, 1982**
Quartz (T_7)	**T(°C) = (-1117,3)/(log[SiO2] – 4,78) -273,15**	**Verma, 2000**
Quartz (T_8)	**T(°C) = 1074/ (4,59 - log[SiO2]) -273,15**	**Giampaolo et al., 1992**

Table.2 Equations of geothermometers

Geothermometres	Equations	Authors
Na-K (T_9)	**T (°C) = 933/ (0.993 + log) -273.15**	**Arnorsson, 1983**
Na-K (T_{10})	**T (°C) = 856/ (0.85 + log) -273.15**	**Truesdel, 1976**
Na-K (T_{11})	**T (°C) = 883/ (0.78 + log) -273.15**	**Tonani, 1980**

Table.3 Results of the physico-chemical parameters

Names	pH	T°	CE	Ca^{2+}	Mg^{2+}	Na^{+}	K^{+}	HCO_3^-	SO_4^{2-}	F^-	NO_3^-	Cl^-	SiO_2	Li
Tafadek	7,9	54,8	2000	6	150	600	180	2300	230	4	2	130	40	0,05
Ingall	9,5	49	4000	9	92	800	170	3000	282	2	1,86	50	28,5	0,02
Ingiténe	9	36	850	7,5	100	750	171	2900	290	2,3	1,1	70	15	0,011
Akakara	8,5	32,5	433	27	20,04	97,06	40,17	300,73	67,2	20,9	63,86	49,34	25	0,5
Tassinik	6,5	35	6780	18,3	2	699,5	99	350	280,8	1,5	4	750	5	0,14
Tighraya	6,8	37,5	3230	6	98,04	1193,93	146,25	366	147,84	18,5	63,86	231,46	18	0,03
Taganjir	9,6	29,3	7450	5	45,96	2512,06	121,68	2990,22	282,24	0,38	16,12	2737,05	17,1	0,06
Teghazer	7,9	30,2	2980	7	86,96	597,04	181,13	2290,16	97,92	1,95	1,86	136,03	16,8	0,09
Tiffadakéne	7,9	29	615	23	14,04	86,02	3,9	189,1	48,96	1,14	42,7	47,25	30	1,07
Tekarkar	9,2	26,7	218	21	15,96	13,11	3,12	101,26	12,96	0,96	17,98	23,075	25	0,03
Awlizdig	9,8	27,2	202	28	21,96	32,89	5,07	203,74	13,92	1,9	21,7	47,57	35	0,07
Agassara	8,2	34,9	235	29	6	19,09	5,85	114,68	22,08	0,57	1,86	13,135	28	0,078
Tozayate	7,1	31,8	375	30	12,96	34,04	5,07	210,45	21,12	0,95	1,86	14,91	21,05	0,06

Analyse et interpretation des geothermometres a silice, na/k, na-k-ca

Table.4 shows the results of the (12) classical geothermometres

Names	T_1	T_2	T_3	T_4	T_5	T_6	T_7	T_8	T_9	T_{10}	T_{11}	T_{12}	T°(em)
Tafadek	91,68	93,77	34,47	63,01	75,894	47,19	78,42	86,29	361,49	371,85	429,24	353,85	54,8
Ingall	77,30	81,20	30,51	48,68	64,062	44,06	62,86	69,41	311,78	316,35	365,75	396,85	49
Ingiténe	52,96	59,60	25,60	24,66	46,475	40,17	36,87	41,44	311,78	316,35	365,75	396,85	36
Akakara	72,04	76,56	29,27	43,47	60	43,08	57,21	63,30	447,85	470,53	543,66	161,85	32,5
Tighraya	59,528	65,46	26,72	31,11	50,911	41,07	43,83	48,91	218,91	215,13	251,48	378,85	37,5
Taganjir	57,761	63,89	26,41	29,37	49,695	40,81	41,96	46,89	218,91	215,13	251,48	378,85	29,3
Teghazer	57,01	63,22	26,28	28,63	49,185	40,71	41,16	46,04	361,49	371,85	429,24	385,85	30,2
Tiffadakéne	79,40	83,05	31,04	50,77	65,726	44,48	65,13	71,86	163,00	155,68	185,28	60,85	29
Tekarkar	72,04	76,56	29,27	43,47	60	43,08	57,21	63,30	311,78	316,35	365,75	42,85	26,7
Awlizdig	85,88	88,71	32,77	57,21	70,992	45,85	72,12	79,45	278,27	279,47	323,88	56,85	27,2
Agassara	76,58	80,56	30,34	47,97	63,498	43,92	62,08	68,57	361,49	371,85	429,24	58,85	34,9
Tozayate	65,37	70,66	27,85	36,88	55,056	41,95	50,07	55,61	278,27	279,47	323,88	58,85	31,8

