Iranian Int. J. Sci. ***5****(1), 2004, p.43-62*

Alteration and Geochemistry of Mount Taftan Geothermal Prospect Southeastern Iran

Fereydoun Ghazban
Faculty of Environment, Tehran University, P. O. Box 14155-6135, Tehran, Iran
E mail: fghazban @ ut.ac.ir

(received: 21/4/2003 ; accepted: 4/1/2004)

Abstract

Geologic and geochemical investigation in Mount Taftan indicates a viable geothermal resource probably centered and upflowing beneath the volcano. This volcanic region in SE Iran has a very high potential for generation of geothermal energy. The presence of volcanos is intimately related to the subduction of Neotethys oceanic lithosphere under the Central Iranian continental plate. Magmatism in Mt. Taftan is represented by subalkaline volcanics that vary from basaltic through andesitic to dacitic composition. Springs with temperatures ranging from 10 to 35°C are located in the prospect area, fed by the sedimentary aquifers. Based on geochemical and hydrological data, the thermal Cl-Ca-SO_4 waters rise toward the surface from reservoirs made up of a volcano-sedimentary sequence through faults and fractures. Fumerolic and thermal discharges from this volcanic region contain deeply derived H_2S with subsequent oxidation to SO_4^{-2} in the system. Based on Na-K-Mg ternary diagram, none of the discharge waters could be representative of deep fluids in “full equilibrium” with the reservoir rocks. The acid alteration in the shallow parts of Mt. Taftan results from the oxidation of H_2S. Steam, accompanied by H_2S rises from depth and produces acid sulfate fluids, which react with the surficial rocks to generate alteration mineral assemblages. The temperature range established from alteration mineralogy, overlaps with that determined from chemical geothermometers. The occurrence of hydrothermal alteration minerals at the surface indicates a low to moderate geothermal system. Clay mineral alteration assemblage encountered in Taftan geothermal system might have been superimposed on older and higher-temperature stages. The geothermal energy produced in the system is from the cooling magma, which is heating circulating groundwater. The magma-heated water, which emerges at the surface as fumerolic discharges and heats up the descending cold meteoric water, signals the presence of the shallow heat source beneath Mt. Taftan.

Keywords: *Geochemistry, Alteration, Geothermal,Geothermometry, Mount Taftan, Iran*

Introduction

Extensive areas of Iran are made up of volcanic rocks forming thick pile of Tertiary volcanic rocks cross the country in a 2255 km long belt from Turkey to Pakistan. A number of dormant or recently extinct volcanoes occurring within the Tertiary volcanic belt (Figure-1). Based on investigations by Gansser (1966) and Jung et al., (1975) at present there are two active volcanoes along this belt, i.e., Taftan and Bazman, which are at their fumarolic stage.

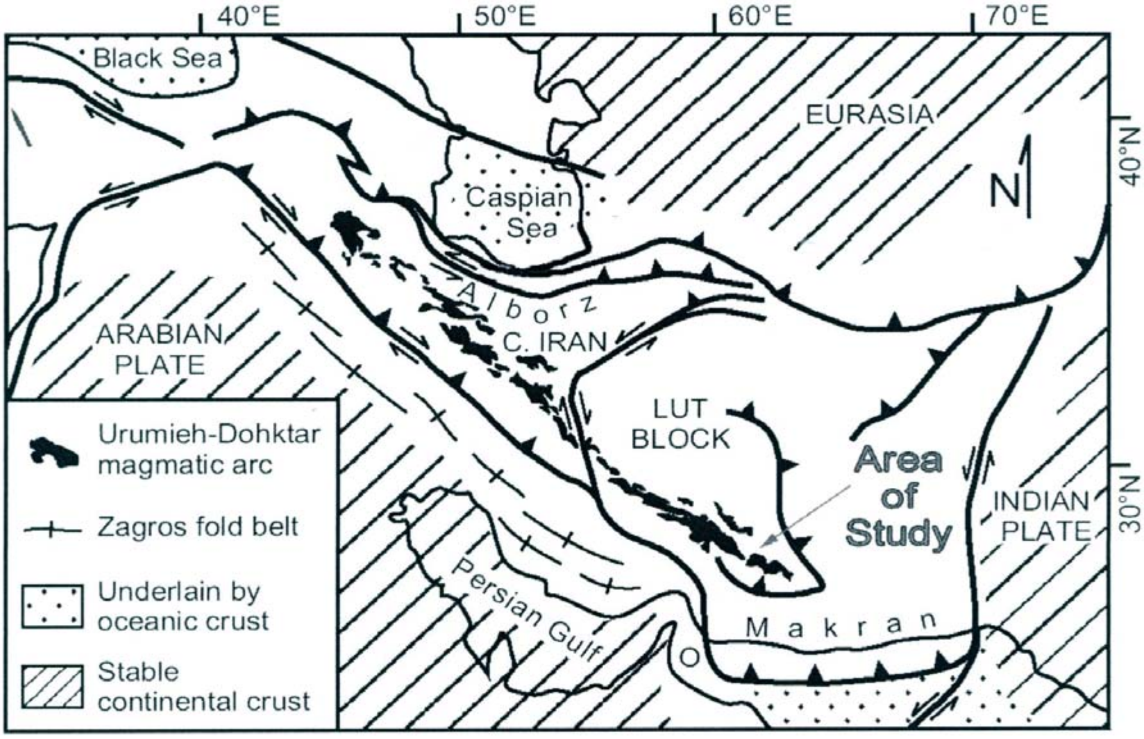

Figure-1. Regional tectonic map of Iran showing the Tertiary volcanic belt (after Alavi, 1994).

