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Stage 2 Exploration and Development, NW Sabalan Geothermal Field, Iran

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ABSTRACT

Three deep exploration wells and two shallow reinjection wells have been drilled at the NW Sabalan geothermal field between late 2002 and May 2004 following detailed geo-scientific surface surveys carried out in the late nineties. Results from well drilling and testing (static, flowing and geochemical) are presented and discussed and a modified resource model is presented. A preliminary resource assessment confirms the presence of a medium grade geothermal resource with temperatures within the drilled area up to 250°C and with at least 5km^2 of resource available for commercial exploitation. A forward delineation drilling program is discussed together with a preliminary development plan. It is expected that a first stage geothermal development of between 20 and 40 MWe will be committed by the end of 2004. This will be the first geothermal power development in both Iran and the Middle East.

1. INTRODUCTION

After initial interest in the nineteen eighties in the development potential of geothermal resources in Iran, a series of progressively more detailed investigations have been undertaken in the Mt Sabalan area in NW Iran. Work undertaken jointly by SUNA and Sinclair Knight Merz at Mt Sabalan since 1998 includes the following.

Stage 1 Exploration and Development Program:

- A review of previously collected geothermal field data
- Sampling and analysis of all surface geothermal manifestations
- A detailed MT geophysics survey over the greater Sabalan area which identified five geothermal anomalies, the most prospective being located in the Moil Valley on the NW flanks of Mt Sabalan
- Detailed geological mapping of the Moil geophysical anomaly
- Preparation of a predrilling exploration model

Most of the results from the Stage 1 work program have been published. This includes the detailed geophysics survey (Bromley *et al*., 2000), a multidisciplinary interpretation of all geoscientific data and the development of the predrilling resource model (Bogie *et al*., 2000), and a summary overview of the Stage 1 exploration program which concluded that the NW Sabalan area was sufficiently prospective for high grade geothermal temperatures to warrant conducting an exploration drilling program (Barnett *et.al.*, 1999).

Stage 2 Exploration Drilling Program:

A three well deep exploration drilling and testing programme was carried out in the NW Sabalan area between November 2002 and December 2004. The results of this programme are discussed both here and in a number of papers presented elsewhere in these proceedings. These latter papers include:

- a review of geological results from the three exploration well program (Bogie *et al*., 2005)
- a detailed analysis of the geology and hydrothermal alteration mineralogy of the third deep exploration well (Eshaghpour, 2005)
- an analysis of well measurements from the first of the 3 deep exploration wells (Talebi *et al*., 2005a)
- a reinterpretation of the earlier obtained MT resistivity data, based on improved methods of interpretation and the now known subsurface distribution of clays as determined from the well logs (Talebi *et al.*, 2005b)

The objectives of this paper are to review results from well testing (static, flowing and geochemical), present a modified resource model based on the additional data obtained during the Stage 2 exploration drilling program and to comment on a preliminary resource assessment and the results of a feasibility study carried out by Sinclair Knight Merz in the third quarter of 2004.

2. PROJECT AND WELL LOCATIONS

The location of the NW Sabalan project and a detailed map of the drilled area are given in Bogie *et al*. (2005). The 3 deep exploration wells 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 vertically while NWS-3 and NWS-4 are deviated wells with throws of 1503 and 818 m respectively. Additionally, two shallow injection wells for well testing purposes have been drilled to 600 m depth; NWS2R located on pad A alongside well NWS-1 and NWS-5R on pad B alongside well NWS-4.

3. WELL MEASUREMENTS

3.1 Location of Well Permeability Zones

Temperature and spinner surveys during water injection tests conducted at the time of well completions have been used to interpret the location of permeable loss zones in the wells. Temperature and pressure surveys during heating after completion testing have also provided information on the location of permeable zones.

For well NWS-1, permeable zones are indicated at depths of 1600 m, 1900 m, 2150 m, 2400-2500 m and 2900-3030 m.

There appears to be an extended zone of permeability between 2500m and 2900m. Pressure surveys carried out during well heat up showed a pressure pivot (pressure control point or PCP) near 2600 m, confirming the major permeable zone to be located between 2500 m and 2900 m.