Figure.1 Map of study areas

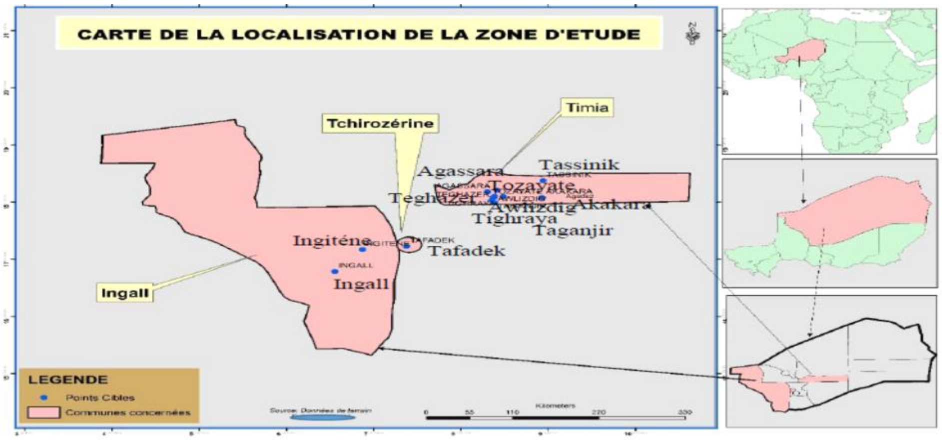


Figure.2 Thermal water temperatures calculated using different geothermometers

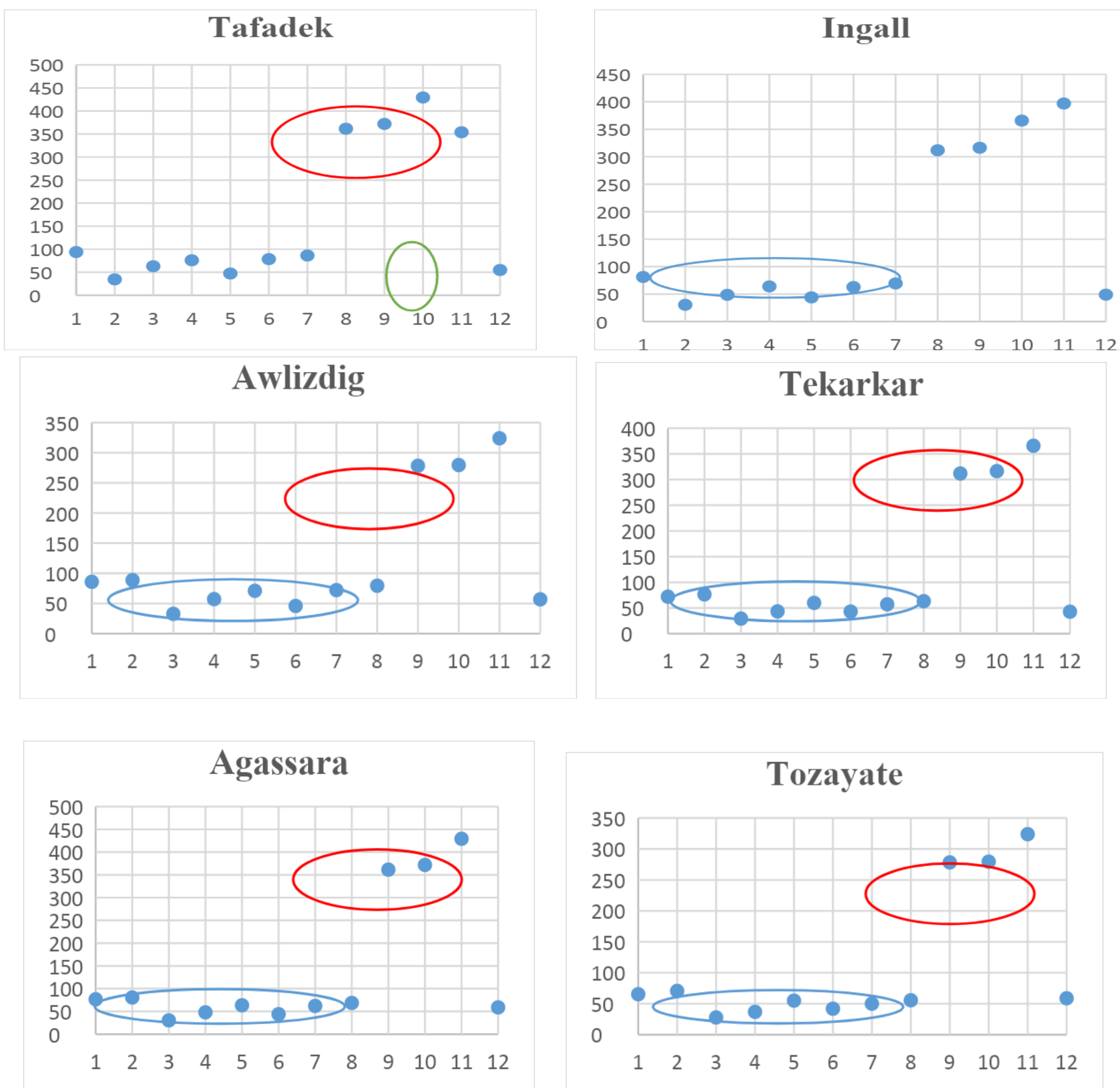
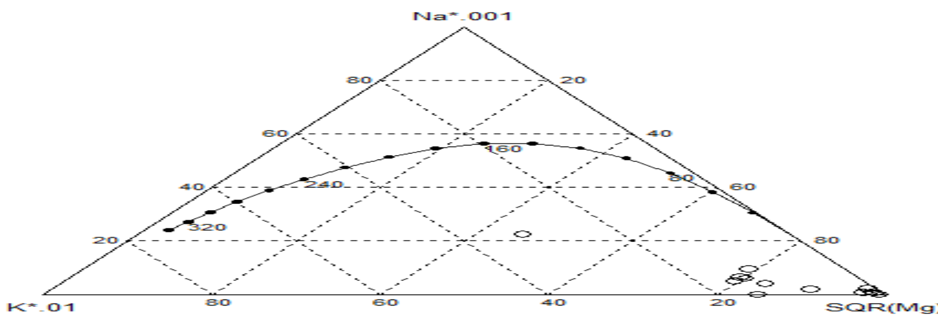


Figure.3 Representation of water on Giggenbach Na-K-Mg diagram



(Tafadek; Ingall, Akakara, Ingiténe, Tozayate, Awlizdig, Agassara)

