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NUMERICAL MODELING OF THE NW SABALAN GEOTHERMAL FIELD, IRAN

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ABSTRACT

The Sabalan geothermal field is situated in the NW of Iran within the vicinity of Ardebil Province. It is the first geothermal field in both Iran and the Middle East to be developing for electricity generation. Three deep exploration wells have been drilled at the NW Sabalan geothermal field during 2003/2004 following detailed geo-scientific surface surveys carried out in the mid to late nineties. The numerical model of the NW Sabalan geothermal field is presented implementing the geothermal simulator TOUGH2. The study has involved the development of a natural state model of the resource, based on assumptions regarding resource area and location of the upflow zone. The model has been successfully validated by matching available downhole temperature and pressure data from existing wells which appear to be located in an outflow which is peripheral to a hot upflow. The model results are consistent with the conclusions of deep exploration drillings that the NW Sabalan geothermal resource may extend to the southeast of the presently drilled area and could have a potential resource area in the order of 19 km2 and maximum temperatures of 260 to 270°C.

INTRODUCTION

The Renewable Energy Organization of Iran (SUNA) has identified a geothermal resource at Mt Sabalan, in the Ardebil Province of Northwest Iran, which is potentially viable for commercial electric power generation. The resource has now been proven by the encouraging results from the initial three deep well exploration drilling program and the results have led to consider further delineation and development drilling in the geothermal resource area. This computer simulation study with the objective of extending the conceptual model of the resource, was undertaken for the primary purpose of predicting and assessing the response of the geothermal system to the planned Stage 1 and Stage 2 developments by implementing TOUGH2 computer code (Pruess, et al., 1999) applying for water/steam/carbon dioxide equation of state. The work carried out to fulfill the specific requirements for the numerical modeling has included the following:
1) Construction of base models and definition of initial and boundary conditions, based upon the conceptual model.
2) Validation of the model by matching available downhole temperature and pressure data from the existing wells with the calculated conditions.

CONCEPTUAL MODEL

The conceptual model aims to bring together all the available information to provide a consistent “picture” of the system that explains as much of the data as possible. This in turn defines the basic physical parameters required to construct the numerical model, such as resource size (area and thickness) and thermodynamic conditions. The conceptual model used as the basis for the numerical model is shown in Figure 1. The geothermal field is interpreted to have an upflow to the south of the existing wells NWS-1, 3 & 4. The NE2 fault appears to mark the northern boundary of the field between wells NWS-4 and NWS-3. The area of the productive reservoir is inferred from the MT geophysics survey and the major structures, and is consistent with the 19 km^2 area. The upflow temperature was assumed to be approximately 265°C, based on the cation geothermometry temperatures from well NWS-1 fluid. The model has a total of 28 kg/s of surface discharge, with an additional outflow of 72 kg/s from the field at depth. This is provided by an assumed hot upflow of geothermal fluids with a flow rate of 100 kg/s at 263°C plus 0.5 kg/s of carbon dioxide (0.5%)m, centered about 4 km south of well NWS-1.

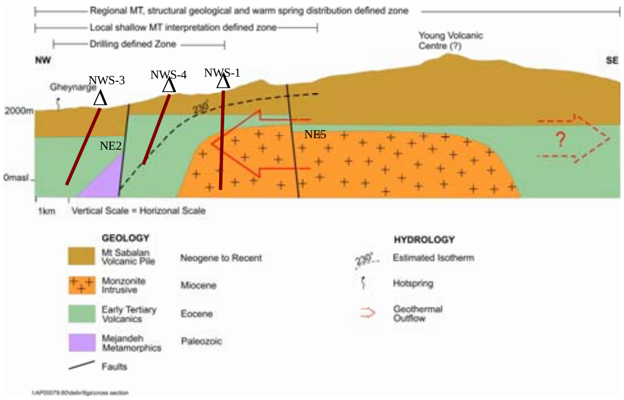

Figure 1. Resource Model for Mt. Sabalan

DESCRIPTION OF NUMERICAL MODEL

The overall size and shape of the NW Sabalan geothermal system have been defined using structural geological data and data from the MT resistivity survey. Downhole data from existing wells have then been used to help define the subsurface geological features and thermodynamic conditions in the outflow from the reservoir and the apparent location of the upflow zone. The numerical model incorporates two major permeable layers in the field.

