Hydrogeochemistry and Geothermometry of Thermal Groundwater from the Gulf of Suez Region, Egypt

Anwar A. El-Fiky

Hydrogeology Dept., Fac. of Earth Sciences,
King Abdulaziz University, Jeddah, Saudi Arabia

Abstract. The combined chemical composition, O and H isotopes, and the basic geologic setting of the geothermal system of the Gulf of Suez, Egypt have been investigated to evaluate the origin of the dissolved constituents and subsurface reservoir temperatures. Hydrochemical characterization of thermal waters discharged from springs and flowing artesian wells in the Gulf of Suez region show that there are two groups. One is Hammam Faroun thermal waters with salinity values exceeding 10,000 mg/l, discharge temperatures reach to 70ºC, and Na-Cl hydrochemical facies. The other group is thermal waters discharged at Hammam Mousa, Ain Sukhna, and shallow flowing artesian wells at Ayoun Mousa and Ras Sudr. They are characterized by salinity values less than 10,000 mg/l, discharge temperatures ranging from 32.5 to 72ºC and Na-Mg-Ca-Cl (Hammam Mousa), Na-Cl-SO_4 (Ain Sukhna), and Na-Ca-Cl (Ayoun Mousa-2 well and Ras Sudr-2 well) water types. Different graphical presentations using major and minor ions indicated that little mixing with sea water is probably a source of dissolved constituents. Water/rock interaction is also a major source for the dissolved constituents as revealed from Ca and HCO_3 enrichment of the thermal waters that is attributed to dissolution of carbonate minerals. Thermal waters from Hammam Faroun and Ras Sudr-2 well have the highest discharge temperatures and SiO_2 concentrations that indicate that ascending hot water at the Hammam Faroun area is slightly mixed with cold water. The thermal waters from the study area are depleted in ^{18}O and ^{2}H and fall on the Global Meteoric Water Line (GMWL) and below the local eastern Mediterranean Meteoric Water Line (MMWL) with d-excess values ranging between 3.42 and 10.6‰, which is similar to the groundwater of the Nubian aquifer in central Sinai and the Western Desert of Egypt and suggesting a common origin. This indicates that these waters are paleo-meteoric water which

recharged and flushed residual saline water in the Nubian aquifer under different climatic conditions than the modern ones. All thermal waters of the study area are undersaturated with respect to sulfate minerals (gypsum and anhydrite) and oversaturated or nearly in equilibrium with respect to aragonite, calcite and dolomite indicating that these minerals occur in the reservoir. All the thermal waters are oversaturated and nearly in equilibrium with quartz and chalcedony indicating equilibration with a sandstone aquifer free of gypsum and anhydrite with minor carbonate minerals. The subsurface reservoir temperatures were calculated using different solute geothermometers and gave temperatures ranging between 13.0 and 190.5ºC. Na/K and Na-K-Ca geothermometers gave the maximum reservoir temperatures (135-190.5ºC), whereas Na-K-Ca-Mg and Mg/Li geothermometers gave the lowest temperatures (13.0-45.9ºC). Quartz geothermometer gave the most reasonable subsurface temperatures (61.5-104.5ºC). The Hammam Faroun and Ras Sudr areas have the highest subsurface reservoir temperatures, which is consistent with the estimated high geothermal gradient of about 48ºC/km.

Keywords: Gulf of Suez, thermal waters, geothermometers, reservoir temperature, paleo-meteoric water, Nubian sandstone aquifer.

Introduction

The chemistry of thermal waters has attracted the attention of numerous studies, in particular investigations of the influence of water-rock interactions and the large diversity of the ionic composition of fluids that are found in geothermal systems (*e.g.* Mahon, 1970; Tonani, 1970; White, 1970; Fournier and Truesdell, 1973; Ellis and Mahon, 1977; Fournier, 1979; Giggenbach *et al.*, 1983; Giggenbach, 1988, Pauwels *et al.*, 1993; Tarcan and Gemici, 2003). The chemical and environmental isotope compositions were used to determine the origin of geothermal waters, in particular to distinguish between meteoric and sea water (*e.g.* Davisson *et al.*, 1994).

The geothermal fields of northeastern Egypt provide a unique setting of high temperature combined with variation in chemical composition. The distribution of the thermal systems follows the tectonic patterns of Egypt. The presence of active structural systems that characterizes the Gulf of Suez region is associated with block faulting where hot springs with temperatures up to 70ºC issue at many localities along the eastern and western coasts of the gulf. The heat for these springs is probably derived from high heat flow and deep circulation controlled by faults associated with the opening of the Red Sea and the Gulf of Suez rifts

(Morgan *et al.*, 1983). Waring, 1965 defined a thermal spring as one being 8.3ºC (15ºF) above mean annual air temperature. According to this definition, all hot springs along the Gulf of Suez can be considered as thermal springs. These springs are historically well known since the Pharaohs time where they used for medical purposes. They owe their existence to tectonic (or volcanic) heating associated with the opening of the Red Sea/Gulf of Suez rift (Boulos, 1990).

Few previous studies have investigated different aspects of the chemical and isotopic composition of geothermal waters of the Gulf of Suez region (Issar *et al*., 1971; Himida *et al*., 1972; El Kiki *et al*., 1978; Morgan *et al.*, 1983; Shata, 1990; and Sturchio *et al.*, 1996). This study presents the chemical and stable isotopic compositions (^{18}O and ^{2}H) of major geothermal water from both sides of the Gulf of Suez where thermal waters were collected from different springs of Ain Sukkna (western coast of the gulf), Hammam Faroun and Hammam Mousa (eatern coast of the gulf). Thermal groundwaters were also collected from abandoned shallow exploratory flowing artesian wells in west Sinai at Ayoun Mousa and Ras Sudr. Figure 1 shows location of these springs and wells on both coasts of the Gulf of Suez. The aim is to provide an overall assessment on the origin of the thermal groundwater and geochemical processes giving rise to salinities of these waters as well as estimation of the subsurface reservoir temperatures.

General Geology and Hydrogeology

The Gulf of Suez represents a typical interior basin. The evolution of this basin is characterized by tectonic extensional episodes producing tension block faulting (horst and graben) and block subsidence (Kingston *et al*., 1983). Schütz (1994) described the Gulf of Suez as a good example of a model extensional regime. It is an intracratonic basin that originated in the early Miocene. The Gulf of Suez graben was formed after the Eocene, as shown by structural trends and sediment distribution of the Cretaceous and lower and middle Eocene. Pre-Miocene sediments were deposited on a craton or in epicontinental seas. Rifting began in the Gulf of Suez after the Oligocene, and is documented primarily by an Upper Oligocene planation surface on both sides of the Gulf of Aqaba and the southern Gulf of Suez (Quennell, 1984). Garfunkel and Bartov (1977) dated basalt intrusions and flows in the Gulf of Suez as early

Miocene. In the Gulf of Suez, major uplift and rifting clearly occurred simultaneously. Schütz (1994) stated that the opening of the Gulf of Suez is certainly related to the initial opening of the Red Sea based on the sediment and evaporite record in both basins.
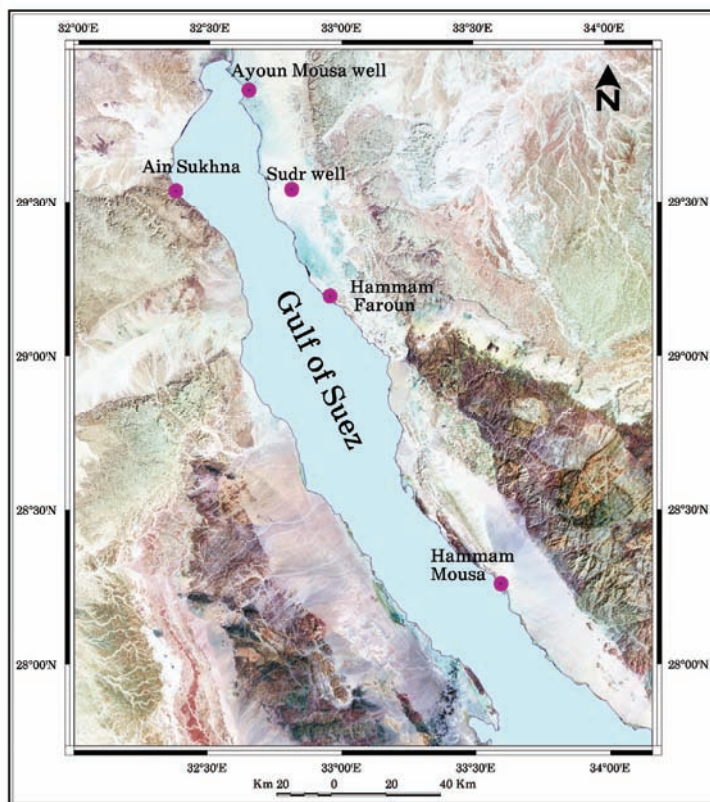

Fig. 1. Location map of the thermal groundwaters at the Gulf of Suez region.