Figure.4 Saturation index of different minerals in thermal springs

Saturation index greater than zero **Saturation index less than zero**

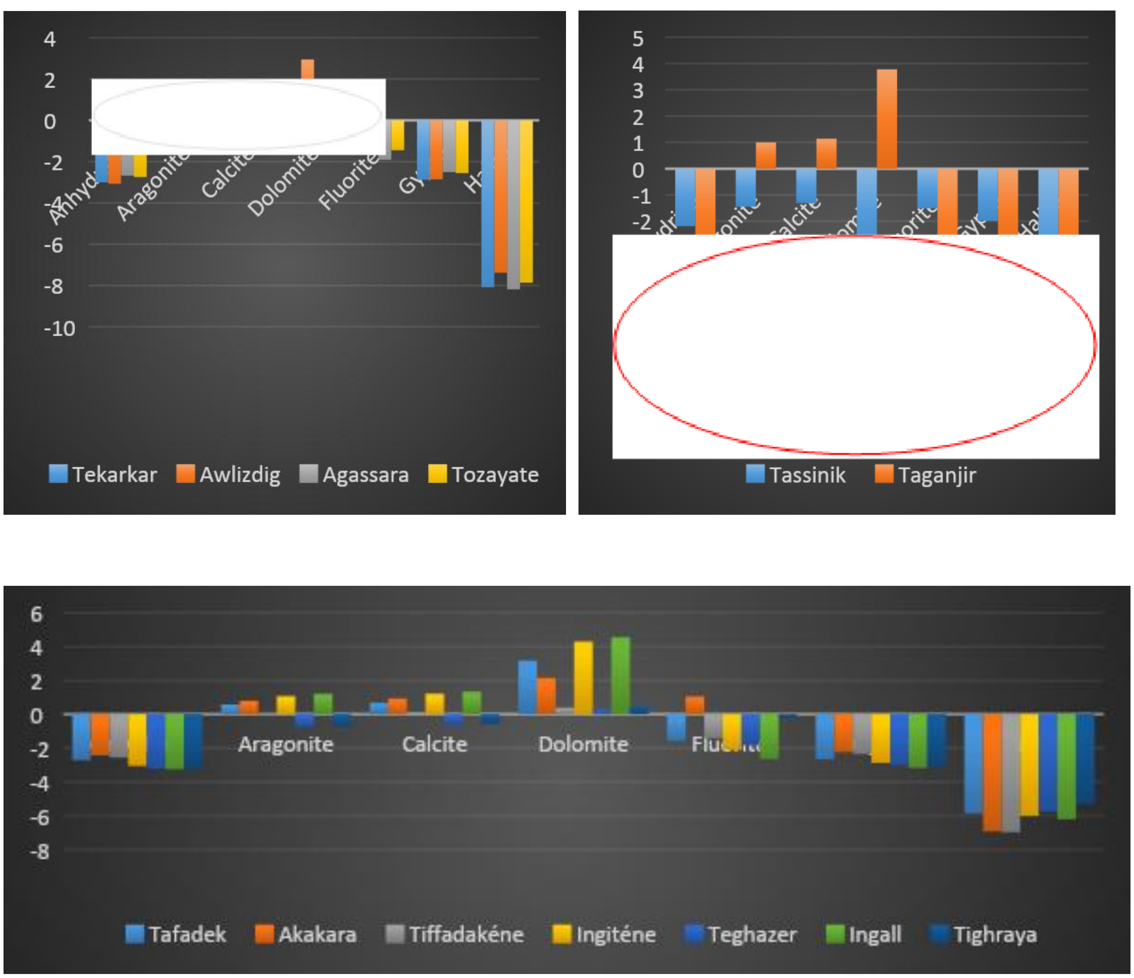
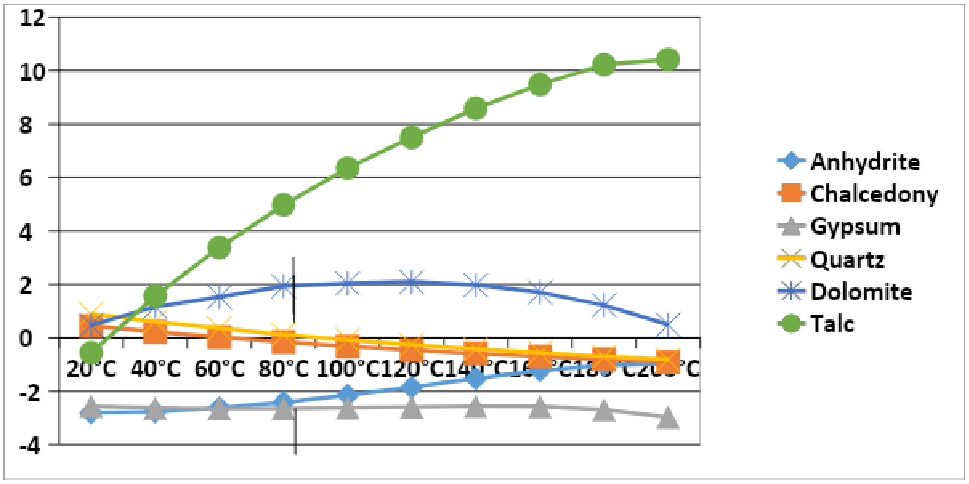
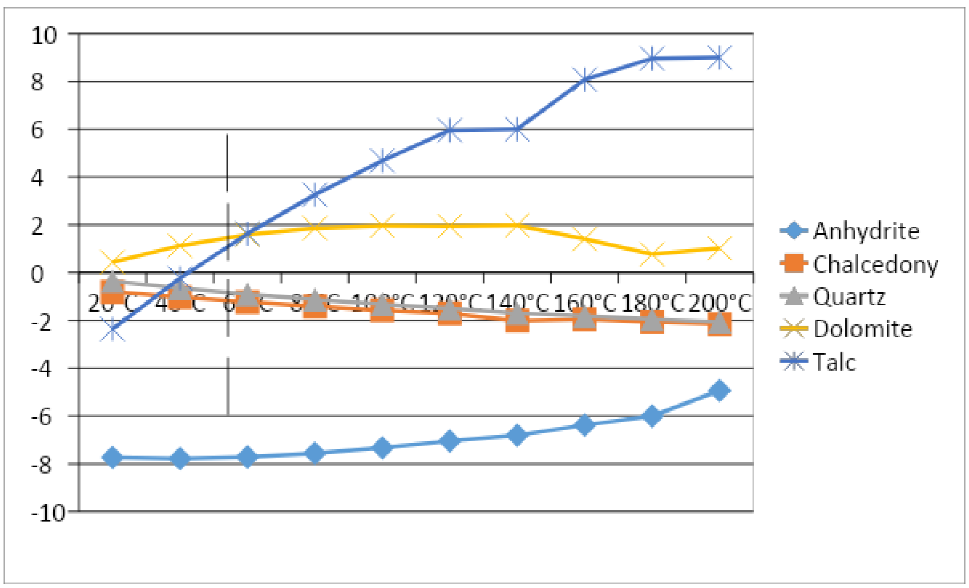


