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An Analysis of Well Measurements from the Sabalan Geothermal Area, NW Iran

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ABSTRACT

Three deep exploration wells have been drilled in the Sabalan geothermal area since 2002. The first well, NWS-1, was vertically drilled down to 3197 m depth. After drilling completion, NWS-1 was tested for its pressure response to step injection. Data was analyzed by using semi-log analysis. Result shows that the permeability thickness is about 7 d-m. Temperature and pressure profiles of the well obtained during injection test, heat up and discharge period were evaluated in order to determine locations of possible aquifers in the well. Two main and two minor feedzones recognized in the well. NWS-1 has been successfully discharged as a commercial well with power potential of about 2 MWe and the third well, NWS-4, was also able to sustain a commercial output of about 4 MWe. These results therefore represent the first successful exploration drilling programme of an intraplate trachyandesite volcano.

1. INTRODUCTION

The Northwest Sabalan Geothermal Project is located in the northwestern flank of the Sabalan trachyandesitic stratovolcano, in the province of Ardebil in the northwest of Iran (Figure 1) where significant amount of geo-scientific studies have been performed by Iran Ministry of Energy since 1975. The project area is within the Moil Valley that is the dominant topographic feature and a major structural zone 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 valley (Bogie *et al*, 2000). One of these, the Gheynarge spring, has a Cl concentration of 1800 mg/kg. The isotopic composition of the spring waters and their seasonal variation in flow with little change in temperature or chemistry suggested that a large regional ground water aquifer overlies the potential geothermal reservoir.

An MT survey (Bromley *et al*. 2000) established the existence of a very large zone of low resistivity (≈70 km^2) in the project area. An area of very low resistivity (< 4 Ωm) associated with the thermal features was initially selected to define a target area for exploratory deep drilling. Therefore, in order to access the deep reservoir, and to find structural permeability within it, a deep well exploration programme was adopted. Three deep exploration wells drilled in the Northwest Sabalan geothermal project initially encountered Quaternary terrace deposits and Pliocene trachyandesitic volcanics. Relatively shallow occurrence of the conductive smectitic clays was also encountered in the wells.

The MT data was reinterpreted in terms of the elevation of the base of the clays and a conductive zone increasing in elevation to the south can be partially distinguished from the much larger and deeper resistivity anomaly to the west. This new interpretation is indicative of the current system's upflow occurring south of the drilled wells (Talebi *et al*., 2005).

Figure 1: Project Location Map

A regional Miocene monzonite batholith was interpreted to make up the deep reservoir on the basis of a gravity high that extended from the area of the monzonite's surface exposure in the west into the project area and beyond. (Bromley *et al.*, 2000).

2. WELL NWS-1

NWS-1 (Figure 2) was sited at the highest surficial elevation (2630 masl) of the three wells above the resistivity anomaly as originally interpreted and along NW-SE trending fault. It is a vertically drilled well that developed a significant inclination near its bottom and it has a measured depth of 3197 m with casing program shown in Figure 3.

The well encountered losses of circulation between 600 and 1400 m that corresponded to zones of increased veining and intensity of illite-quartz-anhydrite-pyrite alteration.

