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Success of Geothermal Wells Drilled in Olkaria Domes Sector (Greater Olkaria Geothermal Area, Kenya)

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ABSTRACT

Geothermal energy is a low carbon, reliable, and renewable energy that has been in use for over 100 years. At Olkaria electric energy from geothermal resources has been harnessed for slightly over three decades. Despite its relatively low cost compared to other energy sources it is associated with high exploration risks and upfront costs. This prevents its wider adoption. In a typical geothermal development drilling costs comprise of between 35-40 % of the total capital costs. Developing and financing of geothermal projects need a clear understanding of the risks inherent in the project. In the Olkaria Domes Sector of the Greater Olkaria Geothermal Area we have more than 60 wells drilled to date. These wells provide a large data base from which the probability of drilling a successful well are assessed. The wells range in output from 1.5 MWe in well OW-901 (drilled as an exploration well) to ~ 24.7 MWe in well OW-921 A (a production well). Factors that may influence drilling success such as completion date, power capacity (MWe), depth to which the wells are drilled, feed zones, casing depth, deviated or vertical well, geological controls, permeability, etc are assessed. Findings from this paper are aimed at determining the success in drilling at each stage from exploration, appraisal, to production drilling. Conclusions from this study would aid in increasing an understanding of selecting sites for drilling, reduce the risk of drilling a dry well, review the depth to which wells are drilled with regard to reservoir conditions, reduce the costs of drilling.

1. INTRODUCTION

The Greater Olkaria Geothermal Area (GOGA) is one of the most exploited and one of the largest geothermal systems in the world. It is located approximately 120 km north west of Nairobi, the capital city of Kenya. The Greater Olkaria Geothermal Area is located within the Kenyan rift of the East African Rift System (EARS). The EARS extends from the Afar Triple junction in the Gulf of Eden in the north to Beira, Mozambique in the South (Abbate et al, 1995). The EARS is part of a divergent continental plate where spreading results in the thinning of the crust, lava eruptions and associated volcanic activity (Lagat, 2004). There are two divisions of the EARS, namely: The Western and the Eastern rift valleys. The Kenyan rift falls along the Eastern rift valley of the EARS. Geothermal activity is more intense along the Kenyan rift which extends from Lake Natron to south in Tanzania to Lake Turkana in the north. The intensity of geothermal activity extends further north from Lake Turkana in the Kenyan rift into the Ethiopian rift of the EARS, all the way to the Afar region near the Gulf of Eden. There are about fourteen (14) geothermal prospects (Figure 1) that are associated with Quaternary volcanic centres occurring in the axial region of the Kenyan rift (Omenda, 1998) and about five (5) that are outside the Kenyan rift and are not associated with quaternary volcanics. These volcanic centres are characterised by shallow intrusions which have resulted in high thermal gradient.

Currently two (2) geothermal systems i.e (Olkaria and Eburru) are under exploitation for electricity generation. At Menengai drilling has been going on. Three (3) firms have been contracted to exploit steam at Menengai for power plant development.

1.1 Over view of Geothermal Development at Olkaria

Geothermal exploration began in the 1950's with geology and geophysical surveys in the Kenya Rift. This was done between 1952 to 1956. The study revealed that in the Central Kenya Rift and in particular Olkaria, there existed potential for geothermal energy resources. From the findings a proposal was made to drill an exploration well in Olkaria. Two wells were sited and wells X1 and X2 were drilled to depths of 950 and 1200 meters respectively and temperatures of close to 235 º C were encountered. The two wells failed to discharge on discharge testing. No further work was done until around 1970 when interest in geothermal energy resources was revived.

Exploration work along the Kenya Rift was revived from Lake Bogoria to the north to Olkaria in the South with a Werner configuration resistivity array. This work revealed a number of resistivity anomalies. However, results from the resistivity surveys indicated Olkaria Geothermal field was the most promising of all detected anomalies. Further exploration work supported by the United Nations Development Programme (UNDP, 1972) was conducted between 1970 and 1972. From this work, a decision was made to concentrate efforts in Olkaria. A technical review meeting was held that recommended the drilling of 4 exploratory wells in Olkaria. The drilling of the four wells commenced in 1973, funded by UNDP. By 1976 six (6) wells had been drilled and a feasibility study conducted by (SWECO-VIRKIR, 1976) on reservoir assessment and steam utilisation recommended the development of 2X15 MWe power plant. After completion of the feasibility study, active drilling for the development of a 30 MWe power plant was conducted by Geothermal New Zealand Ltd (GENZL).

Additional wells were drilled thereafter to provide enough steam for power plant development and in 1981 the first unit of 15MWe of Olkaria I power plant was commissioned. The 2nd unit of this power plant was commissioned in 1982 and 3rd in 1985. Drilling in Olkaria North East Field for the development of Olkaria II power plant was done in the late 1980's and 33 wells had been drilled by 1992. From the available steam in the Olkaria North East (SKM 1994), conducted feasibility studies and recommended the development of a 64 MWe Olkaria II power plant. Olkaria II power plant was commissioned in 2003 *c*omprising of two units of 35 MWe which totalled 70 MWe. A third unit of 35 MWe was added and commissioned in 2010. Olkaria II power plant has a total installed capacity of 105 MWe. For purposes of development the Olkaria Geothermal Field is divided into seven sectors of which one of the sectors is Olkaria Domes. This is shown in Figure 2 below

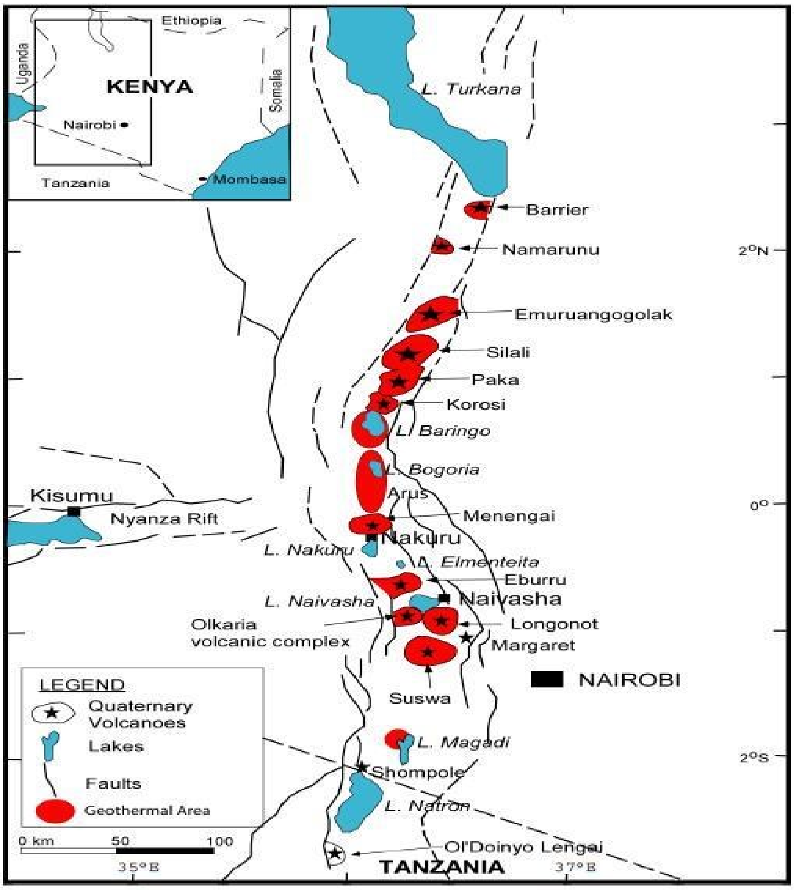


Figure 1: Map Kenya rift showing the location of Olkaria Geothermal Field and other quaternary volcanoes along the rift axis(Lagat, 2004).

