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Magnetotelluric Survey of NW Sabalan Geothermal Project, Iran

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ABSTRACT

2-D-resistivity modeling of the data from the latest MT survey undertaken in 2007 was used to map a shallow resistivity anomaly located east of Pad E and west of the young lava domes of the Post-caldera Kasra Volcanic Formation. The anomaly is postulated to represent the possible upflow region of the NW Sabalan geothermal field. The interface between the conductive layer and the underlying higher resistivity body lies beneath Moil Valley at an elevation of ~2000 m asl and shoals toward the southeast. It is shallowest east of Pad E at an elevation of ~2500 m asl. This interface coincides with the base of the smectite zone in Wells NWS-1 and NWS-4, where temperatures exceeding 180ºC were measured. It is inferred that elevated temperatures most likely exceeding 240ºC could be encountered beneath the shallowest part of the interface of the conductive and the high resistivity layers.

The general NW trend of the resistivity anomaly at a depth of 800 m and elevations of 2300 m asl and 2600 m asl is consistent with the major structural fabric of the Moil Valley. This indicates that faults along this direction exhibit good permeability and are attractive drilling targets. A resistivity gradient between stations 6 and 7 is inferred to be a possible southeastern extension of NNW3 Fault and is a good drilling target to test the projected higher temperature in the area east of Pad E.

1. INTRODUCTION

The Northwest Sabalan geothermal area lies at the northwest slopes of Mt. Sabalan, an immense stratovolcano located in the province of Ardebil in northwestern Iran, as shown in the map given in Figure 1. The area has been the subject of geoscientific exploration studies since 1978 (Foutohi, 1995). In 1998, a semi-detailed regional MT survey was conducted at 212 stations around the Sabalan Mountains (KML, 1997). Three deep exploratory wells and two shallow reinjection wells were drilled between 2002 and 2004 within the Moil low resistivity anomaly identified by the 1998 MT survey. Well NWS-3, which was drilled farther to the NW, was non-commercial with a temperature of only 160°C. The measured temperature in well NWS-4 was >230°C, while the hottest well, NWS-1, yielded a temperature of about 242°C. Stage 1 drilling, however, failed to identify the location of the upflow region and Sinclair Knight Merz (SKM, 2005) inferred that high temperature fluids probably flow from the south or southeast.

Reinterpretation of 1998 MT data (Talebi et al., 2005) indicated an increasing elevation of the top of the high resistivity basement towards the south consistent with the measured temperatures and suggested that the upflow of fluids originated from the southeast. Hence, new exploration pads, Pads D and E, were recommended and later constructed southeast of NWS-1 in preparation for Stage 2 drilling activities in NW Sabalan.

A technical team from the EDC (formerly known as the PNOC-EDC or PNOC-Energy Development Corporation) was convened in 2007 to conduct a review of available data provided by the Renewable Energies Organization (SUNA) of the Islamic Republic of Iran. The review proposed a hydrological model suggesting that the upflow is more likely situated east-southeast of the Moil Valley. This model was based on the pattern of low-resistivity tongues defined in the apparent iso-resistivity map at 0.33 Hertz given in Figure 2 and the temperature contours at 1500 m asl shown in Figure 3.

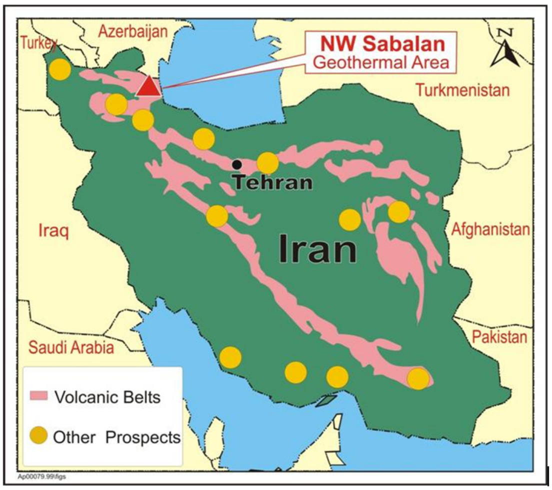

Figure 1: Map showing the geographic location of NW Sabalan geothermal project.

