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THE GEOTHERMAL RESOURCE IN SABALAN, IRAN

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ABSTRACT

Three deep exploration wells and two reinjection wells were drilled at the NW-Sabalan geothermal field between 2002 and 2004 following detailed geoscientific surface surveys. Results from surface exploration, well drilling, well testing and the resource model are presented and discussed here. A preliminary resource assessment confirms the presence of a medium grade geothermal resource with a temperature within the drilled area of up to 250°C and at least 5 km^2 of resource available for commercial exploitation.

1. INTRODUCTION

The Renewable Energy Organisation of Iran has identified a potentially viable geothermal resource at Mt. Sabalan, in the Azerbaijan region of Northwest Iran (Figure 1). The resource has now been proven by the encouraging results from the initial three deep well exploration drilling programme into the geothermal resource. This has led SUNA to consider further delineation and development drilling in the geothermal resource area, as well as an option for early development.

FIGURE 1: Location of NW-Sabalan geothermal project

2. SURFACE GEOTHERMAL EXPLORATION DATA

2.1 Geology

The immediate project area is located within the Moil Valley, which on satellite and aerial photography imagery can be seen to be a major structural zone. Exposed at the surface in the valley are altered Pliocene volcanics, an unaltered Pleistocene trachydacite dome (Ar-Ar dated at 0.9 Ma) and Quaternary terrace deposits (Bogie et al., 2000). These units have been divided into four major stratigraphic units which in order of increasing age are:

- Quaternary alluvium, fan and terrace deposits;
- Pleistocene post-caldera trachyandesitic flows, domes and lahars;
- Pleistocene syn-caldera trachydacitic to trachyandesitic domes, flows and lahars;
- Pliocene pre-caldera trachyandesitic lavas, tuffs and pyroclastics.

2.2 Geochemistry

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). These plot in the immature area of the Giggenbach (1988) Na-K-Mg plot giving geothermometry temperatures of approximately 150°C. One of these, the Gheynarge spring, has a Cl concentration of 1800 mg/kg. Tritium analyses of this spring water indicate no recent interaction with the atmosphere. 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.

2.3 Geophysics

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. Satellite imagery interpretation identified a large area (≈10 km^2) of surficial hydrothermal alteration in lower elevation parts of the project area, with much of the low-resistivity area in the valley covered by Quaternary terrace deposits. The presence of surficial hydrothermal alteration was confirmed by fieldwork. XRD analyses of this alteration reveals the presence of interlayered illite-smectite clays (which are conductive and will have formed at depth) indicating that at least some of the alteration and the resistivity anomaly is relict. At higher elevations unaltered rocks cover the zone of low resistivity. To define a target area for drilling an area of very low resistivity (< 4 Ωm) associated with the thermal features was initially selected. The early interpretation of the MT work (Bromley et al., 2000) shows low resistivities persisting to depth. However, once the relatively shallow occurrence of the conductive smectitic clays was established from the exploration geothermal wells the MT data was reinterpreted in terms of the elevation of the base of the conductor. 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).

2.4 Stage 2 exploration drilling programme

On the basis of the results of the MT survey and the presence of hot springs with significant Cl concentrations a three well exploration program was undertaken. The topography of the valley limits the location of drill pads to interconnected terraces requiring that two of the wells to be directionally drilled to access and extensively test the resistivity anomaly at depth.

2.5 Project and well locations

The location of the project with a detailed map of the drilled area is given in Figure 2. The 3 deep exploration wells that have been drilled are coded NWS-1, NWS-3 and NWS-4 and these have been drilled on well pads A, C and B respectively. The wells vary in depth from 2265 m to 3197 m MD. Well NWS-1 was drilled