Shata (1990) differentiated the sediments of the Gulf of Suez into two major types: a) Pre-rift sediments (1500 to 3000 m) dominated by sand and shale facies and showing an increase of the carbonate members both northward and upward in the succession. These sediments rest on the Pre-Cambrian basement rocks. b) Syn-rift sediments (500-5000 m) dominated by sand, shale and evaporites, with local carbonate interbeds. These sediments rest either on the basement rocks or on the pre-rift sediments. General stratigraphic section of the Gulf of Suez region is shown in Fig. 2.
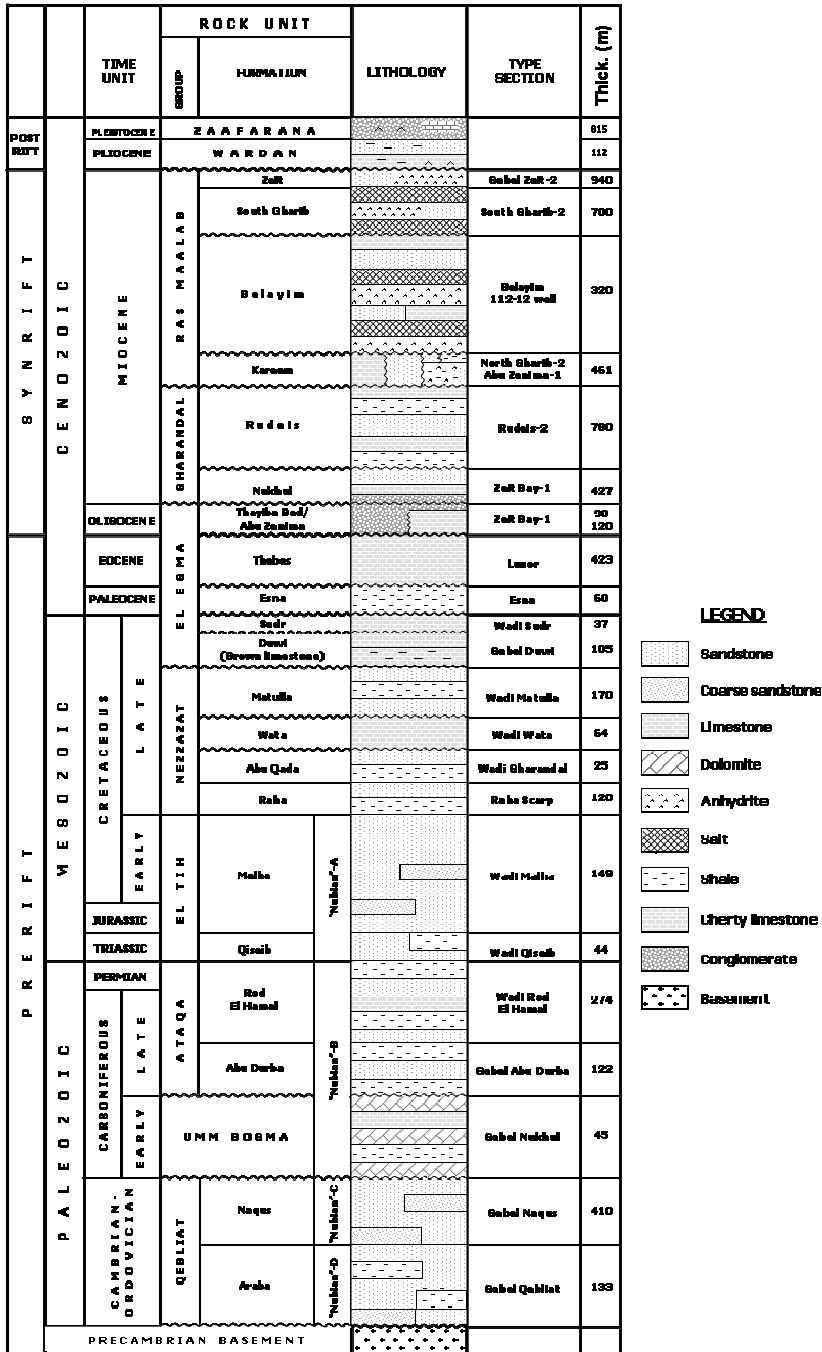
	TIME UNIT	ROCK UNIT			LITHOLOGY	TYPE SECTION	Thick. (m)
		GROUP	FORMATION				
POST RIFT	PLEISTOCENE	Z A A F A R A N A					815
	PLIOCENE	W A R D A N					112
S Y N R I F T / C E N O Z O I C	MIOCENE	RAS MAALAB	Zeit			Gabal Zeit-2	940
			South Gharib			South Gharib-2	700
			Belayim			Belayim 112-12 well	320
		GHARANDAL	Kareem			North Gharib-2 Abu Zenima-1	461
			Rudeis			Rudeis-2	780
			Nukhul			Zeit Bay-1	427
	OLIGOCENE	EL EGMA	Thoyiba Bed/ Abu Zenima			Zeit Bay-1	90 / 120
	EOCENE		Thebes			Luxor	423
	PALEOCENE		Esna			Esna	60
PRE-RIFT / MESOZOIC	CRETACEOUS LATE	NEZZAZAT	Sudr			Wadi Sudr	37
			Duwi (Brown limestone)			Gabal Duwi	105
			Matulla			Wadi Matulla	170
			Wata			Wadi Wata	64
			Abu Qada			Wadi Gharandal	25
			Raha			Raha Scarp	120
	CRETACEOUS EARLY	EL TIH	Malha	"Nubian" A		Wadi Malha	149
	JURASSIC						
	TRIASSIC		Qiseib			Wadi Qiseib	44
PRE-RIFT / PALEOZOIC	PERMIAN	ATAQA	Red El Hamal	"Nubian" B		Wadi Red El Hamal	274
	CARBONIFEROUS LATE		Abu Durba			Gabal Abu Durba	122
	CARBONIFEROUS EARLY		UMM BOGMA			Gabal Nukhul	45
	CAMBRIAN-ORDOVICIAN	QEBLIAT	Naqus	"Nubian" C		Gabal Naqus	410
			Araba	"Nubian" D		Gabal Qebliat	133
		PRECAMBRIAN BASEMENT					

LEGEND
- Sandstone
- Coarse sandstone
- Limestone
- Dolomite
- Anhydrite
- Salt
- Shale
- Cherty limestone
- Conglomerate
- Basement

Fig. 2. Generalized stratigraphic section of the Gulf of Suez (Alsharhan, 2003).

The Gulf of Suez region is surrounded on both sides by extensive mountainous areas that act as major watershed areas, which are dissected by great number of wadis draining either towards east or west. This region receives an average amount of rains of about 1000×10^6 m^3/y that increase periodically to more than 5000×10^6 m^3/y (Shata, 1990). These watershed areas in the Eastern Desert and Sinai are the main recharge areas of groundwater in the Gulf of Suez region. The complex fault systems in this region, which are active in the Quaternary time, play an important role in the recharge and discharge phenomena (Shata, 1990). Such faults allow the formation of discharging conduits for water ascending from depths after being heated and mixed with other water types.

The Ain Sukhna fault is a major important, old structural element in the Gulf of Suez. It is only a part of a much longer fault system, which cuts through the Gulf of Suez to the southeast along the west coast of Sinai near Lagia and farther into the Sinai basement into Wadi Feiran (Schütz, 1994). This fault is probably an older Jurassic fault, but reactivation occurred during the early Miocene, resulting in major displacement. This fault is remarkable for hot spring at Ain Sukhna on the west coast and at Hammam Faroun, south of Lagia on the east coast. The Ain Sukhna spring issues directly onshore at about 55 km to the south of Suez city. According to Diab (1969) and Desouki *et al.* (2006), Ain Sukhna hot spring (32.5ºC) issues from the Cretaceous aquifer where groundwater freely flows by upward rising of the deeply circulating Nubian water through the fissures and fractures under high pressure head. It is mixed with normal seawater intrusion in the Quaternary aquifer. The recharge of this spring is probably from the surrounding high scarps and hills located along the coastal area.