For well NWS-3, a dominant permeable zone is located at a depth of 2165 m MD (1880 m VD) and minor permeable zones are indicated at 1600 m, 1780-1850 m, 1950 m, 2090 m, 2480 m, 2770 m and possibly below 2896 m. None of these zones appear to have high permeability.

For well NWS-4, there is a major zone at a depth of 1620 m MD (1460 m VD) which appears to have much greater permeability than minor zones at 1240 m, 1460 m and 1740 m. It is believed the zone of major permeability is associated with a geological fault (Bogie *et al*., 2005).

3.2 Well Injectivities

Injection tests have been conducted on all five wells. These have generally been short-term completion tests designed to provide initial information on reservoir conditions in the vicinity of the wells. The injectivity and transmissivity values obtained from these tests are only moderate but are expected to be higher in future wells as the nature of reservoir permeability is now better understood. The results of injectivity determinations for the 3 deep wells are given in Table 1.

Table 1: Well injectivities

Well	Injectivity Index *(l /sec-MPa)*
NWS-1	7
NWS-3	8
NWS-4	16

4. WELL OUTPUT TESTING

Well NWS-1 was successfully discharged in May 2004 and flowed for a period of 21 days. It required airlifting to initiate discharge. The well was flowed to a skid mounted portable well test rig designed by Sinclair Knight Merz which has a dedicated silencer, separator and steam/brine flow-metering station. All waste brine from the flow test was reinjected into the adjacent shallow well NWS-2R. Similarly, well NWS-4 was airlifted in September 2004 and flow tested for a total time of two months with reinjection of waste brine into shallow well NWS-5R. An attempt was made to flow well NWS-3 and although a small discharge was initiated, it was not sufficiently permeable to sustain a flow.

Output curves for wells NWS-1 and NWS-4 are given in Figure 1. These show variations in total mass and enthalpy with flowing wellhead pressure. Both wells discharged with enthalpies in the range of 950 to 1000 kJ/kg. which is consistent with production from wholly liquid feed zones with temperatures of 230°C (for NWS-1) and 220°C (for NW-3). These are both lower than the maximum temperatures measured in the two wells of 248 and 230°C respectively. Due to low overall permeability, the discharge of well NWS-1 is sensitive to changes in well head pressure and flow could not be sustained at well head pressures above 4.5 barg. Additionally, as NWS-1 wellhead pressure was increased the discharge enthalpy decreased from 1000 to 900 kJ/kg. It is considered that this was due to an increasing flow contribution under these conditions from a slightly cooler feed zone at 2900m MD.

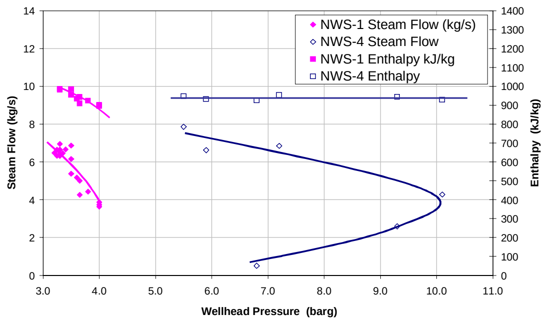

Figure 1: Output Curves for Wells NWS-1 and NWS-4

Well NWS-4 with a significantly higher permeability showed a constant enthalpy of 950 kJ/kg at all well head pressures, reflecting the dominance of the 1620 m feed zone, and a progressive decline in total flow and steam flow up to 10 barg well head pressure.

5. WELL GEOCHEMISTRY

Full suites of brine and steam samples were collected from wells NWS-1 and NWS-4 during the discharge tests. Chemical analyses of these samples are presented in Table 2. The data for well NWS-4 is only partially complete as at the time of writing chemical analyses were still ongoing.

The reservoir fluid produced by these two deep wells is a slightly alkaline, relatively dilute, sodium chloride brine with TD chloride concentrations of 2000 mg/kg and with 0.5% TDS. The concentration of CO_2 and H_2S in separated steam at line conditions averages 2% w/w, which is a typical value for developed geothermal fields.

