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GEOPHYSICAL EXPLORATION OF SABALAN GEOTHERMAL PROSPECTS IN IRAN

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ABSTRACT

Exploration for geothermal resources in the Sabalan mountains of northern Iran, undertaken in the summer of 1998, identified several low resistivity anomalies around the flanks of the volcanic complex that are worth investigating by deep drill-holes. Interpretation of 212 magnetotelluric soundings was assisted by the use of coincident TEM and shallow DC resistivity measurements. Large areas (>50km^2) of relatively low resistivity (<5 ohm-m) were found in the vicinity of mixed chloride-sulphate-bicarbonate springs at Gheynarge (to the NW) and at Sareyn (SE). Other significant areas containing low resistivities were found near Dollar Spring, along an inferred southern outflow path towards the Bouchli higher-chloride springs, and near the acid-sulphate spring at Ghotur Suii, which is near the northern rim of an inferred caldera collapse structure. Another significant low resistivity anomaly is located close to the northern caldera margin, between Tous Goali and Houshang Meidani. Here, there are relatively young trachydacite/rhyolite lava domes and flows and some surface evidence of hydrothermal alteration, but no active thermal features. On the north-eastern side of the volcanic complex, a thick layer (1-1.5km) of moderately low resistivity (7-15 ohm-m) is associated with surface exposures of relict alteration. This layer overlies a dome-shaped resistive basement in an area of high Bouguer gravity values, which supports an inferred structural model of a dense intrusive mantled by conductive clays. Evidence of structural control on the location of some of the low resistivity anomalies is also noted, particularly where strong 2D effects occur along NW and NE trending corridors, and along the caldera margin. Conceptual hydrological models, based on layered resistivity sounding interpretations, support the geochemical evidence, from springs, of fluid mixing processes in the upper few hundred meters. Rising chloride fluids tend to discharge in valleys where the lowest resistivity layer is closest to the surface, while mixed and steam-heated waters discharge from overlying layers of intermediate resistivity, and cold groundwater springs occur within an uppermost high resistivity layer.

1. INTRODUCTION

During the summer of 1998, a resistivity survey of the Mt Sabalan geothermal area, in northwest Iran, was undertaken for SUNA (Renewable Energy Organisation of the Ministry of Energy, Islamic Republic of Iran). The primary objective of this survey was to carryout geothermal exploration of the Sabalan area to delineate any resistivity anomalies that may be associated with high temperature geothermal resources. The subsurface resistivity structure was modelled to assess the size of the geothermal resources, to facilitate the choice of initial exploration well sites, and to prepare conceptual models for the hydrology of the geothermal fluid reservoirs.

The planning of the resistivity survey called for a flexible approach for both method and site selection. The types of structures that the survey was designed to target included: lateral resistivity boundaries - to assess resource extent; vertical resistivity layers - to assist hydrological modelling and drillhole planning; and two-dimensional (or 3D) structure - to assist in locating fault zones, caldera and graben structures or intrusives.

The scope of the project involved a total of 212 resistivity stations in an area of about 860 km^2 on the slopes of Mt Sabalan, near Meshkinshahr and Sareyn (Ardabil). Three complementary resistivity methods were chosen to achieve the desired accuracy and penetration depth range for practical drilling target purposes: DC (direct current, AB/2=25m Schlumberger array), TEM (transient electromagnetic, 50 or 100m central loop array) and MT (magneto-telluric, frequency range 8kHz - 0.02Hz). Station locations were selected by the survey crew to fulfil the exploration objectives of the survey while taking into account considerations of terrain (to minimise topographic distortions in the data) and site accessibility. By maintaining a flexible approach to survey planning, it was possible to expand the survey coverage into less accessible areas at high elevation, using horses, donkeys and camping equipment. This provided a better regional picture of the resistivity anomalies in the vicinity of the Sabalan volcano.

2. SETTING

The geological setting and the geochemical character of thermal springs in the Sabalan area is discussed in detail elsewhere (Bogie et al., in press, Khosrawi, 1996, Fotouhi, 1995). A summary is presented here. The main peaks of Mt Sabalan consist of fresh trachyandesite lavas that infill a 14 km diameter caldera. Along the northern rim of this caldera several relatively young domes and flows of trachydacite and rhyolite are K-Ar dated at 1.3 Ma. The outer ediface of trachyandesite lavas and pyroclastics are dated at 2.9 Ma. Extensive exposures of hydrothermal alteration occur within the older volcanics, particularly to the east and west of the caldera. Underlying the volcano is a Miocene monzonite batholith and Paleozoic sediments.

