Geothermal Exploration of Mount Sabalan, NW Iran

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ABSTRACT

A detailed surface exploration program carried out in 1998 has provided sufficiently good indications of geothermal resource potential at Mt. Sabalan to justify deep exploration drilling with the objective of generating power from geothermal resources. An integrated DC/TEM/MT resistivity survey has identified five conductive anomalies to depths of approximately 2000m. Four of these are associated with areas of surface thermal springs with discharge temperatures up to 85°C. An exploration model is proposed which describes the following key features: a large intrusive underlying a resurgent caldera is the primary heat source, the intrusive is locally exsolving magmatic volatiles at temperatures in excess of 250°C, the ascending volatiles condense into an extensively developed carapace of shallow groundwater and partially equilibrate at relatively low temperatures of about 150°C. Peripheral to the magmatic system, and below the groundwater system, there is a convective meteoric water system which receives heat and mass from the magmatic system; the convective system is the main exploration drilling target.

Introduction

Although one of the world largest producers and exporters of oil and gas, the Government of the Islamic Republic of Iran has recently embarked on a program of investigation into the use of renewable energy sources to increase diversification in the future energy supply mix of the country. Of high priority in this program is the possible development of geothermal resources contained in a volcanic complex in Ardabil province, Northwest Iran. ENEL (1983) identified the Khoy-Maku, Sahand and Sabalan areas in the Northwest and Damavand in the North central of the country. Delifin *et al.*, (1998) presented the results of an exploration study conducted at the Khoy-Maku prospect in 1997.

This paper presents the principal scientific findings from a detailed surface exploration program at Mt. Sabalan conducted during 1998, using modern exploration methods developed over the past two decades in circum-Pacific volcanic geothermal systems.

Several further papers are currently in preparation which provide greater detail the acquisition and interpretation of the data generated in this Program.

The Renewable Energy Organization of Iran (SUNA) an affiliate of the Iran Ministry of Energy is responsible for the exploration and possible development of the Mt. Sabalan geothermal prospect.

Geological Setting

Mt. Sabalan is located on the South Caspian Plate in NW Iran (Figure 1, overleaf) in a region of complex tectonics where crustal thickening is occurring (McKenzie, 1972). Recent magmatism at Mt. Sabalan is presumed to be associated with partial melting of the mantle wedge beneath the South Caspian Plate.

Volcanic activity in the Sabalan area commenced in the Eocene with eruption of lava flows and pyroclastics of trachydacite and trachyandesite composition. Volcanism resumed in the Pliocene and a large trachyandesite complex was built up through a succession of eruptions of pyroclastics and less voluminous lava flows with a stratigraphic thickness of at least 2000m. This activity culminated in the Pleistocene with caldera collapse, accompanied by the eruptions of peripheral domes and lava flows of dominantly trachydacite composition from the caldera rim and several nested ring fractures around the caldera. Resurgence of volcanism in the Quaternary has led to the development of voluminous trachyandesite domes in the floor of the caldera, forming three major peaks. The highest of these is kuh-e sabalan attaining a height of 4811m ASL (Figure 1). Late stage magmatism has occurred in the Holocene along the northern rim of the Sabalan caldera as evidericed by extensive, fresh ignimbrite flows and pumiceous pyroclastied, and the ongoing exhalation of magmatic gases from a young shallow intrusive.

