PROCEEDINGS, 43rd Workshop on Geothermal Reservoir Engineering
Stanford University, Stanford, California, February 12-14, 2018
SGP-TR-213

An updated numerical model of the Greater Olkaria geothermal system, Kenya

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Keywords: Reservoir simulation, conceptual model, numerical model

ABSTRACT

Olkaria geothermal field is an important source of reliable, cheap and environmentally friendly source of electricity in Kenya. It is a high temperature geothermal field located within the Kenya Rift system where the heat source is upwelling magma, coming near the surface through volcanic activity.

Kenya electricity Generation Company (KenGen) is the main developer and operator of the field and it has been under exploitation for over 37 years. The company has also employed an early generation strategy by use of a wellhead technology in order to fast track geothermal development in Olkaria. Drilling operations are in progress to avail steam for installation of additional power plants. Furthermore, a feasibility study for an industrial park for supplying hot water and steam for industrial use is in the final stages of completion. It is therefore necessary that the geothermal resource in the field be developed and managed in an optimal, sustainable and environmentally friendly manner. This paper presents an updated numerical model of the Greater Olkaria geothermal system based on newly acquired data through the on-going drilling operations and production in the field.

Numerical reservoir modeling is an important management tool, which has been used successfully in the past to guide decisions on exploitation and management of geothermal resources in Olkaria and other geothermal fields in the world. The research involved first updating the conceptual model based on all available reservoir and geo-scientific data and reports. The numerical model is then constructed based on the conceptual model by use of PetraSim, which is an interactive pre-processor, and post-processor for the TOUGH2. First, the natural state model calibration was carried out using the temperature and pressure data obtained in the field to establish the initial conditions of the reservoir before exploitation. Secondly, the initial state reservoir conditions and parameters were used as input for production model calibration.

The results of the simulation study shows that a numerical model, which is a representative of the Olkaria geothermal reservoir, was set up and calibrated. The good match between the measured temperature and pressure data with the model-calculated values confirms this. The model was further refined based on the long-term production history and the pressure monitoring data. The model may be used to predict field performance under different exploitation scenarios as well as field development plans that may include reinjection and production strategy in the field.

1. INTRODUCTION

Electricity demand in Kenya is growing at an annual rate of 8-10% p.a. as the country work towards the realization of the Vision 2030 goals, which requires Kenya to have at least 30-35% electricity connections by 2018. The Least Cost Power Development Plan (LCPDP) 2011-2031 forecasts a demand of 4,755MWe by the year 2020.

KenGen through its Geothermal led strategy for sustainable electricity provision is expected to increase its installed geothermal capacity to 1,110MWe by 2020. The main objectives of this geothermal led strategy are to diversify energy sources to minimize over reliance on hydro, which is adversely affected by changing weather conditions and to avoid use of expensive thermal sources of energy. The aim of the strategy is also to mitigate against climate change by utilizing the available power from geothermal sources with less green gas emissions than other sources like thermal and to reduce the country's import bill in the long term by saving on money used to import the expensive fossil fuels.

Furthermore, Kenya aims to become the provider of choice for basic manufactured goods in Eastern and Central Africa according to the Economic Vision & Strategy of Kenya Vision 2030. Under the strategy, the government intends to establish at least five Small and Medium Enterprise (SME) Industrial Parks as flagship projects for manufacturing. The target is to construct these industries near the source of energy generation in order to cut on cost of transmission and power losses and Olkaria geothermal field has been proposed as one of the potential sites for these industries (Rotich; 2016).

In its endeavor to achieve this, KenGen is installing both conventional and non-convectional power plants in Olkaria geothermal field. The company is also promoting direct uses of geothermal energy through setting up of industrial parks, geothermal heated swimming pools and agriculture. This has necessitated drilling for new geothermal wells to avail more steam to support these upcoming power plants and direct uses. As a result new reservoir data is being obtained both production data, temperature and pressure data and therefore the numerical model has to be continuously updated to guide new development plans and sustainable reservoir management. In addition, human resource capacity in advanced reservoir engineering requires development to support these expanding reservoir studies.

This report therefore presents an updated numerical model of the Greater Olkaria geothermal system based on newly acquired data through the on-going drilling operations and production in the field.

Reliable models are set up by including most of the characteristics of the system as possible but this is limited by computational power and the inability to measure all the parameters of the system and therefore simplifying assumptions are made. The industry best practice for geothermal reservoir simulation is to first set up a conceptual model that gives a better understanding of the most important physical and chemical aspects of the system. The next step is to construct a numerical model based on the conceptual model. Calibration is performed in two steps, first natural state calibration and then production or exploitation model calibration.

The study involved updating the temperature and pressure model of the Olkaria field based on the newly obtained measured reservoir data after well complication. This updated temperature and pressure model is then interpreted together with geological, geophysical and geochemical data to come with an updated conceptual model. The simulation software PetraSim was used to set up both the natural state and the production model. PetraSim is an interactive pre-processor and post-processor for the TOUGH family of codes. TOUGH2 is a general-purpose simulator, which is used for modeling non-isothermal flows of multicomponent, multiphase fluids in porous and fractured media.

The main objectives of this research were as follows:-

- Update the temperature and pressure model of the Olkaria geothermal field based on the newly acquired data.
  Point out the changes observed in the conceptual model by comparing with the geophysical, geochemical, geological data and reports.
- Set up a reliable updated numerical model using PetraSim.
- Perform natural state calibration using the updated temperature and pressure model.
- Perform production model calibration based on field production and long-term pressure monitoring (drawdown) data.

2. THE OLKARIA GEOTHERMAL FIELD

The Olkaria geothermal field is located within the eastern branch of the Kenyan rift valley (Gregory rift), which is part of the East African Rift System (EARS). The rift system was formed as result of tectonics involving lithospheric spreading, fracturing and eventually faulting (Bonini et al., 2005; Biggs et al., 2009; Corti et al., 2007; Corti, 2012).

The Olkaria Geothermal field is one of the high temperature geothermal prospects within the Kenya rift system. The estimated geothermal resource potential in the Kenyan rift is 7,000 MWe – 10,000 MWe. The Olkaria geothermal field is located in Naivasha at approximately 120 km North West of Nairobi city as shown in Figure 1. The geothermal energy in Olkaria is mainly utilized for electricity generation.

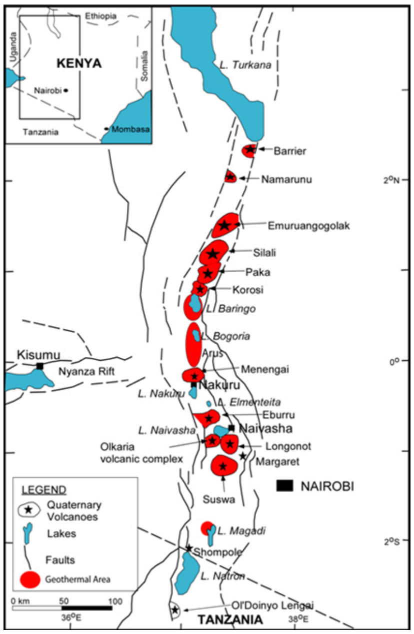


Figure 1: Map showing the Greater Olkaria Geothermal prospect within the Kenyan Rift Valley (Ofuona, 2002).

