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Review of Resistivity Surveys from the NW Sabalan Geothermal Field, Iran

Behnam Talebi[1], Khosrow Khosrawi[1], Greg Ussher[2]

[1] SUNA Renewable Energy Organisation, Yadegar-e-Emam Highway, Poonak-e-Bakhtary Ave, Shahrak Ghods, Tehran, Iran

[2]Sinclair Knight Merz, PO Box 9806 Newmarket, Auckland, New Zealand

[1] talebib@iranenergy.org.ir, [1] kh_khosrawi@yahoo.com, [2] gussher@skm.co.nz

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ABSTRACT

MT field survey data from the NW Sabalan geothermal field in Iran which was presented at WGC2000 have been remodelled using improved methods available today and the now known depth distribution of subsurface clays determined in three deep exploration drill holes. The results of this work are presented and discussed and these are used to refine the conceptual hydrogeological model for the field. This has focussed ongoing exploration/delineation drilling to an area of high ground to the southeast of the area drilled to date.

1. INTRODUCTION

Magneto-telluric (MT) data was collected and interpreted over the entire Sabalan stratovolcano located in Ardebil Province in the northwest of Iran (Figure 1) by the NZ Institute of Geological and Nuclear Sciences (GNS) under subcontract to Sinclair Knight Merz Limited (SKM) in 1998 on behalf of SUNA the Renewable Energy Organisation of Iran who is the owner and developer of this project.

Figure 1 : Project location in northwest Iran.

Two hundred and twelve (212) MT measurements were collected across most of the 4811 m high Sabalan volcano, but it was impractical to collect data above about 3500 m elevation.

This data, in combination with geochemical and geological considerations, led to the selection of the Northwest Sabalan area for drilling as a geothermal project.

The current reinterpretation focuses on the data collected in relation to information obtained from the wells drilled within this northwest section of the original exploration area (Figure 2).

The Moil Valley is the dominant topographic feature on the northwest slope of Sabalan. Warm and hot springs with neutral Cl-SO_4, acid Cl-SO_4 and acid SO_4 chemistries are found within the Moil valley (Bogie *et al*, 2000) (Figure 3). These give geothermometry temperatures of approximately 150°C and one of these, the Gheynarge spring, has a Cl concentration of 1800 mg/kg.

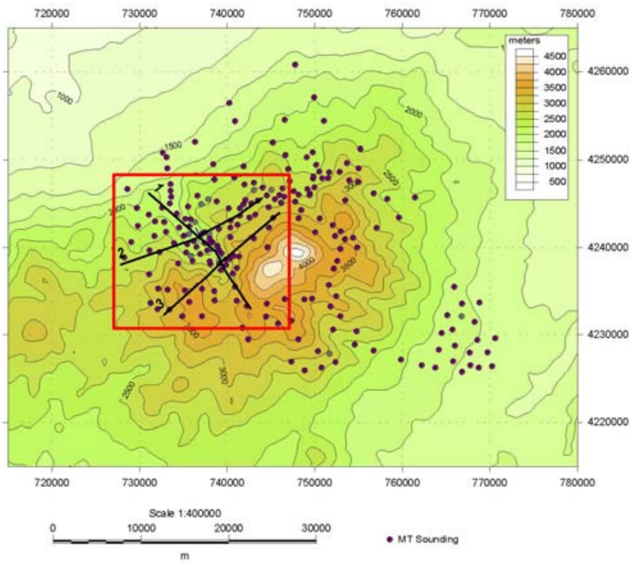


Figure 2 : The distribution of MT measurements across Mt Sabalan. The current re-interpretation covers the northwest area (red rectangle) that has now been tested by 3 deep exploration wells. Cross-section lines shown in black.

The broader geological and geophysical setting of the area is described by Bogie *et al* (2000) and Bromley *et al* (2000).

The original interpretation of the MT showed low resistivities (<5 Ωm) to depth throughout much of the Moil Valley in which the Northwest Sabalan geothermal project is located (Bromley *et al* 2000). This was considered to be indicative of a geothermal resource.

Recent approaches to interpretation of the resistivity structure of andesitic stratovolcano geothermal systems has shown that the most favourable geothermal target is in general where the conductive layer is thin and up-domed above a deeper resistive structure (Anderson *et al* 2000).