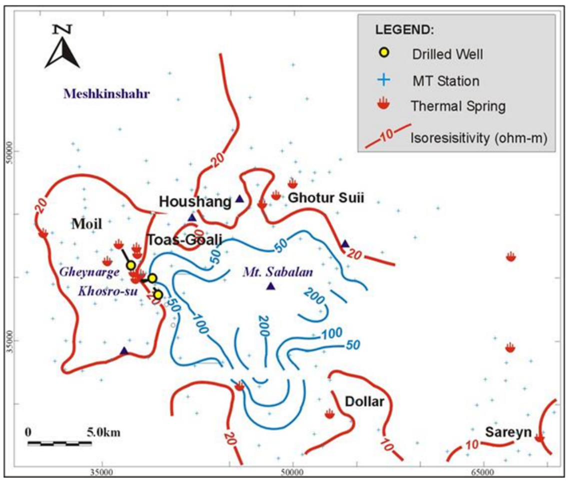

Figure 2: Proposed hydrological model of NW Sabalan (after Bayrante et al., 2007 based on the regional resistivity anomaly map of Bromley et al., 2000).

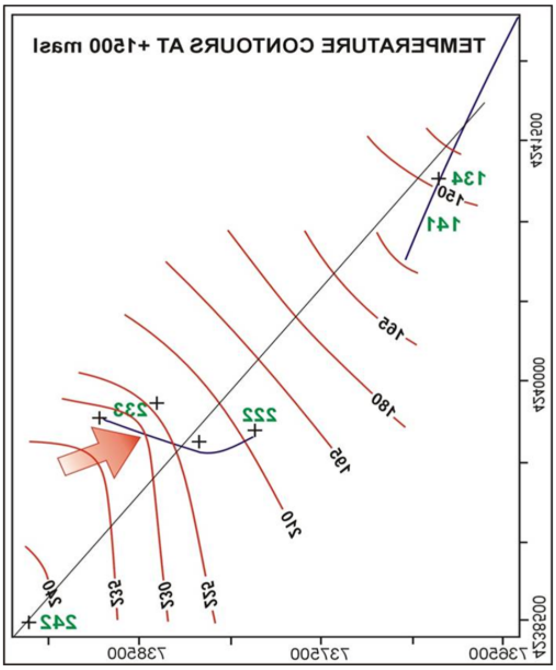

Figure 3: Temperature contours at 1500 m elevation. The arrow shows the inferred origin of higher temperature geothermal fluid (after Bayrante et al., 2007).

In order to confirm the proposed hydrological model, PNOC-EDC recommended as early as 2006 that a deep-penetrating MT survey be conducted prior to any future drilling in the project. The 70-station program was proposed to be conducted in two phases, which are detailed in Figure 4. In Phase 1, the high-elevation regions east and southeast of Moil Valley were studied. The goal of this phase was to determine the possible center of the geothermal system and identify drilling targets for the development of a 55-MW geothermal power plant. In Phase 2, the northern, eastern and southern regions of Mt. Sabalan Volcano will be studied. The overall goal of the two-phase project is to define a hydro-geophysical model of the entire Sabalan volcanic complex.

The results of Phase 1 are presented in this paper. During this phase, 28 MT stations were occupied during a one-month survey beginning on October 16, 2007.

2. MAGNETOTELLURIC DATA

A Phoenix MTU-5A data acquisition system with a standard frequency range from 0.0005 to 380Hz was used in this study. A total of 28 MT stations were occupied and tested. Of these, sounding curves from 23 stations exhibited good data quality and were used in the resistivity modeling. The other five stations contained high background noise levels (~400 mV DC) and were excluded in the final processing and modeling.