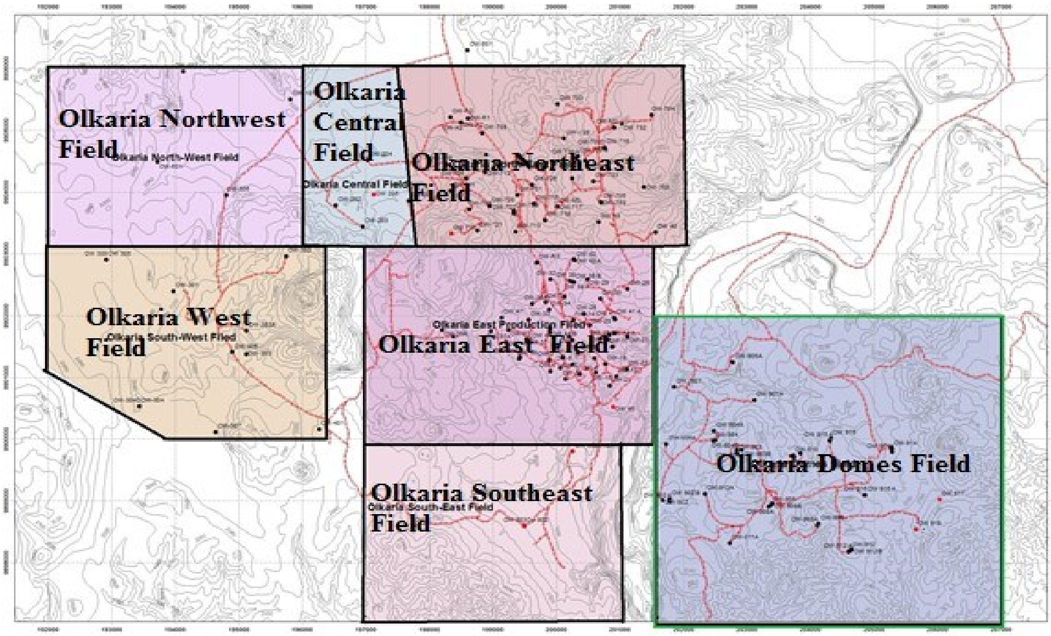


Figure 2: Greater Olkaria Geothermal Area showing the seven sectors in Olkaria for Development purposes

In the year 1998 the first Independent Power Producer (Orpower 4 Inc) was licensed to develop a power plant in part of Olkaria (Olkaria North West Sector). They initially developed a 12MWe pilot power plant in the year 2000, added another 36 MWe in 2009, and 52 MWe in 2014. This has since been expanded to the current installed capacity of ~160 MWe In 1998 to 1999 the Olkaria Domes Sector was explored by drilling three (3) exploration wells. This had been preceded by geo-scientific studies that had been conducted between 1992 and 1997. This proved the existence of a high temperature resource. Drilling activities slipped upto the year 2007 due to challenges in funding. Appraisal wells were drilled in Olkaria Domes from the year 2007 and since then drilling has been continuous in the KenGen concession in Olkaria. An Optimisation study done by (WESTJEC, 2009) on the KenGen concession of Olkaria recommended the development of a 280 MWe power development scheme. An updated optimisation studies by an Icelandic consortium (MANNVIT consortium, 2012) recommended that the KenGen concession of Olkaria could support an additional 560 MWe . Since 2012 to present KenGen has developed ~ 380 MWe additional capacity, the newest being Olkaria IV and Olkaria I Additional Unit 4& 5 commissioned in 2014 and 2015 respectively. These two power plants added ~300 MWe. The other development of ~ 81.3MWe were modular units (Wellheads) which were installed on selected wellpads. Currently, KenGen is implementing two projects, the 165 MWe Olkaria V and 83.3 MWe Olkaria I Additional Unit 6.

2.0 THE GEOLOGY OF THE GREATER OLKARIA AND OLKARIA DOMES

The geology of Olkaria has been described by several workers, e.g. Odongo,1986, Browne,1984, Clarke et al, 1990 , Marshall, 2009,, Musonye, 2014, Munyiri,2016). The Greater Olkaria Geothermal Complex is characterised by numerous volcanic centres of quaternary age and also the only area within the Kenyan Rift with occurrences of commendite on the surface. Other quaternary volcanic centres adjacent to Olkaria include Longonot, Suswa caldera to the south, and Eburru volcanic complex to the north. The surface geology in Olkaria is predominated by comendite lavas, pumice fall, pyhroclastic deposits. It is hypothesized that the pyhroclastic deposits could have originated from Longonot and Suswa Volcanoes. The pyhroclastic activity at Longonot is presumed to post date volcanism at Olkaria (Omenda, 1998). Clarke et al, 1990, listed six (6) stages in the evolution of the Olkaria complex based on their geological work.

Several workers have studied and documented the structural geology of Olkaria Volcanic Complex and surrounding areas since 1971 (e.g. Baker and Wohlenberg, 1971, Clarke et al, 1990, Omenda, 1998, Munyiri, 2016). The structural geology of Olkaria is dominated by NE-SW, and NW-SE, striking faults and sub-ordinate to N-S, NNE-SSW, and ENE-WSW structural trending patterns (Figure,8). The oldest faults of the complex, are NW-SE, (e.g, Gorge Fault), and ENE-WSW (e.g. Olkaria Fault Zone) (Clarke, 1990, Omenda, 1998). The most recent fault systems i.e N-S NE-SW, and NNW-SSW trending ones and could be considered of a different structural regime, and thus are interpreted to be of a later tectonic activities (Figure 3).