According to the geological information, geothermal resources are available throughout Iran in variety of geologic form and settings with hot springs are utilized for bathing and therapeutic purposes. In recent years, the potential of some of these resources such as Mt. Sabalan and Mt. Damavand as likely power source and direct commercial utilization have been investigated (ENEL, 1983 and Ghazban, 2000). All of the available data indicates that Iran has a very important geothermal energy potential.

The primary goal of the present research is to emphasis the potential of the Taftan geothermal system and its recognition in terms of geothermal energy. The geothermal fluids ascending from a reservoir and emerging at the surface provide information concerning the subsurface conditions. The alteration minerals provide the opportunity to examine geochemical processes from the perspective of fluid chemistry and relate how this impacts upon rock chemistry through alteration and deposition reactions.

Regional Geology

The principal morphologic feature of the investigation area is the Taftan stratovolcano, forming a peak at 4050 meters above sea level. The most distinct geological characteristic in the area is the presence of widespread thick Quaternary volcanic rocks. The local stratigraphy has been examined for possible occurrence of permeable aquifer beds or cap rocks and porosity and permeability. The Taftan volcano structure can be visualized from bottom to top as follows:

Pyroclastics and dacitic flows form the main body of the volcano and overlie the Upper Cretaceous and Eocene sedimentary units consisting of flysch and limestones and igneous rocks. This unit is the most extensive and the main part of the system. In general, Taftan has a flysch sub-stratum. The presence of hematite causes the pink appearance of the rocks. Geologically, the limestone aquifer of Cretaceous age plays an important role in effecting the thermal gradients.

Tuffs and ignimbrites form a sequence of about 50 meters thick. The ignimbrites contain large phenocrysts of amphibole and biotite and the rocks containing these minerals could be as young as 2 Ma (Moinvaziri and Aminsobhani, 1978).

Andesitic flows, less than a million year old, have kept their original morphology and porphyritic texture. The porphyroblasts are mainly plagioclase, amphibole and pyroxene. Lavas have covered an extensive area, they are mostly uneroded and there is no sign of alteration associated with them. However, in the southeastern summit there is extensive fumarolic activity with ejection of steam and sulfurous gases.

The entry of the molten material has led to fracturing in the area, thereby providing significant pathways for convective fluid flow. A simplified geological map of the area is presented in Figure 2.