Hammam Faroun springs issue from the shore cliff of Gebel Hammam Faroun. The thermal water (70ºC) issues from faulted, dolomitic Eocene limestones. The Hammam Mousa spring (known as Moses Baths) is located to the south of Hammam Faroun springs at El-Tor city (Fig. 1), where thermal groundwater issues with a temperature of 37ºC from faulted Miocene rocks near the shore. Its waters have been used for bathing since ancient times and are said by many to have the ability to cure skin diseases and arthritis due their high percentage of magnesium, sodium and sulfur (El Ramly 1969).

Oil exploration wells at Ayoun Mousa in western Sinai have shown that the Nubian sandstone is found at rather shallow depth (75-100 m) unconformably overlain by Miocene sediments (Issar *et al*., 1972). The Nubian sandstone layers were found to contain water at artesian pressures with salinities ranging from 1000 to 4000 mg/l. Groundwater at Ayoun Musa-2 well is discharged under artesian pressure from the shallow Jurassic Nubian sandstone aquifer with a temperature of 37ºC. This aquifer is composed of friable sands and sandstones of Bajocian age that is capped by thick Bathonian-Callovian compact clays and claystones (Issar *et al*., 1971; and Himida *et al*., 1972). Groundwater is also discharged from Ras Sudr-2 flowing well that is tapping the Eocene aquifer (Issar *et al*., 1971) where the thermal water discharge temperature reaches 72ºC.

Issar (1979 and 1981) concluded that Tertiary marine waters have been thoroughly flushed from the Upper Jurassic-Lower Cretaceous (Nubian) sandstone aquifer of the Sinai Peninsula. Residual saline waters of marine origin are also present in older and deeper formations of Mesozoic and Paleozoic age (Bentor, 1969; Fleischer *et al*., 1977; Issar, 1979 and 1981). The entire study area is also strongly affected by deep-seated faulting which may facilitate infiltration of sea water and mixing with other groundwaters and residual saline water. It is suggested that high geothermal gradients occur mainly in the immediate proximity of major faults (Issar *et al*., 1971; Morgan *et al.*, 1983). Therefore, sources of the different chemical constituents in thermal waters are variable and include mixing between groundwater of meteoric origin and modern Red Sea water and/or residual saline water. Rock-water interaction plays also an important role in modifying the chemical composition of the thermal waters.

Methods

Thermal Water Sampling and Analyses

Eight thermal groundwater samples were collected during January 2005 from the coastal springs on both sides of the Gulf of Suez and from shallow artesian wells at Ayoun Mousa and Ras Sudr (Fig. 1). Temperature (T), specific electric conductance (EC) and pH were measured in the field. Total alkalinity was also measured in the field by acid titration from unfiltered water samples. Groundwater samples were

field-filtered through a 0.45 µm filters and filled into acid-washed bottles and acidified. Water samples were analyzed for major and minor dissolved chemical constituents. Ca, Mg and Cl were determined by titration methods. SO_4 was determined using turbidimetric method. Na and K were analyzed using flame photometer. SiO_2 was determined using ammonium molybdate spectrophotmetric method. All the previous analyses were carried out in the Department of Environmental Sciences, Faculty of Science, Alexandria University. Lithium (Li) was determined using PerkinElmer ICP Optima 2000 DV at the Faculty of Earth Sciences, King Abdulaziz University, Jeddah, Kingdom of Saudi Arabia. Br was determined using ion selective electrode Ionometer, Orion-930 at the Desert Research Center, Cairo. Stable isotopes of oxygen and hydrogen (^{18}O, ^2H or D) were performed at the Institute for Groundwater Ecology (GSF) in Munich, Germany according to methods given in Moser and Rauert (1980). Stable isotope compositions ($^{18}O/^{16}O$, D/H) are expressed using the usual δ notation:

$$\delta\ (‰) = [(R_{sample} - R_{standard})/R_{standard}] \times 10^3$$

where R is the ratio of the heavy to light isotope abundances. For ^{18}O and ^2H, the V-SMOW standard was used. In addition, chemical and isotopic compositions of the Red Sea water (Wilson, 1975 and Craig, 1969) have been taken into account in this study. The chemical analysis was carried out as per the procedure given in APHA (1998). The analytical precision for the measurements of ions was determined by calculating the ionic balance error, which is generally within ± 5%.

Mineral saturation indices for a number of common minerals potentially present in the studied localities were calculated at measured discharge temperatures by PHREEQC (Parkhurst and Appelo, 1999) interfaced with AquaChem 5.0.

Results and Discussion

Hydrogeochemical Properties of Thermal Waters

Results of chemical and isotopic analyses of thermal waters discharged at both sides of the Gulf of Suez are given in Table 1. Dissolved ions in the sampled waters in the study area could be mainly derived from reactions of thermal waters with host rocks in addition to

Table 1. Chemical and isotopic compositions and field data of the thermal groundwaters sampled from the Gulf of Suez region. (Major and minor constituents are in mg/l).

No.	Sample name	Location	T°C	pH	EC (µS/cm)	TDS (mg/l)	Ca	Mg	Na	K	HCO$_3$	SO$_4$	Cl	Br	SiO$_2$	Li	δ^{18}O (‰)	δ^{2}H (‰)	d-excess (‰)
1	Hammam Faroun 1	West Sinai	70	6.48	30000	16800	1039	489	4750	130	132	1450	9654	50.2	53	0.38	-5.59	-41.3	3.42
2	Hammam Faroun 2	West Sinai	60	6.94	28000	15000	1002	430	4560	115	86	1450	8634	43.1	52	0.37	-5.81	-41.2	5.28
3	Hammam Faroun 3	West Sinai	51	7.16	28000	15000	1039	422	4280	117	103	1450	8713	44.5	51.8	0.36	-5.78	-41.5	4.74
4	Hammam Faroun 4	West Sinai	39	7.03	31000	16900	1039	445	4850	120	103	1440	9423	49.6	52	0.36	n.d.	n.d.	n.d.
5	Ayoun Mousa-2 well	West Sinai	37	7.02	5100	3500	205	75	710	40	155	410	1450	8.2	19	0.11	-5.88	-39	8.04
6	Ras Sudr-2 well	West Sinai	72	6.66	12300	8000	594	267	1794	60	287	1250	3768	6.6	48.7	0.35	-6.14	-42.4	6.72
7	Hammam Mousa	West Sinai	37	7.61	12800	8192	540	335	1610	58	132	1160	3710	36.2	23	0.11	-6.1	-38.2	10.6
8	Ain Sukhna	Eastern Desert	32.5	7.61	13200	8400	408	250	1970	75	207	1300	3730	17.4	22	0.13	-6.7	-45.7	7.9

mixing of these waters with other water types. Hydrochemical water types were determined using total equivalents of cations and anions of 100% and ions more than 10% were evaluated in the classification. Thermal waters vary from slightly acidic to slightly alkaline where the pH values range from 6.48 to 7.61 and may be divided into two main groups on the basis of the concentrations of their dissolved solids. One group is of hot water discharged at the Hammam Faroun springs on the eastern coast of the Gulf of Suez. These waters are characterized as Na-Cl type, having average total dissolved solids (TDS) value of 15,925 mg/l and discharge temperatures reach 70°C. Average concentrations of sodium and chloride are about 4,610 and 9,106 mg/l, respectively. The high salinity and the Na-Cl water type may reflect that the seawater component of these thermal waters may be high. However, this water type may result from dissolution of Middle Miocene evaporites, which are common in the Gulf of Suez region and reaches a thickness of about 610 m in Ras Lagia in the vicinity of Hammam Faroun (Sturchio et al., 1996). The second group of hot waters (Hammam Mousa, Ain Sukhna, Ayoun Mousa-2 well and Ras Sudr-2 well) having TDS ranging from 3,500 to 8,400 mg/l and discharge temperatures varying between 32.5 and 72°C. This group is characterized by different water types of Na-Mg-Ca-Cl (Hammam Mousa), Na-Cl-SO$_4$ (Ain Sukhna), and Na-Ca-Cl (Ayoun Mousa-2 well and Ras Sudr-2 well). Variable water types may indicate different hydrogeochemical processes such as mixing and water-rock interaction.

A Piper trilinear diagram (Fig. 3) shows that all the thermal waters are characterized by the dominance of Cl+SO$_4$ over HCO$_3$ and Na+K over Ca+Mg. Their chemistry probably results from mixing with sea water. It also indicates that the thermal waters show increasing trend of Ca and Mg from Hammam Faroun towards Hammam Mousa which is reflected in the closeness of Hammam Faroun plot to that of the Red Sea.