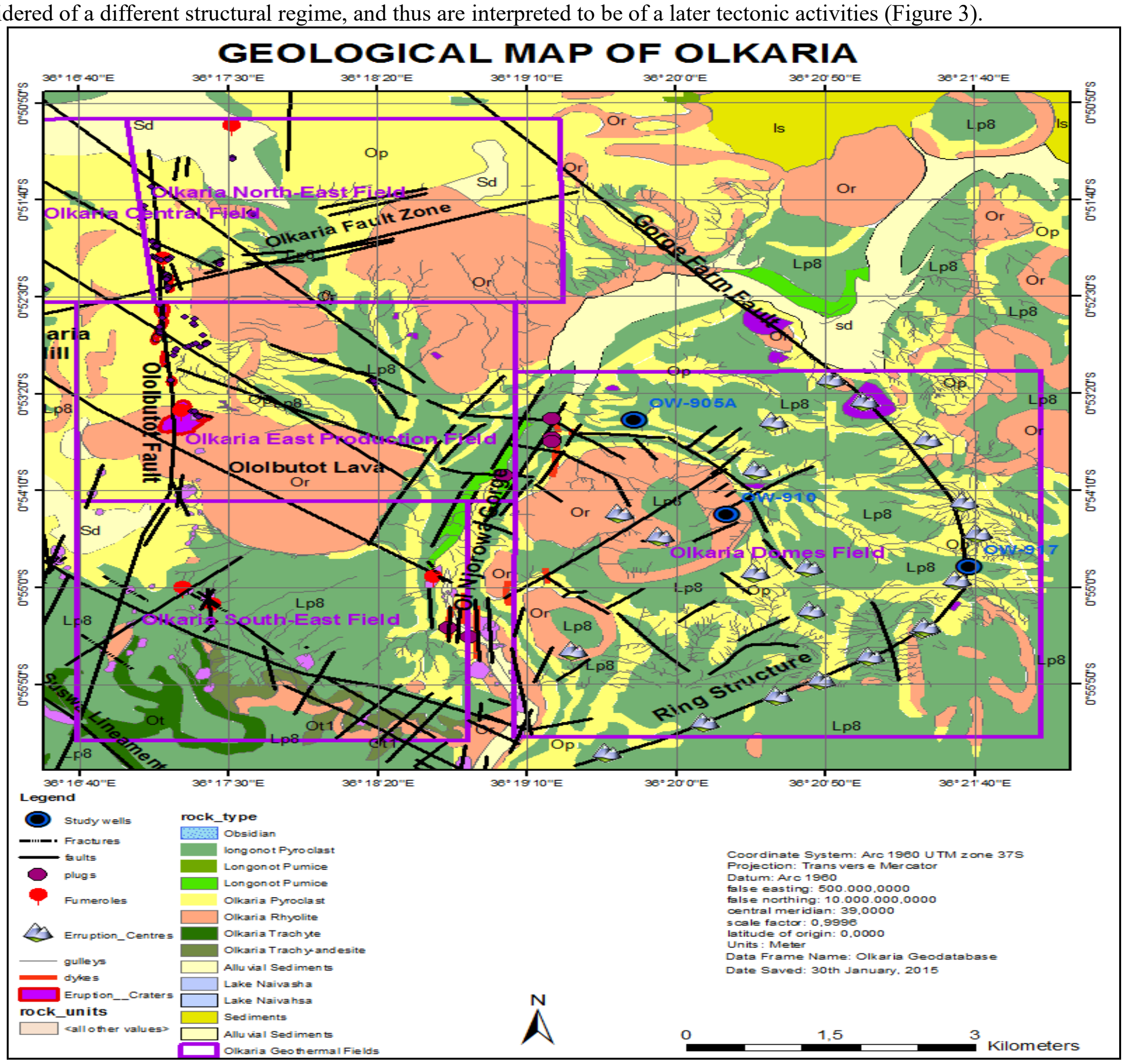


Figure 3: Map showing the surface geology and structures in the Greater Olkaria Geothermal Area (Modified from Clarke et al, 1990)

In Olkaria Domes more recent studies by (Munyiri 2016) has an updated structural map. In his work most faults mapped are oriented NW-SE, NNW-SSE, and NNE-SSW. This is shown in Figure 3 above. Munyiri's, (2016) study indicated that normal faults are dominant in Olkaria Domes and dip to the west. In the study, a unique set of E-W faults were observed along ridges east of Olkaria ring structure which cut through layers of pyhroclastic ash and gullies east of Olkaria Domes. Further, the subsurface geology of Olkaria Domes has been described by Njathi, 2012, Mwangi, 2012, Musonye, 2016,.) From their studies the lithostratigraphy of Olkaria Domes consists mainly of five units. These are Phyroclastics, tuffs, trachytes, rhyolites, and basalts. These consist of the major units in Olkaria Domes sector. Aquifers occur mainly in stratigraphic contact zones between trachytes and tuffs: trachytes and rhyolites, fracturing of rocks while others were associated with intrusions. The aquifer rock in Olkaria Domes is mainly trachyte.

3.0 A SUMMARY OF RESERVOIR PROPERTIES OF OLKARIA GEOTHERMAL FIELD AND OLKARIA DOMES

A brief summary of the reservoir properties of the Olkaria Geothermal System is hereby provided. WESTJEC, 2009, Mannvit 2012; have reviewed the properties of the reservoir around Olkaria. Currently the geothermal system in Olkaria supports approximately 690 MWe (installed capacity) with an additional ~ 250 MWe under development. The power plants are operated by KenGen and Orpower 4 Inc, (a subsidiary of Ormat Industries). The reservoir in Olkaria is two phase, dominated with average enthalpies ranging between 1800 kj/Kg to ~ 2400 kJ/kg in Olkaria East and Olkaria North East while in Olkaria Domes the well enthalpies range between ~ 1000 kJ/Kg in well OW-903 to ~ 2500 kJ/Kg in wells OW-915A. The hydrological features of the Olkaria Geothermal Field are distinguished by four (4) upflow zones (Mannvit Consortium 2011). Formation temperatures in Olkaria Domes range between 250 ° C to 360° C. Figure 4 below shows well pad location in Olkaria Domes Sector