This conductive zone is produced by the occurrence of smectitic clays created by hydrothermal alteration. These clays have strong ion exchange properties that render them electrically conductive and as they are produced pervasively at shallow depths they have a high degree of interconnection creating significant zones of low resistivity in the cooler parts of geothermal systems.

These clays include pure smectites and interlayered illite-smectites with a high proportion of smectite. The correlation of the distribution and degree of interlayering of the smectitic clays with measured temperature profiles in drilled andesitic stratovolcano geothermal fields indicates that the base of the conductive layer occurs at about the 180 to 200°C isotherm. The hydrothermal alteration products at higher temperatures (above about 200 ºC) tend to be less conductive. The base of the conductor can therefore be a good indicator of where temperatures are about 200 ºC and provides a useful indicator of reservoir extent (Ussher *et al* 2000, Anderson *et al* 2000).

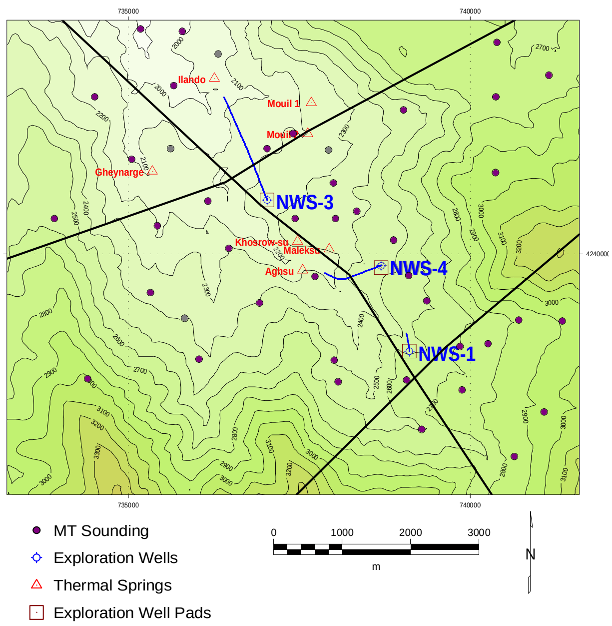


Figure 3 : The Moil Valley showing location of exploration wells and thermal springs. Topographic contour interval is 100m.

An advantage provided by modern MT surveying has been the ability to secure deep resistivity images of geothermal systems that allow the application of this reliable correlation between resistivity, alteration and temperature. This depth of penetration is enabled by the wide frequency range that can be measured with modern high resolution equipment. Unfortunately, the Zonge MT equipment utilised for this original survey at Sabalan was not able to measure reliable data at low frequencies and so the depth of penetration that could be achieved has been limited in this survey.

Upon drilling of the first exploration well NWS-1, a zone of smectitic clays was found between 200 and 600 m depth. Below this there are sporadic occurrences of illitic clay and insufficient indicators of porosity to support significant electrical conduction by pore waters. The upper part of the 2000+ m thick electrical conductive layer that was originally modelled in the valley is in agreement with the smectite zone. However the drilling results indicate that it is less likely that the conductive layer is so thick. This study was commissioned in order to re-evaluate the effective depth of penetration of the original survey and provide 2D interpretations of the data from the Southwest Sabalan geothermal project as a guide to future well targeting.

2. METHODOLOGY

The original soundings were collected at single site soundings (no remote reference) and were recorded for a maximum of up to 2 to 4 hours. The apparent resistivity and phase that were calculated from the measured MT time-series data by GNS have been filtered and re-modelled.

The MT data recorded from 1000 Hz to 2 Hz was of reasonable quality (Figure 4). Only sparse data was recorded below a frequency of 2 Hz and, from subsequent experience with this type of Zonge equipment, this lower frequency data is regarded as having poor reliability and has therefore been masked so that it is not used in subsequent modelling. Each MT sounding curve was manually edited to also mask any data points that are clearly anomalous and that may incorrectly affect the modelling. Tensor strike directions were not calculated and so no electrical strike can be extracted from the resistivity and phase data, but most curves show little difference (apart from static shift) between the measured X and Y curves over the frequency range being modelled.