This may indicate that mixing with sea water is possibly high at Hammam Faroun, which is consistent with the high salinity values of thermal water discharged at this locality. However, high salinity values may also be derived from dissolution of thick Miocene evaporites, which can also give rise to the Na-Cl water type.
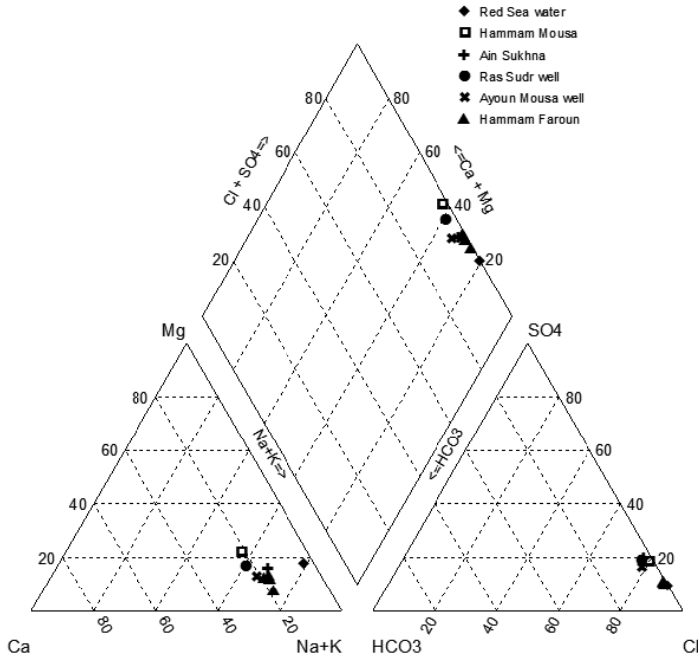
Fig. 3. Distribution of the thermal waters from the study area in Piper diagram.

As shown in the Schoeller diagram (Fig. 4), thermal waters and sea water give similar signatures except for the relative proportions of Ca and Mg, where thermal waters are enriched in Ca. This reflects that mixing with sea water is probably one of the factors responsible for the current hydrochemistry of thermal waters. Due to less sea water but more groundwater mixing, thermal water of Ayoun Mousa well plot at lower levels on the Schoeller diagram. Hammam Faroun thermal waters plot near sea water reflecting more mixing with sea water. Enrichment of Ca in thermal waters than sea water may be attributed to dissolution of carbonate rocks encountered along the flow path of groundwater, which is enhanced by the increase of temperature.

Correlation coefficients of major and some minor ions were computed using values of concentrations of the different ions in mg/l. The concentrations of ions were plotted against chloride (Cl), which is regarded as chemically conservative. The relations of the constituents in thermal water samples from the study area are presented in Fig. 5. The high positive correlation (0.99) between Cl and Na indicates that high Cl

concentrations of thermal water arise from the contribution of sea water. Similarly, the other major and minor constituents show good positive linear correlations (0.78-0.98) with Cl. A negative correlation (–0.61) is observed between Cl and HCO_3. This indicates that the contribution of sea water causes an increase in the Cl concentrations but a decrease in the concentrations of HCO_3 in the thermal waters. Enrichment of HCO_3 together with Ca in thermal waters may be caused by dissolution of carbonate minerals.
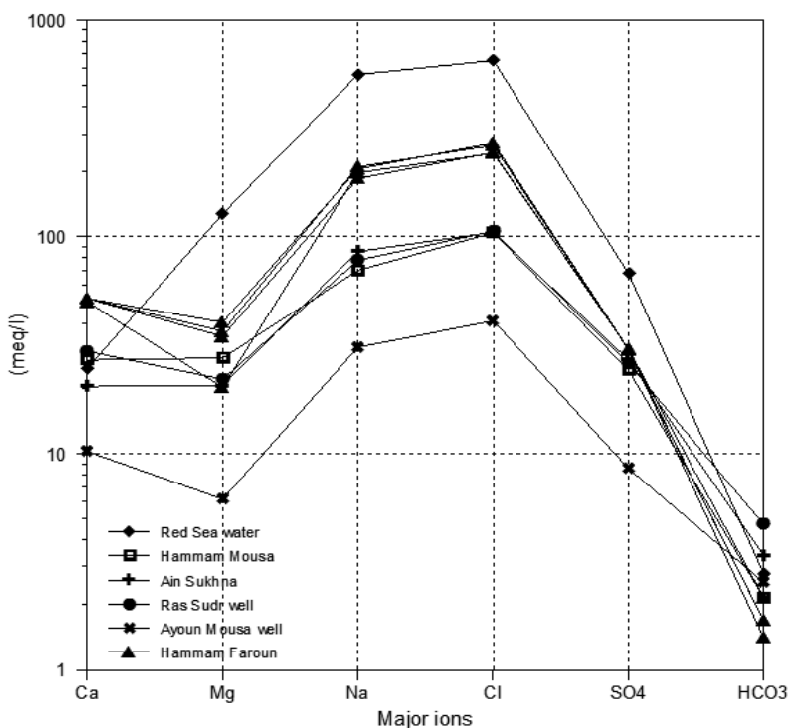
Fig. 4. Schoeller diagram for the thermal waters from the study area.

In high temperature thermal systems, Mg is incorporated into secondary alteration minerals by ion exchange reactions resulting in very low Mg levels (Nicholson, 1993). Since the Cl concentration of water from deep reservoir is generally high, a negative correlation is expected between Cl and Mg. However, a high positive correlation (0.93) or high concentrations of Mg, indicates that ascending hot water is mixed with cold water.
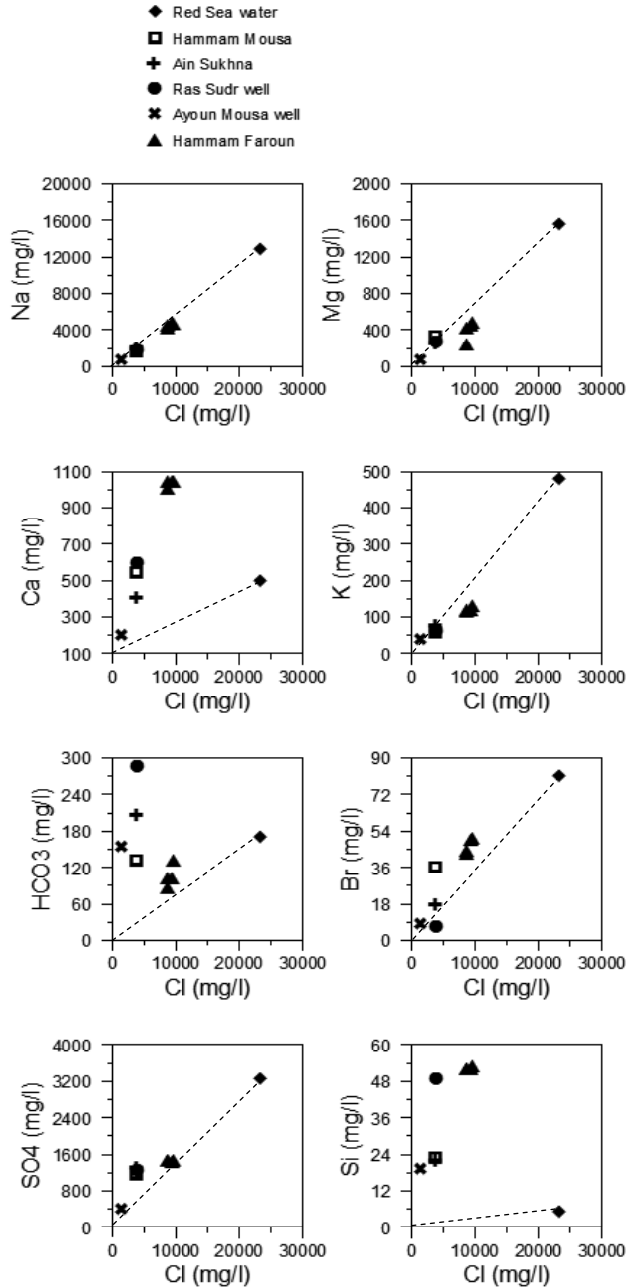
Fig. 5. Relations between various ions versus chloride for the thermal waters from the coastal area of the Gulf of Suez.

Figure 5 shows that the relations between Na, K, Mg, Br, SO_4 and Cl strongly confirm the mixing process and contribution of sea water where the plotted points can occur along the mixing line between thermal waters and sea water end member. However, thermal groundwaters are enriched with Ca, where they are plotted above the mixing line. This can be attributed to the dissolution of carbonate rocks. Thermal waters discharged at Hammam Faroun show high Ca levels, which are possibly derived from faulted, dolomitic Eocene limestones commonly encountered at this locality. According to the relations of the ions (Fig. 5), it is suggested that the initial aqueous solution was a mixture of sea water and local meteoric water.