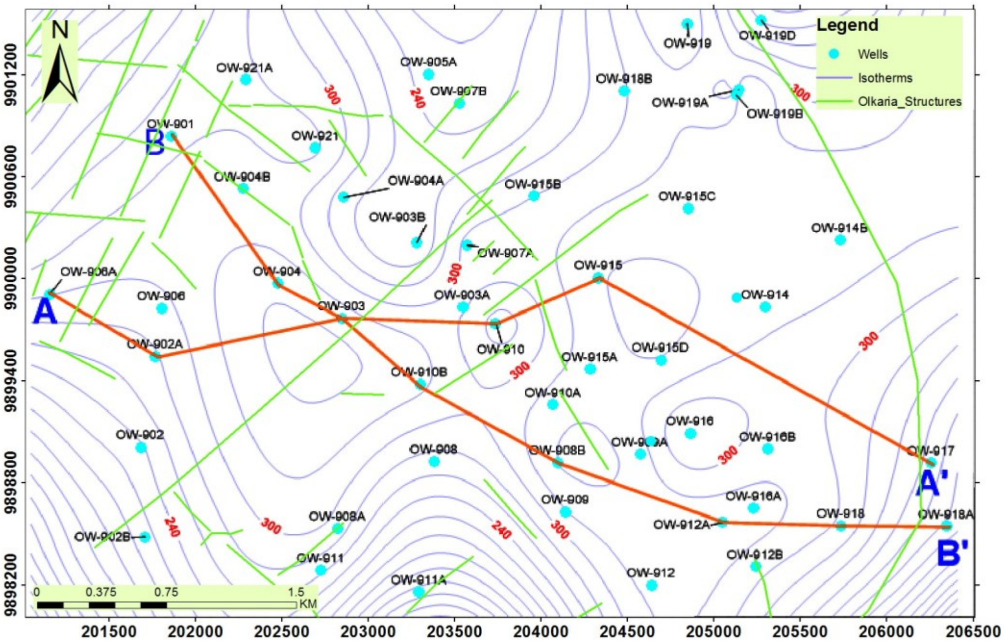


Figure 4: Well locations in Olkaria Domes sector of Olkaria

Ambunya 2014 describes the natural state model of Olkaria Domes sector based on temperature and pressure. From NW-SE cross section developed for Olkaria Domes wells for temperature and pressure, hot plumes are evident in the central part of Olkaria Domes based on the temperature isotherm of 260° C (Figure 5 a.) Mbithi 2011, suggests that the upflow in Olkaria Domes is located around the central parts i.e wells OW-909, OW-910, OW-915, OW-914 and OW-916. These wells showed boiling point with depth profiles and also registered higher mass flows and maintained higher wellhead pressures. Wells on the periphery e.g well OW-902 seems to have been drilled on the outflow of the geothermal system in Olkaria Domes (Figure 5 a) below.

From the cross section, the hot plumes occur around wells on pads, 908, 909, 910, 9114, 915, 916 ,921. To the southern part of the field around wells on pad 911, to the south east around pads 917 and 918 and to the northwest around pads 905 and 907 have lower temperatures. Other minor areas of hot plumes occur around well pad 914 to the east and pad 901 to the west of the Olkaria Domes Field.

Pressure drives the flow of fluids in a reservoir and during production there is usually pressure drawdown. The pressure logs in the Olkaria Domes field have been studied and the pressure contours plotted at different depths (Ambunya, 2014). High pressure regions are associated with upflow zones (Figure 5 b)

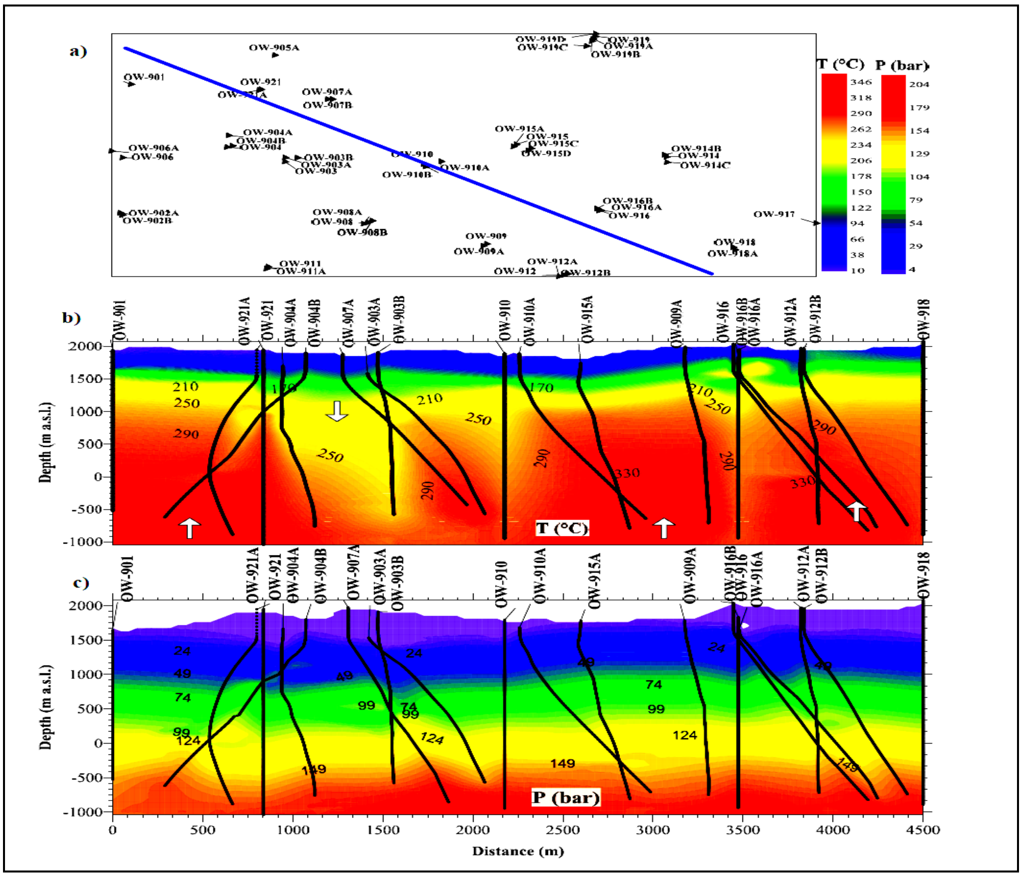
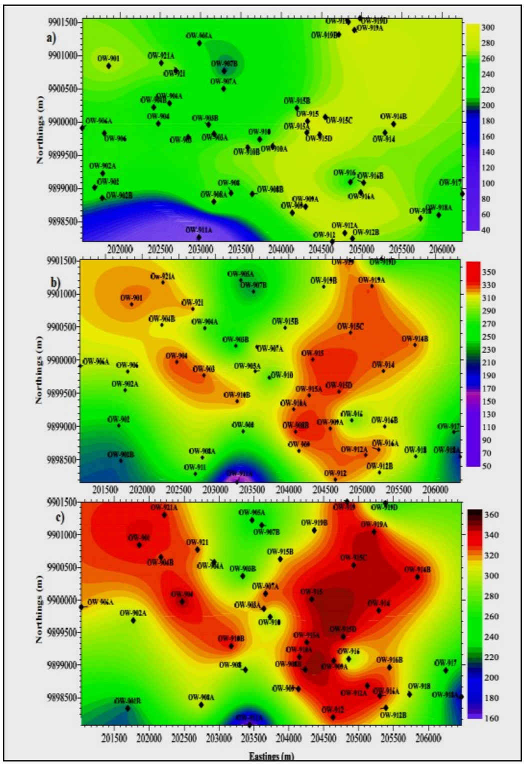


Figure 5 a): NW-SE cross section a) location: vertical contours, plotted for b) temperature and c) pressure; arrows indicate estimated direction of flow from the Olkaria Domes Reservoir Geological Overview of Olkaria Domes (After Ambunya, 2014)