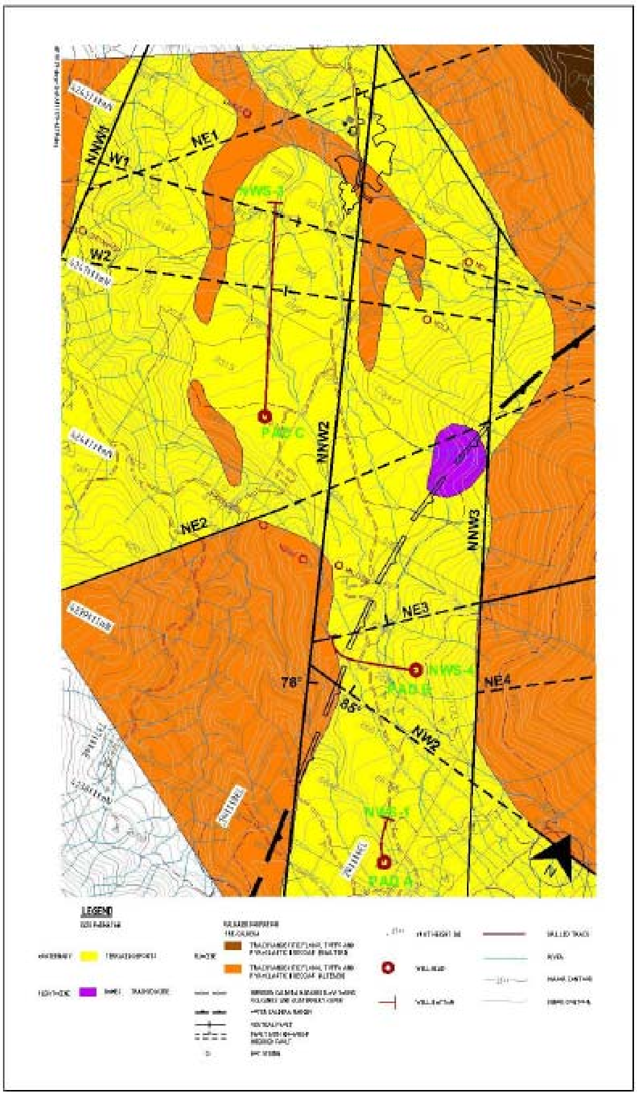

FIGURE 2: Well location and surface geology, NW-Sabalan geothermal project

vertically while NWS-3 and NWS-4 are deviated wells with throws of 1503 and 818 m, respectively. Additionally, two shallow injection wells have been drilled to 600 m depth. The basic well completion data are summarised in Table 1.

TABLE 1: Basic completion information for wells

Well	Spud Date	Completion Date	TD mMD (mVD)	Prodn Casing		Prodn Liner	
				Size (in)	Depth (mMD)	Size (in)	Depth (mMD)
NWS-1	22 Nov 02	1 Jun 03	3197	9-5/8	1586	7	3197
NWS-3	2 Jul 03	27 Nov 03	3166 (2603)	13-3/8	1589	9-5/8,5	2638,3160
NWS-4	17 Dec 03	27 Mar 04	2255 (1980)	9-5/8	1166	7	2255
NWS-2R	7 Jun 03	25 Jun 03	638	13-3/8	360	9-5/8	638
NWS-5R	7 Apr 04	2 May 04	538	20	139	9-5/8	482

2.6 Geology of the exploration wells

Geological results from the three wells exploration drilling program can be summarized as follows (Figure 3):