As the temperature increases, the concentration of SiO_2 is expected to increase, which is observed from the thermal waters of the study area. Thermal waters from Hammam Faroun and Ras Sudr-2 well have the highest discharge temperatures and SiO_2 concentrations. This may indicate that ascending thermal waters at the Hammam Faroun springs is slightly mixed with cold water.

Isotopic Properties of Thermal Waters

The oxygen (^{18}O) and hydrogen isotope (deuterium, ^2H or D) compositions of the thermal waters from the Gulf of Suez region show narrow ranges of variation, with $\delta^{18}O$ and δD values ranging from –6.7‰ (Ain Sukhna) to –5.59‰ (Hammam Faroun) and –45.7‰ (Ain Sukhna) to –38.2‰ (Hammam Mousa), respectively (Table 1). The relationship between $\delta^{18}O$ and δD (Fig. 6) for the thermal waters from the study area shows that these waters fall on and just below the global meteoric water line (GMWL), $\delta^2H = 8\ \delta^{18}O + 10$, given by Craig (1961) with d-excess value of ~10‰. The points representing thermal waters plot away from that of the Red Sea water, which indicates that the thermal waters are depleted in ^{18}O and D with respect to sea water and reflects their meteoric origin and little contribution of sea water. The thermal waters have d-excess values ranging from 3.42 to 10.6‰ (Table 1).

Figure 6 also shows that the thermal waters plot away from the local or eastern Mediterranean meteoric water line (MMWL), $\delta^2H = 8\ \delta^{18}O + 22$, given by Gat *et al*. (1969) and IAEA (1981), which represents modern Mediterranean precipitation. This line indicates deuterium enrichment in

the modern Mediterranean precipitation with d-excess value of ~22‰. It has been suggested that low d-excess values around 10‰ indicate paleo-recharge (>30 ka BP), while higher d-excess values (>20‰) indicate modern-day recharge (Vengosh, 2007). The thermal waters from the study area are depleted in deuterium with d-excess values around 10‰ similar to the groundwater of the Nubian aquifer in central Sinai (Issar *et al*., 1971; Vengosh, *et al*., 2007) and the Western Desert of Egypt (El-Fiky and El-Maghraby, 2004), which indicate that these waters have a common origin. These waters are meteoric waters, which recharged the Nubian aquifer under different climatic conditions than the modern ones, where they have d-excess values around that of the global meteoric water line (GMWL). Therefore, the thermal waters from the study area are paleowaters of meteoric origin that flushed and mixed with residual saline water in the Nubian sandstone aquifer. This is also consistent with works of Issar *et al*. (1972), Gat and Issar (1974) and Sturchio *et al*. (1996).
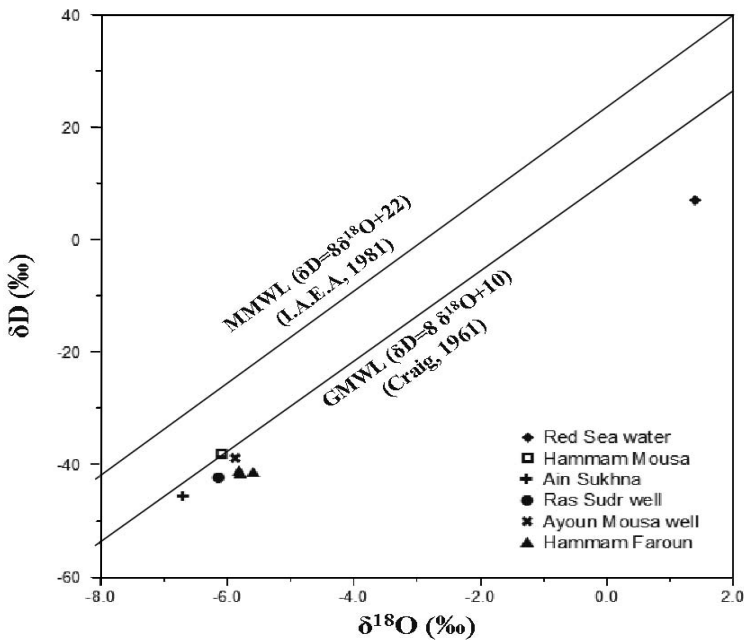

Fig. 6. Plot of ^{18}O-^{2}H for the thermal waters from the Gulf of Suez region and the Red Sea water. GMWL, global meteoric water line (Craig, 1961); MMWL, Mediterranean meteoric water line (I.A.E.A., 1981).

The isotopic composition of the Hammam Faroun thermal water, of the highest salinity values, is quite similar to that of Ayoun Mousa-2 well

of much lower salinity value. This may indicate that the source of salinity of thermal waters at Hammam Faroun is not totally mixing with residual marine water but may be dissolution of Miocene evaporites and/or dissolution of marine aerosols or evaporite dust (from coastal sabkahas) in the recharge area as suggested by Sturchio *et al*. (1996).

Mineral Saturation Status

Mineral equilibrium calculations are useful in predicting the presence of reactive minerals and estimating mineral reactivity in a groundwater system. By using the saturation index approach it is possible to predict the reactive minerals in the subsurface from the groundwater chemical data without examining samples of the solid phases (Deutsch, 1997). It is important to know saturation indices for some carbonate (calcite, aragonite and dolomite), sulfate (gypsum and anhydrite), and silica (quartz and chalcedony) minerals to predict which ones may precipitate or dissolve during flow paths of thermal waters. A saturation index of zero indicates that the ion activity product and the solubility product are equal, and that thermodynamic equilibrium exists with the solid phase. A negative or positive index indicates undersaturation or oversaturation, respectively. Mineral saturation indices for a number of common minerals potentially present in the studied localities were calculated at measured discharge temperatures (Table 2).

Table 2. Saturation indices of the thermal waters from the study area.

No.	Sample name	Aragonite	Calcite	Dolomite	Gypsum	Anhydrite	Quartz	Chalcedony
1	Hammam Faroun 1	−0.04	0.08	0.30	−0.37	−0.24	0.40	0.09
2	Hammam Faroun 2	0.11	0.23	0.61	−0.35	−0.33	0.50	0.17
3	Hammam Faroun 3	0.32	0.44	1.02	−0.33	−0.38	0.61	0.25
4	Hammam Faroun 4	0.04	0.18	0.48	−0.34	−0.48	0.77	0.38
5	Ayoum Mousa-2 well	−0.20	−0.07	−0.12	−0.99	−1.15	0.32	−0.08
6	Ras Sudr-2 well	0.39	0.50	1.07	−0.41	−0.27	0.31	0.01
7	Hammam Mousa	0.53	0.67	1.58	−0.48	−0.63	0.41	0.02
8	Ain Sukhna	0.55	0.69	1.58	−0.51	−0.70	0.45	0.05

All thermal waters of the study area are undersaturated with respect to sulfate minerals (gypsum and anhydrite). Most are oversaturated or nearly in equilibrium with respect to aragonite, calcite and dolomite

indicating that these minerals occur in the reservoir. Regarding SiO_2 minerals, all thermal waters are oversaturated and nearly in equilibrium with quartz and chalcedony indicating equilibration with a sandstone aquifer free of gypsum and anhydrite with minor carbonate minerals. This is consistent with the nature of the Nubian sandstone aquifer, which is considered as the main source of thermal waters in the Gulf of Suez region.

Solute Geothermometry

The chemical composition of thermal waters can provide valuable information on their origin. Various chemical geothermometers have been developed to predict the subsurface reservoir temperatures in geothermal system (Fournier and Truesdell, 1973; D'Amore *et al*., 1987; Giggenbach, 1988). Dissolved silica and certain cation ratios in deep waters that have experienced prolonged interaction with rocks are usually controlled by temperature-dependent reactions between minerals and the circulating fluids (*e.g.* Fournier, 1973). Geothermometers represent the equilibria of these temperature-dependent reactions, and geotherm-ometric analysis can indicate the temperature of the reservoir yielding the deep waters. Because they use only a few chemical components analyzed, variable temperatures can be frequently predicted for a same fluid. These temperature variations may be due to the lack of equilibrium between solutes and minerals or due to additional processes (including mixing with cold water in the upflow). If a geothermometer is to represent accurately reservoir conditions, not only must equilibrium conditions be reached between the ions and the water, but the water must rise relatively rapidly to the surface without chemical alteration due to processes such as evaporation, precipitation or mixing. Chemical analyses of thermal waters from the study area (Table 1) were used to estimate the subsurface reservoir temperatures by several solute geothermometers. Different geothermometers were applied to the thermal waters of the Gulf of Suez region: chalcedony and quartz (Fournier, 1973 and 1977), Na/K (Giggenbach, 1988), Na-K-Ca (Fournier and Truesdell, 1973), Na-K-Ca-Mg (Fournier and Potter, 1979) and K^2/Mg (Giggenbach, 1988), Na/Li and Mg/Li (Kharaka and Mariner, 1989). Temperatures calculated by these geothermometers for the thermal waters discharged from springs and flowing artesian wells in the Gulf of Suez region are given in Table 3.