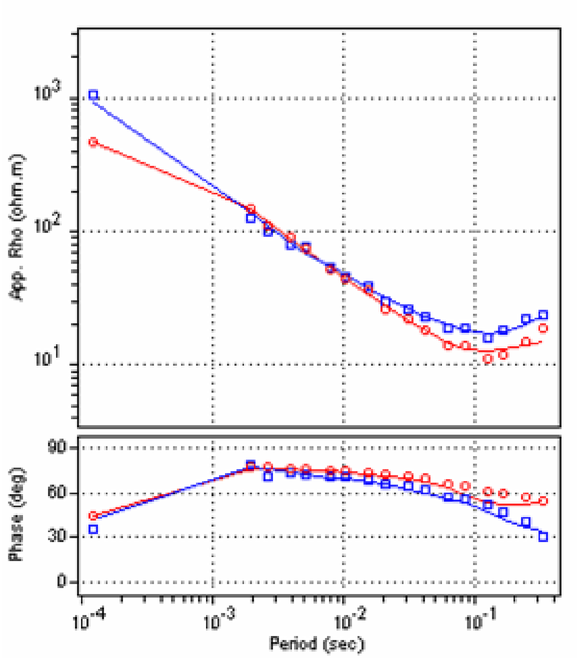


Figure 4 Typical MT sounding curve. Reliable data was only obtained within the AMT band at frequencies above 2 Hz.

Using the WinGLink geophysical software system, the edited MT curves have been modelled using 1-dimensional (1D) and 2-dimensional (2D) methods. The 1D methods are reliable for modelling the shallow, high frequency data and can be useful for providing a simple analysis of shallow resistivity structure for comparison with the 2D modelling. The 2D method is more robust than the 1D modelling as it attempts to concurrently model several soundings along a profile, and is able to include the effects of any lateral changes in resistivity as part of the model.

The limitation to 2 Hz data indicates that reliable modelling should be possible to depths of 500 to 1000 m depending on the resistivity encountered. This has meant that the deeper resistivity structures in this modelling will be different from those interpreted in 1998.

Many of the sounding curves in the upper parts of the Moil Valley indicate that, even with the limited frequency range, the data are detecting the base of the conductive layer in some locations (see for example the shape of the sounding curve in Figure 4). The base of the conductor was not generally detected in the northwest indicating a thicker conductor in that area. Soundings made at elevations above 3000m did not usually find any significant conductor layer, possibly because any such layer was too deep to be detected with this frequency range.

TDEM measurements were collected at each MT site but due to recording problems were not used for processing of static shift corrections. To resolve this, we have utilised 2D inversion modelling that is able to estimate static shift effects as part of the modelling process. This has proven effective in building models that are consistent between adjacent profile lines and that fit with observed alteration patterns seen in the wells drilled so far.

Modelling was conducted along multiple 2D sections, running NW-SE along the Moil Valley and transverse across the valley in the SW-NE direction. Representative examples are presented as contoured model sections in Figures 5 and 6.