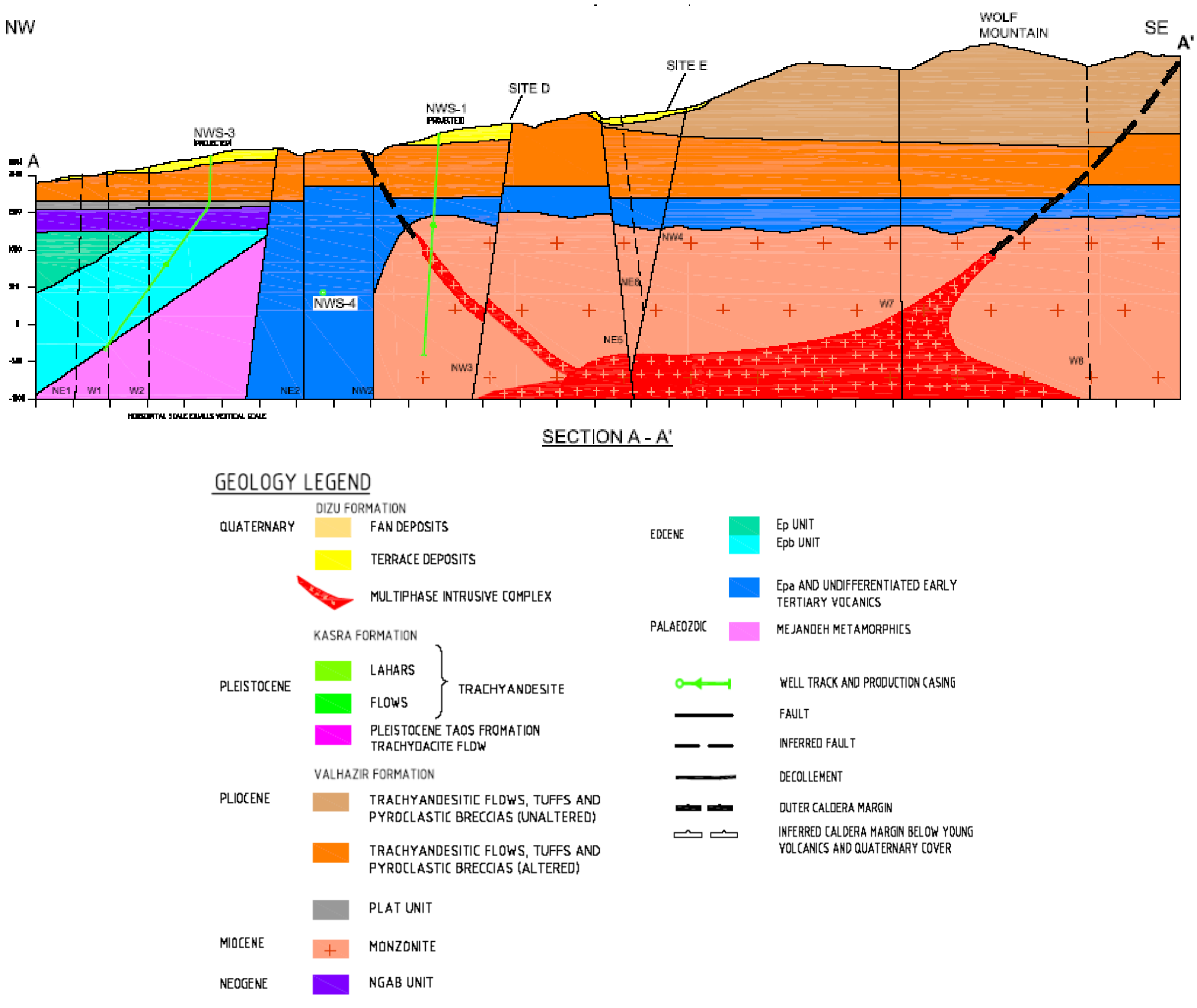

FIGURE 3: Geological cross section based on 3 wells exploration drilling

- An Eocene volcanic pile unconformably overlies the Paleozoic Metasediments making up the area's basement. These rocks were intruded during the Miocene by a regional monzonite batholith.
- The rocks older than the terrace deposits have undergone a complex alteration history with the older rocks being affected by at least three alteration events. Generally where there is agreement between fluid inclusion homogenisation temperatures and temperatures interpreted from clay mineralogy current alteration can be recognised and this takes the form of illite-calcite-quartz-pyrite as narrow zones. This is consistent with the measured temperatures of approximately 230°C and an apparent increase in temperature with depth towards the south.
- Some of the narrow current alteration zones can be related to the surficial fault pattern, but it is also apparent that the terrace deposits have obscured much of the faulting directly within the valley. Overall, the nature of the original lithologies and the long history of hydrothermal activity in the area mean that there is unlikely to be productive primary permeability in the reservoir and that permeability is of a structural origin where there are suitably competent rocks.
- Targeting faults has thus generally proved to be an effective means to gain permeability, although the low temperatures encountered in NWS-3 and the absence of competent rocks around the fault intersections has meant that they are not productive in this well.
- NWS-1 has been successfully discharged as a commercial well and NWS-4 shows good indications of being able to sustain a commercial output. These results therefore represent the first successful exploration drilling programme of an intraplate trachyandesite volcano.