Structurally, the Sabalan area is located in a very complex compressional tectonic zone, on the NE moving South Caspian sub-plate, near the junction of the Eurasian, Iranian, and Arabian plates. Three main directions of faulting have been recorded: NE, NW and N-S. The latter are expected to be conjugate tensional faults between major NE trending strike-slip faults. However, other fracture sets and structural lineations trending WNW to W and NNW have also been observed or interpreted from SPOT satellite imagery. The hydrological significance of these various structural trends is difficult to determine with any confidence.

Thermal springs are located on the northern slopes of Sabalan, seven in the Mouil Valley near Meshkinshahr, one further west at Yel Sou, and three aligned along a major NE trending structure near Ghotur-Suii (Figure 1). Temperatures range from 21°C to 82°C, and geochemical analyses indicate a range of types including steam-heated bicarbonate, acid-sulphate, mixed acid-sulphate-chloride, and neutral-chloride springs.

The highest chloride springs at Gheynarge and Khosrow-su in the Mouil Valley contain 1541 mg/L and 1147 mg/L Cl respectively.

On the southern slopes of Sabalan there are two steam-heated springs at high elevation (Dollar and Shor-Chaman, Figure 1), and a set of high chloride (up to 3000 mg/L) springs at low elevation (Bouchli, 20 km south of Dollar). To the southeast, the area of Sareyn contains several warm springs, mostly of diluted and mixed geothermal fluids, of the bicarbonate-chloride-sulphate type. Steam-heated, acid-sulphate springs are also found at higher elevation near Vakil Abad, to the east.

3. GEOPHYSICAL SETTING

Although no previous resistivity surveys had been conducted in the Sabalan area, a regional gravity survey of the area was conducted in 1977-1979 (TBCE, 1979) on behalf of the Iranian Ministry of Energy. A regional aeromagnetic anomaly map of the area was also published by the Geological Survey of Iran in 1978 (Yousefi et al., 1978). More than 1000 gravity stations were occupied at this time, with typical station spacings of 1.5 km along roads and trails. The Bouguer anomaly maps show two significant areas of high density, probably originating from intrusives (Miocene batholith) or thick lava sequences. These are centred about 20 km NE of Mt Sabalan (apparently aligned along NE trending structures), and about 40 km to the west. The positive gravity anomalies also coincide with exposures of Eocene-age trachyandesite. On the flanks of the mountain range, there are three significant negative residual gravity anomalies, implying the presence of basins containing low density formations. These are located near Meshkinshahr, to the north, Sarab, to the SW, and Sareyn, to the SE. Near surface formations in these areas contain low density Quaternary alluvium, conglomerate and sandstone. Deeper formations may include tuffaceous volcanics or other porous sediments.

Interpretation of the regional aeromagnetic anomaly map is limited by the flight line spacing (7.5 km) and survey altitude (2400 m, draped over the high mountain peaks). One significant positive anomaly centred about 15 km north of Meshkinshahr is inferred to be caused by an intrusive (Miocene batholith), about 15 to 20 km in diameter and several kilometres depth. Smaller positive magnetic anomalies, of shallow origin, occur on parts of the western and southern flanks of the Sabalan Mountain, where thick sequences of lava flows are not hydrothermally altered, and have therefore retained a high magnetite content.

Calculations of natural heatflow from Sabalan geothermal systems, using the spring temperatures and discharge flowrates reported in a May 1978 survey, result in a total of about 45 MW (thermal) relative to an ambient temperature of 7°C. However, the recent discovery of additional thermal springs, and the marked seasonal variation in flowrates (but not temperatures) make this heatflow estimate highly uncertain.

4. RESISTIVITY FIELDWORK: DC, TEM AND MT

The purpose of the DC resistivity measurements at each site is to obtain an independent measure of the shallow resistivity in the two orthogonal directions (east and north) using the same 50 m electrode array as for the deeper penetrating magneto-telluric (MT) soundings. A typical penetration depth for the Schlumberger DC measurement is about 12 m. Variations in this shallow resistivity can be correlated with near surface lithology, clay content and groundwater saturation. Significant differences in resistivity with orientation can be attributed to local shallow inhomogeneity or anisotropy, which may influence the interpretation of the MT soundings (static shift corrections).