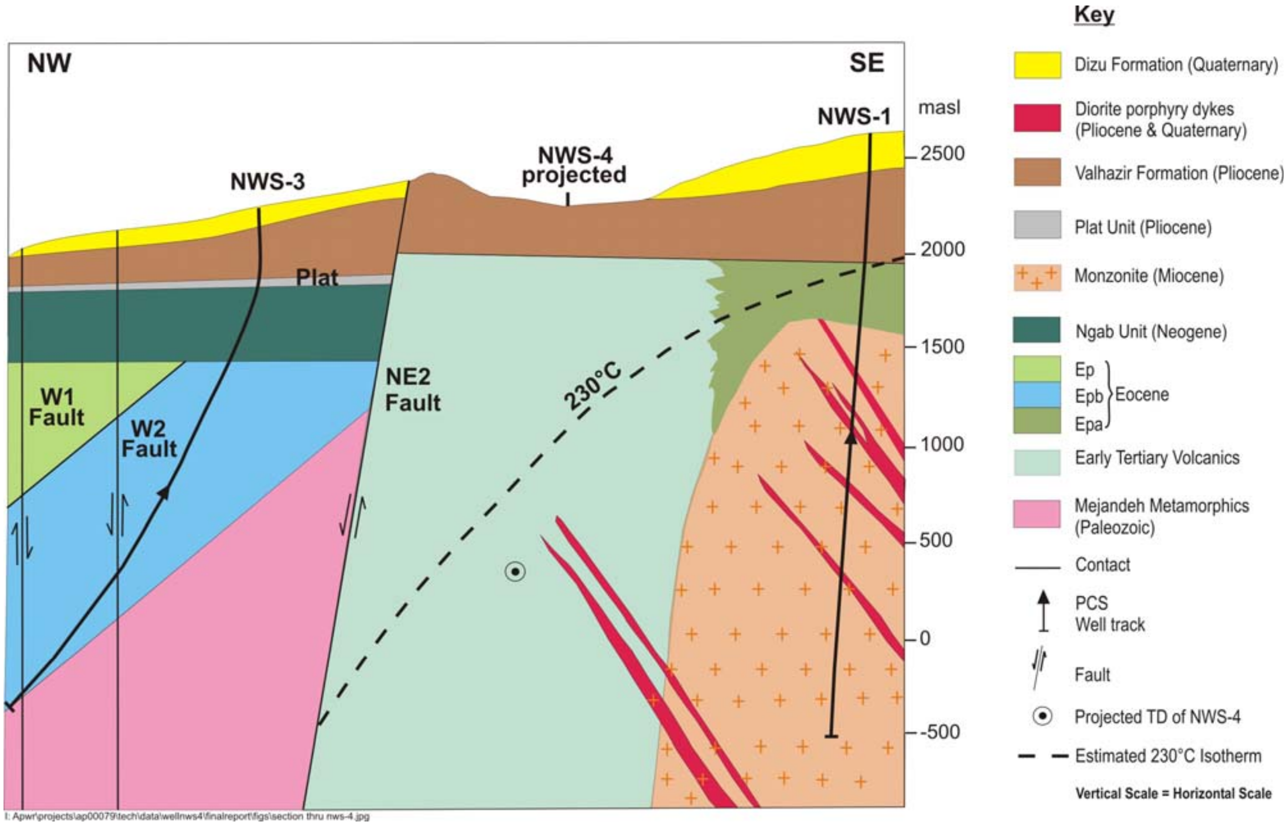

Figure 2: Geological Cross Section and Wells Track

TABLE 1: Drilling plan, completion and casing program of well NWS-1

Casing type and diameter (inch)	Planned depth (m)	Casing actual depth (m)
Surface - 20	103	110
Anchor – 13 3/8	369	380
Production – 9 5/8	1600	1587
Liner - 7	3000	3197

Since the well drilled vertically, measured depth used as true vertical depth to correct observed data.

2.1 Injection test

After drilling completion, well NWS-1 was initially injected with 4 BPM water for three hours to clean out the formation from invasion of filtrate and cuttings formed during drilling. This helps to alleviate the skin effect problem, and achieve a stabilized flow rate before the injection test.

Injection test was performed on 28-29 May 2003 and flow rates were charged in steps of 8, 12 and 16 BPM in the well for duration of each injection step being 4, 2.5 and 7 hours respectively. Downhole pressure tool was located at the depth of 3000 m prior to starting the injection test. The injectivity indexes, I_i, were obtained after analyzing the pressure changes due to change in the flow rates. Results of 12 BPM step because of water leaking problem are not reliable and considered in this analysis.