2.7 Well measurements

2.7.1 Subsurface temperature distribution

The stable temperature profiles for wells NWS-1, NWS-3 and NWS-4 have been determined based on interpretation of the survey data presented in Figure 4. It is possible to make a number of observations regarding the nature of the geothermal resource based on changes in temperature with depth:

- The temperatures are all below the BPD curve, indicating that the reservoir in this area of the field does not contain a two-phase mixture of steam and water. Temperatures behind the casing of NWS-1 at an elevation of about 1900 m a.s.l. are close to BPD conditions, indicating possible proximity to two-phase fluid.
- From +1500 m a.s.l. to between +600 and -200 m a.s.l. a slight temperature inversion is evident.
- Below +200 m a.s.l. in NWS-1 and +600 m a.s.l. in NWS-3 temperatures increase with depth.

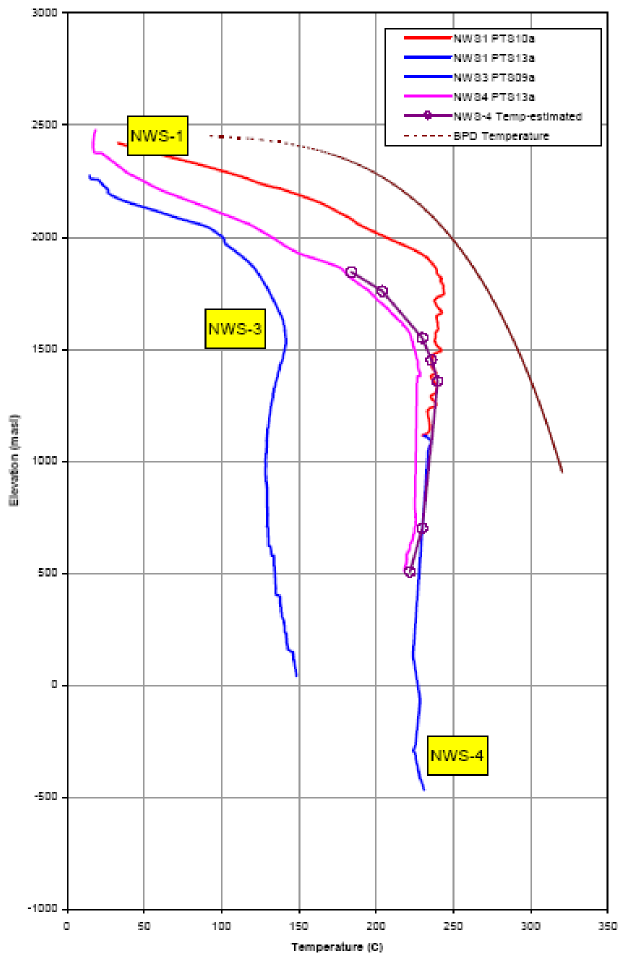

FIGURE 4: Estimated reservoir temperatures for the NW-Sabalan exploration wells

- The hottest temperature has been measured in NWS-1, suggesting that it is located closest to a deep upflow located in a generally southern direction. A cross-section (Figure 5) generated by Winlink software is shown for comparison. It is apparent from the temperature contours that the highest temperatures at all levels are in the vicinity of well NWS-1. The cross-section indicates there is a hot outflow coming past NWS-1 in the general direction of NWS-3, but not necessarily along the line of the cross-section.