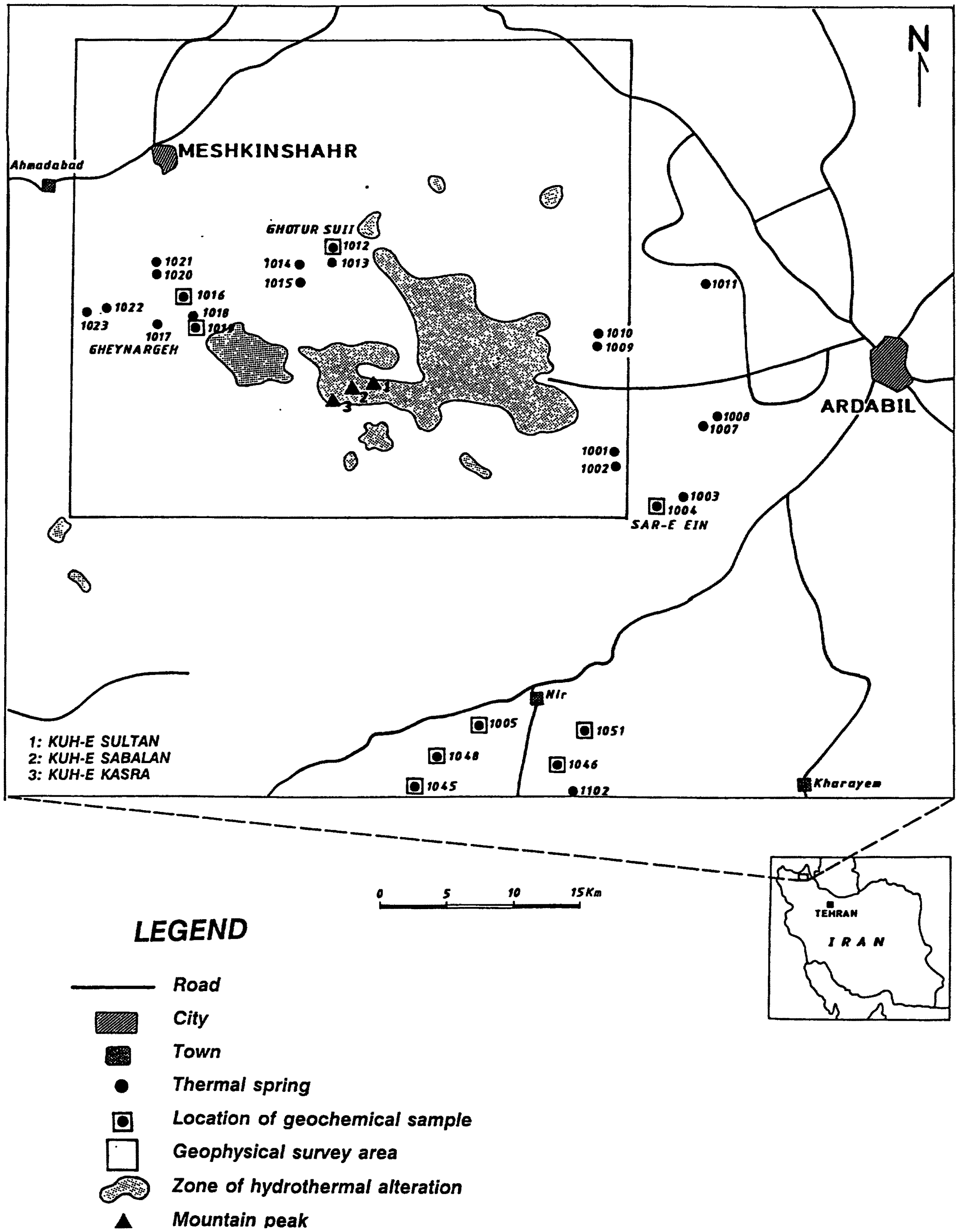

Figure 1. Geographical location of Sabalan geothermal exploration area.

Geological Structure

A photo analysis of the Sabalan prospect was undertaken from panchromatic stereo pair of SPOT satellite images and the gross geological structure over approximately 2000 km[2] of the prospect area has been established as follows (Figure 2):

- the Sabalan volcanic complex lies within a large fault block contained between two major NE trending sinistral strike slip faults;
- well developed linear structures transect the central area of the volcanic complex from N to S, with parallel lineations developed on the flanks;
- W-E and WNW striking lineations are prominent over the central fault block and to the south. These form a major foult zone which appear to link surface thermal activity on the northwest and southeast flank of Mt. Sabalan;
- the Sabalan caldera is slightly elongated central collapse with dimensions of about 14×12 km. It is considerably eroded on the western side where the major WNW fault zone intersects it.