MT data conversion from time domain to frequency domain and initial data editing were performed using Phoenix Geophysics SSMT2000 and MTEDIT software. Geosystem's WinGLink software was used in the final data editing and resistivity modeling.

1-D and 2-D models were constructed to determine the subsurface resistivity structure of the geothermal field. 1-D resistivity Occam modeling was used to map the shallow conductive layer and was subsequently used to outline the most probable hydrology of the geothermal system. Thickness and depth of the conductive layer was defined in 2-D models. Static shift correction was manually applied on individual MT sounding for 1-D models. For 2-D models, static shift effects were included in the modeling process.

3. RESISTIVITY STRUCTURE

The 1998 MT survey identified five areas of low resistivity anomalies within the Sabalan volcanic complex: Gheynarge-Moil Valley in the southwest, Toas Goali-Houshang Meidani in the northeast, Ghotur Suii farther north, Sareyn farther east, and Dollar in the southeast, as shown in the apparent iso-resistivity map in Figure 2 (Bromley et al., 2000). These anomalies generally coincide with the area where the surface thermal manifestations are found. For example, high chloride and high temperature springs, Gheynarge and Khosro-su, are located within the large area (>20 km^2) of low resistivity situated throughout much of Moil Valley.

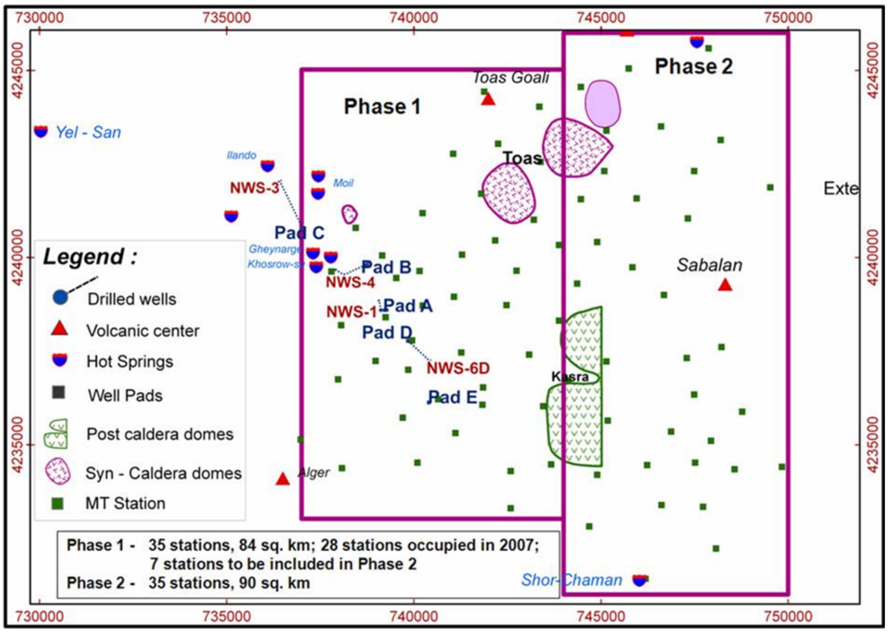

Figure 4: Location of MT stations.

Preliminary 1-D resistivity modeling showed that the conductive layer within the Moil anomaly has a thickness of >2000 m (Bromley et al., 2000). Drilling data, however, show that the smectite zone encountered in NWS-1 occurred only at depths between 200 and 400 m within the Vallazir Formation (Bogie et al., 2000). This indicates that the basement of the conductive layer is much shallower than initially thought.

Using modern techniques of MT modeling, Talebi et al. (2005) conducted re-analysis of the 1998 MT data. Correlation between the distribution of clay alteration, temperature, and variation of resistivity with depth (shown in Figure 5) indicated the possibility of higher temperature fluids coming from the southeast. Hence, new exploration pads Pads D and E were sited southeast of well NWS-1. An increasing elevation of the shallow conductive body (15 Ω-m) is apparently extended beneath Pad D, as shown in Figures 5 and 6, but the area immediately south of Pad E is modeled to have a resistive body from surface to bottom.