TABLE 2: Injectivity indexes

Flow rate (BPM)	Injectivity Index
4	3.8
8	9.5
16	1.9
Fall of test	6.3

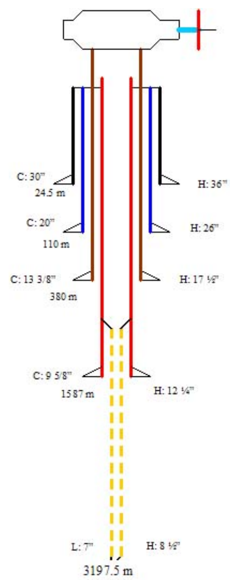

Figure 3: Casing design of well NWS-1

The best step and reliable data was selected and analyzed by using a semi-log plot (Figure 4) to calculate permeability thickness for the well. In the semi-log plot of ΔP *vs.* Δt, care was taken in identifying the acting radial flow straight

–line part of the plot, in order to avoid the wellbore storage effect in the early time of the plot. Then, the straight line was inferred, and its slope deduced to calculate permeability thickness. Correction was made twice for pressure fall of test data, and early values removed and low quality data point corrected to find the general behavior of the curve. Log-log plot indicated that the initial period (well bore response) was not reliable. This might be due to wellhead leakage or failure in recording system. Thus, identifying well bore effect was not possible.

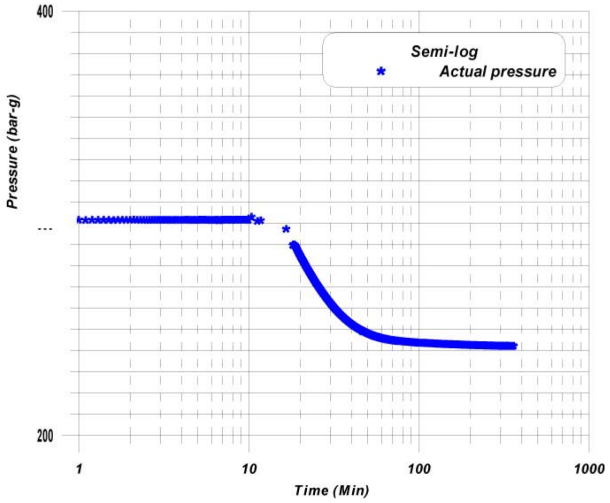

Figure 4: Semi-log of fall of test data

The result of the semi-log analysis for permeability thickness is shown in Table 3.

TABLE 3: Result from Semi-log analysis of fall of test

Fall of test	Permeability Thickness (d-m)
Semi-log	7

The permeability is moderate due to possible mud damage. An interference test between NWS-1 and NWS-4 is suggested to find out more reliable understanding from permeability.

2.2 Temperature and pressure logs of NWS-1

Information obtained from pressure and temperature logs during drilling and the injection tests form the basis for the first guesses for location of aquifers and flow patterns inside the well. Furthermore, determination of minimum reservoir temperature, and main loss or feed-zones obtained during drilling, are useful, in addition to the temperature and pressure logs, in blow-out risk evaluation, and in determining the physical state of the reservoir.

Temperature and pressure logs were measured in NWS-1 during drilling, during the injection test, and after completion. These data were analyzed to estimate the formation temperature and pressure, location of possible feed zones, and to simulate the flow pattern of the well. Downhole temperature and pressure profiles from NWS-1 are shown in Figure 5. The pressure profiles measured during the injection test gives the first measurement of the physical state of the reservoir. The temperature profiles include two runs during injection, six profiles during the heat up period, and one profile while the well was flowing. According to the temperature profiles, a few aquifers can be recognized. In the temperature gradient some jumps are observed in cased part of the well between 800 m to 1380 m depths, which appear to be several permeable zones. Other possible feed zones are observed at 1600 m, 1900 m, 2500 m and 2900 m. Major feedzone appears to be at 2500 m where the pressure has taken stable place for more than two months. Therefore, based on pressure profiles, this feedzone is considered to be the major aquifer in the well. Evaluation of pressure profiles with the boiling point curve shows that boiling has occurred in 1100 m (V.D.) in the well.