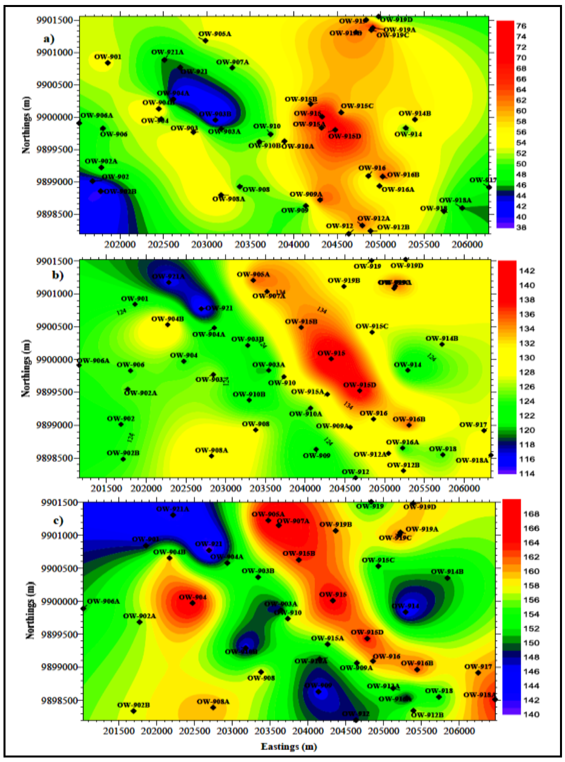


Figure 5 b) , Temperature contours at a) 1000 masl b) 0 masl c) 400 masl

After Ambunya, (2014)

Pressure contours at a) 1000 masl b) 0 masl c) 400 mas

4.0 SUCCESSFUL WELLS IN OLKARIA DOMES.

Wells success for purposes of this work was defined as a well whose electrical power capacity could be estimated when the wellhead pressures were greater than 5 bars during well discharge testing. The wells were deemed to be successful when they sustained discharge during well testing. This assumption was made based on power plants that have been developed in Olkaria in the KenGen concenssion.. The turbine inlet pressures for all the power plants in the KenGen concession of Olkaria are single flash steam turbines with turbine inlet pressures ~ 5 bars a and above. For wells with WHP of less than 5 bars these were considered not successful although some had good injectivity and were converted to injector wells. Most of the wells drilled in Olkaria Domes, besides the wells for exploration and appraisal, are production wells. Some wells had very low injectivity and filled with water during step pumping. These type of wells were not productive. Some of these wells have been converted to monitor wells for reservoir monitoring. This description of successful wells may vary from operator to operator depending on the intended use of the wells.

4.1 Well Depth.

In Olkaria Domes most of the wells were drilled to a total depth of approximately 3000 meters except the 3 exploration wells which were drilled to depths of approximately 2000 meters. Other wells which did not reach target depths of 3000 meters went to depths between 2580 to 2990 meters. All appraisal and production wells were drilled to total depths of more than 2500 meters. There is no obvious relationship between depth to which wells are drilled and well capacity. This may imply there are other factors that influence well out puts in Olkaria Domes Sector.

4.2Well Casing depth and Well Output

The wells in Okaria Domes are cased to various depths. The casing programme for wells in Okaria Domes which is also typical of wells in Olkaria is illustrated in Figure 6

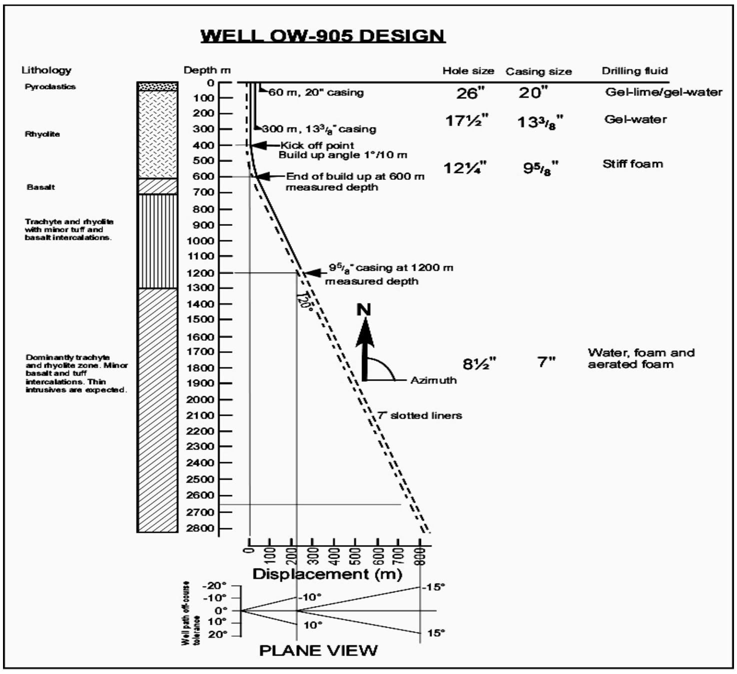


Figure 6: Typical casing and well design for Olkaria wells (Both vertical and directional)

During the exploration phase of Olkaria Domes (1998-1999) the 3 exploration wells drilled to a total depth of ~ 2200 meters were cased fairly shallow. These wells, OW-901, OW-902 and OW-903 had their production casing set, between 648 meters in well OW-902 and 759 meters in well OW-901. Well OW-903 had a cyclic output and the production casing was set at a depth of ~ 697 meters. It was thought that part of the feeder zones in the shallow parts of well OW-903 were not cased off.

During appraisal drilling it was recommended that the production casing for wells in Olkaria Domes be set at ~ 1200 meters. This was informed by the characteristics of well OW-903. Thus the production casing for wells drilled in Olkaria Domes post 2007 were set mostly between 800 meters to 1200 meters.

4.3 Feed zones and permeability in Olkaria Domes

Feed zones for wells in Olkaria Domes have been described by Mbithi, (2016). He described feed zones for about thirty six (36) wells in Olkaria Domes. In his works he deduced feed zones ranging between 1000-2000 meters for 10 wells and from 2000-3000 meters in twenty six (26) wells. The feed zones were determined by injection profiles and these are shown in Figure 7.