Silica geothermometry calculations for NWS-1 brine samples yield well production zone temperatures of 238 to 240°C (see Table 1), equivalent to liquid water with an enthalpy of 1030 kJ/kg. NWS-4 brine yields silica temperature estimates of up to 235°C, equivalent to liquid water at 1010 kJ/kg. Both of these temperatures estimates are close to the maximum temperatures measured in the two wells but the estimated enthalpies are somewhat higher than actual discharge enthalpies. Cation geothermometry estimates for well NWS-1 fluids are in the range 265 to 267°C (Table 1) and are therefore significantly higher than temperatures measured in the well. It is expected that well NWS-4 will also show similarly high cation geothermometry temperature estimates when chemical analyses have been completed.

The Giggenbach (1996) Na-K-Mg diagram in Figure 2 shows that NWS-1 well fluids are mature reservoir fluids equilibrated at reservoir temperatures of 270 to 280°C. Additionally, the diagram provides a strong suggestion that the neutral chloride surface springs that occur several km to the north of well NWS-1 derive from the same reservoir fluid encountered in wells NWS-1 and NWS-4. The geochemical data are therefore consistent with wells NWS-1 and NWS-4 being located in an outflow from an upstream geothermal resource where temperatures of at least 270°C are likely.

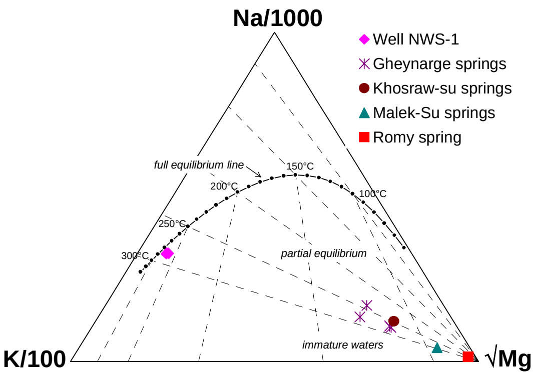

Figure 2: Giggenbach Plot, Well NWS-1 & Sabalan Springs

Given the constancy of chloride in brine samples from both wells and the relatively small temperature decline over the 1 km distance between the two wells, the geothermal outflow appears to be affected by only minor conductive heat loss and little if any dilution with cooler ground water. Further downslope from wells NWS-1 and NWS-4 some of this outflow discharges at surface as a diluted admixture of reservoir brine and ground water.

6. REVISED RESERVOIR MODEL

6.1 Reservoir Temperature Distribution

The temperature distribution within a geothermal system is of fundamental importance in resource assessment. It is probably the most useful information that can be obtained as it indicates both the quality of the resource and the fluid flow paths within the reservoir. Temperature, pressure and spinner surveys have been regularly conducted in each of the Sabalan exploration wells from the time of drilling completion. These data have been used to determine the distribution of sub-surface temperatures through interpretation of the measured temperature surveys to establish the ‘stable’ reservoir conditions as a function of depth for each well. Contour plots and vertical cross sections are prepared at selected depths and locations to show temperature variation within the reservoir, both horizontally and vertically. These plots are useful in showing how hot and cold fluids interact within the geothermal system and are therefore important in the formulation of a hydro-geological model for the system.

Stable temperature profiles for wells NWS-1, NWS-3 and NWS-4 have been determined by interpretation of the down hole surveys. The resultant profiles are shown in Figure 3. A representative ‘Boiling-Point-for-Depth’ (BPD) curve is also shown, based on a measured water level of 2450 masl in well NWS-1. The well temperatures generally reflect stable reservoir conditions once thermal equilibration has taken place because there are no two-phase fluids within the wellbore. Wells NWS-1 and NWS-4 are affected by minor downflows between the upper and lower permeable zones which mask the intermediate temperatures. The temperature gradients appear to be small and the upper and lower zone temperatures are similar, so a small temperature inversion has been assumed, based on measured inflow temperatures when NWS-1 was on discharge. By plotting the well temperature profiles together as in Figure 3, it is possible to make a number of observations regarding the nature of the geothermal resource based on changes in temperature with depth:

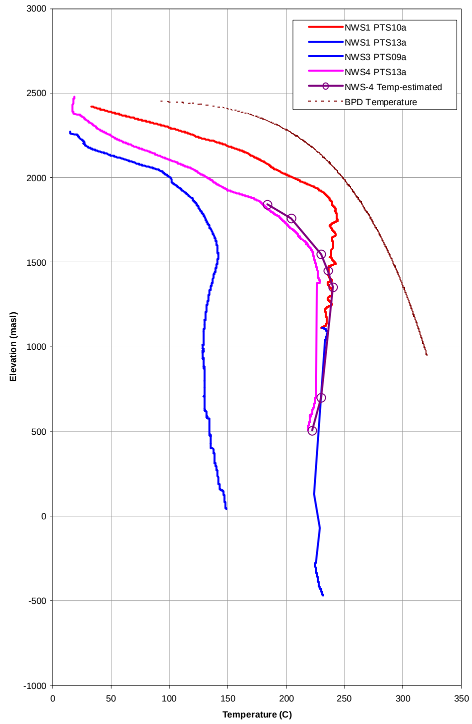

Figure 3: Estimated Stable Reservoir Temperatures

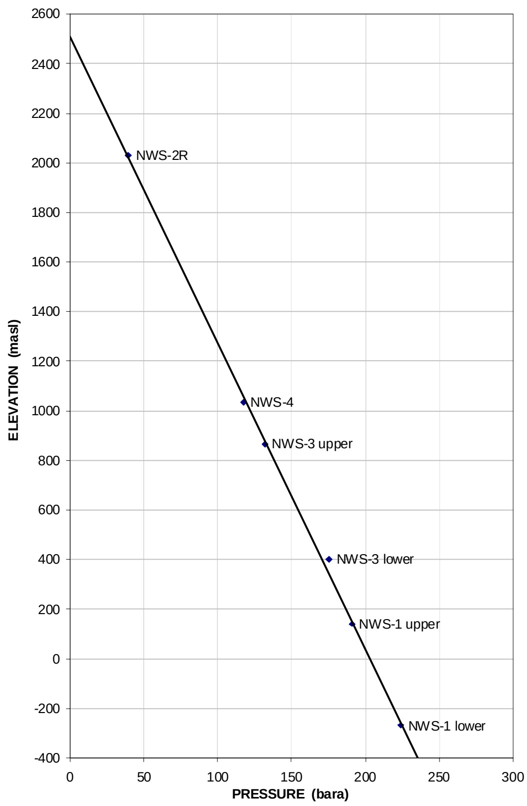

Figure 4: Well Pressure Control Points for Depth

- Well temperatures are all below the BPD curve, indicating that the reservoir in the area of the field so far drilled does not contain a two-phase mixture of steam and water. Temperatures behind the casing of NWS-1 at an elevation of about 1900 masl are close to BPD conditions, indicating possible proximity to two-phase fluid
- From +1500 masl to between +600 – 200 masl a slight temperature inversion is evident
- Below +200 masl in NWS-1 and +600 masl in NWS-3 temperatures increase with depth
- The hottest temperature measured is in NWS-1, suggesting that it is situated closest to a deep upflow located in a generally southern direction

A vertical cross section orientated from southeast to northwest, running from NWS-1 through to NWS-3, is shown in Figure 6. This provides strong evidence for a hot outflow running past NWS-1 in the general direction of NWS-3, but this may not necessarily be along the line of the cross-section.

6.2 Reservoir Pressure Distribution

Interpretation of sub-surface pressures is more difficult than sub-surface temperatures because the pressure profile within the wellbore does not generally reflect the pressure profile with depth in the surrounding formation. The wellbore pressure is often in equilibrium with the formation pressure only at the major permeable feed. If there are two or more significant permeable zones then the depth of equilibrium will lie between these zones. 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 Sabalan wells, including shallow well NWS-2R, the PCP pressures are plotted versus elevation in Figure 4. 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 in the area of these 2 wells.

6.3 Hydrogeological Model

Based on the material and interpretations presented here, together with the well geology data presented by Bogie *et al*. (2005) and the re-interpretation of the original surface geophysics data (Talebi *et. al*., 2005b), a revised hydrogeological mode has been developed for the NW Sabalan resource. This is shown in Figure 7. The essential 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 associations.

The most prospective of these geothermal anomalies is located in the Moil valley where the original resistivity anomaly indicated a potential resource of some 10 km2. This anomaly was the principal basis for siting the 3 deep exploration wells.

As detailed by Talebi *et al*. (2005b) the original MT resistivity survey (Bromley *et al.*, 2000) did not achieve the depth of penetration that can be expected from this method. It is now considered that the thick conductive sequences in areas of moderate temperature 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 a geothermal upflow zone.