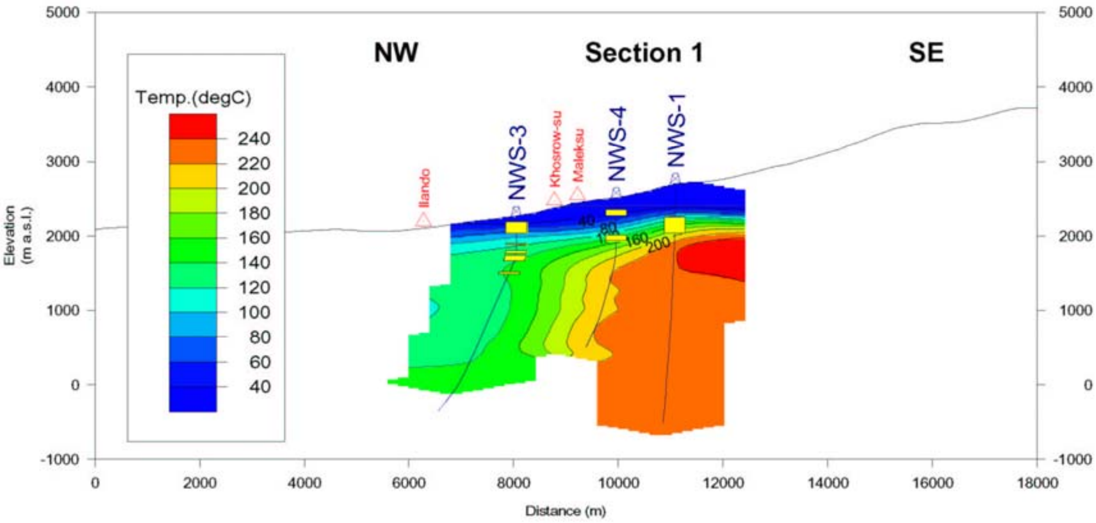

FIGURE 5: Sabalan vertical-section temperature contours

2.7.2 Subsurface pressure distribution

As the wellbore fluid heats up after drilling the hydrostatic gradient in the wellbore will change and the pressure profile measured in the well will pivot about the 'pressure control point' (PCP). Plotting the pressure at the PCP for each well against elevation gives the best estimate of the pressure profile in the geothermal reservoir. For the deep wells plus NWS-2R the PCP pressures are plotted versus elevation in Figure 6. All the wells fit a linear trend (except the deep zone in NWS-3). There is no evidence of a pressure gradient along the outflow. There is also little evidence of excess pressure gradient caused by an upflow as the pressure gradient corresponds to that of water at 231°C, which is close to the average reservoir temperature.

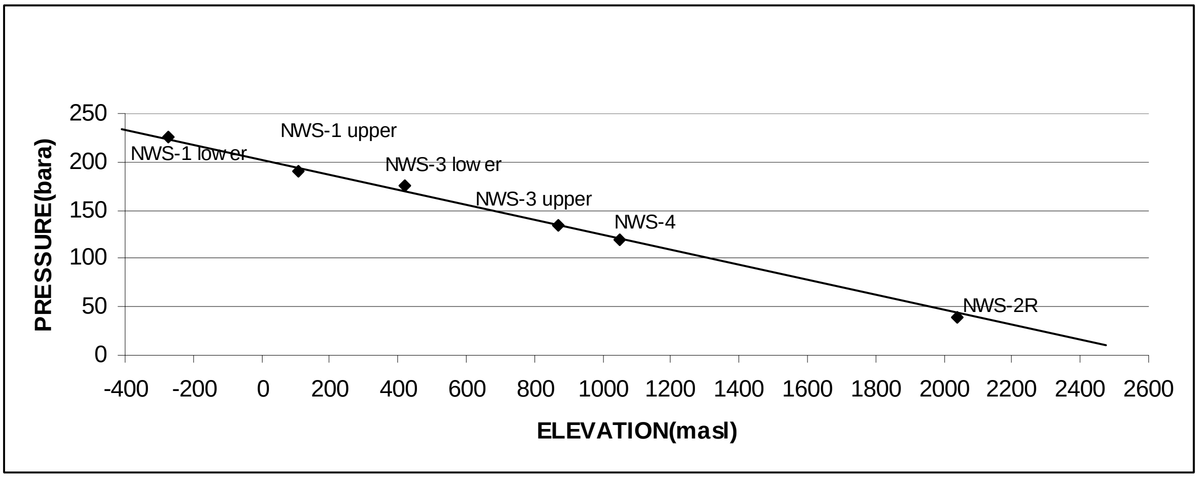

FIGURE 6: Pressure profile with depth (PCP plot)

2.7.3 Injection tests

The injection tests were conducted by injecting water at various flow rates and measuring the corresponding downhole pressure changes in the vicinity of the major permeable zone. The slope of the resulting plot of injection flow rate versus pressure is referred to as the injectivity index and provides a comparative measure of the overall permeability encountered by the well. The data can also be used to estimate reservoir flow capacity (transmissivity). The results from the tests are summarised in Table 2.

TABLE 2: Results from injection tests

Well	Date	Injectivity Index (l/s-Mpa)	Transmissivity (d-m)
NWS-1	1 Jun 03	7.3	5
NWS-2R	25 Jun 03	-	-
NWS-3	27 Nov 03	8	low?
NWS-4	27 Mar 04	16	2
NWS-5R	2 May 04	30	-

The injectivity and transmissivity values are only moderate by international standards, but are likely to be higher for future wells as the nature of the permeability will be better understood.