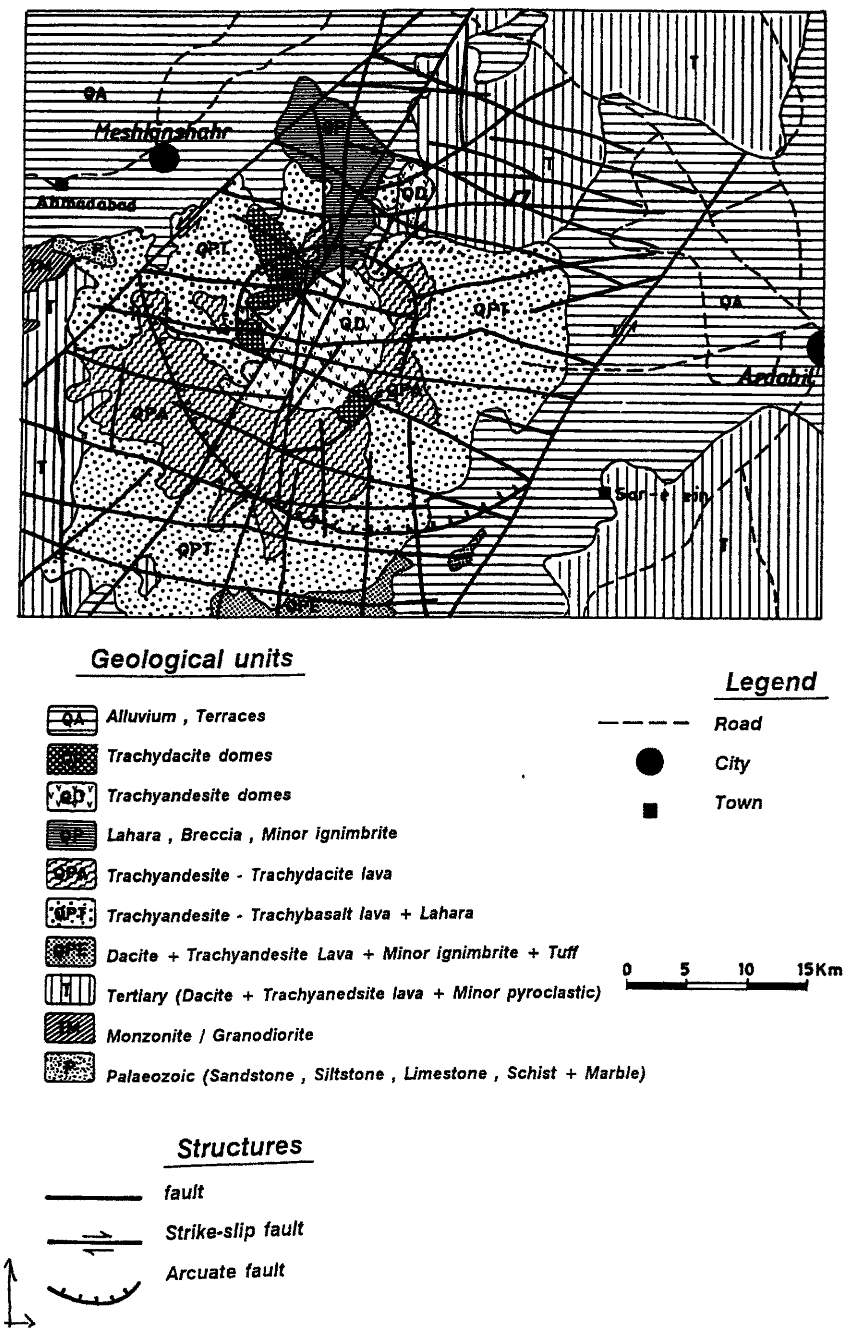

Figure 2. Geological map of Mt. Sabalan Volcano.

Surface Thermal Manifestations

Surface thermal activity at Mt. Sabalan consists of warm to hot springs and a sole weak solfatara. The thermal springs are located generally around the flanks of the Sabalan volcanic complex, clustered in five groups which show close association with geological structures. These include the Meshkinshahr springs (1016-1023) on the western and northwestern flank, the Ghur Suii springs (1012-1015) in the north and the Sar-e Ein spring, and others (1001 -1004 and 1007), on the easren flank (Figure 1). There is further group of thermal springs at Borjli (1005,1045-1049,1051), some 35 km south of Mt. Sabalan. From geochemical and hydrological considerations the Borjli group appears to be associated with a separate geothermal system and were not therefore included in the present study. Although none of the Sabalan springs are boiling, discharge from a number of the larger springs exceed 100 kg/sec mass output and 5 MW thermal output. The total heat flow above ambient air temperature from all springs in the Sabalan area is estimated at 45 MW thermal.

Extensive hydrothermal alteration exists at surface over the project area (Figure 1). This is largely confined to the Pliocene pre-caldera volcanics, is of variable intensity, and ranges from argillic secondary mineral assemblages comprised of smectite, kaolinite cristobalite, opaque, opal and chalcedony, to advanced argillic alteration comprised of abundant quartz and kaolinite, frequently with alunite indicating acidic hydrothermal conditions.