- The upper layer which was partly cased off in NWS-1 and extends from 1800 masl down to 1000 masl.
- The deeper permeable layer which was intercepted by NWS-1 and extends from 200 masl down to about –100 masl.

To represent the shape of the resource as closely as possible and to be consistent with the major flow directions in the system, the numerical grid has been orientated approximately NW-SE, as shown in Figure 2. This also shows the basic grid block layout used in each layer of the model, locations of the existing Sabalan wells, future well pads and locations of the major surface springs which are overlain on the results of the MT survey and the block areas used in the stored heat calculations. The overall dimensions of the model are 9.6 km x 14 km, giving a total model area of 134 km^2. In each layer of the model there is a “regular” set of rectangular grid blocks, with 120 blocks per layer. In the vertical plane, the model has been split into 13 layers of varying thickness, extending from a maximum of 3,000 masl to -1,200 masl, as shown in Table 1. With the grid layout and layers, there are a total of 1,560 grid blocks within the model. The outflow sources and the upflow blocks used for each of the models are defined in layers AG and AM respectively. The top surface of the model has been set at elevation between 2,200 and 3,000 masl as this coincides approximately with the elevation of the ground surface, which rises to the south-east.

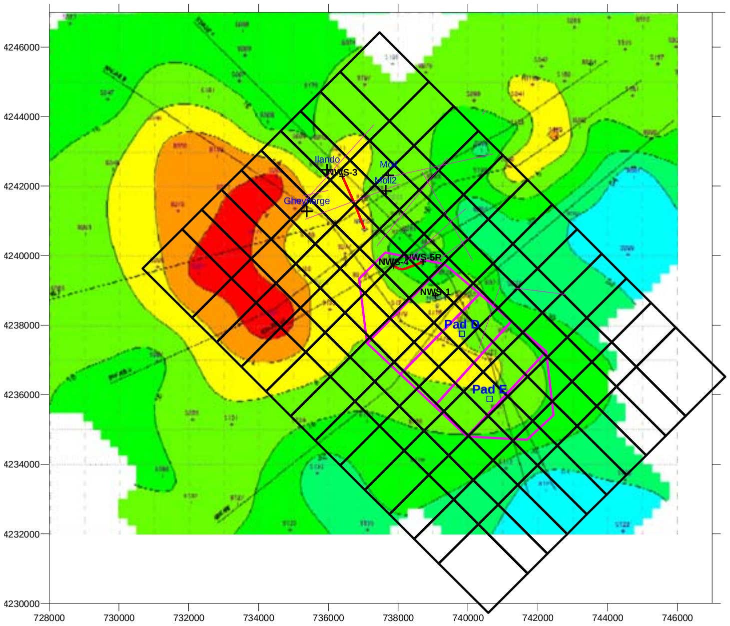

Figure 2. Map of NW Sabalan showing model grid overlain on MT survey results

Layer	Thickness (m)	Top(masl)	Node Level (masl)	Bottom (masl)
AA	variable	variable	variable	2100
AB	100	2100	2050	2000
AC	100	2000	1950	1900
AD	100	1900	1850	1800
AE	100	1800	1750	1700
AF	100	1700	1600	1500
AG	200	1500	1400	1300
AH	200	1300	1175	1050
AI	250	1050	925	800
AJ	250	800	550	300
AK	500	300	50	-200
AL	500	-200	-450	-700
AM	500	-700	-950	-1200

Table 1. Basic Layer Model Properties

The following boundary conditions were defined to simulate the main inflows and outflows to/from the model:

☐ Upflow of mass and heat to the model from depth was defined as occurring in two blocks approximately four km south-east of well NWS-1. Based on the available data from the existing wells, the source fluid was defined as liquid water at a temperature of 263°C and containing 0.5% of carbon dioxide.