This re-interpretation of the geophysics data is supported by physical, geological and chemical data obtained from the drilled wells which confirm that:

- Well NWS-3 is situated on the northern boundary of the geothermal resource
- Wells NWS-1, 4 and 3 are progressively located down a geothermal outflow and this is the source of the neutral chloride springs at lower elevations beyond the field boundary, such as the Gheynarge hot springs
- Of the 3 drilled wells, NWS-1 is located closest to a central upflow zone, but the upflow still lies some distance further to the south or southwest of the well. Assuming a typical geothermal outflow gradient of 10^{o}C/km and the geothermometry indications from well NWS-1 chemistry for upstream resource temperatures of at least 270^{o}C, then it is likely that the upflow zone is at located at least 3 km to the south of and upslope from well NWS-1.

8. FEASIBILITY STUDY

An engineering feasibility study was conducted in August 2004 by Sinclair Knight Merz to assess possible development options for the NW Sabalan field. The major issues considered in this study are as follows.

8.1 Resource Size

The revised hydrogeological model suggests that there is good geothermal development potential over a likely resource area of some 20 km^2. This greater resource is located to the south and upslope of the area in which the three deep exploration wells have been drilled. Nonetheless, the successful results from wells NWS-1 and NWS4 test and prove a resource area of 5 km^2 which lies between unproductive resource to the north, as confirmed by well NWS-3, and as yet undrilled, potential resource to the south.

For the purpose of assessing the development potential within the 5 km^2 proven resource, an area of 3 km^2 was blocked out around well NWS-4 on geological criteria and an area of 2 km^2 similarly blocked out around well NWS-1. A 3-layer volumetric stored heat model was then developed for each of these two blockx for which extractable heat and power generation potential was assessed with a Monte Carlo simulation model. The results of the simulation were assessed from a histogram of potential power generation outcomes from the model as shown in Figure 5. This indicates that at a 90% confidence level the generating potential of the 5 km^2 resource block can be expected to vary from 45 to 75 MWe, with a most likely value of 58 MWe. A median value of 60MWe is obtained at a cumulative probability of 0.5, which means that there is a 50% probability that the 5 km^2 resource may have a generation potential greater than 60Mwe.

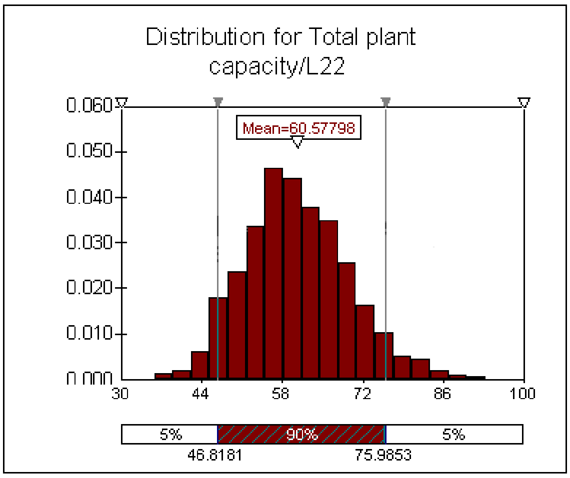

Figure 5: Monte Carlo Simulation Results

8.2 Constraints on Steam Field Layout

Based on the Monte Carlo analysis, the feasibility study recommended that a Stage 1 power development of up to 40MWe be undertaken on well pads A and/or B, utilising existing wells NWS-1 and NWS-4, which have a combined power generating capacity of 7 MWe, and further production wells yet to be drilled. Reinjection is to be based on well pad C, utilising well NWS-3 and other injection wells yet to be drilled.

Steamfield layout and power plant options for well pads A and B are seriously constrained by geotechnical issues associated with a deeply incised river course which cuts through the project terrain between well pads A (with well NWS-1) and well pad B (with well NWS-4). This feature makes the routeing of two phase, steam and brine line piping between pads A and B both difficult and costly. As a result, there are few options for steam field and power plant layouts and these are limited to developments of 1x10 MWe, 1x20 MWe, or 2 x 20MWe, located on or close to either wells Pad A or Pad B.