Geochemistry

Several historical sets of geochemical data are available for the Sabalan thermal features, collected in 1979 and 1983 (ENEL, 1983).All thermal features were nonetheless resampled and analyzed during the present survey. The chemistry of Sabalan thermal springs includes neutral pH NaCl waters, secondary Na-HCO_3-SO_4 waters and acid-SO_4 and acid-Cl waters. These compositional ranges are shown in Figure 3 (overleaf) in a Cl-SO_4-HCO_3 plot which distin-

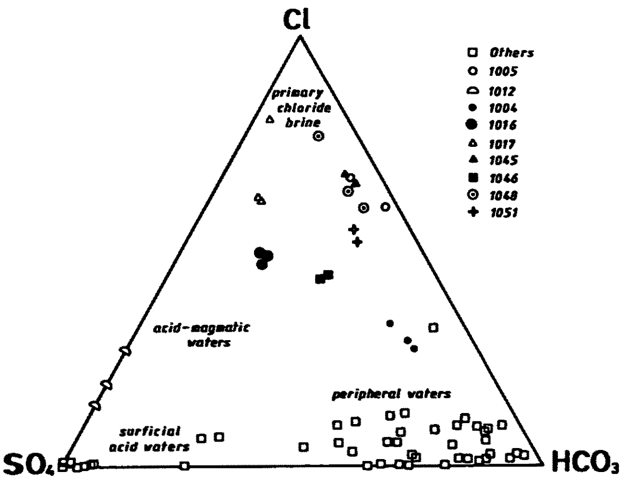

Figure 3. $Cl\text{-}SO_4\text{-}HCO_3$ anion diagram for Sabalan spring.

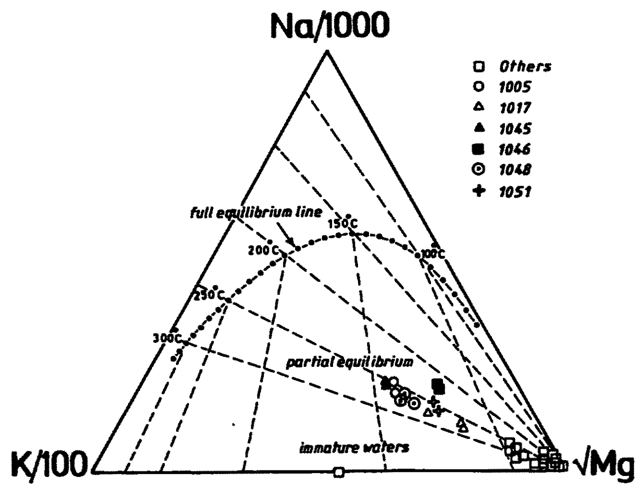

Figure 4. Na-K-Hg Cation diagram for neutral chloride spring.

guishes deep sourced, neutral pH, Cl waters (that plot near the Cl apex) from secondary peripheral ($HCO_3\text{-}SO_4$) and volcanic ($SO_4^{=}\text{-}Cl$) waters. The neutral chloride waters are further plotted on the Na-K-Mg ternary diagram in Figure 4 from which it can be seen that they range from immature to only partially equilibrated chemical compositions.

Few of the Sabalan spring waters meet the necessary assumptions for applying chemical geothermometers for estimating subsurface geothermal temperatures and these are limited to the Meshkinshahr springs. The Gheynargeh spring in the Meshkinshahr group with a discharge temperature of 85°C is the hottest spring at Sabalan and has neutral pH and 1600 mg/kg Cl. Chemical geothermometry calculations of estimates of subsurface temperatures yield 145°C for quartz conductive cooling and 127°C for chalcedony. The Gheynargeh waters have both high Ca and Mg concentrations, hence the NaK geothermometers are not appropriate, rather the K-Mg geothermometer and the Mg correction to the Na-K-Ca geothermometer are the most applicable and these yield temperature indications of 117°C and 112°C respectively.