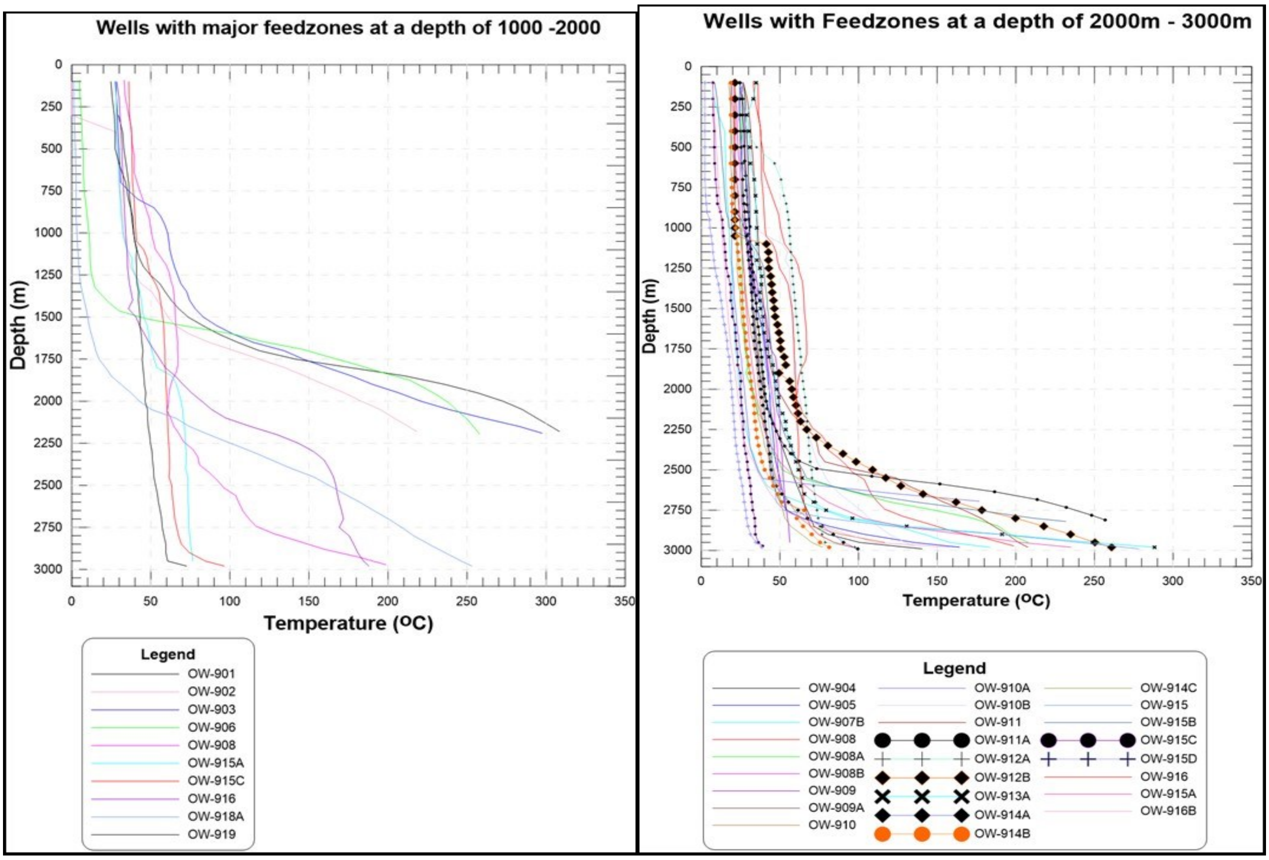


Figure 7: Feed zones for wells in Olkaria Domes have been described by Mbithi, (2016).

In his study he superimposed the feedzones to a temperature model and observed that the feed zones are aligned to some geological structures in a NW-SE, N-S, and ENE-WSW direction. The feed zones also showed the regional distribution of permeability across Olkaria Domes field. Mbithi (2016), deduced that permeability in Olkaria Domes field is good in the upflow zones and poor on the periphery of these upflow zones. Wells that were in the upflow zones had high injectivity capacities e.g well OW-914, OW-915 A, OW-916. Figure 8 shows the injectivity in lpm/bar for some 24 selected wells in Olkaria Domes.

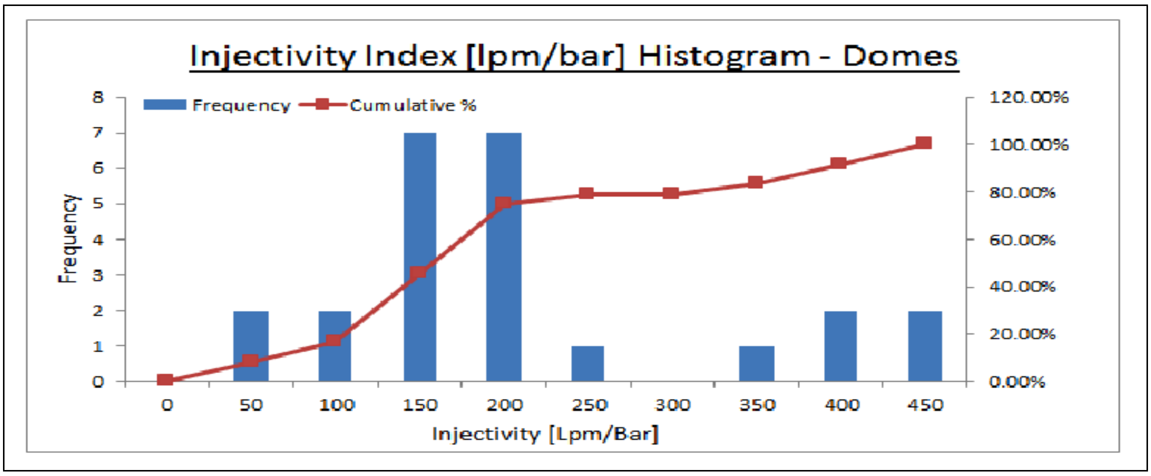


Figure 8. Summary of injectivity of twenty (24) sampled wells from Olkaria Domes

From the graph, about 15 wells had an injectivity index of between 150 -250 lpm/bar. Only about 5 wells had an index of ~ 350 lpm/bar and more while 4 had an index of less than 150 lpm/bar. Wells that have high injectivity index are also associated with high output. The major feed zones for some of the wells are in the upflow e.g well OW-914A which was observed at ~ 2200 meters coincide with the faults associated with the inferred collapsed caldera. Some minor feed zones are associated with intrusions (Musonye, 2012).

4.4 Well Capacities and production casing depths.

The capacity of wells in Olkaria Domes sector of Olkaria were estimated using Russel James discharge test method. The outputs represents the wells electrical capacity for wells with a well head pressure of above 5 bars. The capacity used in this study are capacities for the most stable conditions during discharge tests. Some wells were drilled as production or exploration wells and later converted to injector wells. In Olkaria Domes sector about 80 wells have been drilled with varying electrical capacity outputs.

This range between 1.5 MWe to ~ 24 MWe. In Figure 9 is presented the distribution of well capacities in the Olkaria Domes Sector.

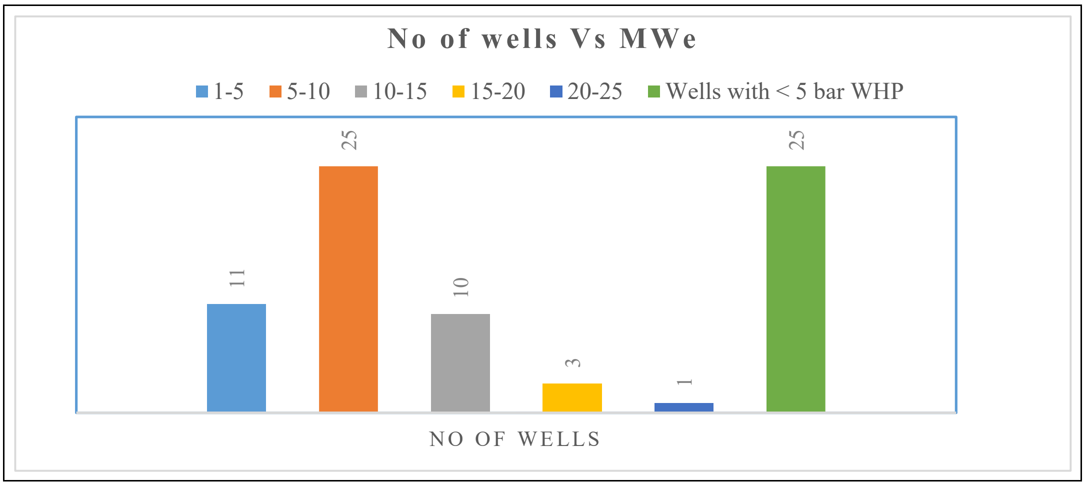


Figure 9: Number of wells and output capacities of wells in Olkaria Domes.