☐ Conductive inflow/outflow of heat over the remainder of the base layer. Heat sources were used to supply heat (no mass) into the blocks in the bottom layer of the model. A typical geothermal heat flux of

100 mW/m^2 was used as the initial basis for calculating the heat inflow to each block, based on the block base area. This was then adjusted to achieve a match to deep temperatures in well NWS-3, which is outside the main geothermal reservoir. The final value was 0.2 W/m2. The larger boundary blocks had the same heat input (MW), which gave lower fluxes and hence temperatures at the edges of the model.

- To model the discharges from the system at Sabalan, pressure dependent sink terms have been defined in the layer AG blocks (Figure 3) that correspond to the main springs. This allows for discharge against a specified pressure, which was consistent with the natural state pressure profile. The temperature profiles in the wells show a conductive profile above 2000 masl which is not consistent with a flow to the surface within the model. Future models could incorporate smaller blocks and have more variable surface elevations to match the valley where the Gheynarge springs reach the surface via a lateral flow, but it was felt that there was insufficient well data to justify such a detailed representation of the springs at present.

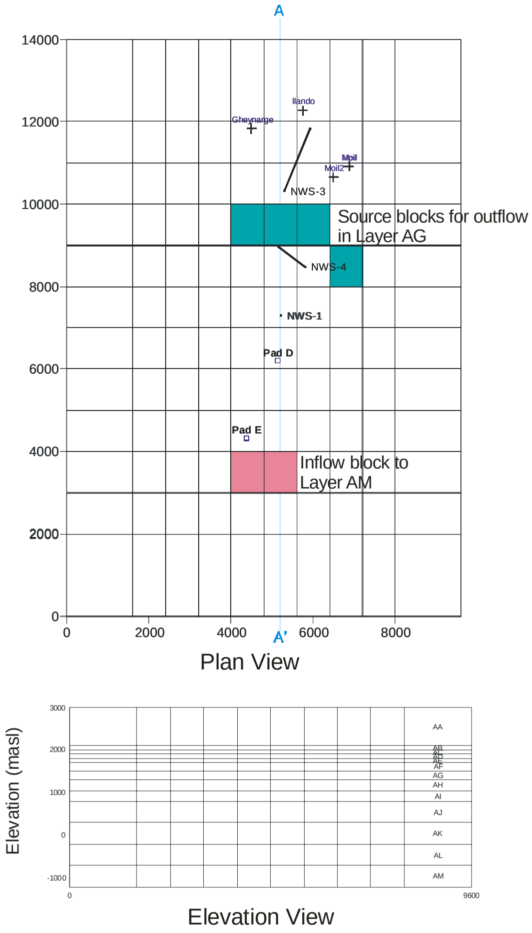

Figure 3. Plan and elevation views of grid block layout and cross-section (A-A')

- An additional pressure dependent sink was used to model deep outflow from the field at the north-eastern boundary of the model, at the intersection with the NE2 fault which acts as a boundary to the field.
- Over the top of the simulation model, an atmospheric block has been defined, with a temperature of 15°C, to allow conductive heat loss to occur. The thickness of the upper layer was varied to approximate the surface level. This is to make the simulation model more realistic by reducing the heat loss under the high elevation areas.