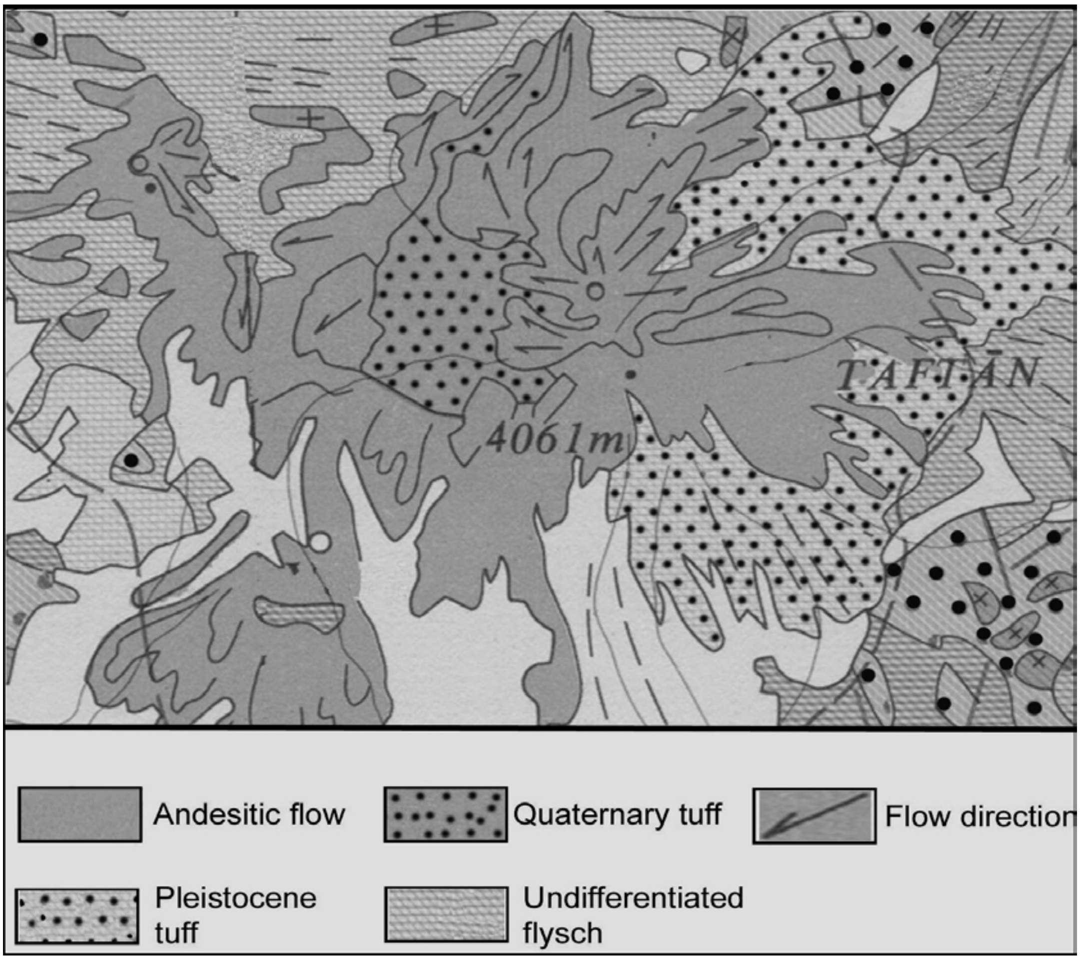

Figure 2. Simplified geological map of the Taftan prospect and surrounding area (Scale= 1:100,000).

Volcanism

To understand the nature and occurrence of geothermal resources, the process that leads to the formation of geothermal anomalies must be considered. In southeastern Iran, the most intensive geothermal area is associated with Taftan and Bazman, which are at their fumarolic stage (Gansser 1955; Ghazban, 1999 and Ghazban, 2000). The magmatic and related volcanic activities are associated with geothermal anomalies, which may have persisted from Upper Pliocene until recent time.

Taftan volcano is a calc-alkaline type, and the magma, which generated it, is the result of a compressive regime (Berberian and King, 1981). The main volcanic activity belongs to Neogene compressional phase but the volcanic intensity has continued from Upper Pliocene through recent time. The calc-alkaline rocks of Baluchestan in southeastern Iran are composed of tholeiitic to rhyodacite basalts, with isotopic ages of 4Ma. The rocks are similar to island arc calc- alkaline series and are possibly related to the subduction of the Arabian plate underneath Makran in the Oman region (Girod and Conrad, 1979, Dupuy and Dostal, 1978). The subduction which was probably initiated about the Paleocene (Platter et al., 1988) and its associated tectonism has been triggering volcanism and magmatic events.

The general geologic features presented here are of fundamental importance to geothermal research as it implies the existence of magmatic activity and masses, compressed within relatively superficial zones of the crust, giving rise to relatively superficial thermal anomalies. Confirmation of thermal anomalies at relatively shallow depth is provided by the presence of numerous hydrothermal manifestations distributed over almost the entire area studied. The magmatic activity developed in Taftan began with explosive eruptions and terminated with lava flows.

Magmatic/volcanic activity and melting processes associated with subduction constitute an enormous heat source. Thus, the Taftan volcano with the associated geology makes the area as a primary target for geothermal exploration.

Characteristics of Taftan Geothermal field

Taftan volcano and associated geothermal system is one of the most intense geothermal surface activities in Iran with a variety of hydrothermal phenomena such as the emission of sulphurous gases observable from long distance. Hydrothermal explosions are evidenced by breccia with fragments made up of dacite and agglomerate in several localities. Active and recently active hydrothermal features are mostly within the Taftan caldera, close to the outer edge of the main ring.

Thermal activity extends from steaming features (fumaroles and perched acid sulfate springs) at an altitude of 1000 meters on the flanks of volacano. Fumaroles and steam discharges have resulted in white coatings on the rocks, possibly calcium and aluminum sulfate (binachetto), and have formed opal and carbonates. At the southeastern flank of the volcano, there are zones of high gas emissions and fumaroles. Warm springs and altered ground with steaming vents are the most impressive features present in this locality.

In the valleys near the Taftan summit, gypsum crystals cover the surface of the rocks. The formation of this mineral is due to the interaction of dissolved sulfuric acid more likely from the air fall or from steam plumes in the runoff waters and calcium in the rocks.

Volcano-sedimentary sequences, which are locally extensively altered, are exposed over an extensive area along the valleys and drainage system and are evidence of the existence and character of the Taftan geothermal system (Figure-3). Acidic alteration and exposure of hydrothermally altered minerals to clay minerals, iron-oxides (mainly hematite), alunite (K, Na) $Al_3(SO_4)_2(OH)_6$ and sulfides can be observed in the area.

Significant sulfur and salt deposits are observed in the valleys. Native sulfur is precipitated along fractures and pores in altered rocks. Silica sinter and silica residue are abundant in Taftan area and this is a reliable indication that the depositing fluids are derived from a reservoir hotter than about 180°C (Hochstein and Browne, 2000). Areas of former siliceous sinter deposition and alteration are forming small relieves, indicating previous surface discharge in the southeastern flank of Taftan. Thus, the presence of strong fossil hydrothermal activity as a manifestation of a geothermal system is observed in southeastern part of the Mt. Taftan volcano.