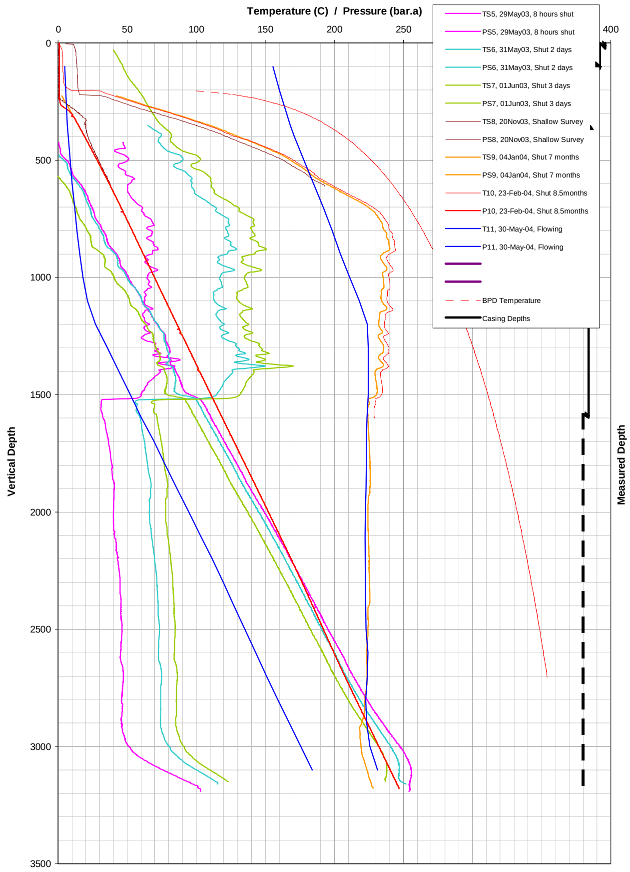

Figure 5: TP downhole logs of NWS-1

The aquifers deduced from the temperature and pressure profiles are summarized in Table 4.

TABLE 4: Possible aquifers (feedzones) in NWS-1

Possible aquifer location M.D.	**Aquifer potential**	**Remarks**
800	Minor	Temperature profiles
1350	Minor	Temperature profiles
2500	Controlling aquifer in production part	Pressure profiles
2900	Major	Temperature inversion in temperature profiles

Temperature profiles show inversion at bottom hole that is indicative for presence of possible cold inflow into the well.

With respect to the geological cross section (Figure 2), inferred aquifers are interlayer media and correlated with lithological contacts in the well. Proposed interlayer media in four possible feedzones are Valhazir and Epa, Monzonite and intrusive Diorit, Hornfels and Monzonite respectively. Total loss circulation data also confirms the same fact.