The remaining outer boundaries of the model are closed, with no heat or mass transfer occurring across them. The "relative permeability" functions that basically control the flow of vapour and water between the grid blocks were defined by using the Grant (1977) curves, with residual saturations of zero for both vapour and water. For modeling of geothermal systems, the validation process normally involves matching of the natural state conditions in the resource, as defined by available sub-surface information, and history matching to the known changes that occur in well and reservoir parameters during testing or production. However, this is not always a simple process as changes that are made to the permeability distribution can have a significant effect on the temperature and phase distributions, which in turn have an effect on the physical properties of water. Hence, it generally becomes an iterative process and can require a significant number of model runs. In terms of validating the model, the main focus has been to match the available downhole temperature and pressure data from the Sabalan wells (Figure 4) as a way of constraining the natural state model of the total system. The natural state conditions generated by the model are obtained based on a "trial-and-error" process and by changing and then re-running the model until "steady state" conditions are reached. The major parameters of importance that are changed during this process are:

- the permeability distribution, which controls where and how the fluid moves through the model, and;
- the locations and magnitudes of the inflows and outflows of mass and/or heat.

The final phase of model validation normally involves matching of data collected during production, and requires that production and injection histories be entered into the model at specified grid blocks and running the model to reproduce the specified production period. This is similar to the natural state matching, and normally requires a "trial and-error" process before a reasonable match is obtained. To obtain a match, the important parameters that may be changed include the permeability distribution and also the storage terms, such as porosity and heat capacity.

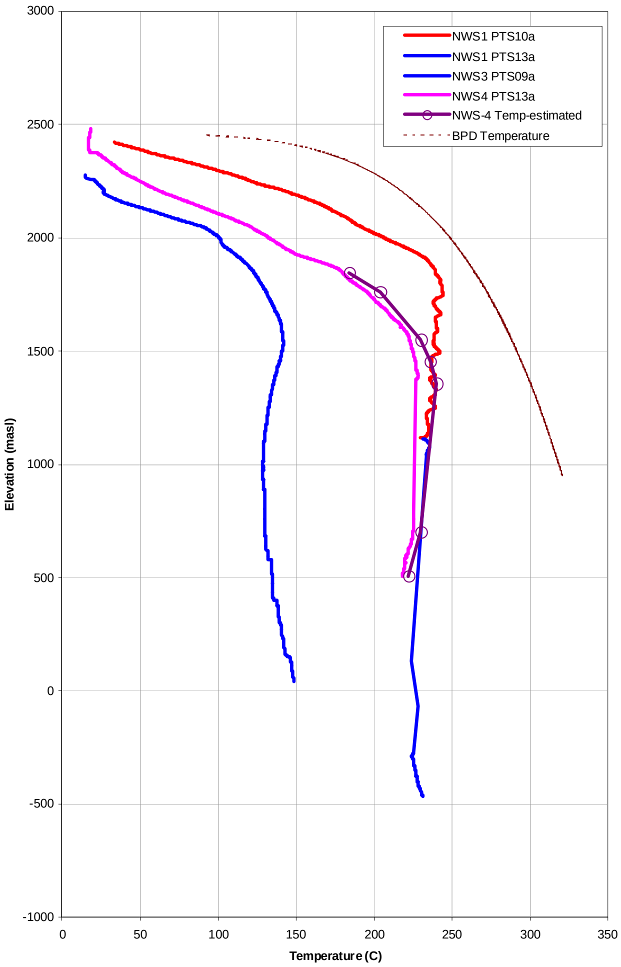

Figure 4. Stable well temperatures for Sabalan wells

Flow tests were conducted on two of the Sabalan wells, NWS-1 and NWS-4, and both proved to be commercially productive with flow rates of 25 - 55 t/hr at 5 bar well head pressure. The zones of maximum temperature were also cased off in NWS-1. The available flow test data from the existing wells are of limited value for calibrating the Sabalan model, as the Pad A and B area is only a small part of the overall model and the two commercial wells are located relatively close together. The discharge tests were of short duration at high flow and no pressure monitoring data is available from other wells. Hence, matching of the flow test data has not been conducted for this study.

DISCUSSION

After defining the basic resource size and the locations of the "outflow" and "upflow" blocks, the properties of the various "rock types" and their distribution was defined in order to match the steady-state model results with the measured sub-surface data from the wells. The final set of rock types used in the Sabalan model and the properties of each rock type are summarized in Table 2.