The new resistivity maps generated from the 2007 MT data are shown in Figures 7, 8, and 9. Two low resistivity anomalies were mapped at a 2600 m elevation, and are shown in Figure 7. The larger and more prominent low resistivity area lies between the new exploration pads and the Kasra lava domes and extends farther northwest beyond Pad A and Pad B. It also stretches toward the southeastern part of Pad E, an area modeled by previous studies as very resistive from surface to bottom (Bromley et al., 2000 and Talebi et al., 2005). The other low resistivity zone is mapped in the northeastern sector within the Toas syn-caldera dome and coincides with the location of the Toas Goali-Houshang Meidani anomaly identified by Bromley et al. (2000). The northwestern and western sectors are dominated by high resistivity at this level, including the area within NWS-1.

A conductive layer underlies the drilled area including Pad D and Pad E at a deeper level of 2300 m asl, as shown in Figure 8. The sector east of Pads D and E, which is conductive at 2600 m asl, now exhibits increasing resistivity at depth.

Contours of resistivity at a constant depth of 800 m are shown in the map in Figure 9. The map indicates a NW-SE trending resistivity structure, which could reflect hydrological flow in the geothermal system of NW Sabalan. It appears that the fluids originate from the area east of Pad E and outflow northwest toward the drilled sector. The NW trend of this anomaly is consistent with the strike of the major faults in the area. This indicates that these faults, which trend along the same direction, likely exhibit good permeability and are excellent drilling targets. Permeable structures intersected by NWS-1 and NWS-4 are aligned in this direction. An apparent resistivity contrast within the vicinity of NWS-4 defined by the 40 Ω-m contour possibly marks the northwestern boundary of the reservoir.

The thickness and depth of the conductive layer were determined from four resistivity profiles. A better-defined conductive layer can clearly be seen in the 2-D models than in 1-D models. For comparison, 2-D models are shown in Figure 10, and 1-D models are shown in Figure 11. The 2-D models are more robust and smoother than 1-D models, which exhibit abrupt changes in resistivity.

Profile P01 cuts across drilled wells NWS-4 and NWS-1 and Pads D and E. The ~500-m thick, <14-Ω-m conductive layer was modeled at depths between 200 and 500 m along the entire length of the profile and generally follows the topography of the area. The interface between the conductive layer and the resistive basement is deeper within the drilled sector at about 2000 m asl and shallower in the southeast at approximately 2500 m asl. This elevation difference indicates geothermal fluids outflowing from the southeast towards Moil Valley.

P02 runs parallel to P01 but at a higher elevation and cuts across the eastern edge of Moil Valley. The conductive layer along this profile is weaker (less conductive) on the northwest end below MT stations 1 and 19. This may signify that the northwest boundary of the geothermal resource is near Pad B. The base of the <10-Ω-m conductive layer increases in elevation towards the southeast from 2000 m asl in station 27 to 2400 m asl in station 7.

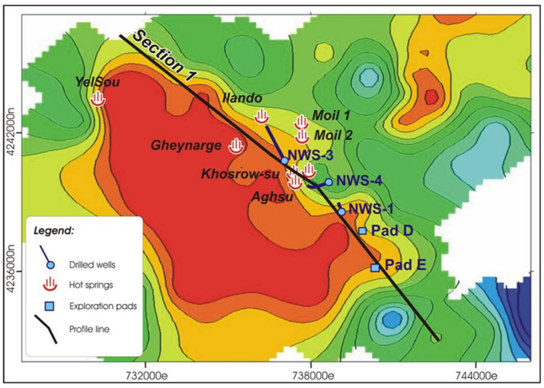

Figure 5: Resistivity map at 500 m depth obtained from 2-D models (after Talebi et al., 2005).