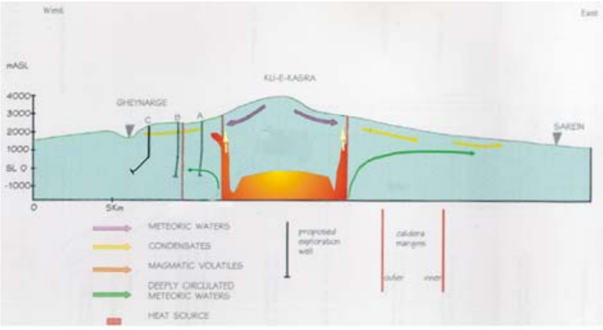

Figure 6: Hydrological model of Mt. Sabalan volcano

3. CONCEPTUAL MODEL OF THE MT. SABALAN VOLCANO

Figure 6 shows refined conceptual hydrological model of the Mt. Sabalan volcano that is derived based on data obtained during deep exploration drilling. Since inflow of cold water from up hill has affected the well, the upflow zone seems to be found towards the more southerly of current drilling site. A minor intruded body seemed to be existed beneath the Moil valley acting as a local heat source for surrounding area. Downhole temperature data were used to find out temperature distribution pattern in vicinity of the drilled wells (Figure 8-Bottom). With respect to this data, presence of the minor intruded body beneath the Moil valley is not confirmed by refined conceptual hydrological model. Downhole pressure data shows smooth and uniform distribution in the vicinity of NWS-3 and minor changes are observed in NWS-1 locality (Figure 7). However, higher temperature in SE part of the cross section emphasis that the wells were drilled into outflow zone and therefore upflow can be found further south. Result shows that northern boundary of the reservoir is limited to vicinity of well NWS-3 where temperature and pressure are not high enough. Upflow direction from up hill to the flanks awaked interest to indicate that future drilling should be undertaken further south where additional targets have been identified.

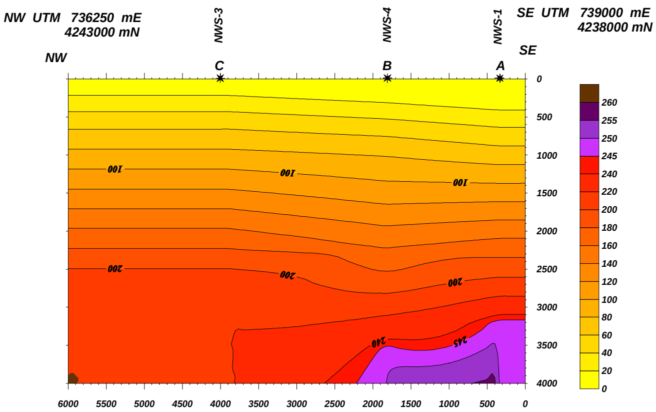

Figure 7: Pressure cross section of drilled area

MT field survey data from the NW Sabalan geothermal area which was presented at WGC2000, have been remodeled using improved methods available today and the now known depth distribution of subsurface clays determined in three deep exploration drill holes (Figure 8-Top). The re-modeling of the data has shown that the data is consistent with temperature distributions observed from exploration drilling. The method has shown 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. 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 the low resistivity zones at high elevations tends to indicate the upflow origin being south of well NWS-1 that has highest measured temperature of 242 ºC.

4. CONCLUSION

NWS-1 expletory well is the nearest drilled hole to the upflow zone with moderate permeability. The injection, heat up and dynamic temperature profiles revealed four possible feed zones located at about 800, 1350, 2500 and 2900 m measured depth in the well. The pressure pivot point is located at about 2500m measured depth where the main feedzone inferred to be located. Based on injection test data, the injectivity index was found to be about 7 l/s/MPa. Permeability thickness of the reservoir is evaluated to be moderate with value of 7 d-m, however, interference test between two wells is recommended to ensure more.

Temperature inversion observed at bottom hole and subsequently cooler deep aquifer will influence the hottest aquifers at shallower depth and therefore will reduce power capacity of the well. There are indications of permeable zones which have been cased off between 800 to 1400 m. Therefore, perforating shallower anchor casing and cementing off cooler deep zone are recommended to improve capacity of the well for production phase. NWS-1 has been successfully discharged as a commercial well with power capacity of about 2 MWe. The results of this initial round of exploratory drilling have allowed for the identification of further drilling targets off the current pads for the first stage power development, and indicate that future drilling should also be undertaken further south where upflow zone is expected to be located in.