Rock Type	**Density (kg/m3)**	**Porosity (%)**	**k, x (10-12 m2)**	**k, y(10-12m2)**	**k, z (10-12m2)**	**Heat Cond (W/m°C)**	**Heat Capacity (J/kg°C)**
BOUN2	2500	10	0.003	0.003	0.003	2.5	1000
BOUN3	2500	10	0.02	0.02	0.02	2.5	1000
CAPRK	2500	10	0.001	0.001	0.001	2.5	1000
ROK01	2500	10	0.1	0.1	0.1	2.5	1000
ROK02	2500	10	0.4	0.4	0.4	2.5	1000
RSFLO	2500	10	0.32	0.32	0.32	2.5	1000
RSFL2	2500	10	0.05	0.05	0.05	2.5	1000
UPFLO	2500	10	0.32	0.32	0.32	2.5	1000
ATMOS	2500	10	0	0	0	2.5	boundary

Table 2. Rock Type Definitions and Properties

The rock types with the highest permeability are ROK01, ROK02, and UPFLO and these rock types therefore control the flow through the model. Although the rock type names are generic and no attempt has been made to associate any particular rock type with any particular identified geological formation, but their distribution on the various model layers and in the cross section (Figure 5) show more clearly how flow is controlled from the inflow at depth to layer AM to the outflow in the springs. The main reservoir for the model is located in layers AK (deep) and layers AD – AH (shallow), with permeable areas of 19 and 17 km2, respectively. Layer AK also has moderate permeability BOUN3 blocks to allow a deep outflow from the N-E boundary of the model, representing an outflow along the NE2 fault.

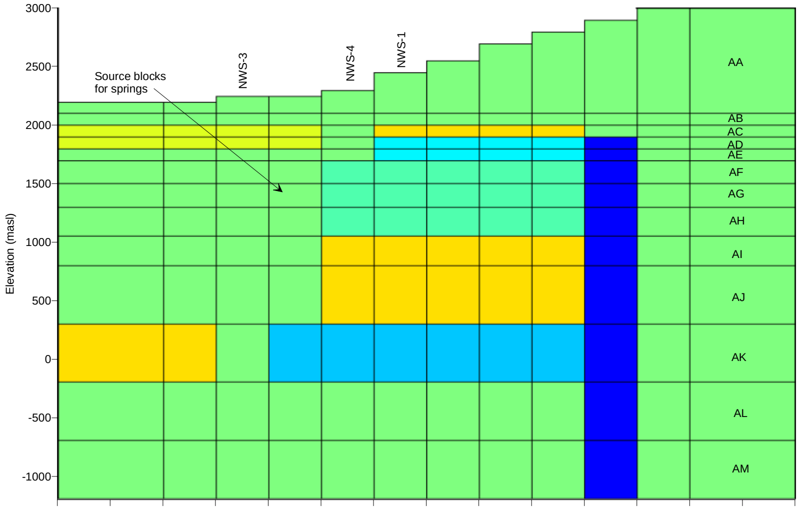

Figure 5. Rock type distribution on a cross-section (with vertical exaggeration)

Lower permeability CAPRK blocks are used at the outer boundary of the permeable reservoir, as defined by the UPFLO, ROK01, ROK02 and RSFL2 blocks, and they therefore confine the reservoir. There is little or no flow from the permeable reservoir into these blocks although conductive heating can occur. Rock types BOUN2 and BOUN3 have intermediate values of permeability and have been used to adjust the main flow paths to improve the matches to individual wells. These rock types are also used to allow a small flow past well NWS-3 to the north-west. Rock type ATMOS has zero permeability and is used for modeling the conductive heat transfer boundaries at the top of the model (15°C sink).

The calculated temperatures from the grid block columns that correspond to the wells at Sabalan (Figure 4) are compared with the corresponding measured data in Figure 6 to Figure 8. Where a deviated well crosses into a second column, temperature profiles from both columns are shown at the relevant depths. In general, the matches to the well data are good, particularly in reproducing the temperature inversion in the deep aquifer in wells NWS-1 and NWS-4.