Figure.5a Mineral saturation index at different temperatures for Tafadek and 5b for Ingall

a)



b)



The various saturation index calculations make it possible to specify an interaction with salts and carbonates for almost all of the sampling points.

The second step in calculating the saturation indices provides an indication of great interest on the temperatures reached in the reservoir and thus constitutes an additional control in the use of Chemical geothermometers. The method consists of introducing the chemical composition of the solution into the thermodynamic model used (Wateq4f) and performing the calculations for all temperatures within a range around the emergence temperature [25].

We plot the variation of the saturation index of solutions with respect to different minerals, as Fonctions of temperature [26]. Usually, we find that the solutions are out of balance with all minerals except for a narrow range of temperatures for which several minerals simultaneously present a situation close to equilibrium. This range will then be retained as the range of the most probable values of the Tank temperatures.

The IS were therefore calculated for different temperatures, with increasing temperature from 20 to 200 ° C in steps of 20 ° C. These calculations were carried out for some of our sources with the highest emergence temperatures, particularly those of Tafadek and Ingall. The intersection of the curves of quartz, chalcedony, gypsum, anhydride, dolomite and talc with the line IS = 0 or very close to zero allow the temperature of the deep reservoir to be approximated at 90 ° C for the thermal spring of Tafadek and 60 ° C for the thermal spring of Ingall. These results were close to those found by silica geothermometers and Na-K-Mg geothermometers.

In conclusion, the application of different geothermometers, the Gigembach diagram and the saturation indices allowed us to estimate the temperatures reached in the geothermal reservoirs of our thermal springs. Geothermometers based on silica and quartz, gave temperatures that were close, in a range of 42°C to 100°C for the majority of our thermal springs. The ternary diagram (Giggenbach, 1988) as well as the IS method (saturation indices) also make it possible to obtain temperatures which were close, 40°C to 100°C for the Gigembah diagram and 60°C to 90°C. for the saturation indices, which leads us to conclude that the reservoir temperatures of the sources in the Agadez zone are between 40°C and 100°C. This interval makes it possible to classify these sources among sources with medium-energy geothermal energy (90 to 150°C) on the one hand and low-energy geothermal sources 30 to 90°C). Therefore, the temperature of the Agadez thermal spring reservoirs could be used as well as for power generation, agricultural products drying and metal recovery (especially the Tafadek thermal spring). The calculated saturation indices (SI) highlight the importance of interactions between waters and carbonates on the one hand and between water and evaporites on the other. They show that the waters of the study area are under saturated (saturation index less than zero) with respect to Halite (NaCl) and under saturated with respect to Gypsum ($CaSO_4$, $2H_2O$), fluorite and anhydrite. ($CaSO_4$). The disparity in the calculated temperatures can be linked to the numerous modifications of the element contents, in particular those due to water-rock interactions as well as the phenomena of dissolution, precipitation and mixing.

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