Table 3. Geothermometric temperatures (ºC) calculated using different methods.

Sample	Hammam Faroun 1	Hammam Faroun 2	Hammam Faroun 3	Hammam Faroun 4	Ayoun Mousa-2 well	Ras Sudr-2 well	Hammam Mousa	Ain Sukhna
Discharge temperature (ºC)	70	60	51	39	37	72	37	32.5
Geothermometry								
(a) SiO_2 (Chalcedony)	74.8	73.9	73.7	73.9	29.4	70.6	36.9	35.1
(b) SiO_2 (Quartz)	104.5	103.6	103.5	103.6	61.5	100.6	68.8	67.1
(c) Na/K	146.6	142.1	146.5	141.1	190.5	157.9	162.3	165.6
(d) Na-K-Ca	139.1	135.2	137.5	135.0	155.9	137.8	140.2	147.9
(e) Na-K-Ca-Mg	29.1	34.2	37.5	33.0	45.9	29.8	20.2	24.9
(f) K^2/Mg	80.9	79.5	80.1	80.1	75.0	69.7	66.3	75.7
(g) Na/Li	51.8	52.2	53.2	49.6	72.0	79.6	47.3	46.3
(h) Mg/Li	31.1	31.8	31.4	31.0	25.7	35.2	13.0	18.2

Results of the different solute geothermometers show that the subsurface reservoir temperatures varied between 13.0 and 190.5ºC. Na/K and Na-K-Ca geothermometers gave the maximum reservoir temperatures (135-190.5ºC), whereas Na-K-Ca-Mg and Mg/Li geothermometers gave the lowest temperatures (13.0-45.9ºC).

A geothermometric technique that discriminates between ''immature waters'' and ''fully equilibrated waters'' coming from deep geothermal reservoirs was proposed by Giggenbach (1988). This technique offers a clear distinction between waters suitable or unsuitable for the application of ionic solute geothermometers. The technique involves combining the Na/K and K^2/Mg geothermometers by means of a Na-K-Mg$^{1/2}$ triangular plot. Giggenbach (1988) divided thermal fluids into three main groups depending on the equilibrium of Na, K and Mg ions as (i) fully equilibrated waters (ii) partially equilibrated waters and (iii) immature waters. Because the Na/K geothermometer readjusts relatively slowly in cool environments that encounter rising warm waters and is not strongly affected by mixing with shallow waters, it generally indicates temperatures of deep equilibrium. In contrast, the K^2/Mg geothermometer is very sensitive to cooling and mixing with shallow waters.

Figure 7 shows a Na-K-Mg$^{1/2}$ triangular diagram for the thermal water samples from the Gulf of Suez region. Some samples (Ayoun Mousa-2 well, Ras Sudr-2 well, Hammam Mousa and Ain Sukhna) plot

adjacent to the $Mg^{1/2}$ corner, which is typical of ''immature waters'', that do not attain equilibrium with their associated rocks. This is because of their relatively high Mg concentrations, which results in K^2-Mg temperatures (66.3-75.7ºC) that are far lower than the maximum estimated Na/K temperatures (157.9-190.5ºC). For samples falling in the immature field, estimates of reservoir temperatures using the K^2/Mg or the Na/K geothermometer (Giggenbach, 1988) could produce doubtful results. However, Hammam Faroun samples plot only slightly above the $Mg^{1/2}$ corner and relatively close to the partially equilibrated waters curve. Since the thermal waters in the study area have contributions of sea water, K^2/Mg geothermometry has given reliable results because it is useful in situations when Na and Ca do not equilibrate rapidly enough as in sea water mixing systems (Henley *et al*., 1984). K^2/Mg geothermometer data for the Hammam Faroun thermal water samples suggest equilibration temperatures ranging between 79.5 and 80.9ºC (Table 3). Geothermometers based on Na/Li and Mg/Li (similar to Na-K-Ca-Mg) gave lower reservoir temperatures than the measured surface temperatures and they are both unreliable for most of the thermal waters from the Gulf of Suez region. This can be attributed to relatively rapid exchange reactions of lithium and magnesium with clay minerals (Kharaka and Mariner, 1989).
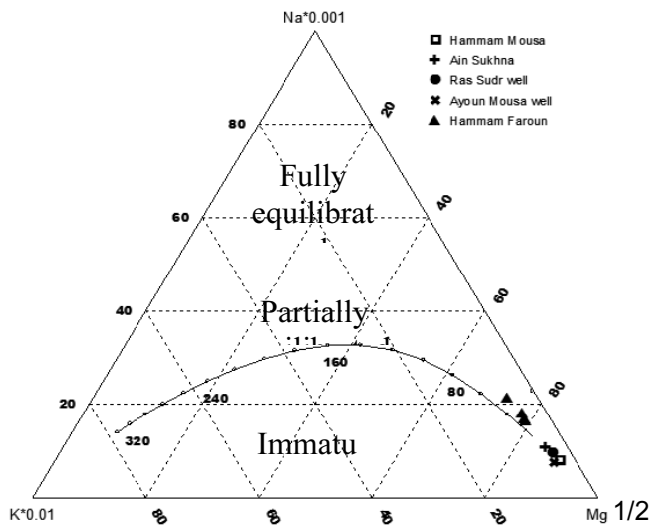

Fig. 7. **Distribution of the thermal waters from the study area in the Giggenbach (1988) Na-K-Mg$^{1/2}$ triangular diagram.**

According to the chalcedony and quartz geothermometers (Fournier, 1977), the subsurface temperatures of the Gulf of Suez region range between 29.4 and 104.5ºC. In general, the quartz geothermometer is applied in high temperature reservoirs, and the chalcedony geothermometer in low temperature reservoirs. Chalcedony geothermometer gave temperatures close to the measured discharge temperatures (29.4-74.8ºC), whereas quartz geothermometer gave the most reasonable subsurface temperatures (61.5-104.5ºC) for all the investigated thermal waters. These subsurface temperatures are similar to those estimated by Swanberg *et al.* (1983 and 1984), who concluded that there is no evidence of a significant geothermal anomaly. The results in Table (3) indicate that the Hammam Faroun and Ras Sudr areas have the highest subsurface reservoir temperatures. This is consistent with the high geothermal gradient of about 48ºC/km, which was estimated by Boulos (1990) from measurements in a well drilled at the Hammam Faroun area. The average geothermal gradient in the Gulf of Suez region is approximately 27ºC/km (Boulos, 1990). The highest measured temperature in the Gulf of Suez region was about 148ºC at a depth of 4002 m (Boulos, 1990). Therefore, the regional geothermal gradients are the major heat source for the thermal waters in the Gulf of Suez region, provided that they reach a depth of at least 3 km. Generally, most of the thermal waters from the study area acquire their temperatures due to heating of percolating water through fractures in a normal geothermal gradient. Hammam Faroun and Ras Sudr-2 well thermal waters have the highest subsurface reservoir temperatures as the result of the high geothermal gradients at those localities. Furthermore, the fault systems in the Gulf of Suez facilitate the rise of deep heat sources.

Conclusions

Geochemical and isotopic studies of thermal waters from hot springs and flowing artesian wells in the Gulf of Suez region were carried out in order to investigate the origin and sources of solutes and estimate the subsurface reservoir temperatures. Two groups of water salinity were found, the first has salinity values exceeding 10,000 mg/l, discharge temperatures reach to 70ºC, and Na-Cl hydrochemical facies at the Hammam Faroun area. The other group is the thermal waters discharged at Hammam Mousa, Ain Sukhna, and shallow flowing artesian wells at Ayoun Mousa and Ras Sudr. They are characterized by salinity values

less than 10,000 mg/l, discharge temperatures ranging from 32.5 to 72ºC and Na-Mg-Ca-Cl (Hammam Mousa), Na-Cl-SO_4 (Ain Sukhna), and Na-Ca-Cl (Ayoun Mousa-2 well and Ras Sudr-2 well) water types. All thermal springs are related to adjacent fault systems, which characterize the Gulf of Suez region. These faults facilitate the rise of deep heat sources. The relations between Na, K, Mg, Br, SO_4 and Cl strongly confirm the mixing process and little contribution of sea water. However, thermal groundwaters are enriched with Ca, that can be attributed to the dissolution of carbonate rocks such as faulted, dolomitic Eocene limestones encountered at the Hammam Faroun area. The thermal waters are depleted in ^{18}O and ^{2}H and plot on the global meteoric water line (GMWL) and away from the local or eastern Mediterranean meteoric water line (MMWL), which represents modern eastern Mediterranean precipitation. The thermal waters from the study area have d-excess values around 10%, which are similar to the groundwater of the Nubian aquifer in central Sinai and the Western Desert of Egypt, indicating a common origin. The d-excess values of the thermal waters suggest that they are paleowaters of meteoric origin that flushed and mixed with residual saline water in the Nubian sandstone aquifer.