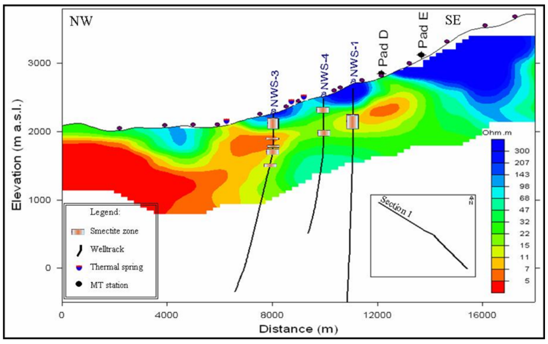

Figure 6: 2-D resistivity profile along section 1 (after Talebi et al., 2005).

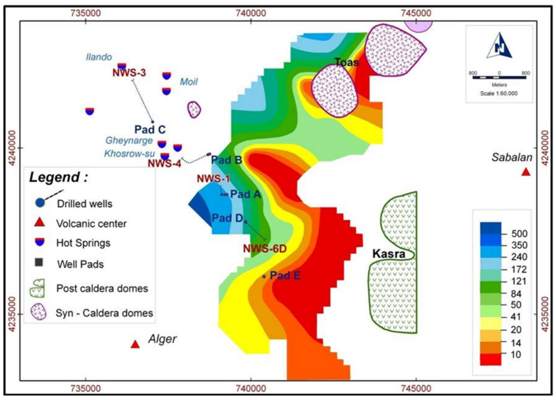

Figure 7: Resistivity map at 2600 m elevation obtained from 1-D Occam models.

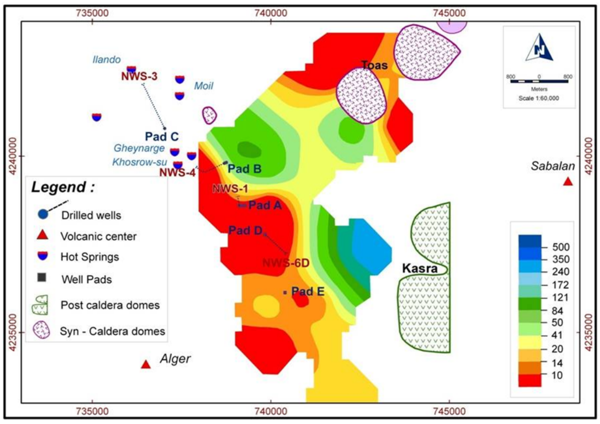

Figure 8: Resistivity map at 2300 m elevation obtained from 1-D Occam models.

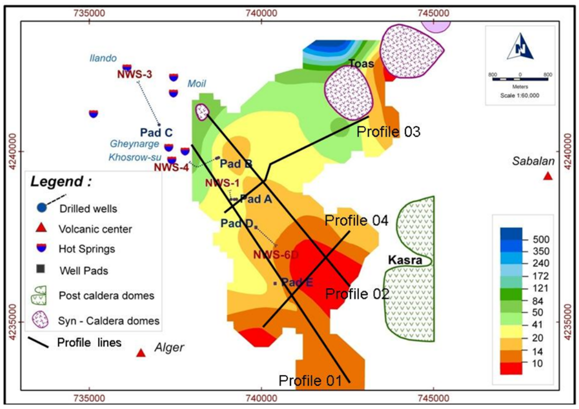

Figure 9: Resistivity map at 800 m depth obtained from 1-D Occam models.

A higher resistivity body beneath station 12 (Profile 03) separates the conductive layer underlying the Moil Valley and the northeastern area covered by stations 13 and 14. This higher resistivity body possibly defines the northeastern boundary of the geothermal resource within the area.