Given these constraints, the feasibility study concluded that a first stage power development should be undertaken on a stand alone basis at Pad B. This is the preferred option as it would leave Pad A available in the future for a potentially larger second stage development on the basis that resource indications upslope from Pad A are encouraging and further drilling in this area is planned.

8.3 Process Issues and Constraints

Calcite Scaling

With resource temperatures in the vicinity of well Pad B in the range of 220 to 240C, it is possible that well bore deposition of calcite may become a future production problem. Such deposition occurs at the liquid flash point in wells where the loss of carbon dioxide from solution upon initial boiling drives the following reaction strongly to the right.

$$Ca^{2+} + 2HCO_3^- = CaCO_3 + CO_2 \qquad (1)$$

Computer modelling of this process using the RESCHEM software shows that although the fluids are under saturated with calcite in the reservoir, upon flashing they will become supersaturated. The likelihood of calcite deposition will then need to be factored into any future development plan with allowance being made for the cost and operating requirements for downhole injection of calcite antiscalent chemicals, as and when may be required.

Silica Scaling

A beneficial consequence of developing medium grade geothermal resources is that brine temperatures can be reduced substantially during utilisation before silica supersaturation and scaling in reinjection piping and reinjection wells becomes problematic. For the case of the NWS-4 fluids, brine separated from steam at 3.0 bara (133°C) would be just at saturation with respect to amorphous silica and at these levels would not pose any deposition problems. In practice silica supersaturation levels of even up to 110% can be operationally tolerated in which case separator pressure could be reduced further, down to about 2.3 bara (125°C).

8.3 Power Plant Considerations

With the moderate resource temperatures accessible from well pad B, the thermal efficiency of the utilisation of geothermal fluids in a geothermal power plant will be important. Cost and economic modelling studies for the NW Sabalan project for conventional steam turbines with single flash steam yield levelized costs for power generation which range from \$55 to \$45 per MWh for 1 x 20 or 2 x 20 MWe units, respectively. Although this is an acceptable outcome when compared to other geothermal developments around the world, there is, nonetheless, good potential for improving on this through the addition of second stage flash plant or brine binary cycle bottoming plant to improve the thermal efficiency of the overall geothermal utilisation.

9. SUMMARY AND CONCLUSIONS

The Stage 2 geothermal exploration drilling at NW Sabalan has been most successful. Key achievements to date include:

- Resource temperatures of 248°C have been confirmed by drilling and well testing
- Two wells have sustained commercial discharges and have a combined output of 7MWe. Furthermore, it is expected that a workover of well NWS-1 will increase total steam from these two wells to at least 10 MWe
- The geothermal fluids that have been encountered are well suited for commercial utilisation being relatively dilute neutral chloride brine with about 2% non condensable gases.
- Well NWS-3 has successfully proven the northern field boundary of the NW Sabalan field and has provided the basis to confirm a future reinjection strategy
- The original hydrogeological model for the field has been revised based on a reinterpretation of the original MT geophysics data, and geological, geochemical and physical measurements from the exploration drilling and evaluation program. These data confirm that the three wells have been drilled into a geothermal outflow and are located downstream of an upflow zone where central resource temperatures of at least 270C are expected. The upflow zone is probably some 3 or more km further to the south of well NWS-1

- Although the temperatures encountered in the current wells are of medium grade, an engineering feasibility study has confirmed that it will be economic to undertake an initial power development of between 20 and 40MWe in the currently confirmed resource area of 5km2 which from a Monte Carlo simulation of extractable heat has a 90% probability of being able to sustain an output of 40MWe over a field life of 25 years.

SUNA is rapidly advancing the development of the NW Sabalan field with the following activities now being implemented:

- Two deep drilling rigs will be mobilised by mid 2005 to commence production drilling for a first stage power development and to undertake a parallel program of ongoing exploration and delineation drilling upslope from well NWS-1 to size the greater field in the area to the south. In total, this program will involve the drilling of some 30 wells over a total of 5 rig-years

- Detailed negotiations are in progress for placing a BOT contract with an IPP to build and operate the first stage geothermal power development

These successes resulting from the initial three well exploration drilling are impressive and match best practise standards in the geothermal industry.

With this rate of progress, SUNA expect to have a first stage power development constructed and commissioned within the next 30 months while continuing to delineate the NW Sabalan reservoir with the objective of developing a further stage of 100 MWe or greater.