The TEM (central loop) soundings, at each site, were also conducted to obtain an independent measure of the subsurface resistivity, but at depths between about 100 m and 300 m. The equipment used was a Zonge NT20 transmitter and GDP32 receiver, with a square loop source (50 m or 100 m sides) and a vertical magnetic coil (10 000m^2 effective area) at the loop centre.

The in-loop TEM method is most useful in a layered environment, for vertical soundings, to relatively shallow depth. The practical penetration depth limit is constrained by the maximum current used, the size of the transmitter loop and the background electrical noise level, as well as “window” time (from current switch off). The TEM data can also be useful for the treatment of “static shift” effects in MT soundings because TEM is not as affected by near surface electric field distortions. However, 2D or 3D inhomogeneity can still result in distorted TEM soundings. Local sources of magnetic noise can also contaminate the data, especially at very short or very long window times. For mapping all of the TEM resistivities, to an approximate depth of 200 m, a delay time of 1 millisecond was chosen. This was compared with the MT apparent resistivities (east and north) at a comparable penetration depth (approximately 128 Hz frequency).

The natural source MT method was adopted for deeper penetration using a frequency range of 8 kHz to 0.02 Hz (lower frequency signals penetrate deeper). As anticipated, good levels of natural source signal were obtained in the frequency range of 1 kHz to 3 Hz. This covers the depth range of primary interest for exploration drilling. Intermittent results were obtained at lower and higher frequencies depending on signal level at the time of recording. (In the frequency bands from 0.1 Hz to 1 Hz and 1kHz to 3 kHz natural signal strengths are usually much weaker). At most sites, however, data collected at frequencies below 0.1 Hz and above 3 kHz were of sufficient quality (cc>0.7) to enable the resulting calculated resistivities to be used to constrain the resistivity models. Measurements were always made with orthogonal horizontal arrays of electric field dipoles (Ex, Ey) and magnetic coils (Hx, Hy), using EMI-BF10 antennas. The vertical magnetic field (Hz) was also recorded.

The data acquisition was accomplished with a Zonge GDP-32 receiver. This receiver uses cascade decimation and stacking and averaging of Fourier transformed cross and auto-power spectra of the 6th and 8th harmonics, to obtain amplitude and phase measurements of the electric and magnetic fields. Using robust processing mode, data are accepted or rejected according to coherency and outlier limit tests: typically a coherency limit of 0.7 and outlier rejection limit of two times the median. For all the Sabalan stations, a notch filter to attenuate 50 Hz (and its odd harmonic frequencies) is applied to the incoming signals. A signal pre-conditioner (SC-8) also pre-amplifies the electric field voltages, and filters out RF frequencies and SP drift. Resistivities and phase differences are calculated using standard Cagniard formulae, and then plotted against frequency for interpretation in terms of layered resistivity models.

5. RESISTIVITY RESULTS

The DC resistivity values at the majority of sites show reasonably uniform (isotropic) shallow resistivity structure. The average difference between Ex and Ey oriented measurements is 20%, and only 11 sites have differences exceeding 50%. The DC resistivity differences did not correlate with the MT "static shift" resistivity differences, so distortions of shallow origin (within the measurement array) were generally not significant. The average of the DC resistivity values does clearly correlate with the near-surface geology as illustrated in Table 1.

Older volcanics (pre-caldera) and alluvium are more weathered, and therefore contain a higher percentage of conductive clays. Some local areas, with anomalously low DC resistivities (less than 75 ohm-m), are situated near thermal springs (Ghotur Suii, Aghsu, Yelsou, Sareyn) or exposures of hydrothermal clay alteration (Gharah Gol, Gharah Ghayah, SW Aiger).

The TEM data from many of the sites exhibit polarity reversals at early times (<1 msec). These cause spurious resistivities because of the apparent instantaneous change in voltage gradient. Polarity reversals can be attributed to polarisation effects from local conductivity anomalies, such as 2D structure or shallow inhomogeneity near the receiver coil. However, the calculated "ramp" resistivity at 1 msec (typically 200 m depth penetration) for all stations, when plotted and contoured, showed a pattern similar to the average (Ex and Ey) MT data at a frequency of 128 Hz. Relatively low TEM resistivity anomalies (<30 ohm-m) occur near the thermal springs and areas of hydrothermal clay alteration. Relatively high resistivity anomalies (>100 ohm-m) are observed where the unaltered (or intensely silicified) volcanic formations are at least 200 m thick. At two locations (west of Dollar Spring, and near Gharah Gol) these shallow resistive anomalies match shallow magnetic anomalies (from Yousefi et al., 1978), further supporting their origin as thick surface layers of unaltered, magnetic-rich volcanic lavas (or domes).