Similarity of isotopic values of the most saline waters (Hammam Faroun) and the less saline one (Ayoun Mousa-2 well) suggests that the saline thermal waters acquire their salinity from dissolution of Miocene evaporites in addition to little mixing with residual marine water. Due to little or no mixing of ascending thermal and cold waters, silica geothermometers proved to give the most reliable subsurface reservoir temperatures (61.5-104.5ºC). Hammam Faroun and Ras Sudr-2 well thermal waters have the highest subsurface reservoir temperatures that could be associated with the estimated high geothermal gradients of 48ºC/km for these localities.

References

Alsharhan, A.S. (2003) Petroleum geology and potential hydrocarbon plays in the Gulf of Suez rift basin, Egypt, *AAPG Bull.*, **87**(1): 143-180.

American Public Health Association (APHA) (1998) *Standard Methods for the Examination of Water and Wastewater.* 20th ed. American Public Health Association, Washington, USA.

Bentor, Y. (1969) On the evolution of subsurface brines in Israel, *Chem. Geol.*, **4**: 83-110.

Boulos, F.K. (1990) Some aspects of the geophysical regime of Egypt in relation to heat flow, groundwater, and microearthquakes, In: Said, R. (ed.), *Geology of Egypt*, A.A. Balkema, Rotterdam: 61-89.

Craig, H. (1961) Isotopic variations in meteoric waters, *Science*, **133**: 1702-1703.

Craig, H. (1969) Geochemistry and origin of the Red Sea Brines. In: Degens, E.T and Ross, D.A. (ed.) *Hot Brines and Recent Heavy Metal Deposits in the Red Sea,* Springer Verlag, New York: 208-242.

D'Amore, F., Fancelli, R. and **Caboi, R.** (1987) Observations on the application of chemical geothermometers to some hydrothermal systems in Sardinia, *Geothermics*, **16**(3): 271-282.

Davisson, M.L., Presser, T.S. and **Criss, R.E.** (1994) Geochemistry of tectonically expelled fluids from the northern Coast ranges, Rumsey Hills, California, USA, *Geochim. Cosmochim. Acta*, **58**: 1687-1699.

Desouki, H.A., Gomaa, M.A., Sadek, M.A. and **Ezz El Deen, H.A.** (2006) Hydrochemical and isotopic evaluation of groundwater quality, El Ain El Sukhna and Wadi Araba localities, Gulf of Suez, Egypt, *Mans. J. Geol. and Geophys.*, **33** (1): 31-64.

Deutsch, W.J. (1997) *Groundwater Geochemistry: Fundamentals and Application to Contamination*, Lewis Publisher, USA.

Diab, M. Sh. (1969) Hydrogeological studies on the northern portion of the Gulf of Suez region with special reference to Ayun Musa area, *M.Sc. Thesis, Fac. Sci., Ain Shams Univ., Cairo, Egypt*, 121 p.

El-Fiky, A.A. and **El-Maghraby, M.M.** (2004) Hydrogeochemical evolution of Na-Cl spring waters of Siwa Oasis, Western Desert, Egypt. *6th International Conference on Geochemistry, Alexandria, Egypt*, Abstract.

El Kiki, F.E., Mabrook, B. and **Swailem, F.M.** (1978) Evaluation of trace elements and tritium content in some mineral springs in Egypt, *Isotope & Rad. Res.*, Supplement to Vol. **10**(1): 55-82.

Ellis, A.J. and **Mahon, W.A.J.** (1977) *Chemistry and Geothermal Systems*, Academic Press, New York, 392 p.

El Ramly, I.M. (1969) Recent review of investigations on the thermal and mineral springs in the U. A. R. *Proceedings of the XXIII International Geological Congress 19*: 201-213.

Fleischer, E., Goldberg, M., Gat, J.R. and **Margaritz, M.** (1977) Isotopic compositions of formation waters from deep drillings in southern Israel, *Geochim. Cosmochim. Acta,* **41**: 511-525.

Fournier, R.O. (1973) Silica in thermal waters: laboratory and field investigations. *Proceedings International Symposium on Hydrogeochemistry and Biogeochemistry*, Tokyo: 122-139.

Fournier, R.O. (1977) Chemical geothermometers and mixing models for geothermal systems, *Geothermics*, **5**: 41-50.

Fournier, R.O. (1979) A revised equation for Na-K geothermometer, *Geoth. Res. Council, Transactions*, **3**: 221-224.

Fournier, R.O. and **Truesdell, A.H.** (1973) An empirical Na-K-Ca geothermometer for natural waters, *Geochim. Cosmochim. Acta*, **37**: 1255-1275.

Fournier, R.O. and **Potter, R.W.** (1979) Magnesium correction to the Na-K-Ca chemical geothermometer, *Geochim. Cosmochim. Acta*, **43**: 1543-1550.

Garfunkel, Z. and **Bartov, Y.** (1977) The tectonics of the Suez rift, *Geological Survey of Israel Bulletin*, **71**: 43 p.

Gat, J.R. and **Issar, A.** (1974) Desert isotope hydrology: Water sources of the Sinai desert, *Geochim. Cosmochim. Acta*, **38**: 1117-1131.

Gat, J.R., Mazor, E. and **Tzur, Y.** (1969) The stable isotope composition of mineral waters in the Jordan Rift Valley, Israel, *J. Hydrology*, **76**: 334-352.

Giggenbach, W.F. (1988) Geothermal solute equilibria: Derivation of Na–K–Mg–Ca geoindicators, *Geochim. Cosmochim. Acta*, **52**: 2749-2765.

Giggenbach, W.F., Gonfiantini, R., Jangi, B.L. and **Truesdell, A.H.** (1983) Isotopic and chemical composition of Parbati valley geothermal discharges, NW-Himalaya, India, *Geothermics*, **12**: 199-222.

Henley, R.W., Truesdell, A.H., Barton, P.B. and **Whitney, J.A.** (1984) Fluid-mineral equilibria in hydrothermal systems, *Reviews in Economic Geology*, **1**.

Himida, I.H., Bishay, N.Z. and **Diab, M. Sh.** (1972) Hydrogeological and hydrogeochemical studies on Ayun Musa area, *Desert Institute Bulletin*, **22**(1): 17-32.

I.A.E.A. (1981) Stable isotope hydrology. Deuterium and oxygen-18 in water cycle. In: Gat, J.R., Gonfiantini, R. (Eds.), *International Atomic Energy Agency Technical Report No. 210, Vienna*, 339 p.

Isaar, A.S. (1979) The paleohydrology of southern Israel and its influence on the flushing of the Kurnub and Arad Groups (Lower Cretaceous and Jurassic), *J. Hydrology*, **44**: 289-303.

Isaar, A.S. (1981) The rate of flushing as a major factor in determining the chemistry of water in fossil aquifers in southern Israel, *J. Hydrology*, **54**: 285-296.

Issar, A., Rosenthal, Y. and **Eckstein, R.B.** (1971) Formation waters, hot springs and mineralization phenomena along the eastern shore of the Gulf of Suez, *Bull. International Association of Scientific Hydrology*, **XVI**: 25-44.

Issar, A., Bein, A. and **Michaeli, A.** (1972) On the ancient water of the Upper Nubian sandstone aquifer in central Sinai and southern Israel, *J. Hydrology*, **17**: 353-374.

Kharaka, Y. and **Mariner, R.** (1989) Chemical geothermometers and their application to formation waters from sedimentary basins. In: Naeser, N.D. and McCulloch, T. (Eds), *Thermal History of Sedimentary Basins: Methods and Case Histories*, Springer-Verlag, New York: 99-117.

Kingston, D.R., Dishroon, C.P. and **Williams, P.A.** (1983) Global basin classification system, *AAPG Bulletin*, **67** (12): 2175-2193.

Mahon, W.A.J. (1970) Chemistry in the exploration and exploitation of hydrothermal systems, *Geothermics*, Sp. Issue **2 (**2): 1310-1322.