These will be the first geothermal power developments in both Iran and the Middle East.

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Table 2: Discharge Geochemistry of Sabalan Wells NWS-1 and NWS-4 (partial)

Sabalan Wells - Brine Analyses:

Well	Date	Type	C.P.	pH	Li	Na	K	Ca	Mg	Fe	Cl	SO_4	$tHCO_3$	B	SiO_2
			b.g.					mg/kg							
NWS1	14-Jun-04	SPW	2.4	8.88	8.3	1414	257	15	0.11	0.10	2411	117	105	22	520
NWS1	15-Jun-04	SPW	2.5	8.70	8.1	1402	254	15	0.10	0.05	2375	117	113	22	519
NWS1	16-Jun-04	SPW	3.1	8.56	8.1	1382	255	14	0.09	0.02	2336	118	130	21	506
NWS1	18-Jun-04	SPW	3.0	8.63	8.2	1385	252	14	0.09	0.04	2384	114	115	21	522
NWS4	13-Sep-04	WBX	0.0	8.60				31			2606	123	75	22	418
NWS4	14-Sep-04	ATM	0.0	8.39				31			2482	109	85	21	444
NWS4	15-Sep-04	ATM	0.0	8.42				31			2500	100	85	22	466
NWS4	16-Sep-04	SPW	1.5	8.42				26			2570	116	78	22	484

Analyses for NWS-4 incomplete at time of going to press

Sabalan Wells - Steam Gas Analyses, Molar Ratios and Brine Geothermometry:

Well	Date	Type	C.P. (b.g.)	CO_2 (mM/100M @ SCP)	H_2S (mM/100M @ SCP)	Cl — Ca	Cl — B	Cl — SO_4	Na — K	Cl_{RES} (mg/kg)	T_{QTZ} (°C)	T_{NaK} (°C)	CO_2 — H_2S
NWS1	14-Jun-04	SPW	2.4	917	5.8	185	33	56	9.4	2030	238	266	158
NWS1	15-Jun-04	SPW	2.5	860	3.8	185	33	55	9.4	1991	238	266	226
NWS1	16-Jun-04	SPW	3.1	1002	4.9	189	34	54	9.2	2005	237	267	204
NWS1	18-Jun-04	SPW	3.0			195	35	57	9.3	2050	239	267	
NWS4	13-Sep-04	WBX	0.0			95	37	57		1992	215		
NWS4	14-Sep-04	ATM	0.0	756	6.2	91	35	62		1897	219		122
NWS4	15-Sep-04	ATM	0.0			91	35	68		1911	223		
NWS4	16-Sep-04	SPW	1.5	742	4.6	112	36	60		2065	230		161

Notes: CP = Collection pressure, SPW = separated water, ATM = at atmospheric pressure, WBX= silencer weirbox, b.g. = pressure in bars gauge