Figure-3. Top picture) - Extensive alteration of volcano-sedimentary sequence, exposed over a large area along the valley. Bottom picture) - Intense acid alteration of rock leaving residual silica.

The geothermal system associated with Taftan currently appears to be vapour-dominated and after a period of hot water discharge during the dry seasons, the system produces steam only. Thus, hot springs are scarce in the area and the major hot springs emit steam only during draught.

The basis for generating geothermal energy in Taftan region is the heat from the cooling magma, which is heating the available ground water circulating in the area. As a result, the steam-warmed waters seemed to be escaping at the surface, signaling the existence of the shallow heat source below.

Geothermal Manifestations

Siliceous sinter deposits are observed in the southeastern flank of Mt. Taftan. Such sinter deposits are commonly formed where alkaline-chloride thermal waters flow over the ground. Chloride waters form through incorporation of magmatic gases (CO_2, SO_2, HCl) into circulating meteoric-driven ground waters, and fluid-mineral interaction (Giggenbach, 1988). The dominant aqueous component in surface discharges of these waters is chloride, but before boiling it may contain significant concentrations of dissolved CO_2. Due to sluggish reaction kinetics, amorphous silica precipitates from chloride springs forming sinter deposits. Chloride springs like East Taftan spring, discharge clear water that is typically close to boiling.

In recent years there has been a decrease in precipitation rate in the area causing drought. Under such conditions the fluid pressure within the system seems to have decreased. The decreased hydrostatic head was probably sufficient to allow the development of a dominated-dominated system. Thus, it is likely to generate dominated- dominated conditions at depth. During the warm periods, melting glaciers filling the canyons have raised the regional water table, allowing alkaline-chloride hot springs to flow at relatively high elevations.

As snow and ice diminished in volume, the water table slowly lowered through rock that had previously been heated to very high temperatures by upflowing thermal waters. This could cause the hydrothermal activity in topographically high places to change from outflow of alkaline-chloride water to discharge of high pressured steam, throttled by poor permeability within highly altered and silicified rocks. Alkaline-chloride waters still emerge at topographically low places in the western part of the volcano.

Hydrothermal Alteration

The formation of secondary minerals in geothermal systems is controlled by chemical/physical conditions in the system. For instance the presence, abundance and stability of hydrothermal alteration minerals depends on temperature, pressure, lithology, permeability and the fluid composition of the system. By studying the alteration minerals, estimate of subsurface temperature and permeability and any temporal changes can be deduced (Browne, 1978 and Harvey and Browne, 1991). Thus, studying the hydrothermal alteration in Taftan geothermal prospect provided a good opportunity to determine characteristic features of shallow level and surface of this geothermal system.

Clay geothermometry studies of low-temperature hydrothermal conditions (T<100°C) are scarce (e.g., Sato *et al.,* 1996). Nevertheless, the low-temperature hydrothermal clays represent the surficial evidence of deeper and hidden high-temperature zones, and hence, they have proved to be useful prospecting guides.

Due to their ubiquity and reactivity as a function of the physico-chemical environment of crystallization, clay minerals have been used as markers of paleoconditions in both fossil and active geothermal systems. They have proved to be particularly useful for temperature estimations (Mas *et al.,* 2003). Due to the fact that the investigation was carried out in a dry season thus, attempt was made to study clay mineralogy in order to obtain some thermal information.

Sampling and Analytical techniques

Samples were collected from southern part of the volcano where it was accessible and also represent variations in alteration styles. Alteration was examined for bulk rock samples using standard X-ray diffraction (XRD) and petrographic techniques.

In the XRD study, clay mineral separates were prepared by dispersing the crushed rocks in distilled water and placed in an ultrasonic bath. The clay fraction was extracted using a centrifuge and then mounted on glass slides. Clay mounts were air-dried and ethylene glycol solvated (glycolated) before analysis, with glycolation achieved by saturating the samples in an atmosphere of ethylene glycol for more than 36 hours. X-ray diffraction pattern were collected using a Phillips PW 1050/25 diffractrometer using CuKα radiation.

Hydrothermal Alteration Minerals

A variety of alteration minerals occur in Taftan geothermal prospect. The X-ray diffraction patterns collected from the analysis of the bulk samples and clay minerals revealed that they contained alunite, naturoalunite, calcite, quartz, cristobalite, tridymite, kaolinite, smectite, illite/smectite, jarosite and pyrophyllite.

Most of the rocks in the altered zones are completely altered to an acid assemblage of alunite, sulfur, kaolinite and residual silica. Acid sulfate alteration caused the formation of kaolinite and since the sulfate and potassium concentrations were sufficient, that resulted in alunite formation.

Quartz and tridymite is the only residual product. In some localities the rocks are completely leached by acid solution leaving a pumice-like silica rock (Figure-3). Therefore, it is postulated that the dissolution of wall rock material is incongruent and leads to aluminum enrichment in the solution. The precipitation of alunite, an aluminum and potassium rich sulfate, indicate that H_2SO_4 molality of at least about 10^{-3} was locally reached (Hemley et al., 1969, Henneberger and Browne, 1988). The increase in SiO_2 activity leads to an oversaturation of the system with respect to SiO_2 and subsequent formation of cristobalite.