Geothermal exploration began in Olkaria in 1950,s whereas the first two exploration wells were drilled in 1956. The first geothermal power plant was installed between 1981-1985 with total generating capacity to 45 MWe and is still in operation today. Five convectional power plants are currently operating, generating 550 MWe.

Owing to the long lead times of 10 to 15 years between production drilling and building convectional power plants, KenGen adopted an early generation strategy in Olkaria. Potential revenue is lost by having production wells sitting idle for years and presents the potential of wellhead generators as means to achieve early power and revenue generation for geothermal resources. Under wellhead generation, geothermal development can be fast tracked. The lead time between investment into development of geothermal resource and the time to revenue generation will be substantially shortened from several years to only a couple of months (Saitet et.al, 2015). The wellhead units in operation are 15 with a total capacity of 81.5 MWe.

Several power plants are planned for construction in the Olkaria field and drilling is in progress to avail steam for some of the new power plants, which are in different stages of development. KenGen has been trying to promote direct uses of geothermal energy in Olkaria by constructing a geothermal heated swimming pool and spa. An industrial park is currently in final stages of feasibility study to utilize hot water and steam for industrial uses. The company is also supplying Oserian Development Company with steam for green house heating.

3. CONCEPTUAL MODEL

A conceptual model is an accurate graphic and written description of the reservoir that combines the structures and the processes that determines its existence and response to exploitation. Setting up a conceptual model involves a multidisciplinary approach from different scientific fields where data are interpreted together for a common conclusion. A good conceptual model should be as simple as possible but describe the most important characteristics of the system (Grant et al., 2011). The conceptual model should take into consideration all the available information on geological setting, geometrical properties, hydraulic parameters, solid phase properties, fluid properties, boundary conditions, sources/sinks of fluids and heat, and their spatial time dependent distributions within the study area.

The conceptual model should agree with observed data through a logical interpretation of all the data. The ‘‘art’’ of computer modeling involves the synthesis of conflicting opinions, interpretation and extrapolation of data to set up a coherent and sensible conceptual model that can be developed into a computer model (O’sullivan et al, 2001).

3.1 Past conceptual models

The conceptual model of the Olkaria field has been revised several times during its resource assessment studies with most comprehensive one being presented by the consortium of Mannvit/Isor/Vatnaskil/Verkis in 2011 during a recent resource optimization study as well as a revision between 201-2016. They described the heat source to be deep-seated magma chamber or chambers with three intrusions to 6-8 km depth from the surface lying beneath the Olkaria hill, the Gorge farm volcanic center and in the Olkaria Domes area. They identified four major upflow zones, which are associated with the three major heat sources identified. NW-SE, NE-SW tending faults as well as the ring structure, structurally controls permeability. Cold water flows into the system through the N-S trending Ololbutot fault, acting as a flow barrier between the Western and Eastern part of the field. Saitet et al., (2016) updated the model recently by describing two more up flow zones with the Olnjorowa gorge structure contributing recharge into the dorms and the east field.

3.2 Geology of Olkaria

The Olkaria volcanic center has many volcanic centers with comenditic lava (Lagat, 2004). A caldera rim has been proposed to exist in the field, which is not visible in the surface but characterized, by numerous domes and craters that are rhyolitic in composition. (Omenda, 1998). These domes have been interpreted to be remnants of the buried caldera and have been obscured by recent pyroclastic ash falls from neighboring Longonot volcano (Naylor, 1972).

Lithology of the field is composed of the Olkaria volcanics in the upper, which are normally observed on the surface. This layer consists of comenditic lavas, pyroclacts, basalts, trychytic intercalations, and volcanic ash. The second layer is the Olkaria besalts, which occur at a depth of approximately 500-1000 m below the ground and form the cap rock. This is composed of basaltic flows, trychytes and minor pyroclasts. Plateu trachytes form the third layer at a depth of 1000-1600 m b.g.l major rock types being trachytes with minor occurrence of basalts, tuffs and rhylotes. The layer is deepest in the east field and believed to be related to fissure eruptions along the rift. Mau tuffs are encountered in the fourth layer, which mostly occur in the western field that has been compacted by overburden with ignimbritic texture (Omenda, 1998). The lowest layer that is composed mainly of trachytes may not have been encounter during drilling but normally encountered in the southern flanks of the Kenyan rift (Musonye, 2015). Figure 2 shows the main structures and surface geology of the field.

Normal faulting structurally controls flow of geothermal fluids within the Kenyan rift system. The Aberdare ranges and the mau escarpments form part of the high hydraulic recharge into the rift valley floor owing to the high elevations. The most dominant faults include; N-S, NW-SE, NE-SW, ENE-WSW and rhyolitic domes which are distinctly visible in satellite images (Muchemi, 2000; Omenda, 1998).

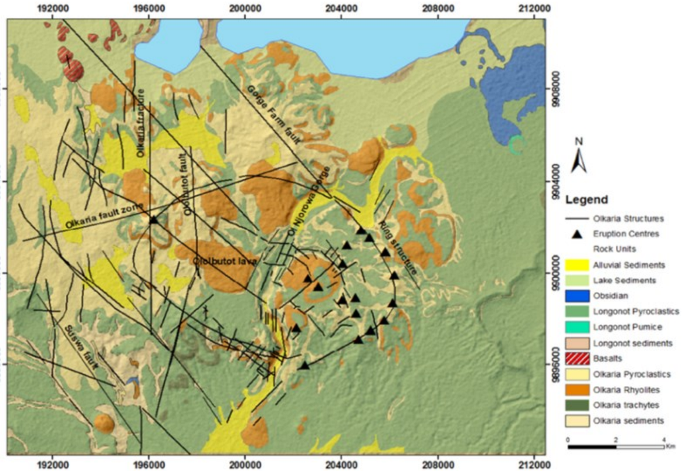


Figure 2: Surface geology and the structures in the Olkaria geothermal field (Clarke et al., 1990; Munyiri, 2015).

3.3 Geophysical and chemistry data

Gravity, resistivity, seismic and magnetics has been used in Olkaria for geothermal resources exploration. Micro-seismic data collected in Olkaria has been used to map out the location of the seismic events, which predicts the patterns of ground water movement along fractures. The information on S-wave attenuation interpreted from the data shows the location of volumes of molten material, which are found below the Olkaria Domes, Northeast and West production fields, with other smaller attenuating bodies possibly indicating further undiscovered geothermal resources. Figure 3 below is an iso-map showing depth to top of S-wave attenuating bodies in Olkaria Geothermal field as interpreted by Mannvit/Isor/Vatnaskil/Verkis in 2011 as heat source locations.

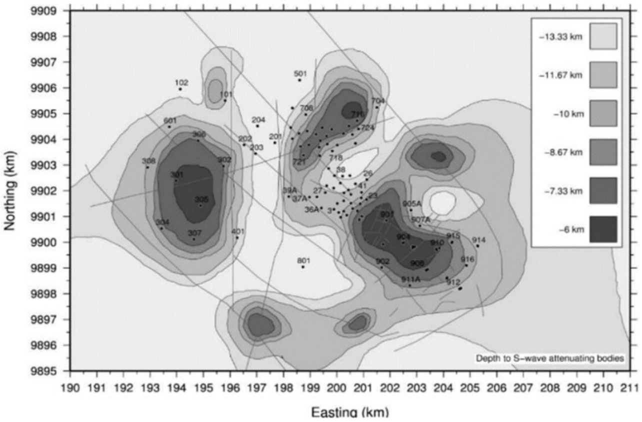


Figure 3: Depth to top of S-wave attenuating bodies in Olkaria Geothermal field (Mannvit/Isor/Vatnaskil/Verkis; 2011).