The hot spring at Ghotur suii plots as a volcanic fluid in Figure 3. This is the most acidic (pH 2.5) of the Sabalan waters and has a ($SO_4^{=}\text{-}Cl$) chemistry, with both Cl and hydrogen ions increasing with spring flow rate. Suggesting that the acidity results from the solution of HCl bearing magmatic vapours. This view is supported by the gas chemistry of a weak solfatara alongside the spring the only surface steam in the greater Sabalan project area, which is indicative of primary magmatic steam being quenched in ground water(Bogie and Lovelock, 1999).

The Sar-e Ein group of thermal springs ('=44°C) (Figure 1), have low salinities but sufficient Cl (at ~ 210 mg/kg) to indicate that they may originate from an outflow from Mt. Sabalan to the NW of either diluted neutral chloride fluids similar to the Meshkinshahr springs, or possibly neutralized fluids of the acid magmatic type evident at Ghotur suii. A shallow drill hole in Sar-e Ein has encountered CO_2 rich thermal waters at 90°C at 200m depth.

In the southeastern area of Sabalan there are two springs of significance. The 23°C neutral pH Shoorchaman spring located at 3390m ASL, is the highest elevatoin thermal feature so far found. The 34°C Dollar spring located between Shoorchaman and Sar-e Ein has a dilute $Na\text{-}SO_4$ composition and neutral pH. These two features confirm that thermal conditions exist in the area between the Sabalan peak, Borjli and Sar-e Ein.

A plot of deuterium and oxygen-18 stable isotope data for thermal and cold springs at Sabalan is shown in Figure 5. The best fit for cold surface water compositions to a local metoric water line is defined by the equation given in figure 5 which is shifted 12 units towatds more positive deuterium values than SMOW (ENEL, 1983). The Meshkinshahr springs show modest shifts in both deuterium and oxygen-18 from the local meteoric water line, but lie on a mixing line between meteoric water and the "andesitic" water field of Giggenbach (1992b and 1992c). This is consistent with these waters originating from volcanic fluids as is now generally accepted to be the case for all hot water volcanic geothermal fields (D'Amore 1995). The stable isotopic composition of the Ghotur suii spring plots very close to the meteoric water line. If magmatic steam is condensing in to ground water to form these springs then either the mass fraction of the magmatic volatiles is small, or there is a large degree of dilution occurring. Given the spring's high flow rate, the latter alternative is favoured. The Sar-e Ein group springs are depleted in oxygen-18 and show no evidence for the addition of volcanic fluids. The negative shift may reflect exchange of oxygen-16 with CO_2 (ENEL, 1983) derived from calcareous marine sediments which are developed in the area.

Geophysics

- A program of 212 geophysical soundings was conducted in mid 1998 over a prospect area of 860 km^2 to delineate subsurface resistivity anomalies thah might be associated with high temperature geothermal resurces and to provide data for hydrogeological modiling. Three complementary resistivity methods were used in the survey:

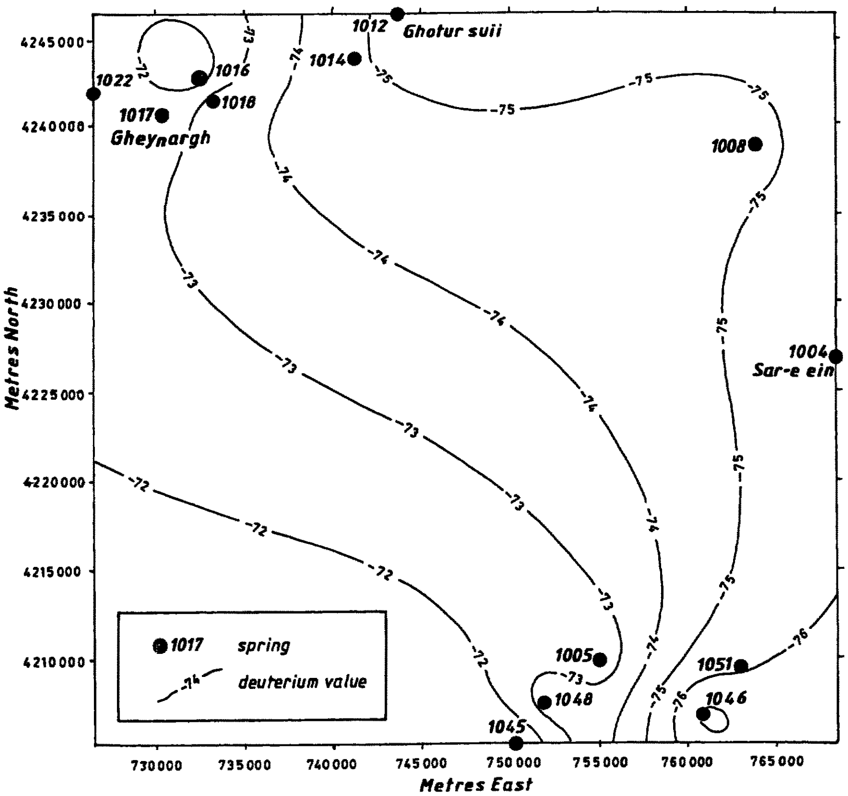

Figure 5. Stable isotope data for surface water and neutral chloride springs.

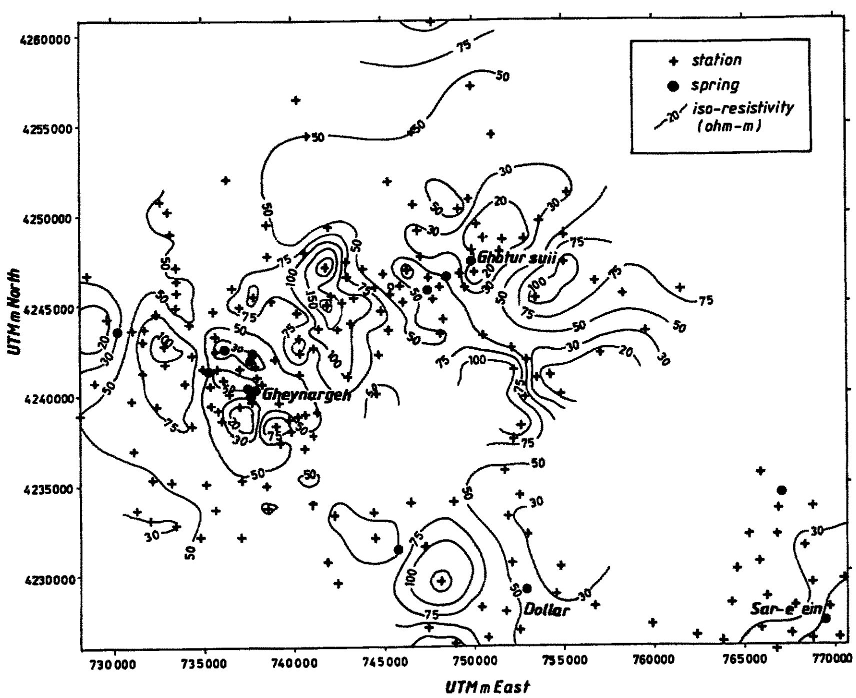

Figure 6. Iso-resistivity contour map for MT data at 3Hz.

- DC (direct current Schlumberger array with an AB/2 spacing of 25 m);
- TEM (time-domain electromagnetic, with a 50 or 100m central loop array); and
- MT (magneto–telluric over a frequency range of 8kHz - 0.02Hz).

A detailed discussion on procedures, data reduction and results is given by (Bromley *et al* – in press).

All MT data have been interpreted and five significant low resistivity anomalies have been identified (Figure 6). Four of these are coincident with the thermal spring areas detailed above. The fifth anomaly, localed on the northwestern flank of Mt. Sablan, is an apparently " blind " anomaly with no surface thermal expression. Each of these areas has resistivities of maximum 5 ohm-m within a depth range of about 400 m to 2000 m and are interpreted to be related either to geothermal systems containing saline fluids, high porosity formations or intense hydrothermal alterations associated with clay minerals. An intermediate resistivity layer of 10-15 ohm-m often overlies and surrounds the very low resistivity and this is interpreted as a zone dominated by groundwater.

Moderately low resistivities (15-30 ohm-m) are found near surface in several places where relict hydrothermal alteration is exposed. At most sites, however, there exists a thin surface layer of high resistivity, ranging in value from about 100 ohm-m to 5000 ohm-m. The highest resistivites are associated with youngest volcanics, whilst the pre-caldera volcanics and terraces, have lower resistivity because of higher clay content.