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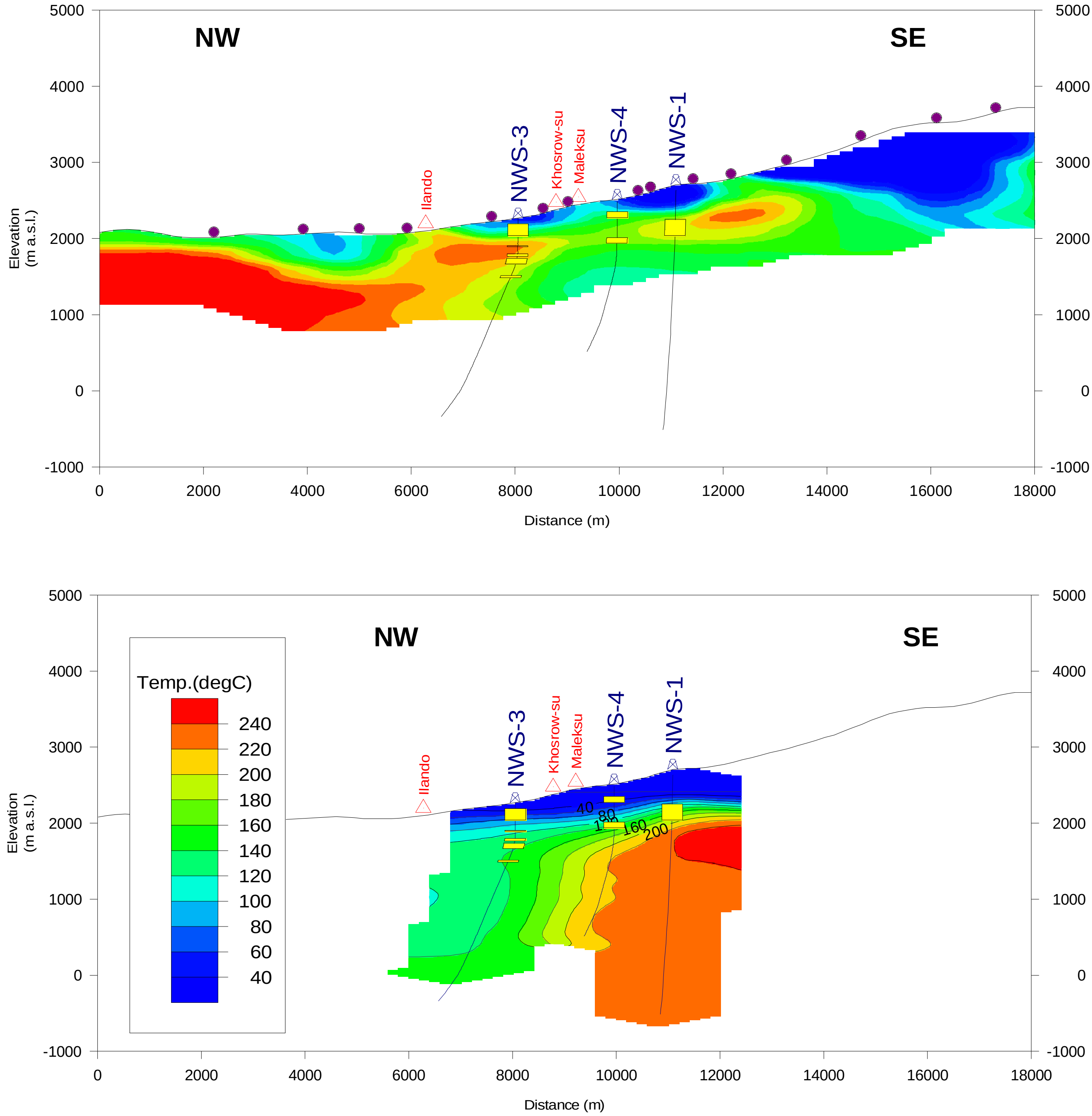
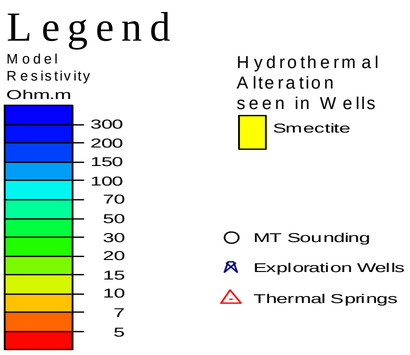


Figure 8 Top: 2D resistivity model. Bottom: Temperature distribution from exploration wells.



Legend for Resistivity model sections.