Ground water movements in a geothermal field may be traced to their origin by analyzing the presence of hydrogen and oxygen isotopes. This may help in knowing the types of up-flow zones the field is tapping from, if they are of a common origin or from different sources. The different concentrations between the eastern half and the western part shows that the two have different sources of fluids which may support the theory that the NS trending Ololbutot fault provides a flow barrier. The fluid in the upflow zone in the domes geothermal field also has a similar isotope signature as that in the upflow zone of the NEF and EPF (Saitet et.al; 2016). West-JEC in their chemical model of the Olkaria geothermal system showed that the fluids of all three sectors have a common origin at depth, as ~325 – 340°C water with Cl concentration at ~450 mg/l. A common NW-SE trending structure may connect all three up-flow zones in their model at great depth (West-JEC, 2009).

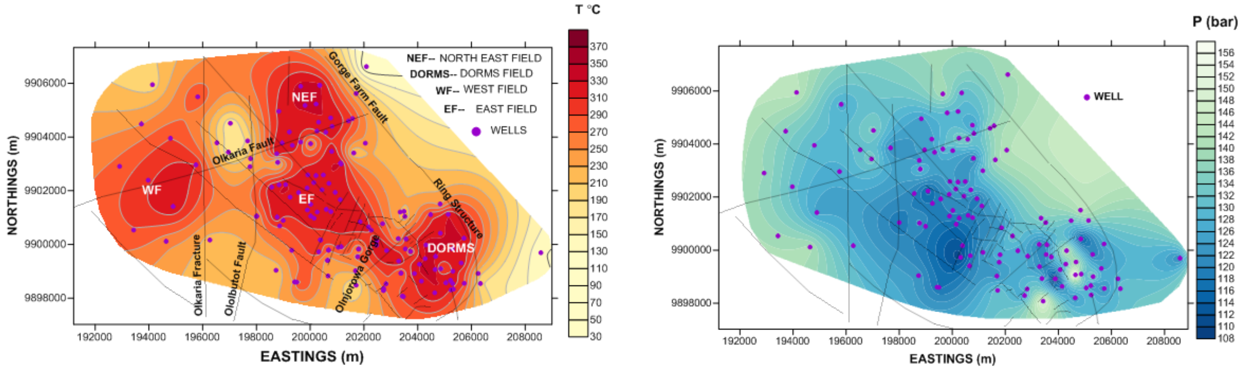
3.4 Temperature and pressure model

The temperature and pressure are important parameters in identifying the upflow zones in a geothermal system and would later be used in the next phase of model calibration. Therefore, it is important that the information used as input into the model is a true representation of the actual field. This is achieved through careful interpretation of the measured data to come up with the best estimates of the reservoir pressure and temperature.

Geothermal wells in Olkaria field are given time to recover from the thermal disturbance during drilling and reach equilibrium with the formation after well completion. The temperature recovery behavior is monitored during the warm period to obtain the information on the location of feed zones and patterns of temperature rate of recovery. This recovery time is insufficient because of the need to discharge test wells to guide next development plans therefore the need to explore reliable ways of estimation.

Usually, in static wells without internal flows or boiling conditions, the aquifers warm up more slowly than the other parts of the well because of the effect of cooling by the circulating drilling fluid.

Well profiles show different scenarios depending on the part of the reservoir they penetrate. In wells located in the upflow area of the field, where the reservoir pressure gradient exceeds hydrostatic, an upflow pattern is experienced from deeper zones to shallow zones. Zones where fluid flow is near horizontal have pressures in equilibrium to hydrostatic and wellbore temperatures shows true formation temperature. Another scenario is where hot floods at upper zones moves over colder fluids on lower zones. Hot fluids are over pressurized in and a downflow condition is experienced. Reservoir temperature profiles are lost in these kinds of wells, which experience internal flows. Figures 4 a and b shows temperature and pressure contour map of the Olkaria field at sea level for newly. The data used include the formation temperature and pressure interpreted for new wells as well data from the work of Ofuona, (2002), Mannvit/Isor/Vatnaskil/Verkis; (2011), Rop, (2013), Saitet, et.al., (2016). The maps show clearly the location of upflow zones associated with each field.



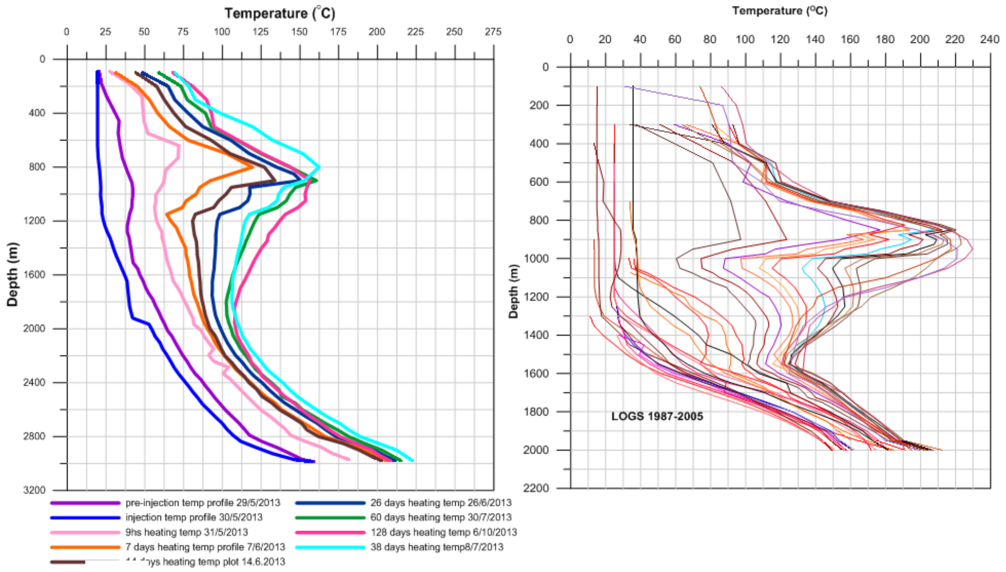
(a) (b)

Figure 4: Temperature and pressure ISO-maps at sea level.

3.5 Updated Conceptual Model

The conceptual model considered in this research work is as described by the consortium of Mannvit/Isor/Vatnaskil/Verkis in 2011 and Saitet et.al 2016 with the following additions:

- An additional recharge into the Olkaria field from the north along the gorge farm fault is considered. The evidence of this recharge is shown by temperature reversal in wells drilled across this fracture as shown by Figure 5a and b below for OW-734 and OW-704 respectively.



(a) (b)

Figure 5: Wells with Temperature reversals (NEF).

- Recharge into Olkaria dorms field from the east as evidenced by temperature reversal in well 918A at a depth of approximately 1700-2000 m below surface. The profiles indicate down flow conditions where the fluids flow out of the reservoir at the major feedzone located at an interval 1700-2100 m and back into the reservoir at a feed zone in the well bottom. This shows that the well traversed a cold permeable structure at 1700-2100 m interval.