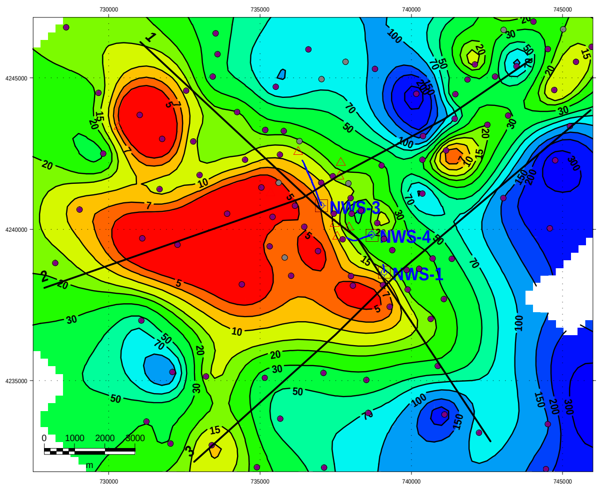


Figure 5 Resistivity at 300m depth – from 2D models

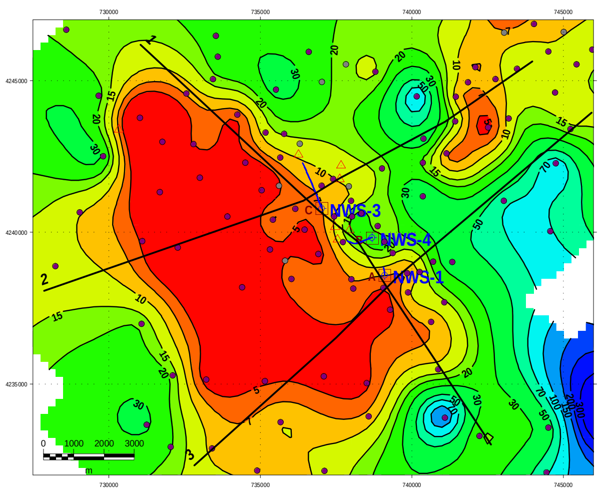


Figure 6 Resistivity at 500m depth – from 2D models

We have not produced maps of resistivity at selected elevation because of this limited depth penetration and the extreme topography.

With the limited depth penetration in this area of major terrain variation we were not able to produce meaningful maps of resistivity at selected elevations. Areal distribution of resistivity is therefore shown through maps of resistivity at a depth of 300 and 500 m produced from the 2D model sections (examples shown in Figures 7, 8 and 9). The zones of smectite alteration logged within exploration wells are shown on the 2D sections.

3. DESCRIPTION AND CORRELATION WITH WELLS

The resistivity maps are dominated by a large area (>20 km² at a depth of 500 m) of very low resistivity (<4 Ωm) situated to the west and on the western slope of the Moil Valley. Slightly higher resistivity (<8 Ωm) lobes run to the southeast and northeast following the general trend of the Valley. A further area of low resistivity (2 km² area at a depth of 500 m) is found further to the northeast approximately at the rim of the inner caldera of the Sabalan volcano.

The resistivity within the western low resistivity anomaly ranges from 2 to 8 Ωm This conductive layer is at least 500 m thick and the top lies at up to 2700 masl. The conductive layer is “exposed” on the steep western wall of the valley in the area near the Gheynarge springs.

The 2D model sections show that the layer is generally at least 500m thick and probably much thicker in the lower elevation areas in the north. The layer tends to follow the general slope of the valley and is at highest elevation in the south.

In section 2, the western anomaly (<8 Ωm), west of the Moil Valley, begins at a depth of approximately 300 m and is indicated to be about 500 m thick. In some other sections, the anomaly is exposed on the western slope of the Moil Valley where its upper contact corresponds to the boundary between unaltered and altered volcanic rocks of the Valhazir Formation. The anomaly then runs beneath the Moil Valley but does not extend across the entire width of the valley. The northeastern anomaly (<8 Ωm) lies at depth between 500 and 1000 m on section 2 (Figure 7).

As this anomaly is exposed at the surface and contains both smectite and interlayered smectite clays it may be related to relict hydrothermal alteration from an old hydrothermal system that has undergone a significant amount of low temperature retrograde alteration. Close association to warm springs indicates that there may still be some thermal component to the low resistivity character of this western area but recent drilling results indicate that it is unlikely that high temperatures exist in this area.

The conductive layer on the eastern side of the Moil Valley is very much weaker (higher resistivity). This indicates that only relict geothermal activity may be present in this area.

The zones of argillic clay alteration seen in NWS-1 (300 m thickness), NWS-3 (over 700 m thick zone) and NWS-4 generally coincide with the location and thickness of the conductive layer modelled through these areas. This, and inspection of the sounding curves, indicates that the modelling has been able to detect the base of the conductor in the valley. However it is probable that in areas of higher elevation, such as on the sides of the valley where the conductive layer is deeper beneath the surface, the base of the conductor is not well constrained by this MT data.

The presence of a strong conductive layer in the western side of the valley, and low resistivity seen only 5 to 8 km to the east of the valley is consistent with SKM's earlier model of a major horizontal shear to the east. This could have exposed the western side of an old hydrothermal alteration dome structure and displaced the eastern side several km to the east.