Magneto-telluric resistivity data from the 212 soundings revealed five significant areas of anomalously low resistivity around Sabalan, at depths typical of exploration drillholes (300 m to 3000 m). To illustrate this, Figure 1 shows the contoured apparent resistivities at a frequency of 3 Hz. The geometric average of the resistivities in the east (Ex) and north (Ey) directions is used, except in a few cases where strong static shifts are observed, and correction using the TEM resistivity is required. The geographic locations, approximate areas and trends of these low resistivity anomalies are listed in clockwise order below:

a) Gheynarge and Mouil Valley, 50 km^2, aligned NW-SE, associated with high chloride and high temperature springs.
b) Toas Goali and Houshang Meidani, 15km^2, NE and NW alignments, linked to hydrothermal alteration but not to springs.
c) Ghotur Suii, 5 km^2, linked to large northern and eastern "outflow" anomalies (probably clay alteration), strong NE-SW trend linking three hot springs.
d) Sareyn, > 50 km^2 , broad south eastern outflow anomaly, lowest values near Sareyn springs.
e) Dollar, > 15 km^2, associated with one steam-heated spring but may link through a deep southern outflow to Bouchli high chloride springs (Fotouhi, 1995).

Approximately 40% of the stations have matching Ex and Ey curves that indicate an isotropic one-dimensional or layered subsurface. Another 40% have static shifts (Ex and Ey curves are parallel) indicating a local distortion in the magnitude of the electric field (independent of frequency). Of the remaining sites, most show evidence of two-dimensional structure at depth (that is, diverging Ex and Ey curves at low frequency). Many of these sites occur along significant structural boundaries. These include: a) the caldera rim, separating high resistivity young volcanics from lower resistivity old volcanics; b) a major NE-SW fault zone through Ghotur Suii-Shahabil-Torsho springs and patches of hydrothermal alteration (silicification) near Gharah Gol and Toas Goali; and c) a NW-SE trending structure along the Mouil side of the Gheynarge resistivity low.

One dimensional modelling of all soundings was undertaken using an iterating best-fit algorithm to minimise the RMS residuals between observed and calculated resistivities and phase differences. The iteration was weighted towards the average values with the lowest standard deviations, and repeated 15 times from different starting models to determine the overall uncertainty in the optimum layered model.

Two dimensional cross-sections have been compiled from the layered models, through the main areas of interest. An example, through the Gheynarge anomaly, is given in Figure 2. Full 2D inversion of these cross-sections is not justified because the sounding locations, being designed for regional coverage, are not spaced closely enough to properly constrain any 2D inversion of resistivity boundary structures. However, soundings located close to boundaries inferred from the cross-sections often reveal evidence of 2D or 3D effects (diverging resistivity curves at low frequencies). In these cases, the layered interpretation at depth, is treated cautiously. The median of the maximum probing depths of all the MT soundings is 3.3 km. This is determined from the skin depth ($/\sqrt{2}$) at the lowest frequency for which there is data of sufficient quality to be used in the layered inversions. For 5% of the stations, however, the data quality at very low frequency is not adequate for modelling, and maximum probing depths in these cases are restricted to about 500 m.

6. INTERPRETATION OF RESISTIVITY MODELS

Interpretation of the layered resistivities generates conceptual geothermal and hydrological models of the Sabalan area, using the known information from surface geology and spring chemistry to infer subsurface conditions. The most likely causes of low resistivity anomalies in a volcanic setting are: (1) intense hydrothermal clay alteration (especially smectite and kaolinite), (2) mineralised fluids in high porosity aquifers, and (3) high temperatures (>100^{o}C). Section A-A', which passes NW-SE through the "Gheynarge-Mouil" anomaly (Figure 2), reveals a significant low resistivity anomaly of 1 to 6 ohm-m, from about 300 m to >3km depth. It forms a NW trending corridor about 9 km by 2 km in area, and is generally bounded by deep resistivities greater than 50 ohm-m.