The conceptual model of Olkaria field can be summarized as follows with 3-D view shown in Figure 6 below:

- Five geological layers namely, Olkaria volcanics, Olkaria basalts (caprock), plateu trachytes, mau tuffs and trachytic base layer in succession has been identified.
- Three hot magmatic intrusions, peaking to a depth of about 6-8 km from the surface located at the West, North and Dorms field.
- Four major upflows zones associated with these intrusions are identified as shown in figure 1, located at the centers of the West, East, Northeast and the Dorms field.
- Permeability is structurally controlled.
- Cold recharge to the system is through N-S Ololbutot, Gorge farm fault, the Oljorowa gorge, and the ring structure near OW-918A.

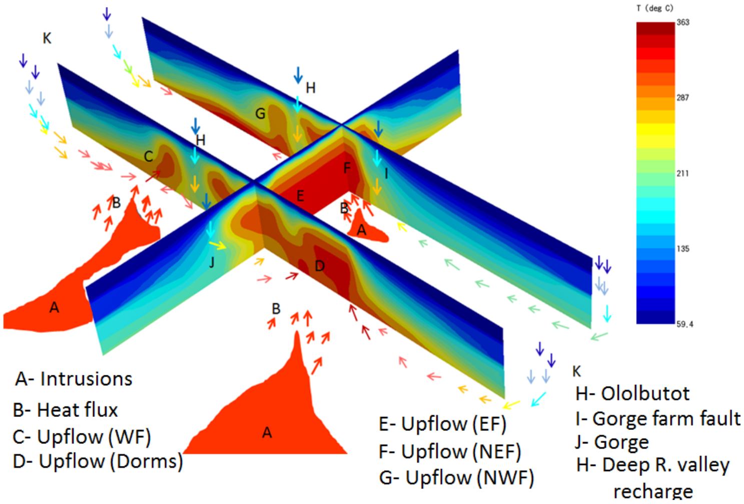


Figure 6: 3-D conceptual model description of the Olkaria field.

4. NUMERICAL MODEL

Numerical models are used to simulate responses of a system due to a disturbance to the system in order to evaluate the dominating influences on the more complex real world systems. Heat and mass transfer in a geothermal system is a very complex physical process because of the heterogeneous nature of geothermal environments. TOUGH2 is a popular simulator widely used for geothermal resource simulations. PetraSim, which is a post and prep-processor for TOUGH2, was used in this study. TOUGH2 simulator solves mass and energy-balance equations to determine the properties of non-isothermal flows of multiphase, multicomponent fluids in porous and fractured media (Pruess et al., 1999).

4.1 Past numerical models of the Olkaria field

The first numerical model of the Olkaria field was carried out in 1987 (Bordvasson et al. 1987b) where five field exploitation scenarios were proposed which included well spacing, reinjection, and power generation strategies and a thirty-year forecasts of field production done. According to the model, the Olkaria east field is composed of a steam cap underline by a liquid dominated region. A post audit was done between 1990 and 1993, which revealed that the model adequately predicted steam rates and their decline. An update of the model was carried out by Ofuona, 2002 where he concluded that the system could be modelled with hot water injection of 565 kg/s and that the system is open system with pressure draw down occurring only within the production zone.

The next project was carried out by West Japan Engineering Consultants Inc. (West-JEC) in the period 2005-2009 for the eastern half of the Olkaria field and the results indicated that the Olkaria domes field, Olkaria East field and the Olkaria North East field could support a generation capacity of 430 MWe for 25 years. A consortium of Mannvit/Isor/Vatnaskil/Verkis carried out numerical simulation of the entire Olkaria field between 2011 and 2012 as part of the field optimization study. The model involved 15 layers each containing 2163 elements. Figure 7 below shows numerical model and the main rock types distribution at layer H as presented by Mannvit/Isor/Vatnaskil/Verkis. Six production scenarios were forecasted after a successful model calibration. The results showed that the field could support an additional generation capacity of 580 MWe for 30 years though the drawdown at full capacity was larger for a wider area. Koech (2014) set up a numerical model of the Olkaria east and southern part of the field where he calibrated the model with temperature and pressure data, production history data and the tracer test data with aim of carrying out forecast on field response to long term reinjection. He concluded that thermal front breakthrough in the most affected well could takes about 4 years at higher injection flow rates of 50 kg/s for temperature to decline from the initial value.

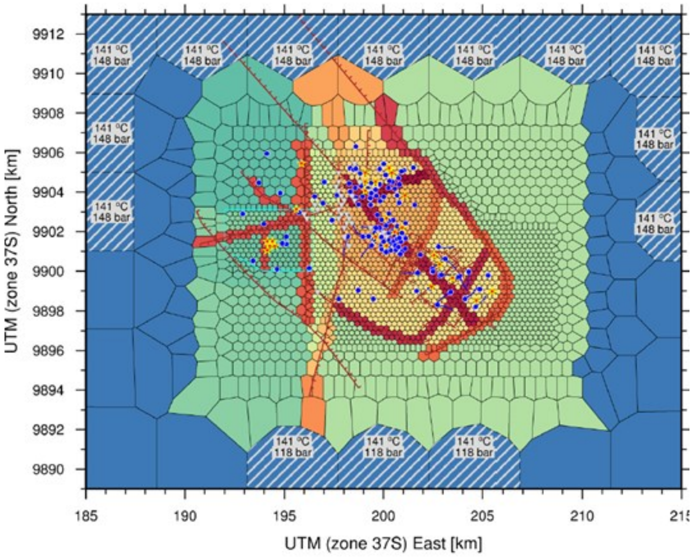
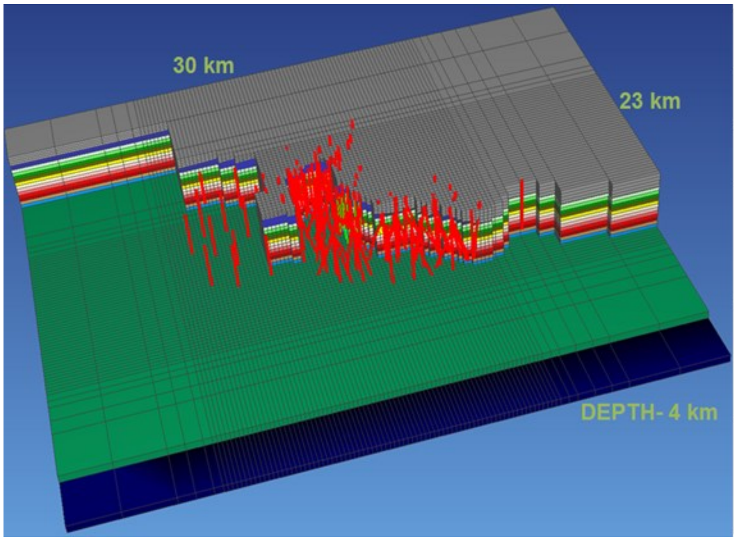


Figure 7: Numerical model of olkaria as presented by Mannvit/Isor/Vatnaskil/Verkis; (2012b).