A weaker extension of the conductive anomaly extends to the southeast of the large western anomaly and its correlation with higher temperature conditions seen in NWS-1 indicates that this is related to the current hydrothermal system.

The shallow conductive layer producing these anomalies has been confirmed to be a layer of smectitic clays in the three wells drilled to date. The extent of smectite alteration is generally consistent with what would be expected for the present temperature distribution.

The elevation of the base of the layer increases towards the southeast and this is consistent with current temperatures that indicate that NWS-1 was drilled into the proximal outflow and NWS-3 into the semi-distal outflow of the current hydrothermal system.

As the shallow conductive layer extends to 5 km to the southeast of NWS-1 the upflow of the system is likely to lie in this direction. Therefore future drilling may be better concentrated generally to the south.

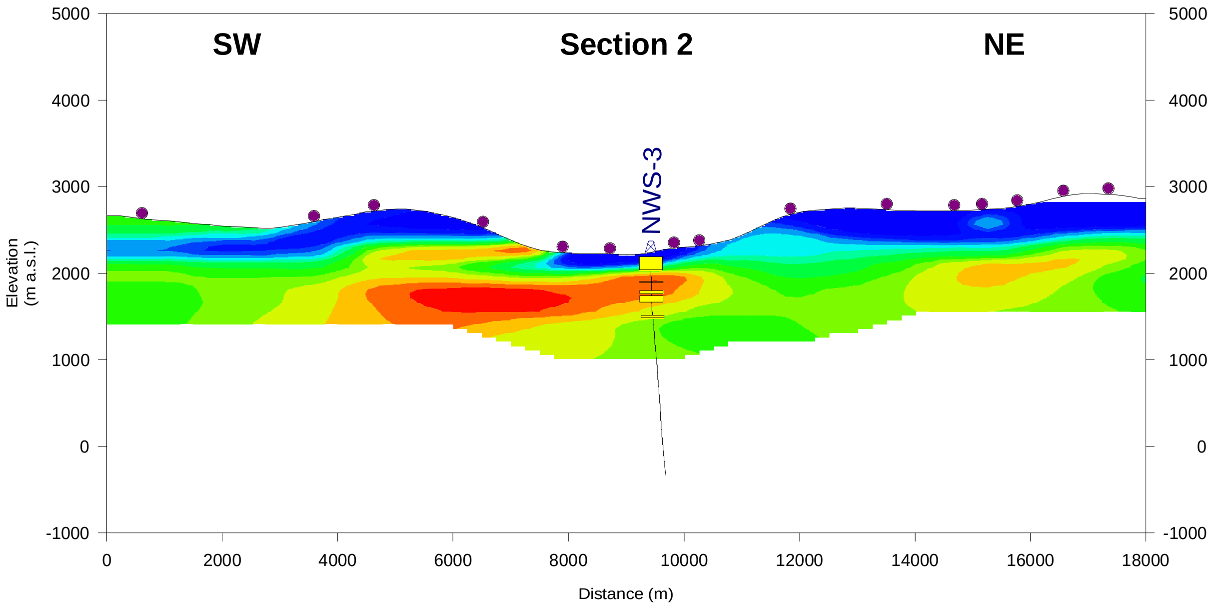


Figure 7 2D resistivity model along Section 2

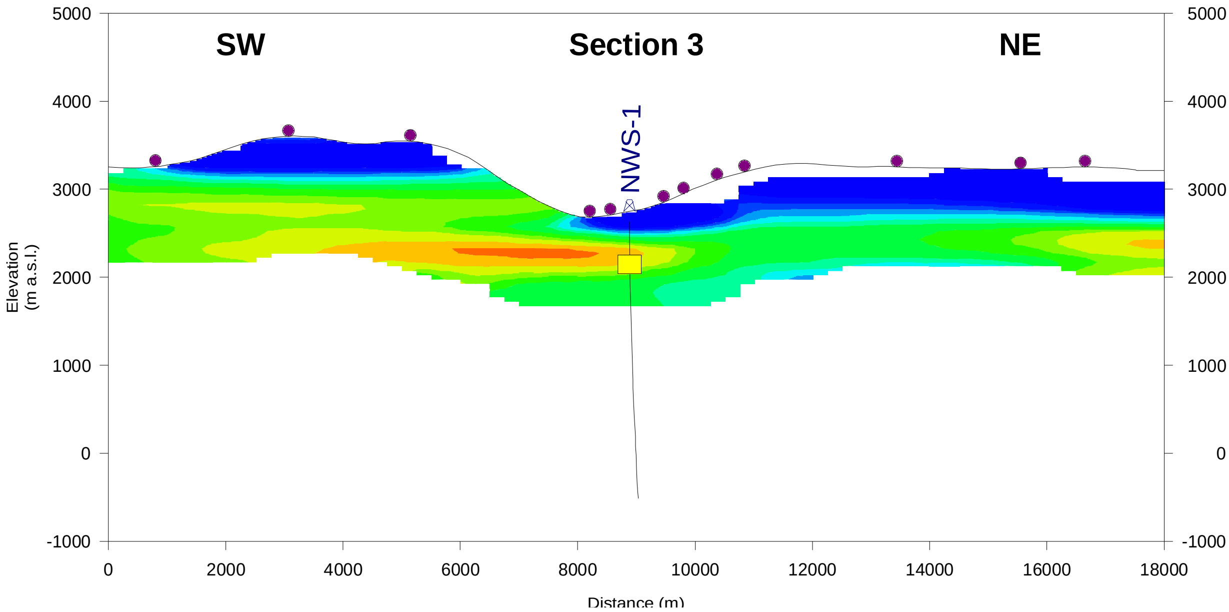
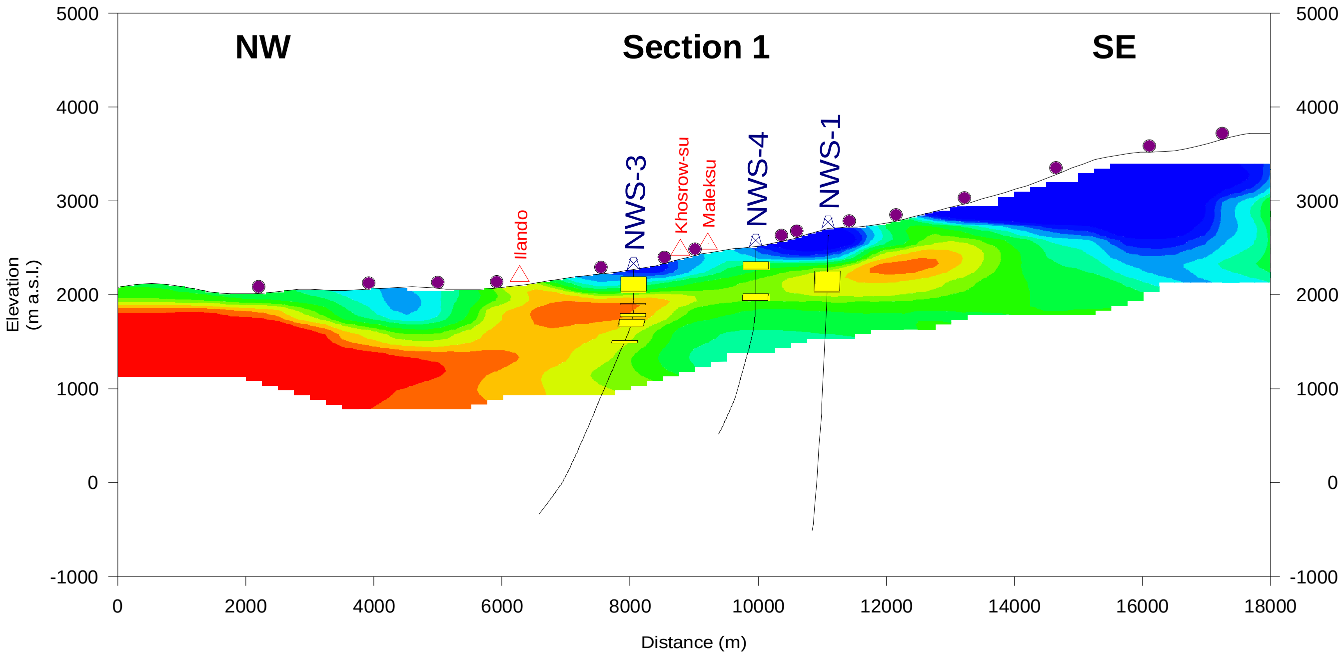