The acid alteration minerals occur in abundant to moderate amounts and are associated with cristobalite, quartz, tridymite, anhydrite and gypsum. Isolated occurrences of cristobalite where the alteration is low, likely represent a metastable phase from alteration of volcanic glass (Browne and Ellis, 1971).

Low-temperature alteration of clay mineral assemblages encountered near the surface of the geothermal systems (mostly minerals of the kaolin subgroup minerals and smectites) in Taftan, might have been superimposed upon older and higher-temperature hydrothermal stages. With a complex mixing of clay minerals, the origin of these minerals is not easy to determine on the basis of alteration petrology.The geothermal waters are close to saturation with respect to kaolinite or somewhat undersaturated, especially at the highest temperatures (Gislason and Arnorsson, 1990). The slight supersaturation in waters below about 100° C may not be sufficient to drive kaolinite precipitation. This mineral is generally not found at depth in geothermal systems although it has been reported and is then accounted for by acid leaching.

When conditions are sufficiently acidic (pH<3), and in the presence of K^+ and with SO_4^{2-} activity more than >3000 µg/ml, jarosite is a common mineral product that can form directly from its constituents (e.g., Alpers et al., 1989). In addition, jarosite can form by reaction of kaolinite with acid-sulfate fluids having Fe^{3+} and K^+ activities.

This acid zone likely formed at relatively low temperature usually about 160°C whereas the presence of pyrophyllite with or without alunite and illite-smectite may have formed at higher temperatures exceeding 180°C.

The association of acid alteration zone with acid fluid inflow confirms the recentness of the acid alteration. Neutral pH alteration occurs in lesser amount at the surface. The assemblage consists of illite/smectite, which may have appeared at temperatures of about 150-180°C, and illite (≥220°C) calcite and silica. Geothermal alteration assemblages including smectite or mixed-layer illite-smectite are typically found at temperatures below 200°C (Jennings and Thompson, 1986; Harvey and Browne, 1991).

Hydrochemistry

The chemical composition of the spring waters is given in Table 1. The thermal springs flow to the surface through a thick sequence of sedimentary rocks that includes carbonates and flysch. Consequently, they are rich in bicarbonates.

The thermal waters are generally characterized by high Ca-Mg content, and relatively low chloride (from 30 to 190 ppm) except East Taftan spring when it was discharging water showed chloride content at about 1250 ppm. Thus, chloride is found in all springs, although most of the springs are dilute when compared with East Taftan. It could be argued that the high Mg is being provided by extensive alteration of Mg-rich rocks. However, it is those waters with the highest chloride contents that have the highest Mg content, and no example of high Magnesium low Chloride is present. The high chloride content of the water may represent a deep thermal component.

Table-1. Taftan hydrochemical results (mg/l) from Shahback, 1990.

Source	Ca	Mg	Na	K	Cl	SiO_2	pH
U.Torshab	180	48	45	4	51	30	4
L.Torshab	307	80	70	10	32	-	4.5
Ganamin	225	59	50	4	190	50	3.2
Morghab	40	9	8	0.1	30	49	5.8
E.Taftan	315	1460	270	2	1250	125	1.5

Steam and gases separate from the rising water and heat the near surface waters. The low K (0.01 to 10mg/l) content is attributed to alteration of volcanic rocks and formation of alteration minerals such as kaolinite and alunite, which are abundant in the area. The acid-sulfate waters, causing the alteration, are formed by dissolution of magmatic gases above the water table in Taftan geothermal waters. The shallow alteration assemblage of kaolinite and rare alunite are interpreted (e.g., Schoen *et al.,* 1974) to have formed from steam-heated acid sulfate water that forms in the vadose zone by the oxidation of H_2S.

Using the stability diagrams by Hemley *et al.*, (1969), the formation of kaolinite and alunite is mainly a function of SO_4^{-2}, K^+ activities and pH. Considering high SO_4^{-2}, activity and low pH from the equilibrium experiments (Gehring *et al.,* 1999), it is feasible that the low K^+ activity is the major factor driving the system into the kaolinite stability field.

As the water diminished in volume, the water table slowly lowered through rock that had previously been heated to very high temperatures by upflowing thermal waters. This could cause the hydrothermal activity in topographically high places to change from outflow of alkaline –chloride water to discharge of high–pressured steam.

An interesting question regarding the spring water from Taftan is how it has obtained its acidity (1.5 to 5.8). Is it because the fluid is a steam condensate or is it ground water mixed with mostly H_2S gas? High concentrations of volatile components often accumulate above or around a relatively shallow heat source. High H_2S in waters may indicate higher temperatures at depth. On the other hand, if the fluid is steam-heated ground water, then the implication is that there is steam somewhere at depth.

Abundance of the H_2S in the system might be the result of boiling of the subsurface hydrothermal fluids. Thus, upflowing steam containing H_2S react with the surrounding rock producing argillic alteration assemblages. Such a boiling system is characterized by very low Chloride concentration; rich sulfate measured at thermal spring emergence (Oxygen is available to oxidize H_2S) and pH is of acidic to neutral. The steam that separates from boiling, alkaline chloride water generally contains H_2S that oxidizes to H_2SO_4 when it comes into contact with air and produces the low pH waters found in the streams and springs.