Morgan, P., Boulos, F.K. and **Swanberg, C.A.** (1983) Regional geothermal exploration in Egypt, *Geophysical Prospecting*, **31**: 361-376.

Moser, H. and **Rauert, W.** (1980) *Isotopenmethoden in der Hydrologie*. Lehrbuch der Hydrogeologie Band 8, Gebr. Borntrager Berlin, Stuttgart.

Nicholson, K. (1993) *Geothermal Fluids; Chemistry and Exploration Techniques,* Springer, Berlin.

Parkhurst, D.L. and **Appelo, C.A.J.** (1999) *User's guide to PHREEQC (version 2)—A computer Program for Speciation, Batch-reaction, One-dimensional Transport, and Inverse Geochemical Calculations*. USGS Water-Resources Investigations Report 99-4259.

Pauwels, H., Fouillac, C. and **Fouillac, A.** (1993) Chemistry and isotopes of deep geothermal saline fluids in the Upper Rhine Graben: Origin of compounds and water-rock interactions, *Geochim. Cosmochim. Acta*, **57**: 2737-2749.

Quennell, AM. (1984) The western Arabian rift system. In: Dixon, J.E. and Robertson, A.H.F. (ed.), *Geological Evaluation of the Eastern Mediterranean Sea,* Geological Society of London, special Publication 17.

Schütz, K.I. (1994) *Structure and Stratigraphy of the Gulf of Suez*, Egypt. In: Landon, S.M. (ed.), *Interior Rift Basins,* AAPG Memoir 59, The American Association of Petroleum Geologists, Tulsa, Oklahoma, USA: 57-96.

Shata, A.A. (1990) Thermal springs and mineralized water in the Gulf of Suez taphrogenic basin, northeast Egypt, *Memoires of the 22nd Congress of IAH, XXII, Lausanne*: 681-688.

Sturchio, N.C., Arehart, G.B., Sultan, M., Sano, Y., AboKamar, Y. and **Sayed, M.** (1996) Composition and origin of thermal waters in the Gulf of Suez area, Egypt, *Applied Geochemistry*, **11**: 471-479.

Swanberg, C.A., Morgan, P. and **Boulos, F.K.** (1983) Geothermal potential of Egypt, *Tectonophysics*, **96**: 77-94.

Swanberg, C.A., Morgan, P. and **Boulos, F.K.** (1984) Geochemistry of the groundwaters of Egypt, *Annals of the Geol. Surv. Egypt*, **XIV**: 127-150.

Tarcan, G. and **Gemici, Ü.** (2003) Water geochemistry of the Seferihisar geothermal area, İzmir, Turkey, *J. Volcanology and Geothermal Research*, **126**: 225-242.

Tonani, F. (1970) Geochemical methods of exploration for geothermal energy, *Geothermics*, Sp. Issue, **2** (1), 492-515.

Vengosh, A., Hening, S., Ganor, J., Mayer, B., Weyhenmeyer, C.E., Bullen, T.D. and **Paytan, A.** (2007) New isotopic evidence for the origin of groundwater from the Nubian Sandstone Aquifer in the Negev, Israel, *App. Geochem.*, **22**: 1052-1073.

Waring, G.A. (1965) Thermal springs of the US and other countries of the world, *US Geological Survey Professional Paper 492*.

White, D.E. (1970) Geochemistry applied to the discovery, evaluation, and exploration of geothermal energy resources, *Geothermics*, Sp. Issue **2** (1): 58-80.

Wilson, T.R.S. (1975) Salinity and major elements of sea water. In: Riley, J.P. and Skirrow, G. (ed.) *Chemical Oceanography,* 2nd Ed., Vol. 1, Academic Press, London, New York: 365-413.

هيدروجيوكيمياء و قياس درجة حرارة الخزان للمياه الجوفية الحارة بمنطقة خليج السويس، مصر

أنور عبد العزيز الفقى

قسم جيولوجيا المياه – كلية علوم الأرض – جامعة الملك عبد العزيز جـــــدة – المملكة العربية السعودية

المستخلص. تمت دراسة التركيب الكيميائى ونظــائر الأكــسجين، والهيدروجين، والوضع الجيولوجى للنظام الأرضي الحار بمنطقــة خليج السويس، مصر، لتقييم نشأة المكونات الذائبة ودرجات حرارة الخزان الجوفي. وتوضح الخصائص الكيميائية للمياه الحارة التــي تخرج من الينابيع والآبار الارتوازية المتدفقة بمنطقة خليج السويس أنه توجد مجموعتان: تشمل الأولى المياه الحارة بحمــام فرعــون، ولها ملوحة تتعدى ١٠٠٠٠ مجم/لتر، ودرجة حــرارة تــصريف تصل إلى ٧٠°م، وسحنة هيدروكيميائية Na-Cl، وتشمل المجموعة الأخرى المياه الحارة التي تخرج عند حمام موسى، والعين السخنة والآبار الارتوازية الضحلة المتدفقة في منطقتــي عيــون موســى ورأس سدر. حيث تتميز بقيم ملوحة أقل من ١٠٠٠٠ مجــم/لتــر ودرجة حرارة تصريف تتراوح من ٣٢٫٥ إلى ٧٢°م، ونوعيــات مياه Na-Mg-Ca-Cl (حمام موسى) و Na-Cl-SO₄ (العين الــسخنة) وNa-Ca-Cl (بئر-٢ عيون موسى و بئر-٢ رأس سدر). ويوضح التمثيل البياني باستخدام الأيونات الرئيسية والفرعية وجود اختلاط بسيط مع مياه البحر، ليكون من المحتمل أنه مــصدر المكونــات الذائبة. بينما تكون عمليات التفاعل بين الميــاه والــصخور هــي المصدر الرئيسي للمكونات الذائبة، حيث تم استنتاج ذلك من غنـى المياه الحارة بالكالــسيوم والبيكربونــات، نتيجــة إذابــة معــادن

الكربونات. وتتميز المياه الحارة عند حمام فرعون وبئر-٢ برأس سدر، بأعلى درجات حرارة تصريف وتركيزات SiO_2 التي تــدل على أن المياه الحارة الصاعدة في منطقة حمـــام فرعـــون تخـــتلط بدرجة بسيطة بمياه باردة. ووجد أن المياه الحارة بمنطقة الدراســة فقيرة في محتوى $^{18}O, \ ^{2}H$، وتقع على خط المياه الجوفية العـــالمي، وتحت خط المياه الجوفية المحلية فى شرق البحر المتوسط حيــث تتراوح قيمة d-excess بين ٣,٤٢ و ١٠,٦٪ الــذي يـشبه الميـــاه الجوفية بخزان الحجر الرملي النوبي بوســـط ســيناء والـــصحراء الغربية، مما يدل على نشأة مشتركة. وهذا يدل على أن هذه المياه هي مياه جوفية قديمة قامت بتغذية وطرد المياه المالحة المتبقية في الخزان النوبي تحت ظروف مناخية مختلفة عن الظروف الحاليـــة. ووجد أن كل المياه الحارة بمنطقة الدراسة غير مـــشبعة بالنـــسبة لمعادن الكبريتات (الجبس والأنهيدريت) ومشبعة أو تقريبًا في حالة اتزان بالنسبة للأراجونيت، والكالسيت، والدولوميت، مما يدل على وجود هذه المعادن بالخزان. ووجد أيضًا أن كـــل الميـــاه الحـــارة مشبعة أو تقريبًا في حالة اتزان بالنسبة للكـــوارتز والكالـــسيدوني، ويدل على حالة الاتزان بين المياه وخزان مـــن الحجـــر الرملـــي الخالي من الجبس والأنهيدريت مع قليل من معـــادن الكربونـــات. وتتراوح درجات حرارة الخزان الجـــوفي المحسوبة بالمقـــاييس المختلفة بين ١٣,٠ و ١٩٠,٥°م. وقد أعطت مقاييس Na/K و -Na K-Ca أقصى درجات حرارة للخزان الجـوفي (١٩٠,٥-١٣٥°م) بينما أعطت مقاييس Na-K-Ca-Mg و Mg/Li أقل درجات حـــرارة (١٣,٠-٤٥,٩°م). وقد أعطى مقياس الكوارتز أفـضل درجـــات حرارة مقبولة للخزان الجوفي (١٠٤,٥-٦١,٥°م). وتتميز منطقتي حمام فرعون ورأس سدر بأعلى درجات حرارة للخزان الجـــوفي وهذا متوافق مع تدرج الحرارة الارضي العالي الذي يـــصل إلـــى ٤٨°م