The low resistivity values are inferred to be caused by saline geothermal fluids of relatively high temperature (>100^{o}C), within porous rocks, and associated with intense hydrothermal clay alteration. Overlying this very low resistivity formation is a layer of intermediate resistivity (7 to 18 ohm-m) which is inferred to represent a mixing zone where cool surface groundwaters meet rising geothermal fluids (and gases), and steam condensates form. The top surface of this intermediate resistivity layer locally intersects the surface where the hot and warm springs discharge. A short extension of this layer to the NW is inferred to indicate an outflow of warm water.

The uppermost layers of high resistivity capping the low and intermediate resistivity anomaly consist mostly of unaltered volcanic formations. These contain perched aquifers of groundwater which discharge as cold springs. In several places, however, erosion has exposed patches of old hydrothermal clay alteration. Faults have also allowed steam and gas to migrate closer to the surface, creating linear patches of hydrothermal alteration. These contribute to lateral variations in the near-surface resistivity.

Interpretation of the resistivity structure of the region surrounding Sabalan is also assisted using visualisation software to enhance different aspects of the layered models. For example, a contour map of the elevation of the top surface of the low resistivity layers (Figure 3) reveals several elevated anomalies that are just outside the rim of the caldera. These high elevation anomalies (>2700 m) are centred near Aiger (to the SW), Houshang Meidani and Toas Goali (to the north), and Gharah Gol - Gezel Barah (to the NE). In each case, there are no thermal springs associated with the low resistivity anomalies, but there are large areas of exposed relict hydrothermal alteration. These anomalies are therefore interpreted to indicate the presence of cooled or extinct hydrothermal systems that had once formed in the pre-caldera volcanics.

A map of the basement resistivities shows that the underlying intra-caldera volcanics in the vicinity of Mt Sabalan are all high in resistivity (>100 ohm-m) as is the area near Gharah Gol and Gezel Barah. In this northeastern sector, a 1 to 1.5 km thick layer of moderately low resistivity (7 to 15 ohm-m), interpreted as a mantle of relict alteration, overlies a resistive basement, interpreted to be an intrusive. The presence of a large intrusive is supported by the existence of a gravity high in this area. Some residual heat may still be present at depth, in this area, as evidenced by the existence of warm, steam-heated springs at Vakil Abad, about 13 km down-slope from Gezel Barah, along a possible eastern outflow path.

To the north and northwest, the underlying basement resistivity is consistently low, but the elevation of the top surface of the low resistivity layer dips steeply from 2500 m down to sea level (Figure 3). There are no known hot springs within the Meshkinshahr - Lahrood basin (elevation about 1500 m), so this part of the low resistivity anomaly is also considered to be attributable to relict alteration from previous phases of hydrothermal activity.

To the southeast, the low resistivity anomaly around Sareyn is extensive (at least 50 km^2). The top surface of the low resistivity basement (<5 ohm-m) is approximately 1150 m (about 350 m depth), and there are numerous hot springs in the area. The surface geology consists of volcanic alluvium forming a gently sloping ring plain. A large residual gravity low implies the presence of a basin infilled with low density pyroclastics, alluvium or high porosity sediments, which could include conductive mudstones. The lowest resistivities are interpreted to indicate the probable presence of high temperature (>100^{o}C) chloride fluids within a high porosity aquifer at about 350 m depth. However, the very low resistivities could also be partly accounted for by a thick layer (>1 km) of very conductive mudstones or clays such as smectites. A new drillhole, deeper than the existing 200m borehole (T=90^o), would be needed to test these hypotheses.

At Sareyn, the thermal fluids discharging to the surface as springs originate from a moderately low resistivity layer (6 to 9 ohm-m). This is interpreted to indicate a mixing zone where the rising high temperature chloride fluids mix with diluting groundwaters, containing some neutralised steam condensates. The resulting cooler temperatures (about 60^{o}C) and less mineralised waters are interpreted to be responsible for the slightly higher resistivities. The upper 100 m layer of high resistivity consists of various alluvium deposits, with a small percentage of clay. This layer contains cool, perched, groundwater aquifers, except in the immediate vicinity of the hot springs.

7. CONCLUSIONS

Recent exploration has successfully identified several low resistivity anomalies around the flanks of the Sabalan volcanic complex, at or beyond the rim of a major caldera structure. The most significant, from a geothermal perspective, are situated near hot springs of mixed chloride-sulphate-bicarbonate chemistry, at Gheynarge/Mouil to the NW, and at Sareyn to the SE. Other areas containing low resistivities are located near an acid-sulphate spring at Ghotur Suii (to the north) and a steam-heated spring at Dollar (to the south). Deep exploration drill-holes are planned to test these geothermal anomalies.