Geothermometry

Knowledge of subsurface temperatures is essential in exploration for geothermal energy. In this study chemical geothermometers developed for geothermal systems have been used to estimate the subsurface temperatures of the geothermal field from the concentration of dissolved species in the waters (Fournier, 1981).

Reservoir temperatures for water samples of the Taftan system according to quartz geothermometers range from 79°C to 150°C (see Table 2). There may have been change in composition during the rapid rise up to the surface by steam loss or dilution by cold meteoric waters. Mixing of waters from different origins or aquifers with different temperatures could alter the concentrations of constituents used in geothermometers. The mixing process may sharply reduce the dissolved silica concentration, resulting in low calculated temperatures from silica geothermometers in the sampled springs. However, the effect of dilution appears to be insignificant in Taftan geothermal field because of small variation in spring temperatures.

Table-2. The temperatures evaluated with geothermomters in liquid phase.

Source	Spring Temp °C	t (calce) °C[1]	t(qtz) °C[2]	t(Na/K)°C[3]	t (Na-K-Ca) °C[4]
U.Torshab	10	49	79	207	110
L.Torshab	15	---	---	249	127
Ganamin	16	72	102	198	104
Morghab	14	79	102	237	121
E.Taftan	35	125	150	63	87

[1] Temperature= $1315/[5.205 - \log SiO_2] - 273.15$°C
[2] Temperature= $1315/[5.205 - \log SiO_2] - 273.15$°C
[3] Temperature= $777/[\log (Na/K) + 0.70] - 273.15$°C
[4] Temperature= $1647/ \log (Na/K) + \beta[\log (\sqrt{Ca}/K) + 2.06] + 2.47$
$\beta=4/3$ for $t<100$C $\beta=1/3$ for $t>100$C

Variation in concentration of chloride (ranging from 30 to 1250ppm) could be due to boiling and steam loss and water-rock interaction, which result in cooling of fluid on their rise towards the surface. As indicated, the thermal spring waters could have been affected by exchange with rocks causing extensive alteration. Thus, a mixing model involving a hot component from depth and a meteoric component from the surface cannot be adopted here.

At depth, temperatures can be estimated from the Na: K ratios as the alkali exchange between ground water and reservoir rocks is temperature dependent using the appropriate equations with corresponding temperature of about 63 to 249°C. The Na-K geothermometer, however, is useful only at temperatures of more than about 150°C. At lower temperatures, calcium usually makes up a significant fraction of the cations, and the Na-K geothermometer seems to have produced anomalous temperature estimates.

The Na/K geothermometer appears to produce higher temperatures (e.g., >198°C) and this may be due to the fact that the aqueous concentrations of Na and K are controlled by their stoichiometric dissolution from the rock and slow exchange rate non-equilibrium conditions between Na and K bearing constituents, and therefore is reflective of temperature at deeper levels of geothermal system. Since all the cations for geothermometry are available an estimation of deep reservoir temperature is possible.

The calculated temperatures using Na-K-Ca range from 87°C to 127°C. Considering the analytical uncertainty, some of the calculated temperatures are in good agreement with each other. However, all these geothermometers point to the existence of a relatively wide range of temperatures over the hydrothermal parts of the Taftan system.

For most samples, two types of temperatures are calculated: (1) a low-temperature calculated with the chalcedony, quartz (79 to 150°C) and also Na-K-Ca, (87-127°C) and (2) higher temperature calculated with the Na/K geothermometers. By applying the geothermometric technique proposed by Giggenbach (1988) and reported in the Na-K-Mg ternary diagram in Figure-4, additions of cations from possible sources are observed.

Most of the waters in Taftan area fall on the line of partially equilibrated waters close to the Mg end of the diagram. As suggested by Giggenbach the Na-K-Mg geothermometers may be applied with confidence only for samples on or close to the equilibrium line. The alignment of springs on a single line suggests a source temperature of about 180°C.

The silica geothermometers in conjunction with K-Ca-Mg applied here may provide a better measure of shallow subsurface temperatures, whereas the high subsurface temperatures of some of the springs (e.g., >198°C) calculated from the Na/K geothermometers are valid for the deeper part of the system as previously mentioned. Overall, the temperature range established from alteration mineralogy overlaps with that determined from chemical geothermometers.