4.2 Numerical Model Setup

4.2.1 Model dimensions

After the formulation of a conceptual model, the next phase in the simulation process is the construction of a mathematical model where all the concepts from the conceptual model are expressed as mathematical equations. A dual porosity approach was used to set up the model with a grid covering an area of 30 x 23 km in x and y direction respectively, and 16 vertical layers with a total of 112,288 grid blocks and 328,548 connections. The lower surface of the deepest layer in the model is at an elevation of -2300 m.a.s.l. Figure 8 below shows the model extend with the different layers. The red lines represent the wells drilled in the field. The lower two layers are 400 m thick while the upper layer follows the cap rock thickness with more subdivision into four layers. The rest of the layers are 200 m thick, a decision made based on the depth of the deepest well OW-49 drilled to a depth of 3600 m from the surface. A regular mesh design was adopted with a layer thickness of 200 m at the reservoir where wells exist and 400 m further away. The largest elements are located at the edges with grid blocks of 2.4 X 2.4 km while grid block refinement at the center of the model is 200 m x 200 m.



Model area	30 X 23 km
Model depth	4 km
Number of blocks	112288
Number of connections	328548
Minimum block area	200 m X 200 m
Minimum layer thickness	200 m

Figure 8: Numerical model set up.

4.2.2 Rock types

The rock types were chosen based on geological successions described by the conceptual model with the idea that the rocks in Olkaria east and the western halves are different with Ololbutot field being the permeability barrier. The cap rock was represented at the top of the model, which was further divided into 4 layers to capture the water table better with the bottom part being set to follow the thickness of this clay cap in contact with the reservoir. Permeability distribution is controlled by known structures in the field with lowest boundary, cap rock and the side cells being assigned low permeability values. The rock types used in each layer was further subdivided into 10 regions to represent permeability variation within the Olkaria sectors while the other three sectors represent regions in the east outside the caldera just immediately after the Dorms, Olkaria East and the Olkaria North East fields. The porosity was set at 10 % and specific heat capacity used is 2 J/kg.K while the density was assumed 860 kg/m^3. Figure 9 below is a 3-D view of permeability distribution in the model.

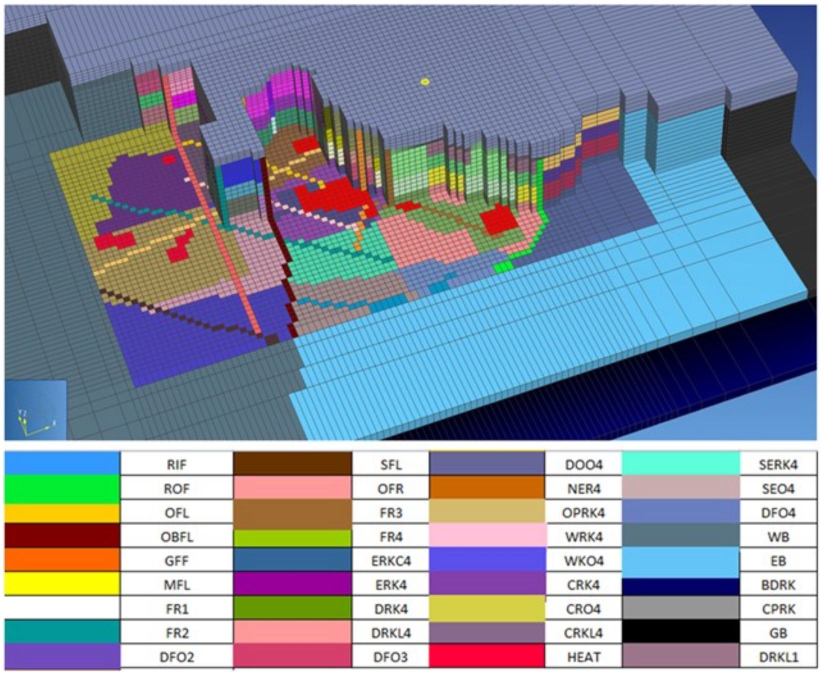


Figure 9: Major rock types and heat source locations.

4.2.3 Boundary conditions

Two approaches have been applied to represent the heat input in the bottom layer in geothermal simulations. The "hot-plate" boundary condition using inactive blocks at the base of the model and the background heat flux approach where heat is applied uniformly at the bottom cells (O'sullivan et al., 2016). The later approach was adopted in the simulation with constant heat flux at a rate of 0.08 J/s.m2 with higher flux at the center of upflow zones of 1.0 J/s.m2. The deep mass flux into the system was represented in the model by assigning heat sources of constant mass at some cells at the lowest layer as shown by the conceptual model as the center of the of upflow zones. Constant temperature and pressure boundary conditions were assumed at the upper layer where the values at the center of the layer was truncated using heat gradient of 90 °C/km and the pressure decided by setting it to coincide with the estimated water rest level in the field. Hot springs and steaming grounds were represented by production from cells at the upper most active layer at the location of this surface features. The side boundaries of the model were decided by setting them as far as possible from the reservoir so that the boundary conditions do not affect the performance of the model. Closed boundary conditions were assumed at the lateral boundaries with the system being open at cells at the northern part of layer F to allow north-south flow.

4.3 Natural state calibration and results

Common procedure for geothermal model calibration is to conduct the natural state calibration, where the model is run for a long time in its development over geological time followed by history matching. Natural state calibration procedure involves comparing the model-calculated values with the measured temperature and pressure distribution as well as the outflow of heat and fluid. The parameters to be adjusted are permeability and for the heat sources, their strength, location and enthalpy.

The calibration was carried out by first assigning a constant permeability values to create a homogeneous reservoir conditions and then setting global initial conditions at a pressure of 1.0 bar and a temperature of 60 °C to create the first realistic conditions and initialize the TOUGH2 model. The top layer was fixed at the global conditions while running the model to steady state and there after the output being used as initial conditions into the model. The heat flux at the bottom of the model was adjusted slowly while changing the permeability and comparing the model calculated values with the interpreted temperature and pressure values after every run. The data used was from 162 wells distributed in the field. Several iterations were carried out before achieving an acceptable match. A plan view of the temperature results at sea level are shown in Figure 10.

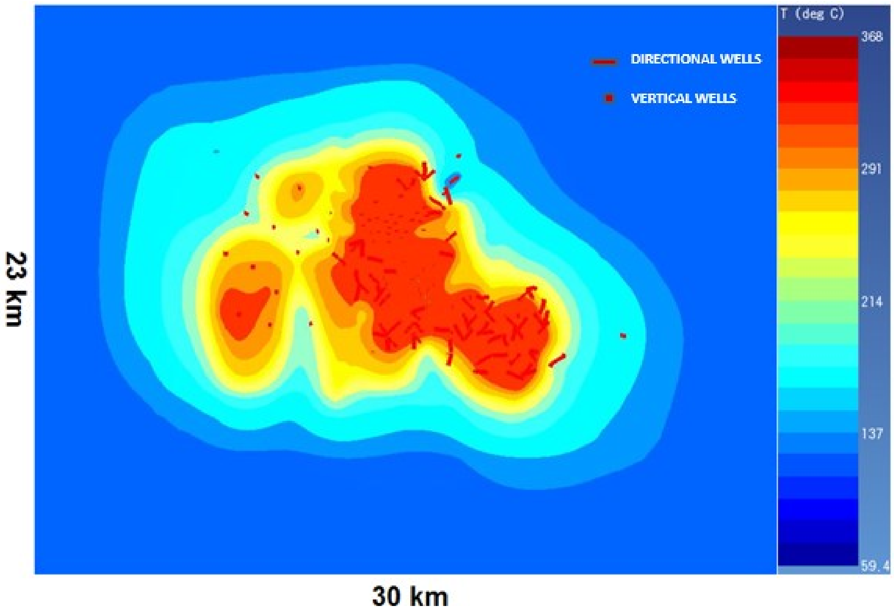


Figure 10: Simulated temperature result at sea level.