The shallowest base of the conductive layer is found beneath station 10 at an elevation of about 2500 m asl, as shown in Profile 04 in Figure 10. The elevated high resistivity basement within this area, which may indicate a higher temperature, is believed to be within or close to the inferred upflow region possibly associated with the young Kasra lava domes located less than 2 km to the east. The decreasing elevation of the high resistivity basement modeled at 2000 m asl to the southwest of the section may reflect the downward flow to the west or southwest.

The correlation of subsurface data with resistivity structure in Profile 01 is shown in Figure 12. Similarly to the resistivity model in previous MT survey, the smectite zone encountered in wells NWS-1 and NWS-4 was found to correlate with the conductive layer. The base of the low resistivity layer coincides with the 180°C isotherm. The increasing temperature towards the southeast is coincident with the increasing elevation of the conductive layer towards the postulated upflow.

4. CONCLUSIONS AND RECOMMENDATIONS

It was previously established that there was good correlation between the distribution of smectite and the conductive layer within the drilled sector and that the elevation of the shallow resistive basement increased with rising temperature toward the south or southeast in the NW Sabalan geothermal system (SKM, 2005, Talebi et al., 2005). This correlation led to the inference that a much higher temperature fluid originates from the southeast.

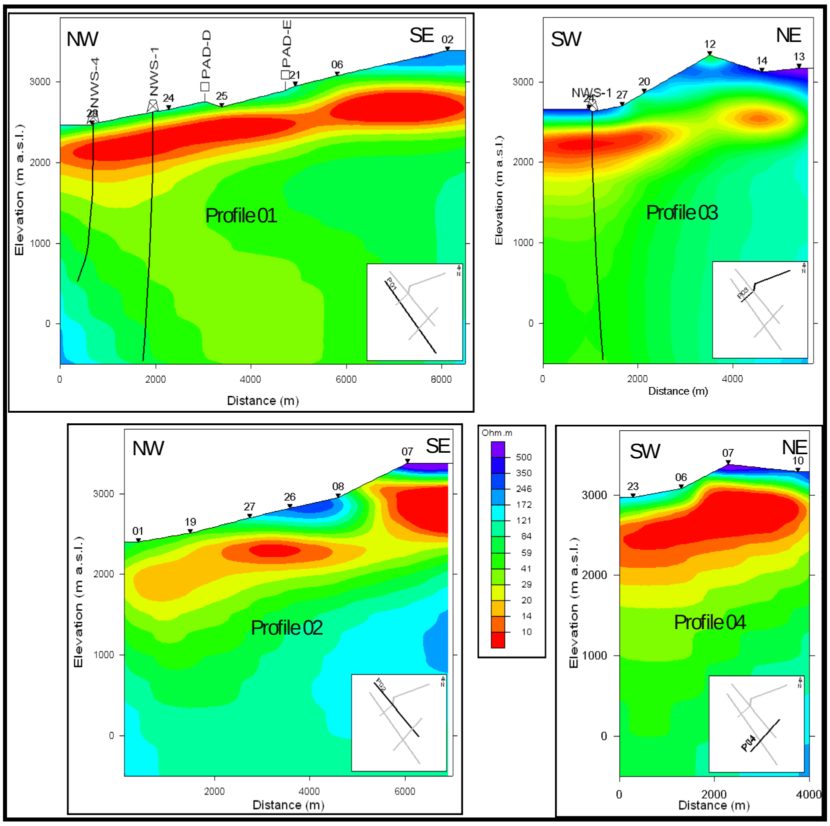

Figure 10: 2-D resistivity models using both TE and TM. Section lines are shown in Figure 9.