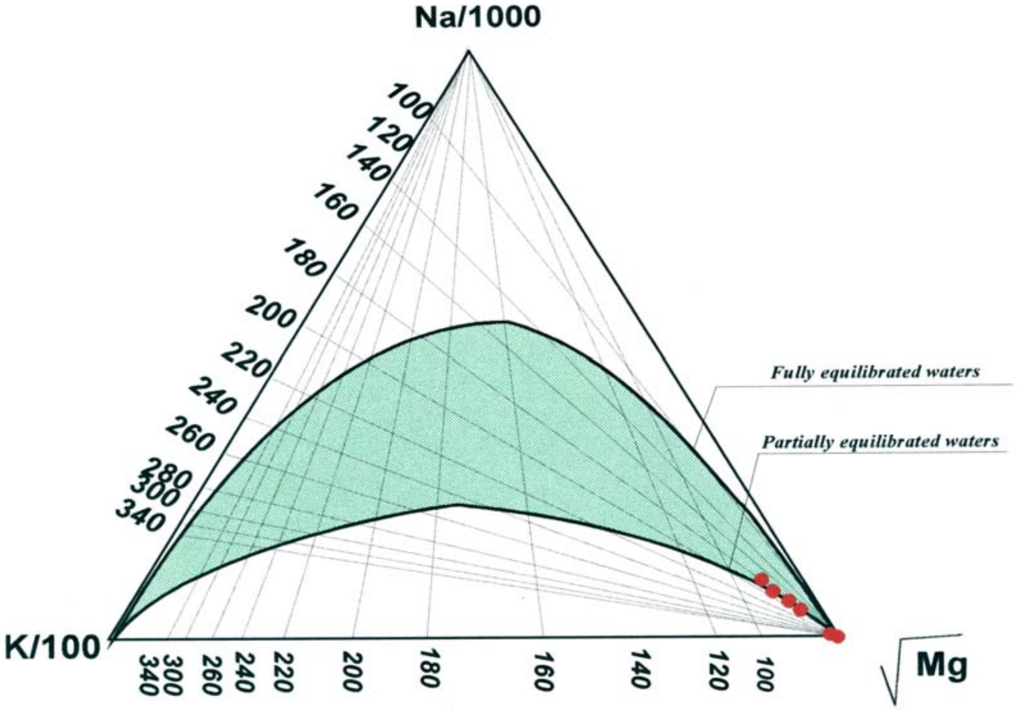

Figure-4. Relative the Na-K-Mg triangular diagram.

Hydrothermal system

A simplified conceptual model for Mt. Taftan thermal area hosting a geothermal system is envisaged here based on geological, alteration mineralogy and geochemical information. The area is within a very tectonically active environment with major fault and fractures. It is quite obvious that the upflow of the geothermal system must be controlled by vertical faults/fractures. In addition alteration surrounding the area is intense, indicating that the rocks were very permeable and subject to a large throughput of fluid. The presence of a low-permeable Quaternary volcanic cover allows only the local upflow of thermal water and a poor flow rate.

The heat source postulated to be centred beneath the coalescing cones of Mt. Taftan. This is based on abundance of a wide variety of hydrothermal features, ranging from warm and acid springs, fumaroles, and presence of acid alteration mineral assemblages. Away from the vent and alteration zones, neutral chloride brine has already evolved by progressive neutralization of a previously acidic fluid by intensive water-rock interaction as the fluid migrates laterally.

The geothermal reservoir is feeding the spring periodically by shallow groundwater. As the steam rises from the reservoir, it may heat the local meteoric water. Thus, the waters discharging at the surface have experienced extensive changes in their composition. Exsolved gases during boiling ascends with steam to shallow depths where they condensed into peripheral groundwater to form acid sulfate steam-heated waters to form overprinting kaolinite and alunite.

Conclusions

It is concluded that the Taftan volcanic zone houses an extensive geothermal system. The Taftan volcano formed as a result of a tectonically compressive regime that has been active from Upper Pliocene until recent time. It can be considered as an enormous heat source and is a favourable thermal anomaly. Thus, the hypothesis of a strong local thermal anomaly and the existence of relatively high temperature fluids at shallow depth are confirmed. Localization of geothermal field is linked to volcanic activity and the geothermal manifestations such as sulfur emanation; hot spring and hydrothermal circulation are present and active in the area. Taftan volcano with its associated geological setting makes the region a primary target for geothermal exploration.

Acid-fluid interaction with wall rock in near surface conditions caused an incongruent dissolution and the formation of a mineral assemblage mainly consisting of kaolinite, alunite and silica. Sulfur gases mixing with snow melt water produces strong sulfuric acid leading to an intense fluid-rock interaction. Thus, In the Taftan geothermal region the occurrence of hydrothermal alteration minerals at the surface indicates low to moderate temperatures.

The present investigation shows that there is exploitable geothermal resource in reasonable proximity to the northern subduction of the Arabian plate underneath Makran in the Sistan and Baluchestan region in Iran. The geothermal prospect in the region is in reasonable proximity to populated areas. At this stage, geologically, the prospect is good for deep geothermal energy for direct use and Mt Taftan might be suitable for installation of a binary power plant to satisfy the local need. In general, the geothermal resources here are unexploited and it is envisaged to exploit these resources in a sustainable manner in the future.

Acknowledgement

The work presented in this article has been supported by a research grant provided by the Faculty of Environment, the University of Tehran. Dr. Mark Simpson and Professor Pat Browne of the Geothermal Institute of the University of Auckland are sincerely acknowledged for their assistance in XRD data interpretation. Thanks are also extended to Mr. Mahmood Jamaledini for assistance in the field. The laboratory work was completed at the Geothermal Institute of the University of Auckland while Mitsubishi Corporation granted the author a scientific fellowship. Comments on earlier versions of this manuscript by reviewers of IIJS improved the final product and their help is greatly appreciated.