Comparison of the model calculated values with the interpreted (measured) values shows good match. The results in this layer compared to the temperature distribution at the same layer in Figure 4a show same temperature distribution pattern. A 3-D view of the simulation results are shown in Figure 11 mapped on a plan view at -500 m a.s.l. The view shows clearly how the simulation has reproduced the major upflow zones associated with each field. The cooler zone between the Olkaria west field and the east field is due to the down flow from Ololbutot fault as described by the conceptual model, which is a conduit for cold shallow recharge into the system while the one separating the southeast field and the dorms field is due to the effects of the Oljorowa gorge. The results also shows hydrological barrier between the west field and the eastern half of the Okaria field while the dorms, east and the north east fields seems to be interconnected at depth. The total mass flow input from the sources located at the major upflow zones for the best model simulation results obtained was 95.4 kg/s with an average enthalpy of 1630 kJ/kg.

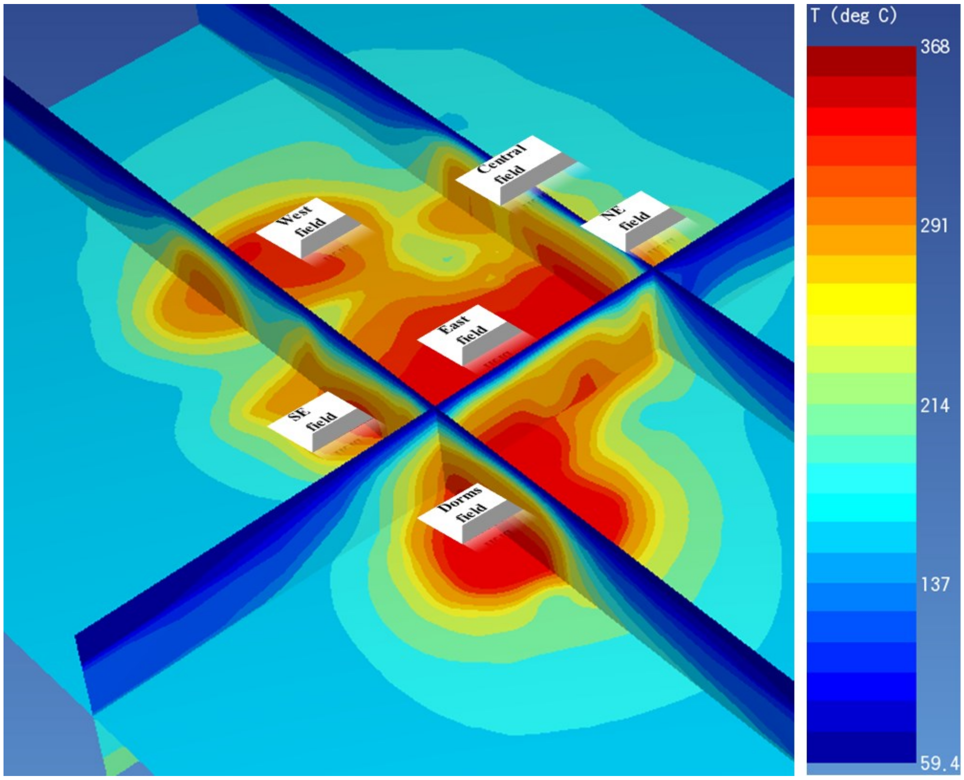
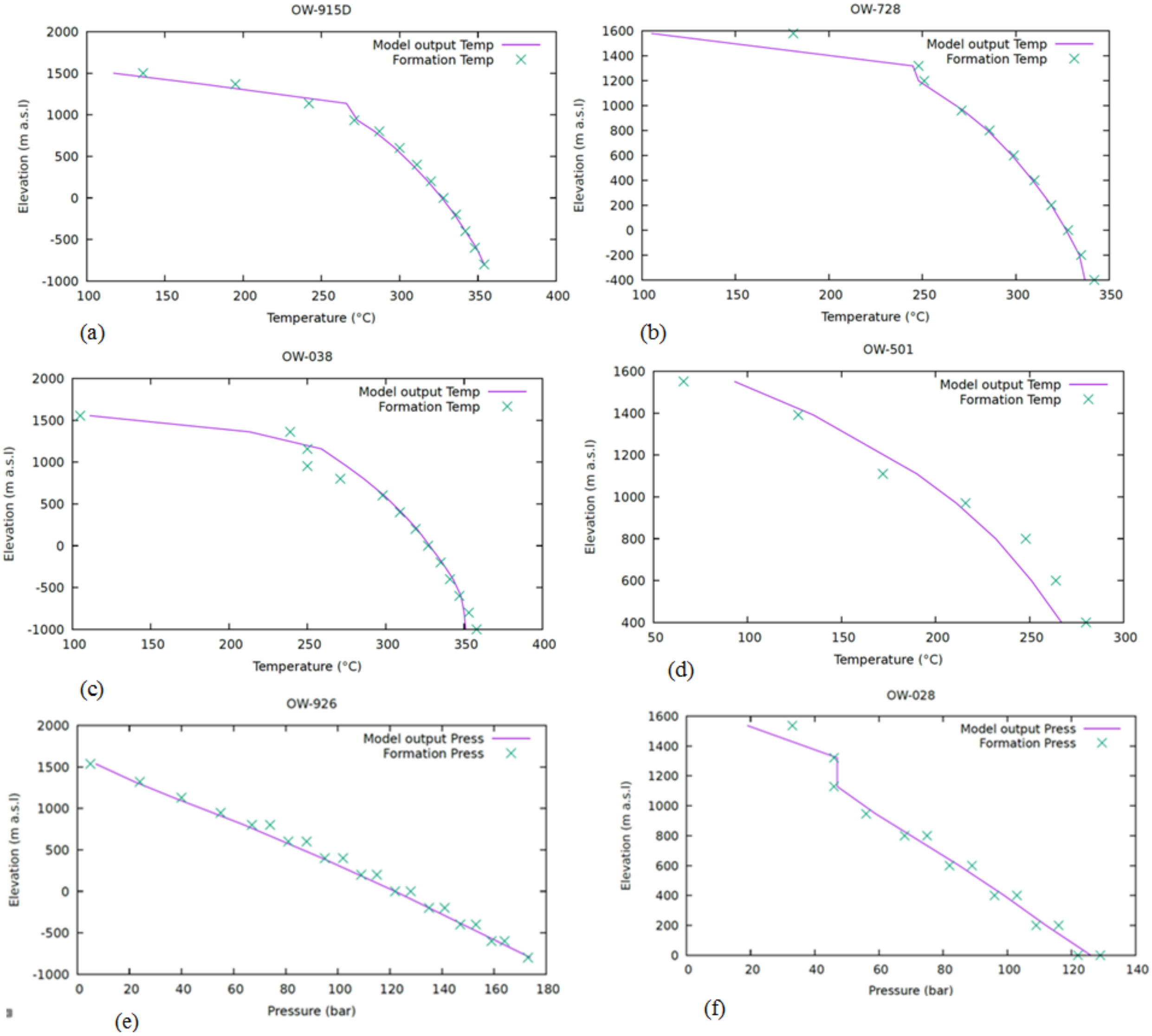


Figure 11: 3-D view of the simulation results.