Figure 8 2D resistivity model along Section 3



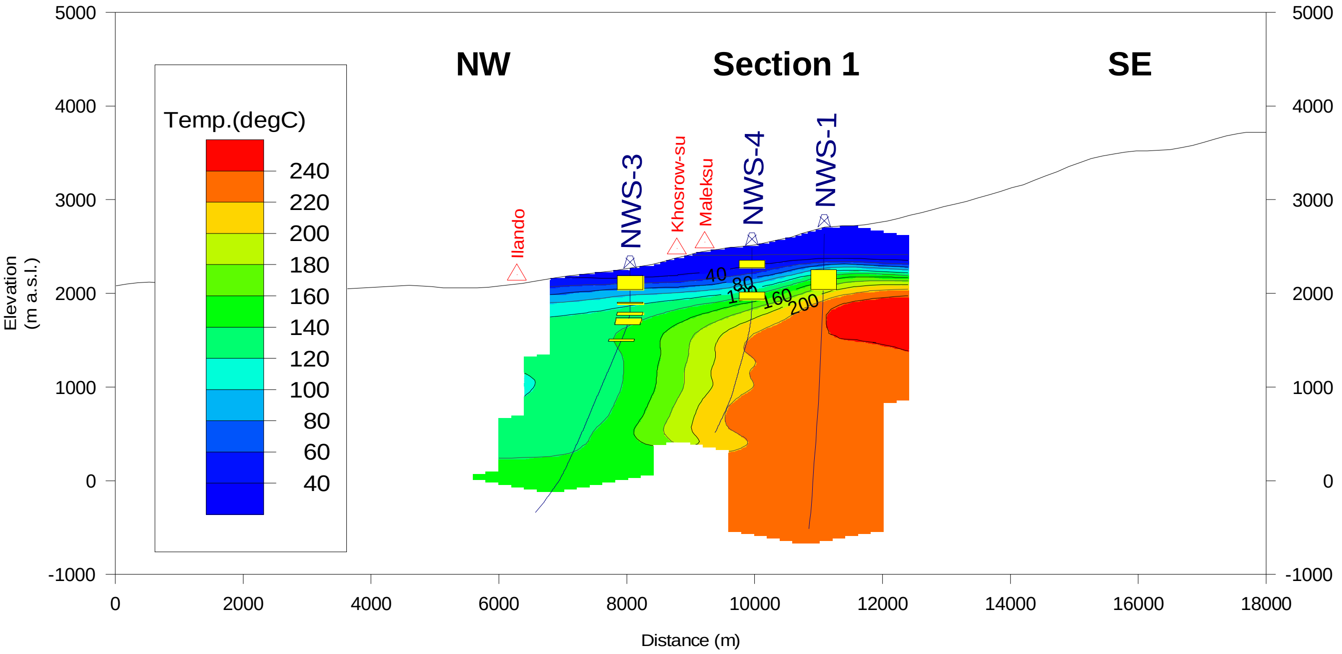
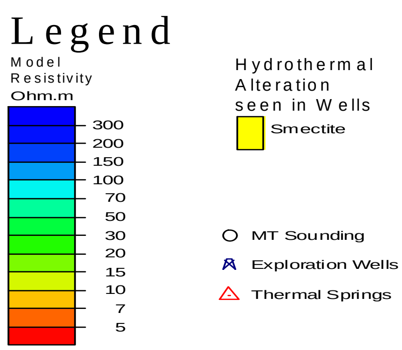


Figure 9 **Section 1. Top: 2D resistivity model. Bottom: Temperature distribution from exploration wells .**



Legend for Resistivity model sections.