Additional low resistivity anomalies found at high elevation (>2700 m) are not associated with active thermal features, but with surface exposures of hydrothermal alteration, presumed to be relict, within the pre-caldera volcanics. These are found near Aiger (west), Toas Goali - Houshang Meidani (north), and Gharah Gol - Gezel Barah (northeast). The latter is underlain by a high resistivity basement at 1 to 1.5 km depth, interpreted to be caused by a dense intrusive.

Where hot fluids rather than relict alteration are thought to be the primary cause of the resistivity lows, layered interpretation of the MT resistivity soundings assists in the construction of conceptual hydrological models. Various aquifers are involved in the mixing and dilution of geothermal fluids rising to the surface. The highest chloride fluids tend to discharge in valleys where the lowest resistivity layer is closest to the surface. Steam-heated groundwaters generally discharge from within an overlying layer of intermediate resistivity, and cold groundwater springs occur within an uppermost high resistivity layer.

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Table 1. Comparison of surface geology and shallow resistivity

Stage	Geology	Location	Average DC rho (ohm-m)
4	Trachyandesite-dacite lavas, domes	Mt Sabalan slopes	5300
2-4	Rhyodacite, trachyte, tuff breccia, ignimbrite	Nth caldera margin	900
1	Pre-caldera trachyandesite-dacite	SW, E Sabalan	600
1	Pre-caldera trachyandesite-basalt	Sabalan outer flanks	400
R	Recent alluvium-terraces	N, SE lower deposits	200