The results of the individual wells in comparison to the measured data are as described in Figures 12 (a-f) for both temperature and pressure, which are few representations wells used in the simulation across all the fields in Olkaria. A good match is observed in most of the wells for both temperature and pressure. Wells from the east field had a very good fit as compared with the other fields. However, some wells show poor fit especially the ones located in the colder zones for both temperature and pressure. Most of these wells are located at the periphery of the field where a temperature reversal is observed.



(a) (b) (c) (d) (e) (f)

Figure 12: Comparison of measured temperature data with model calculated values in some selected wells.

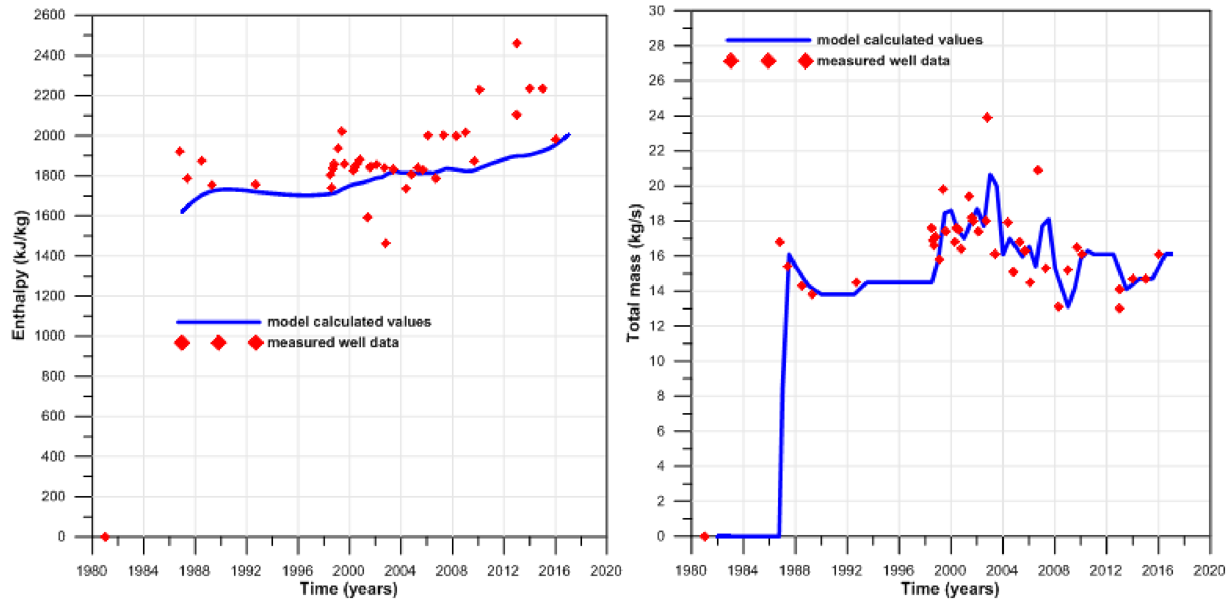
4.4 History matching calibration and results

History matching step is the matching of the measured behavior in response to production with the simulated behavior. The results of the natural state simulation were used as the input for history matching calibration and production assigned to the relevant blocks with medium and large feed zones while ignoring the small feed-zones in the wells. The pressure decline in the model is noted as well as the enthalpy values compared to the known values and adjustments were made with the permeability so as to fine tune the model. The enthalpy value comparison was most useful for Olkaria I and II fields which had long years of production.

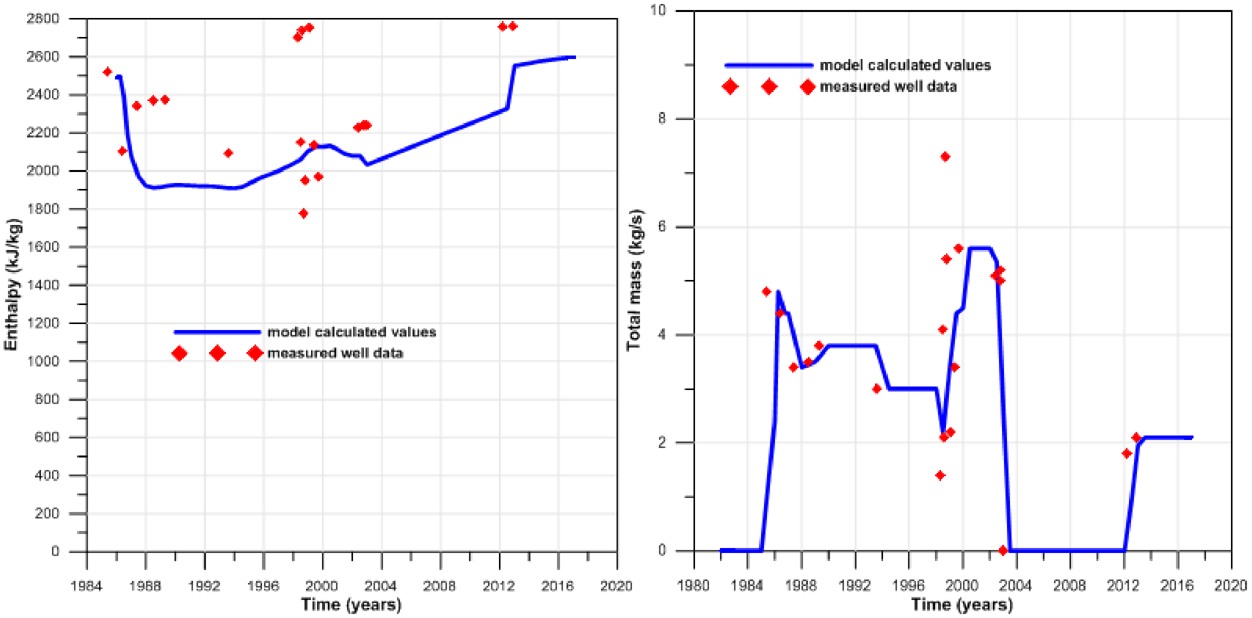
Figures 13 (a-d) show the comparison of the enthalpy and mass flow rates from long-term production since 1981 for the longest producing wells versus model output values. The well production rates assigned were only on the reservoir blocks according to the permeability index on major and medium feedzones ignoring the minor feedzones in the model meaning more permeable grid blocks intersected by wells were assigned higher flow rates than less permeable blocks.

Comparison of well flow rates from model output with the flow rates from long-term production shows comparable results showing that individual flow rates for each well was well captured in the model. A good match is observed in some wells between the model-simulated enthalpy output and the field measured enthalpy values. However, some wells for example OW-21 shows lower enthalpy values in later years while having a good fit initially but shows same trend with time with the measured values.