References

Alavi, M. (1994) *Tectonics of the Zagros orogenic belt of Iran: new data and interpretation*, Tectonophysics, **229,** 211-238.

Alpers, C.N., Nordstrom, D.K., and Ball, W. (1989) *Solubility of jarosite solid solution precipitated from acid mine waters, Iron Mountain California*, USA. Sci. Geol. Bull, **42,** 281-289.

Berberian, M., and King, G.C. (1981) *Towards a paleogeography and tectonic evolution of Iran*. Canadian Journal of Earth Science. **19,** 210-265.

Browne, P.R.L. (1978) *Hydrothermal alteration in active geothermal fields*. Ann. Rev. Earth Planet. Sci. **6**, 229–250.

Browne, P.R.L., and Ellis, A.J. (1971) *The Ohaki-Broadlands geothermal area in New Zealand: Mineralogy and related geochemistry*. American Journal of Science, **269,** 97-131.

Dupuy, C., and Dostal, J. (1978) *Geochemistry of calc alkaline volcanic rocks from southeastern Iran*. Journal of volcanology and geothermal research. **4,** 363-373.

ENEL (Italian Electricity Agency, (1983) *Geothermal power development studies in Iran. Final report*. Ministry of Energy Iran.

Essene, EJ., and Peacor, D.R., (1995) *Clay mineral thermometry. A critical perspective*. Clays and clay minerals. **43,** 540–553.

Fournier, R., (1981) *Application of water geochemistry to geothermal exploration and reservoir engineering. In:* Geothermal systems: Principles and case histories. Edited by L. Rybach and L.J., Muffler, Chap.4. pp.109-134.

Gansser, A. (1966) *New aspects of the geology in Central Iran*. 4th World Petroleum Congress. Rome. Sec. 1/A5 paper 2., pp.279-300.

Gehring, A.U., Schosseler, P.M., and Weidler, P.G. (1999) *Mineral formation and redox-sensitive trace elements in a near-surface hydrothermal alteration system*. Geochemica et Cosmochimica Acta, **63,** 2061-2069.

Ghazban, F. (1999) *Geological and geochemical investigation of Bazman geothermal system, SW Iran*. Geological Society of America. Annual meeting, Denver, USA. Vol. 23.

Ghazban, F. (2000) *Geological and geochemical investigation of Damavand geothermal Prospect, Central Alborz Mountain, Northern Iran*. Geothermal research council transaction. **24,** 229-234.

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

Girod, M., and Conrad, G. (1979) *Les formation volcaniques recentes du sud de l'Iran; donnes petrologique preliminaires implications structurale*. Bulletin volcanologieque, **39(4),** 493-511.

Gislason, S.R., and Arnorsson, S. (1990) *Saturation state of natural waters in Iceland relative to primary and secondary minerals in basalts.* In*:* fluid-minerals interaction edited by R. J. Spencer and I-Ming Chou. The Geochemical Society Special Publication No.2 pp.373-393.

Harvey, C.C., and Browne, P.R.L. (1991) *Mixed layer clay geothermometer in the Wairakie geothermal field, New Zealand*. Clays and clay minerals, **39,**.614-621.

Hemley J.J., Hofstetler, P.B., Gude, A.J., and Mountjoy, W.T. (1969) *Some stability reactions of alunite*. Economic Geology. **64,** 599-612.

Hochstein, M.P., and Browne, P.RL. (2000) *Surface manifestations of geothermal systems with volcanic heat source*. Encyclopedia of volcanoes. pp.835-855.

Jung, D., Kursten, M., and Tarkian, M. (1976) *Post Mesozoic volcanism in Iran and its relation to the subduction of Afro-Arabian under the Eurasian plate. In: A far between continental and oceanic rifting (VII)*. Edited by A. Pilger and A. Roster. E. Schweizerbastsche Verlagsbuch-handlung. pp.175-181.

Mas, P., Patrier, D., Beaufort and Genter, A. (2003) *Clay-mineral signatures of fossil and active hydrothermal circulations in the geothermal system of the Lamentin Plain, Martinique*. Journal of Volcanology and Geothermal Research **124,** 195-218.

Moinvaziri, H., and Aminsobhani, E. (1978) *Etudes volcanologique du Taftan.* Ecole normale superieure de Tehran.

Platt, J.P., Legget, J.K., and Alam, S. (1988) *Slip vectors and fault mechanics in the Makran accretionary wedge*, southwest Pakistan. J Geophys. Res. **93 (B7),** 7955-7973.

Sato, T., Murakami, T., and Watanabe, T. (1996) *Change in layer charge of smectite and smectite layers in illite/smectite during diagenetic alteration*. Clays Clay Miner. **44**, 460–469.

Schoen, R., White, D.E and Hemley, J.J. (1974) *Argillization by degassing acid at the Steamboat Spring, Nevada*. Clay and Clay Minerals. **22,** 1-22.

Shahback, A. (1990) *Thermal springs in Iran*. Geological Survey of Iran.