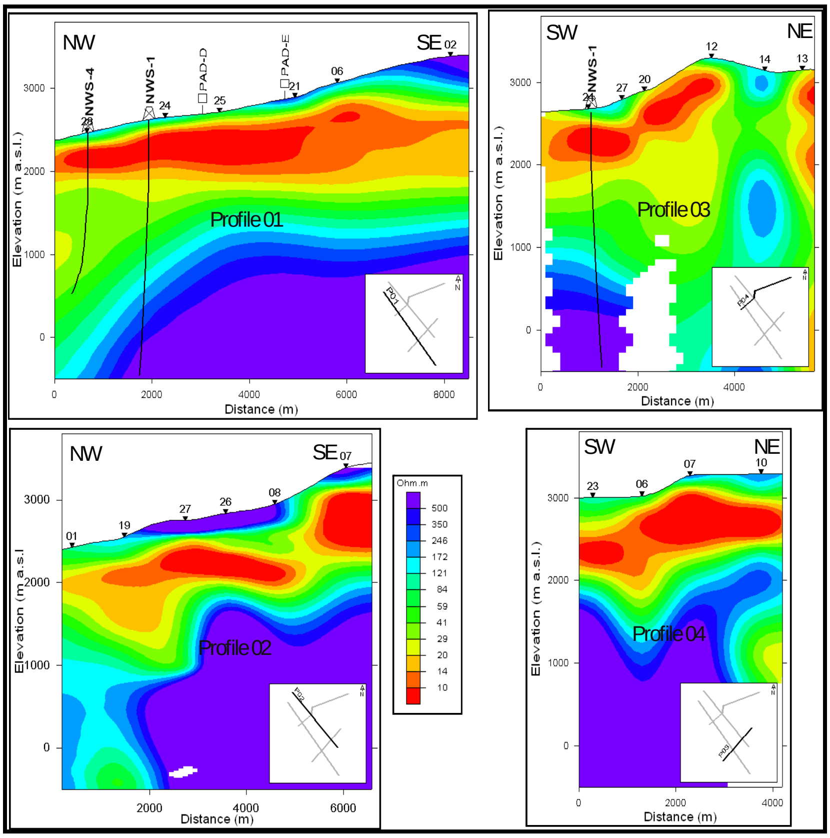

Figure 11: 1-D resistivity models using TE mode. Section lines are shown in Figure 9.

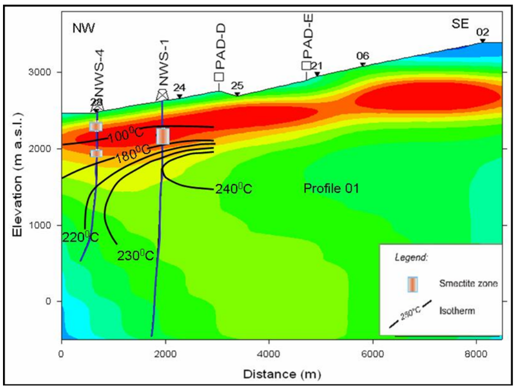

Figure 12: Correlation of resistivity model with temperature and distribution of smectite zone in wells NWS-1 and NWS-4.

New MT data was used to similarly model the resistivity structure beneath NWS-1 and NWS-4 and it was possible to delineate the extent of the increase in elevation of the conductive basement toward the east-southeast of Moil Valley even beyond Pad E. The postulated geophysical model of the resource is shown in Figure 13. The shallowest basement of the conductive layer, which was modeled at an elevation of about 2500 m asl, lies beneath station 10 and is located east of new pads D and E (about 2 km west of the young lava domes of the Post-caldera Kasra Volcanic Formation, the possible heat source of the geothermal system). The electrical basement is deeper (at 2000 m asl) toward the modeled outflow regions, of which one is located to the NW within the drilled sector and the other to the west beneath station 23. The resistivity map at 800 m depth was confirmed by the subsurface data from the drilled wells and indicated that NWS-4 was drilled close to the northwestern boundary of the geothermal resource.

The NW-trending resistivity anomaly observed at a depth of 800 m asl, aligned along the major structural pattern in the Moil Valley, indicates that faults along this direction exhibit good permeability and are excellent drilling targets. Permeable zones in wells NWS-1 and NWS-4 have been largely attributed to fault NNW2 (Bogie et al., 2005). A resistivity gradient between MT stations 6 and 7 is inferred to be a possible southeastern extension of fault NNW3 and is a good drilling target to test the high projected temperature in the area east of Pad E.