2.8 Well testing and reservoir results

2.8.1 Well NWS-1

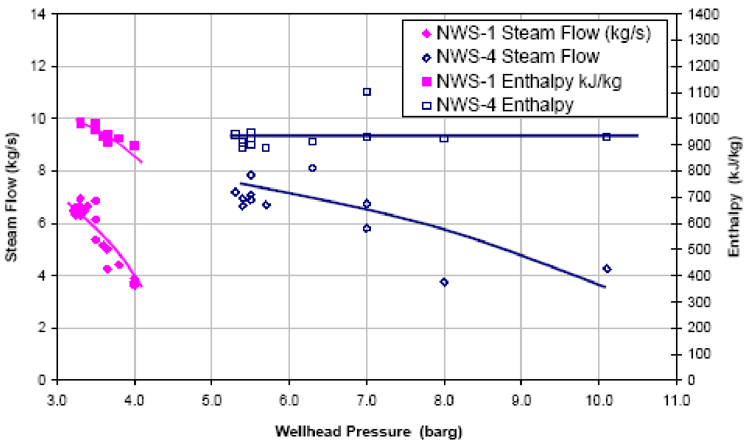

FIGURE 7: Output curves for wells NWS-1 and NWS-4

Well NWS-1 was successfully discharged on 28th May 2004 until being shut on 18th June 2004, for a period of 21 days. The well initially flowed at a WHP of about 3.3 bar-g until the flow stabilised and was then throttled until the WHP reached 4.1 bar-g. Prior to shutting NWS-1 was on discharge to the silencer and the WHP reached a maximum value of 4.5 bar-g. After the initial discharge period there was little change in discharge enthalpy, which stabilised at close to 1000 kJ/kg (Figure 7)

2.8.2 Well NWS-4

Prior to test data becoming available, a wellbore simulator was used to estimate the likely output characteristics of this well from which it was predicted that it would produce around 5 MWe at a discharge pressure of 3 bar-g and to have a maximum discharge pressure of approximately 9 bar-g. The output curves for wells NWS-1 and NWS-4 are shown in Figure 7.

2.9 Well geochemistry

Wells NWS-1 and NWS-4 were able to discharge after stimulation and full sets of chemical samples were collected and analysed. Chemical analyses of these samples are presented in the Table 2. NWS-3 produced a small amount of water upon stimulation, but could not sustain a discharge. This was analysed on site for Cl and since it contains only 100 mg/kg - Cl, it is interpreted to consist predominantly of water from the drilling and is therefore not suitable for a full geochemical analysis.

2.9.1 Discharge water chemistry

The NWS-1 and NWS-4 discharge waters can be classed as alkaline-pH, medium salinity, sodium-chloride waters with total dissolved solids of about 5000 mg/kg. The waters have moderate bicarbonate and calcium concentrations. Calculating back to reservoir conditions using the steam flash fraction, the reservoir chloride concentrations in both wells is about 2000 ppm.

The discharge chemistry is generally stable for most of the discharge test, there are some significant chemical trends with time. For NWS-1, these include: Calcium declined relative to chloride over the first week of discharge. Since the decline occurred while other parameters were stable this raises the possibility that calcite scaling was occurring in the well bore. Another possibility is that the early samples contained higher calcium concentrations from dissolution of suspended solids in the sample (the samples were not filtered). Discharge silica concentrations are in the range 520-540 ppm in the weirbox and these equate to quartz geothermometer temperatures of 230-235°C. This is somewhat higher than the flowing temperature survey temperatures of only 227°C. Cation temperatures are significantly higher than TQTZ temperatures, ranging from 260°C (TNaKCa) to 280°C (TNaK, Fournier and Potter, 1979). This suggests higher geothermal reservoir temperatures exist at Sabalan, outside the immediate area of the NWS1 wellbore, closer to the upflow of the geothermal system. High cation temperatures are evident on the trilinear plot of Giggenbach (1988), shown in Figure 8, where the reservoir water lies close to the full equilibrium line at a temperature of about 280°C. However, it is possible that since primary K-feldspar is more abundant in the reservoir rocks at NW Sabalan than elsewhere then equilibrium conditions have not been achieved and the waters are more K rich than normal with the result that high geothermometry temperature estimates are obtained.