4. INTERPRETATION OF WESTERN ANOMALY

Where it is exposed at the surface, the low resistivity anomaly on the north western side of the Moil valley corresponds to relict hydrothermal alteration of rocks of the Valhazir Formation. The unaltered Dizu Formation lies unconformably upon the altered Valhazir Formation. The Moil Dome, dated at 900 000 years, sits on the Dizu Formation. Thus the alteration is much older than 900 000 years. This is consistent with the fact that the western anomaly reaches the surface, indicating that erosion or tectonism has caused such exposure. Given the area's low rainfall, erosion rates are comparatively slow. The very well preserved volcanic forms of domes in the area with dates of up to 1.3 million years attest to this.

Tectonism is a further factor that suggests that the western anomaly is an old feature. It has been suggested that the Moil valley has been formed by a decollement. A palinspastic reconstruction to pre-decollement times provides contiguity to the western and northeastern anomalies. As the Dizu Formation and Moil Dome post-date movement on the decollement, for the two anomalies to form as one, requires that they formed prior to the movement of the decollement. So, similarly to the stratigraphic relationship to the alteration, decollement movement also requires that the western and northeastern anomalies have formed much earlier than 900 000 years. This leads to the possibility that the alteration giving the anomalous resistivity also played a role in the formation of the decollement by weakening the rocks with the clays produced provided lubrication along the decollement for movement to occur thus exposing the conductive layer to the surface. This adds to a consistent picture of the western and northeastern anomalies being old relict features.

XRD analysis of samples collected from outcrops where the anomaly is exposed at the surface provides an explanation for the low resistivities in old, cold hydrothermal alteration. One of the samples contains abundant interlayered illite-smectite, the other sample is from a vein cross cutting this earlier alteration and it consists of smectite. Therefore not only were conductive clays produced during the height of the hydrothermal system that produced this anomaly, but there was retrograde alteration as this system cooled that produced even more conductive smectite clay. This means that the smectite need not be limited to the shallow parts of the system. As the system cooled the overprinting of older less conductive clays progressively deeper in this system would have produced smectite. This explains why the western anomaly has such a great thickness (1000 m) of low resistivity (<8 Ωm).

A factor against the western anomaly being a relict feature is the very low resistivities of the anomaly. Such low resistivities are generally only encountered in active geothermal systems, marine mudstone sequences or in heavily altered formations that are still warm. The proximity to some warm springs in the valley and the modest temperatures seen in NWS-3 (150ºC) indicates that there may still be warm conditions in this western area, but with limited significance as a geothermal resource.

Hydrologically, there are also arguments to support the relict nature of the western anomaly. Although the Gheynarge springs lie at the base of the western slope and are the hottest springs in the area, there are other springs at higher elevation in the Moil Valley to the southeast, (Khosrowsu 1 and 2, Aghsu and Maleksu springs), which issue from the eastern slope of drainages and have other drainages between them and the Gheynarge spring. Thus, while there could be a flow from these springs towards the lower elevation Gheynarge spring the opposite is unlikely. Thus the source of the springs is more likely to be from the southeast than the west.

5. CONCLUSIONS

Although the original MT survey of Sabalan did not achieve the depth of penetration that could now be expected from such surveying, the re-modelling of the data has shown that the data is consistent with temperature distributions observed from exploration drilling. Where a moderate thickness of conductive layer is present in the upper parts of the Moil valley, the survey has probably properly detected the base of conductive layer.

The method has shown that thick conductive sequences exist in areas of moderate temperature that are distal to the main upflow. Some low resistivity seen in the Moil valley is probably a relict of older phases of hydrothermal activity but much of this alteration is on the margins of current activity and is still warm and so tends to have lower resistivity than if in a cold state. This can make it difficult to differentiate relict and current geothermal activity with resistivity methods in some situations.

However, the low resistivity patterns are correlated with the distribution of smectite clay alteration products and are generally consistent with the temperature distribution seen in the wells. The thickest sequence of low resistivity is seen in the distal outflow areas, and the thinner zones of low resistivity at high elevation lie above what appears to be the upflow areas.

The extension of low the low resistivity zones at high elevations tends to indicate the upflow origin being south of the present well NWS-1 that has highest measured temperature of 242ºC. This well has recently been successfully discharged and provides a sound basis for further exploration / production drilling.

The resistivity and temperature distributions indicate that future drilling should focus towards the south if suitable well pad access can be found in this direction before the valley rises to high elevation.

ACKNOWLEDGEMENTS

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