Figures 14 (a-d) are the pressure decline curves from observation wells (monitoring wells) at some given depth for long term monitoring in comparison with the observed values from the model. The results show a good much in some wells while some shows some variation. The variation in the measured pressures from the model calculated values might be attributed to the fact the course grid blocks of 200 m per layer used in the model causes a poor approximation on pressure as it is taken at the center of the big block.

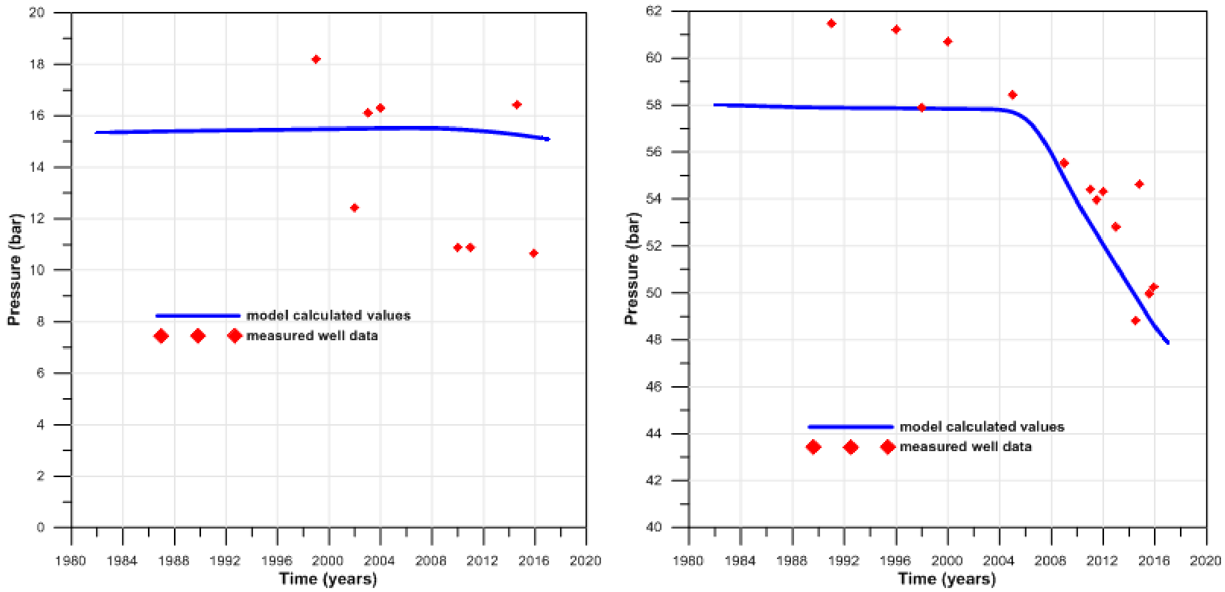


(a) Enthalpy: OW-26 **(b) Mass: OW-26**

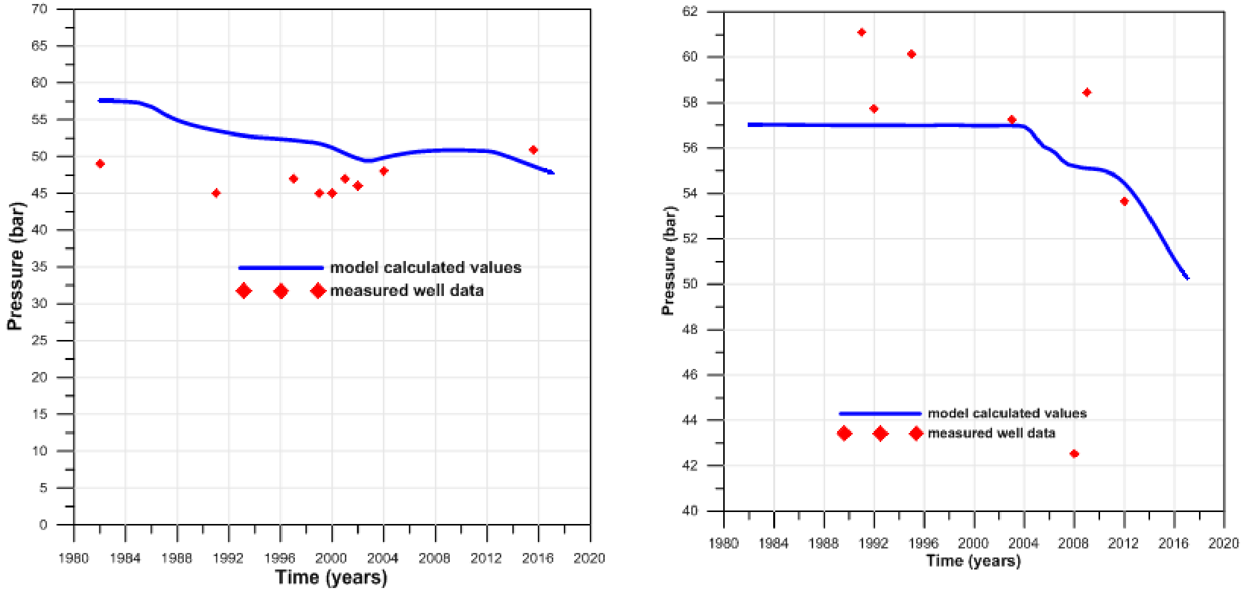


(c) Enthalpy: OW-21 **(d) Mass: OW-21**

Figure 13: Model output mass and enthalpy comparison with measured values.



(a) Pressure monitoring: OW-M1 **(b) Pressure monitoring: OW-724**



(c) Pressure monitoring: OW-21 **(d) Pressure monitoring: OW-723**

Figure 14: Pressure behavior in some wells over the monitoring period.

5. CONCLUSIONS

The Olkaria geothermal numerical model has been successfully updated based on all the available data in the field. First, all the available geological, geochemical, geophysical and reservoir reports were analyzed. This also involved a review of the past numerical and geophysical studies on the field. Secondly, new data were analyzed which were later used to update the temperature and pressure model in the field where some changes on the conceptual model was done. A numerical model measuring 30 x 23 km with 112, 288 grid blocks was set up covering the entire field with a depth of 4 km. An attempt was also made to simulate the deeper reservoir beyond 3 km from the surface that is considered as the deep reservoir and this explains the big number of grid blocks.

The model was finally calibrated in two steps, beginning with the natural state model calibration where temperature and pressure data formed the basis of calibration. The next stage of the calibration process was trying to fit the model parameters to the long-term field production data, taking the results of the natural state model as the initial conditions for the production model calibration. The enthalpy and pressure behavior was monitored with time and then compared with the measured values. The model was calibrated manually by forward calibration.

The results of the simulation indicate a generally good fit to the natural state of the field and the response to the long-term production. The major upflow zones were well captured in the model as well as the recharge zones. The results of the natural state simulation also shows that the Olkaria geothermal field can be simulated with a total mass flow input from the sources located at the major upflow zones of 95.4 kg/s with an average enthalpy of 1630 kJ/kg. However, some parts of the field, especially the Olkaria central field near OW-101, showed some variation from the observed data and therefore more work is recommended to try to improve on the model.

The model may be used to study and understand the various subsurface features controlling fluid movement in the Olkaria field, forecast different development scenarios as well as in making decisions related to sustainable management and exploitation of the geothermal resource.

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