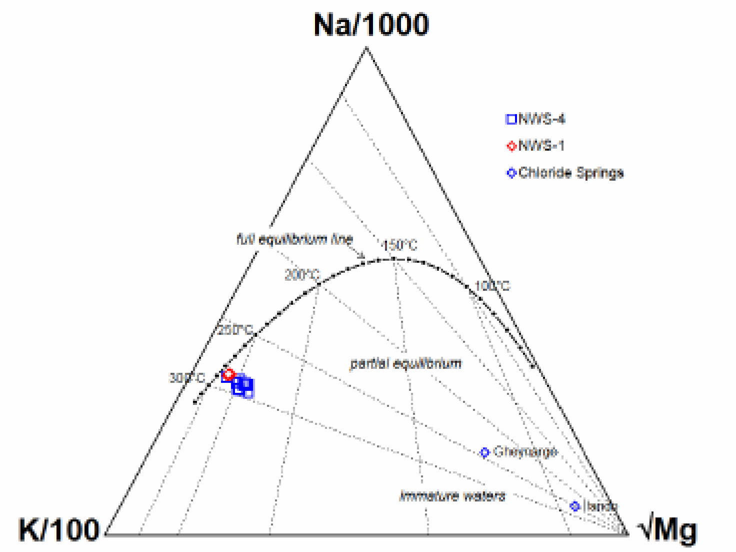

FIGURE 8: Giggenbach's geoindicator ternary diagram

2.9.2 Discharge gas chemistry

About 98% of the total gas content is CO_2 with H_2S and N_2 making up about 2%. Ar, H_2 and CH_4 are all at very low proportions. The gas chemistry is characterised by relatively high helium proportions compared to typical gas analyses from andesitic type systems. The high helium very likely has a radiogenic crustal helium source (^4He) linked to the considerable crustal thickening associated with plate tectonics in the Sabalan area. Steam separated at a production separator pressure of about 5 bar-g has a total gas content of about 2.5%. The corresponding concentration in the deep reservoir is about 0.35%. H_2S concentrations in steam as measured on site are about half those measured by GNS. The latter (6-9 moles/100moles in the sample) are taken to be more reliable. The H_2S levels are somewhat lower than what is typically seen in high-temperature andesitic systems and this may reflect the outflow position of the NWS-1 reservoir (supported by the even lower H_2S concentrations in NWS-4). Alternatively, this may be a particular feature of the NW Sabalan geological setting.

2.10 Interpretation

The geochemistry of the Sabalan wells and surface springs suggests 2 different geothermal sources:

- The wells are associated with geothermal water originating at 270-280°C.
- The springs are associated with geothermal water originating at 240°C. However, isotope data suggests that both fluids ultimately have a common source.
- A deep geothermal reservoir has been encountered which is the source of the fluids produced in wells NWS-1 and 4, at temperatures of 270-280°C.
- A zone of shallow geothermal fluids overlies the deep zone, at about 240°C.
- The two reservoirs are poorly connected with some limited movement of fluid from the deep to the shallow reservoir (apparently accompanied by some boiling).
- The deep zone outflows off the field at depth in a northeasterly direction along the “NE2 fault” (see Figures 2 and 3), which appears to represent a structurally controlled boundary to the geothermal system.
- The shallow zone forms a small outflow off the northern edge of the field at shallow levels where it is extensively cooled and diluted by near surface mixing processes.

2.11 Resource model

Based on the material and interpretations presented here hydrogeological model has been developed for the NW Sabalan resource as shown in Figure 9.