Out of about 50 wells that had a WHP of > 5 bar eleven wells had an electrical capacity of between 1- 5 MWe, 25 had been 5-10, 10 wells had ~ 10-15 while 4 had out puts that were greater than 15 MWe. The remainder of the wells had a wellhead pressure of less than 5 bar.

Wells that were drilled as exploration wells had fairly low outputs. There outputs in MWe ranged between 1.5 to 3.8 MWe. Wells drilled as appraisal wells ranged in output between 2.6 and 7.7 MWe. Some two wells drilled as appraisal wells had WHP pressures that of less than 5 bars and some could not sustain discharge.

Wells drilled close to the ring structure (refer to the structural map) in Olkaria Domes i.e wells on Pad 917,918,919 to the north west and to the East and wells to the south e.g wells on Pad 911 and 913 were less successfull. These wells did not sustain discharge when tested or if they discharged on testing their well head pressures were below 5 bars. Success in output of the wells drilled increased during production drilling.

Some of the wells whose well head pressures was less than 5 bar and have good injectivity have been converted for use as injector wells while some are used as monitor wells. For the entire development Olkaria Domes approximately eleven wells are being used as injector wells while three wells are monitor wells. There are wells that were specifically drilled shallowly as injector wells but these have not been included in this scheme.

The wells in Olkaria Domes are cased to various depths. The distribution of production casing depths and number of wells in Olkaria Domes is shown in Figure 10.

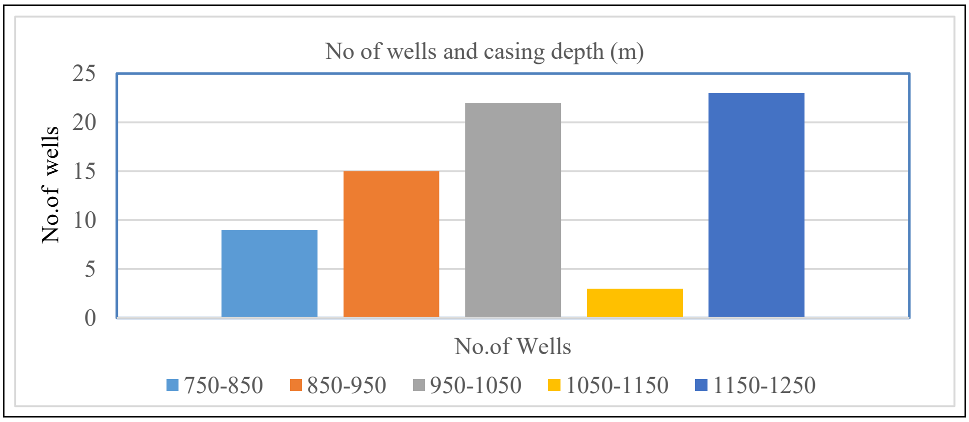


Figure 10: Casing depth (m) and number of wells in Olkaria Domes

From the figure above production casing depths may not provide an obvious relationship with casing depth. It can be observed from figure 10 above that wells that are cased to depths of close to 1200 meters have relatively lower outputs compared to wells cased at ~1000meters. There outputs ranged between 2.6 to 12.5 MWe and average ~ 5.4 MWe . Wells cased at ~ 950 meters had better out put than wells that are cased to 1200 meters. Wells cased to ~ 950 m of production casing range in output between 4.6 MWe and the highest of 18.8 MWe. Of wells cased ~ 950 meters these had an average of ~ 10 MWe. From this assessment it would appear wells that we cased slightly shallower had a better output. Besides the production casing depth, there are other factors that control the output of wells. Geological controls in Olkaria Domes and the injectivity index could also contribute. In Figure 11 is illustrated the casing depth and well outputs in Olkaria Domes.

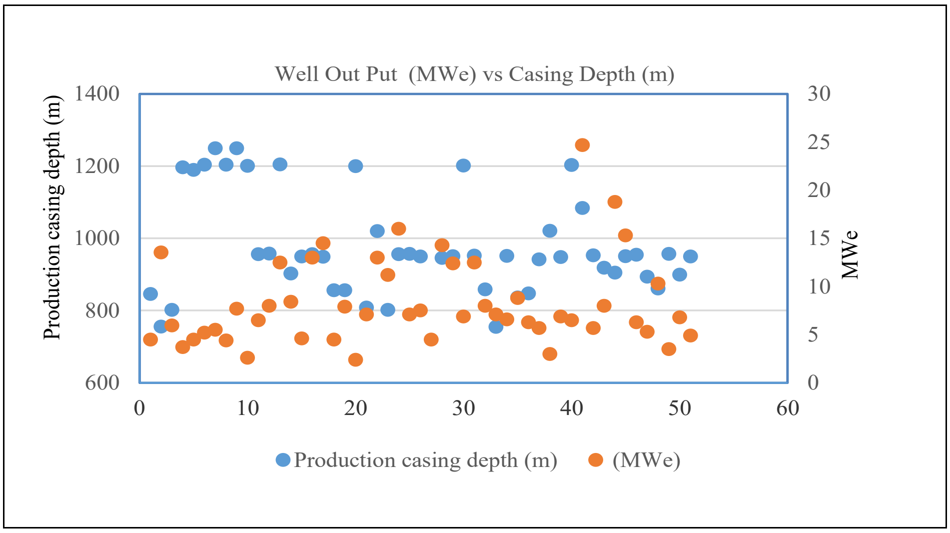


Figure 11: Casing depth (m) and output capacities of wells in Olkaria Domes

4.5 Vertical Vs Directional Wells outputs.

Wells drilled in Olkaria Domes are mix of vertical and directional wells. Of the wells in Olkaria Domes a majority are directionally drilled. Well out puts are hereby assessed with respect to vertical OR directional wells. These are both vertical and directional wells. The wells were superimposed on the structural map of Olkaria Domes as depicted in Figure 12 below. Figure 12 shows well pads in Olkaria Domes with the vertical wells (black dots) and directional wells (blue lines).