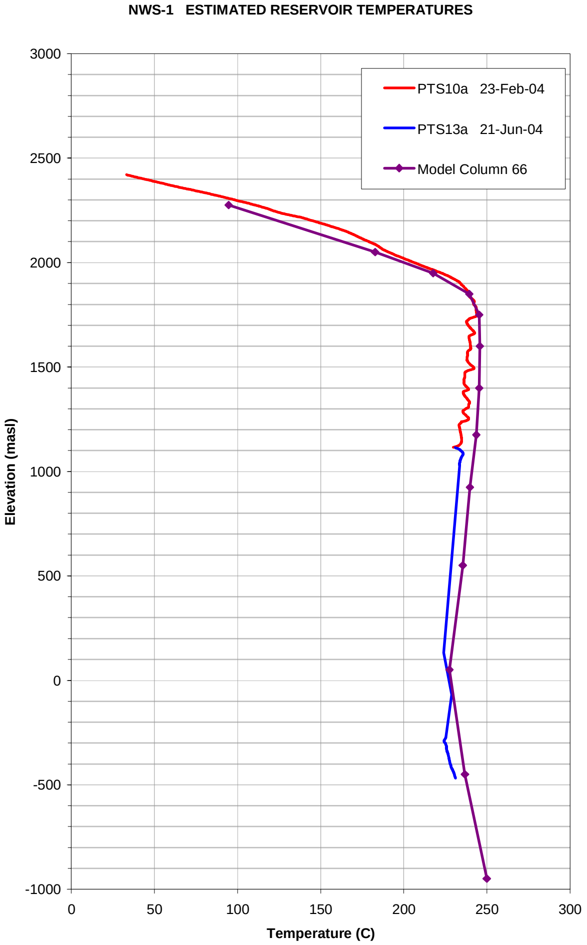

Figure 6. Match to measured downhole temperature for well NWS-1

Well NWS-3 is outside the productive reservoir, on the other side of the NE2 fault. As only one well was available for this area of the field it is not possible to determine the temperature gradients away from NWS-3.