However, the 2007 MT data could not provide a complete picture of the Sabalan geothermal system due to the lack of station coverage to the east. Only the west-northwestern half of the anomaly typical of a stratovolcano geothermal system has been delineated. The east-southeastern half of the anomaly is yet to be established. Thus, it is necessary to collect more data using more closely spaced MT stations east of the postulated geothermal resource.

A better understanding of the NW Sabalan geothermal system could be established upon completion of the MT survey in Phase 2. This includes the possible association of the inferred upflow zone with the low resistivity anomaly mapped near the Syn-caldera domes located northeast of Moil Valley.

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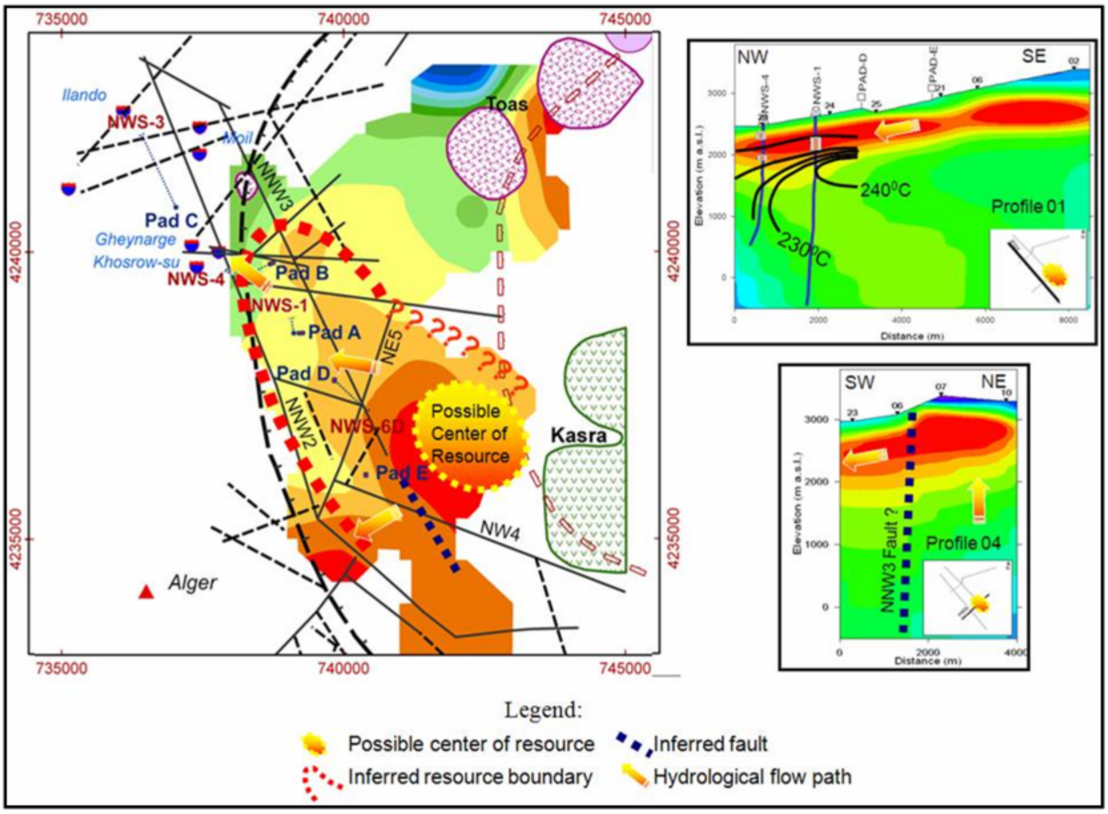

Figure 13: Proposed Geophysical model of NW Sabalan based on resistivity map at 800 m depth and 2-D models of Profiles 01 and 04.

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