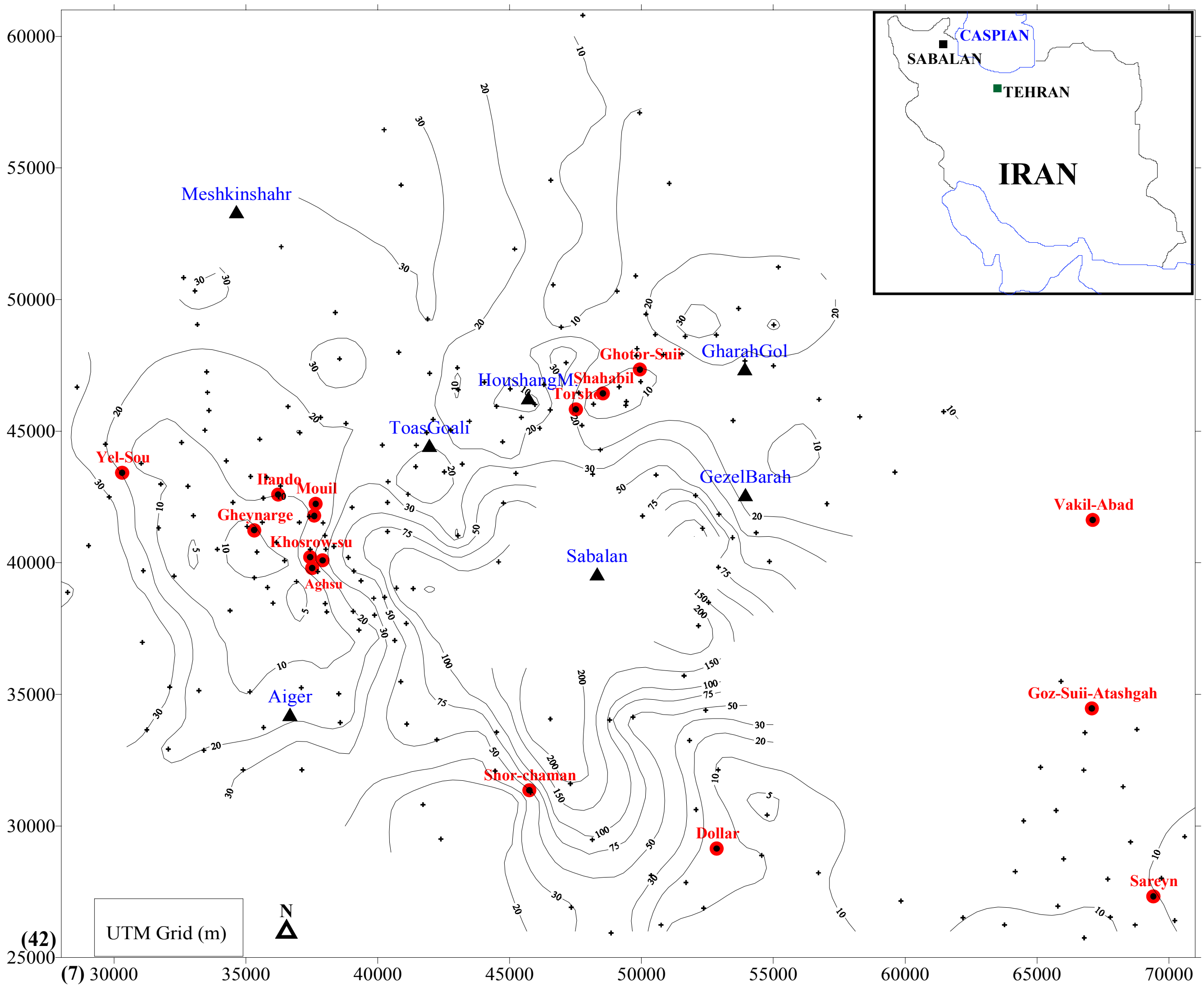

Figure 1. Resistivity anomaly map of the Sabalan region, showing locations of hot springs ● , major geographic features ▲ and resistivity stations + . The grid is simplified from UTM (metres), oriented north. Contours show average MT apparent resistivity (Ω-m) at 3 Hz frequency. Elevations range from 4800m (Sabalan peak) to about 1500m (Meshkinshahr and Sareyn).

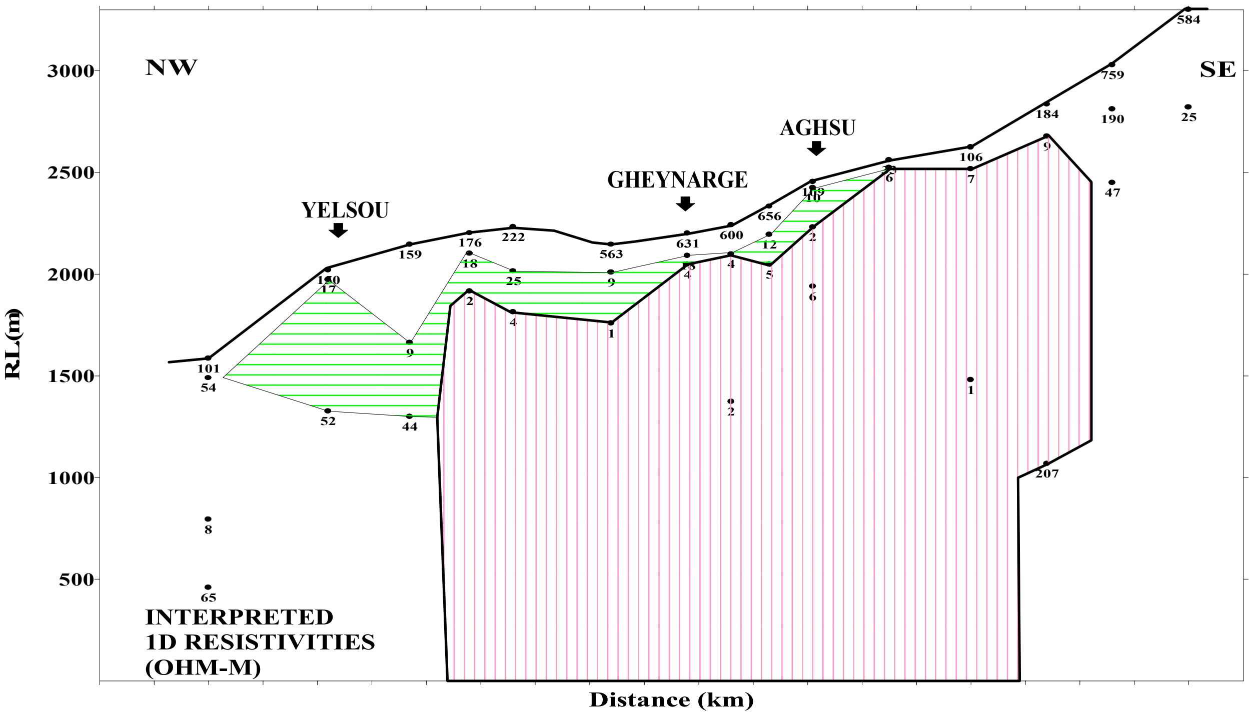

Figure 2. Resistivity cross-section A-A’ (see Fig. 3) through Gheynarge hot spring in the Mouil Valley, northwest of Sabalan. Layered resistivity models (Ω-m) are interpreted from MT soundings, and coded to assist hydrological interpretation.