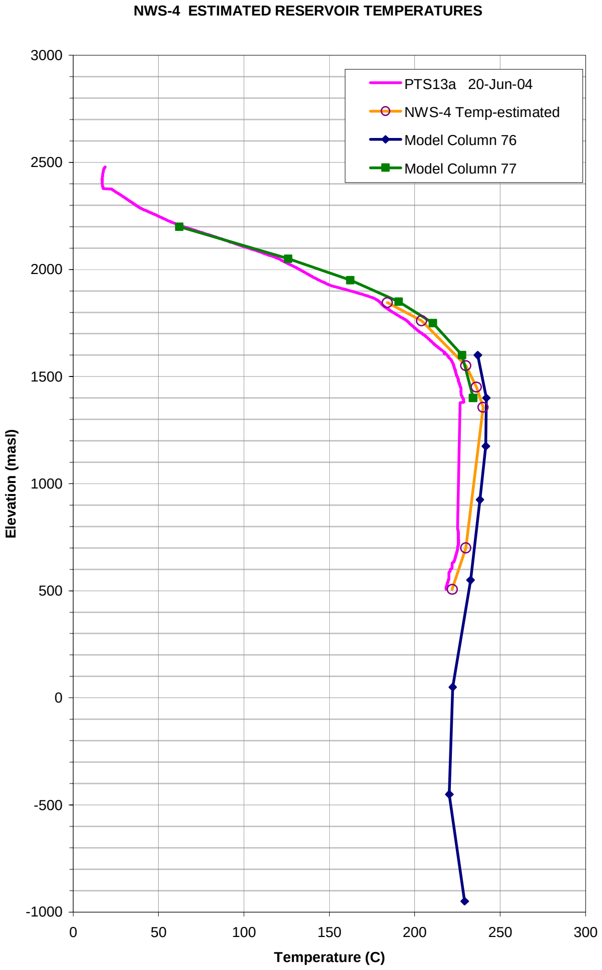

Figure 7. Match to measured downhole temperatures for well NWS-4

There is a broad, shallow temperature inversion centered near 1000 masl which could not be matched easily. As there is little information on temperatures and flows in this area, and as NWS-3 will not be used for production, it was decided not to attempt to match this feature. Increasing the conductive heat flux at the base of the model and introducing a small lateral flow into the model would be possible ways to match the inversion in future models.

In terms of system pressures, data were available from the production size wells and the match between the calculated and measured data is included in Figure 9. A good match has been obtained, particularly in the "reservoir" area (wells NWS-1, NWS-4 and NWS-5R). The match is also good for NWS-3 at depth and there is no shallow pressure data for comparison in this area.

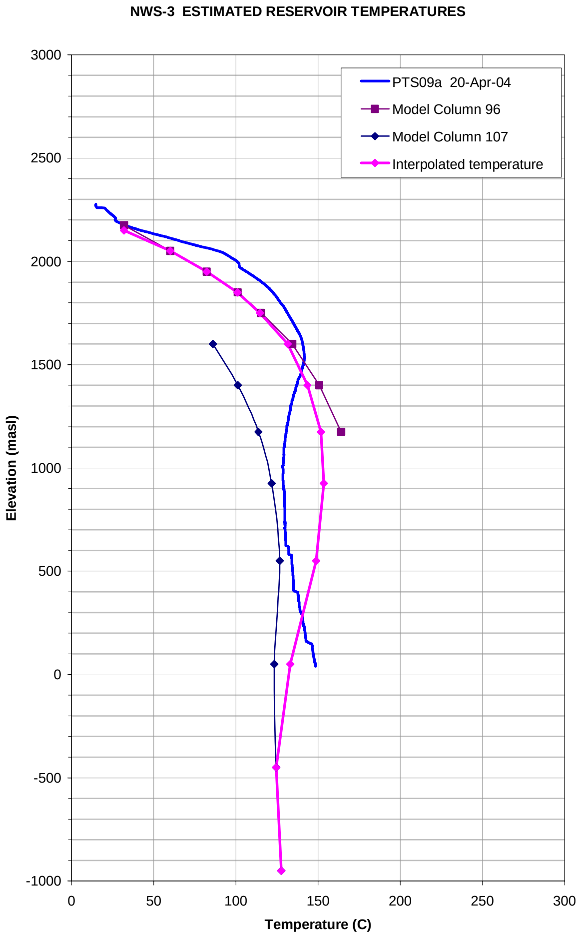

Figure 8. Match to measured downhole temperatures in well NWS-3

The calculated temperatures contours (Figure 10) show the fluid upflow from the inflow point in the base of the model, and an outflow at depth along the direction of the NE2 fault, but this has not been substantiated by well measurements.

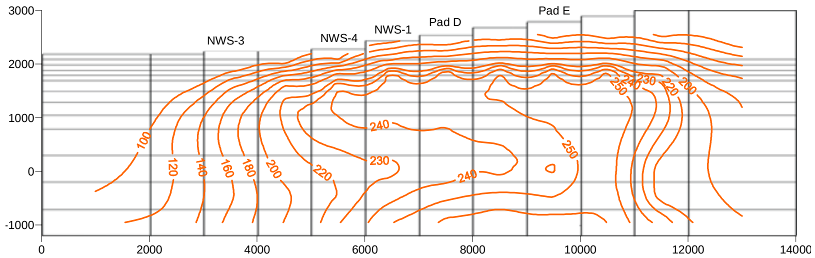

Figure 10. Temperature contours at cross-section A-A'

There is a shallow outflow directed more towards the springs in the vicinity of Gheynarge. The details of the shallow lateral outflow have not been incorporated into the model. There appears to be mixing of cooler water in the deep aquifer to produce the temperature inversions measured in wells NWS-1 and NWS-4.