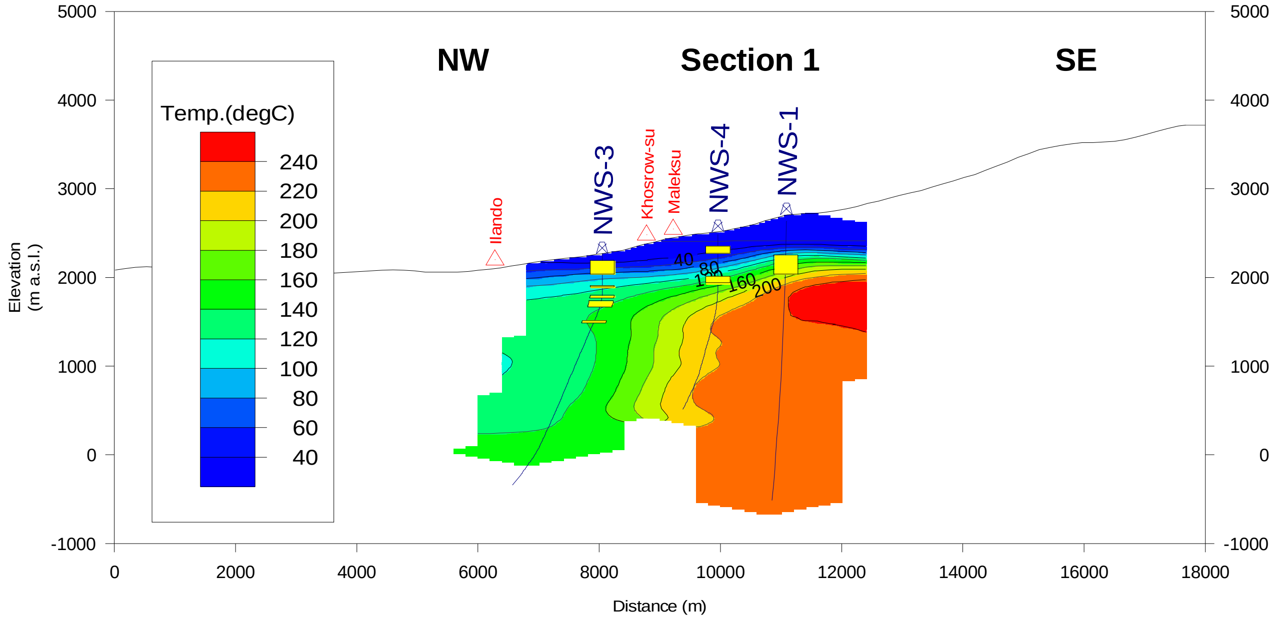

Figure 6: Vertical Temperature Section Through the 3 Deep Sabalan Wells (extracted from Talebi *et al*., 2005b)

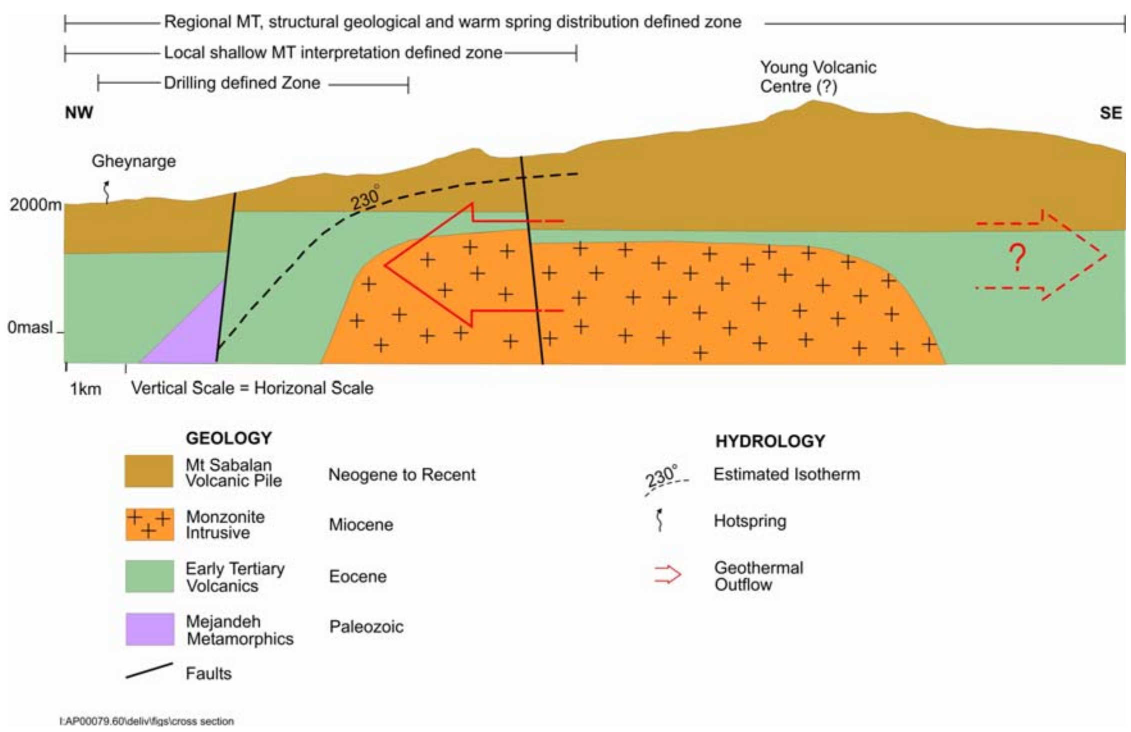

Figure 7: Revised Hydrogeological Model for the NW Sabalan Geothermal System