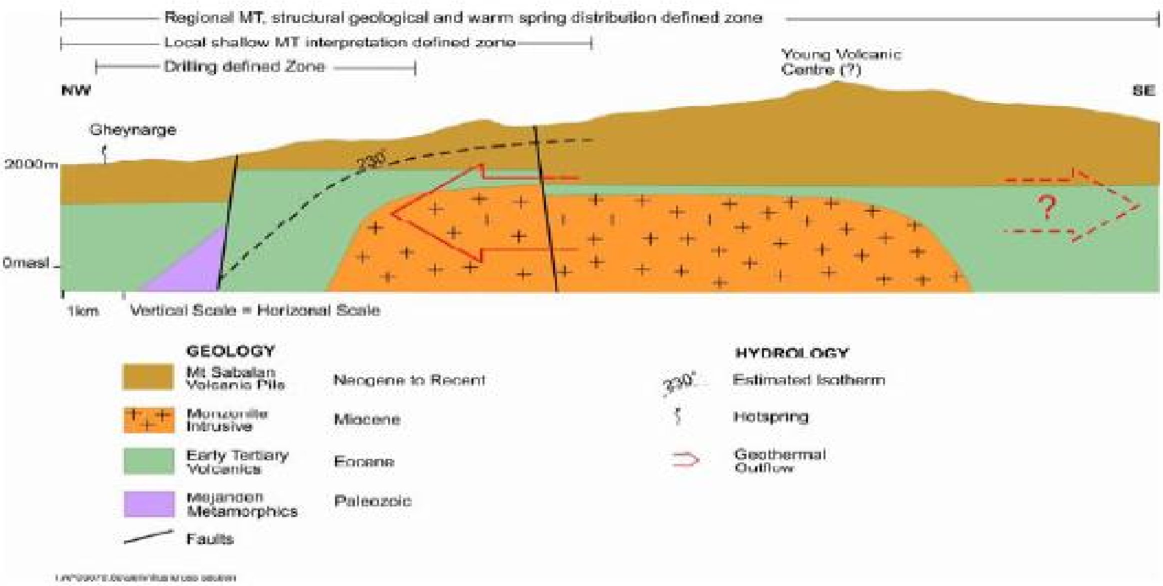

FIGURE 9: Resource model for Mt. Sabalan

The key features of the model are as follows:

- The greater Mt Sabalan volcanic complex shows at least five individual geothermal prospects, distributed over an area of some 800 km^2 as identified by a combination of MT geophysical surveys, surface geothermal activity and structural geological association.
- The most prospective of these geothermal anomalies is in the Moil valley where the original resistivity anomaly indicated a potential resource of some 10 km^2. This anomaly was the principal basis for siting the 3 exploration wells.

- The original MT resistivity survey (Bromley et al., 2000) did not achieve the depth of penetration that can now be expected from such surveying and shows that thick conductive sequences exist in areas of moderate temperature that are distal to a geothermal upflow and the thinner zones of low resistivity at higher elevation to the south and south west lie above what appears to be the upflow area. This re-interpretation of the geophysics model is supported by physical, geological and chemical data obtained from the drilled wells which confirm that:
  - Well NWS-3 was drilled on the northern boundary of the geothermal resource.
  - Wells NWS-1, 4 and 3 progressively show geothermal outflow and this is the source of the neutral chloride springs at low elevation beyond the field boundary such as those at Gheynarge.
  - Of the 3 drilled wells, NWS-1 is located closest to a central upflow zone, but this is still some distance further to the south or south west of the well. Assuming a typical geothermal lateral outflow gradient of 10°C/km and the geothermometry indications from the well NWS-1 chemistry for upstream resource temperatures of at least 270°C, then it is likely that the upflow zone is at least 3 km distance from well NWS-1.

REFERENCES

Giggenbach, W.F., 1988: Geothermal solute equilibria. Deriviation of Na-K-Ca geoindicators. *Geochim. Cosmochim. Acta, 52,* 2749-2765

Fournier, R.O., and Potter, R.W., 1979: Magnesium correction to Na-K-Ca chemical geothermometer. *Geochem. Cosmochim. Acta, 43,*1543-1550.

Bogie, I., Cartwright, A.J., Khosrawi, K., Talebi, B., and Sahabi, F., 2000: The Meshkin Shahr geothermal prospect, Iran. *Proceedings of the World Geothermal Congress 2000, Kyushu-Tohoku, Japan,* 997-1002.

Bromley, C., Khosrawi, K., and Talebi, B., 2000: Geophysical exploration of Sabalan geothermal prospect in Iran. *Proceedings of the World Geothermal Congress 2000, Kyushu-Tohoku, Japan*, 1009-1014.

Talebi, B., Khosrawi, K., Ussher, C.H., 2005: Review of resistivity surveys from NW-Sabalan geothermal field, Iran. *Proceedings of the World Geothermal Congress 2005, Antalya, Turkey,* CD, 7 pp.