The model does not predict two-phase conditions in the outflow or above the hot inflow point for the Sabalan geothermal system in the natural state.

The derived mass and energy flow model for Sabalan is relatively simple. A mass inflow occurs at 263°C into two blocks in the base layer (layer AM), with outflows from four specified blocks in a layer at +1400 masl representing the source of the springs and one boundary block at +50 masl (Figure 3) plus conductive heat inflow to layer AM and loss from upper layer AA.

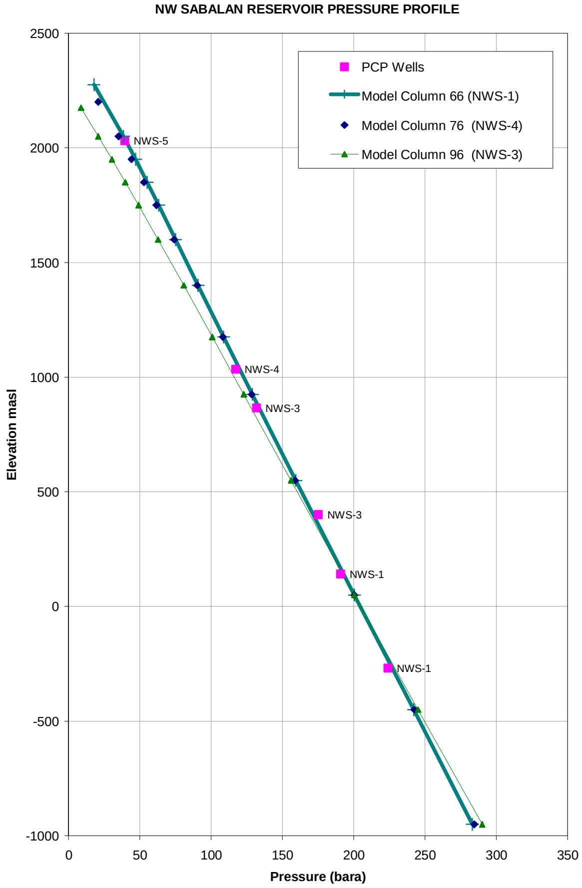

Figure 9. Match to measured downhole pressures for Sabalan wells

The flows calculated by the model are summarized in Table 3 which shows there is a good mass and energy balance over the model, indicating that the model has reached steady state conditions. The calculated mass flow through the system of 100.5 kg/s and the associated heat outflow of 134.7 MWth are relatively low for the size of the system, but it is difficult to quantify the natural heat flow to use for calibration of the model. The inflow was close to the minimum possible to attain the measured temperatures in the wells.

	Inflow		Outflow	
	Mass (kg/s)	Energy (MWth)	Mass (kg/s)	Energy (MWth)
Inflow to Layer AM (water)	100	115.0		
Inflow to Layer AM (CO2)	0.5	0.5		
Conductive heat to Layer AM	--	19.2		
Outflow from Layer AG	--	--	28.03	25.74
Outflow from Layer AK	--	--	72.47	57.51
Conductive Heat from Layer AA	--	--		51.45
Total :	100.5	134.7	100.5	134.7

Table 3. Mass and Energy Balance on the Sabalan Model

CONCLUSIONS

The numerical modeling study of the NW Sabalan resource has involved the development of a natural state model of the resource, based on assumptions regarding resource area and location of the upflow zone. The model has been successfully validated by matching available downhole temperature and pressure data from existing wells which appear to be located in an outflow which is peripheral to a hot upflow. Hence, the numerical model can be considered to provide a reasonable representation of the Sabalan system and the model results are consistent with the conclusions of the exploration drilling program that the NW Sabalan geothermal resource may extend to the southeast of the presently drilled area and could have a potential resource area in the order of 19 km^2 and maximum temperatures of 260 to 270°C.

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