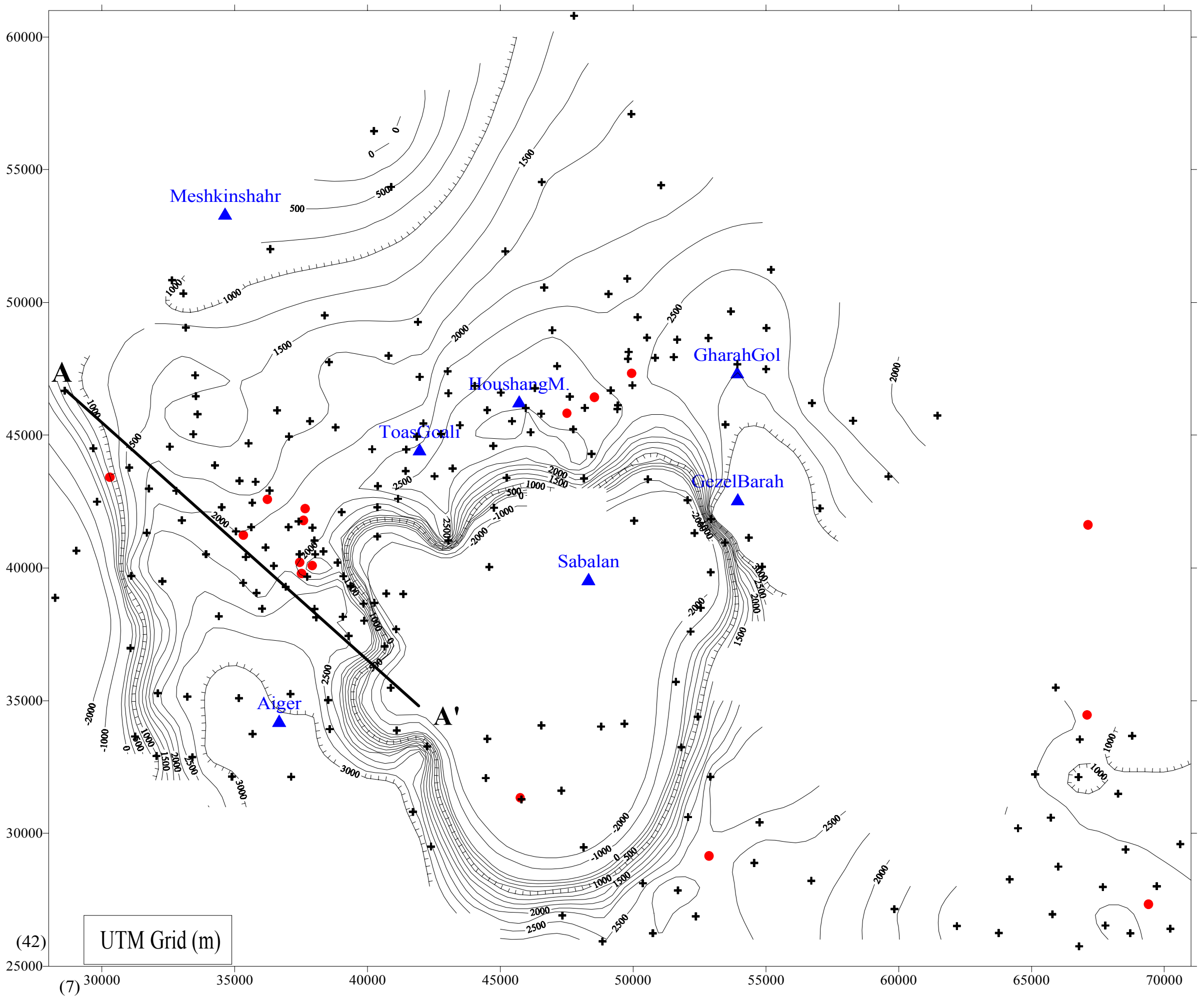

Figure 3. Elevation contours of the top surface of the low resistivity layers interpreted from Sabalan MT soundings. The selection criteria for the low resistivity (Ω-m) is as follows: < 5 to the SE, < 16 to the NE, < 10 to the N and W. Maximum depth, for this plot, is 2 km below sea-level. Areas where low resistivity was <u>not</u> detected within this depth range are also identified (Sabalan peak and west).