Exploration Model

A conceptual exploration model for the Sabalan geothermal prospect based on the results of the surface exportation program, is shown in Figure 7 (overleaf) The key features of this are:

- geothermal activity is widespread over the Sabalan volcanic complex. The primary heat source is a large intrusive underlying the caldera floor and this is the magmatic source of the syn-caldera domes and flows around the caldera rim and associated ring fractures and the resurgent intracaldera volcanics. It is likely that a single large geothermal system exists but is perturbed locally by individual intrusive events e.g. at Ghotur suii on the northern rim of the caldera;
- the Sabaln intrusive is still actively degassing magmatic volatiles and these are being largely condensed into groundwater. This is most evident at Ghotur suii where magmatic condensate spring chemistries are found. The springs at Gheynargeh to the southwest are

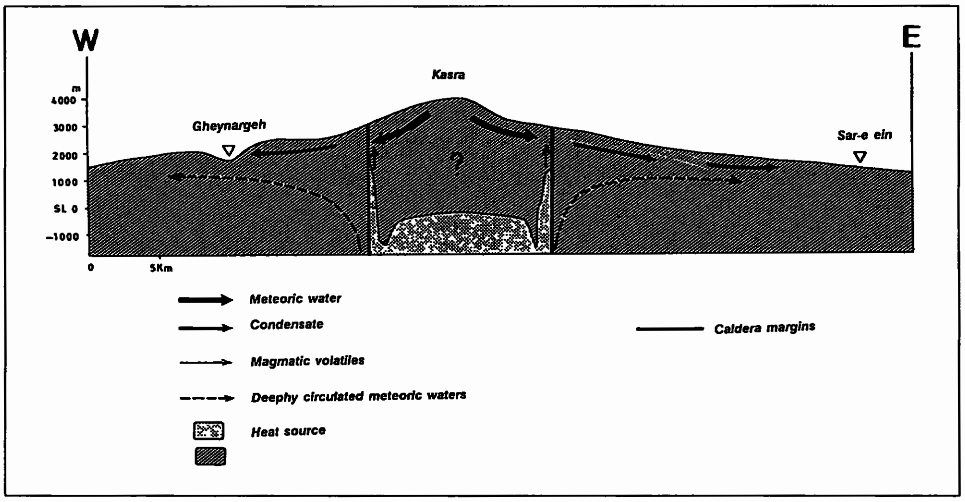

Figure 7. Conceptual hydrogeological model based on surface data.

consistent with being the neutralized equivalents of the Ghotur suii type fluid;

- the groundwater system into which the magmatic volatiles condense form extensive, shallow perched aquifers resulting from the infiltration of meteoric water from high altitude precipitation and snow melt. Very low tritium values in these waters indicate that the groundwater system has a high volumetric storage with underground residence times of 60 years or greater;
- solute geothermometery at the Gheynargeh springs indicates the groundwater aquifers are at approximately 145°C, however, aspects of the chemistry of these springs and the gas chemistry of Ghotur suii fumaroles suggests temperatures in the deeper magmatic system to be ≥ 250°C;
- the geophysical survey results show conductive zones below the groundwater aquifers. These are considered to represent deeply circulating meteoric water. Peripheral to the magmatic system which supplies both heat and chemical mass to the convective system;
- there is close structural control on the location of surface thermal activity at Sabalan and the geophysical anomalies. Permeability along caldera margins is frequently hypothesized but has never been adequately demonstrated at either active geothermal systems or their fossil analogues. It is thus considered that the hydrothermal hydrology at Sabalan is controlled by the N-S faults cutting through the center of the caldera and the conspicuous WNW striking fault zone through the southern part of the caldera which appears to link the Gheynargeh springs in the NW to the spring and resistivity anomalies at Dollar and at Sar-e Ein beyond.

Future Program

Three of the five conductive zones identified in the geophysical survey represent significant exploration targets for finding potentially high-grade, exploitable, convective geothermal systems. The anomaly in the Gheynargeh area has been ranked as the most prospective and an exploration drilling program has been committed which will result in the drilling of several deep exploration wells across the WNW structures. If these wells prove successful, the SUNA then intends to immediately progress the development of a pilot geothermal power plant.

Concluding Remarks

The results of the surface geothermal program presented in this paper confirms the possibility that a commercially exploitable geothermal resource(s) at Mt. Sabalan may be proven by drilling over the near future. This outcome would be of considerable national significance as it would establish a geothermal industry in Iran and also promote the exploration and development of other geothermal prospects elsewhere in the country as alternatives to fossil fuel power generation.

Acknowledgements

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