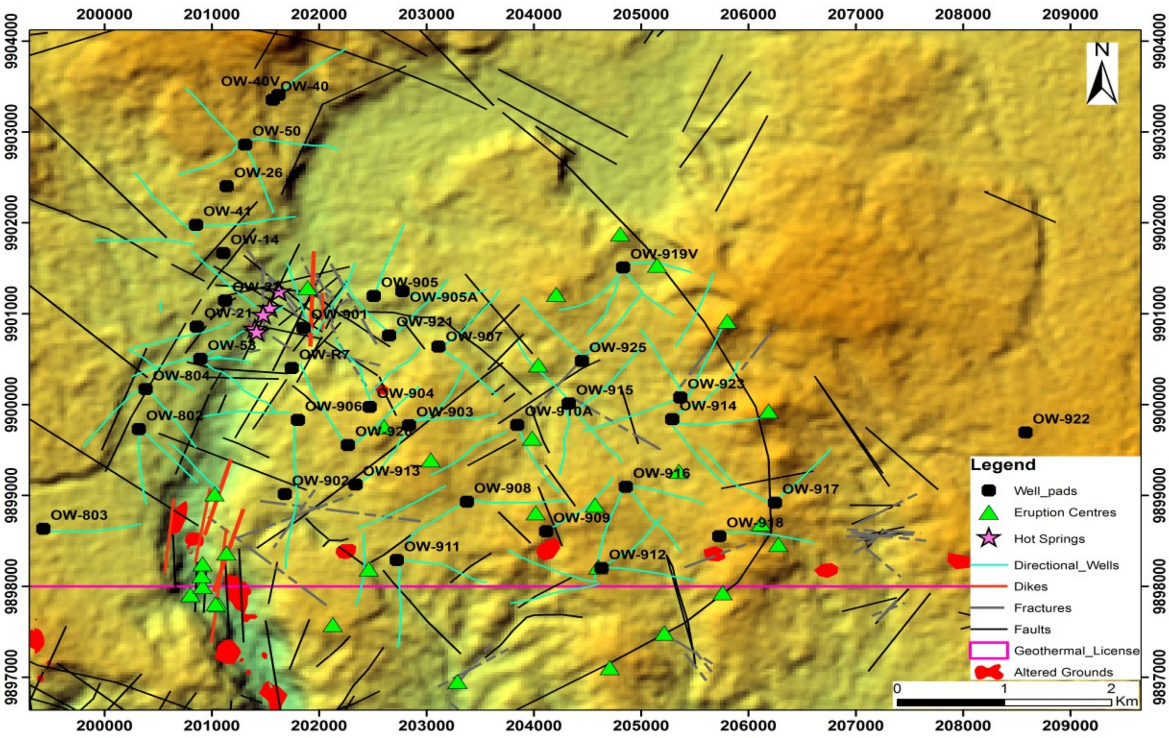


Figure 12: Wells pads in Olkaria Domes superimposed on the structural map

Directional wells were drilled with a view of increasing the chances of intersecting multiple fractures or faults. These out puts from 37 directional wells were compared with out puts from 15 wells drilled vertically. For directional wells assessed for this work the median value for out puts seems to be between 5-10 MWe. Wells with outputs outside this range, either lower or higher were fewer with those above 15 MWe being fewest only two wells. Directional wells that were drilled inside the Olkaria ring structure and Gorge farm faults (refer to Figure 3) had higher outputs compared to wells that intersected the Olkaria ring structure and the gorge farm fault. Outputs for both vertical and directional wells are depicted in (Figure 13 a and b) below

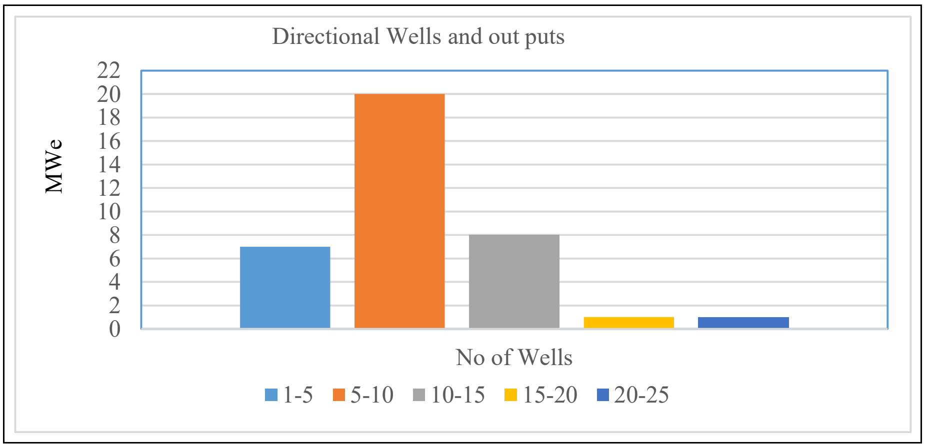


Figure 13 a: Outputs of wells drilled directionally. The median value is between 5-10 MWe

Vertical wells were fewer than the directionally drilled wells and their outputs are depicted in the figure 13 b below. Vertical wells with a median output of between 5-10 MWe were much fewer than directional wells in this group.

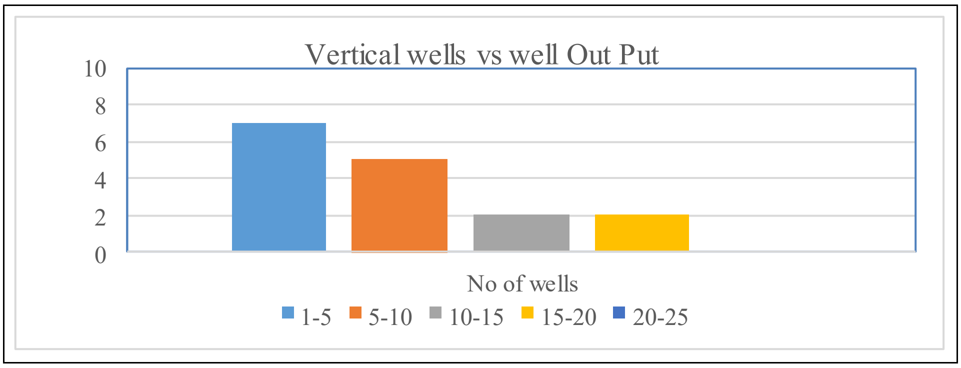


Figure 13 b: Outputs of vertical wells . The median value is between 5-10 MWe.

The highest outputs from the vertical wells was ~ 16 MWe compared with 24.7 MWe for directional wells. In both directional and vertical wells, cases for wells with outputs above 15 MWe were very few i.e only four wells out of 53 that are assessed in this work. This could imply that in both cases chances of striking wells with outputs of greater than 15 MWe are low, probably as low as less than ten percent. The median value for well outputs for the both vertical and directional wells is in the range of 5-10 MWe

5.0 DISCUSSION AND CONCLUSION.

Wells in Olkaria Domes were drilled to varying depths. These average about 3000 meters for appraisal and production wells while exploration wells were drilled to ~ 2000 meters. The geology of Olkaria Domes consists mainly of five units i.e Pyroclastic, tuffs, rhyolites, trachytes and basalts. This units are found in the subsurface. Production casing depths for wells drilled in Olkaria Domes varied with exploration wells cased fairly shallowly between ~ 650 meters to 748 meters. Production casing depth for appraisal and production wells were cased between ~ 800 to 1200 meters. Recommendations to change where to set production casing depths for appraisal and production wells was informed by characteristics of exploration well OW-903 which was cyclic and some shallow feed zones had not been cased off.

The structures in Olkaria Domes are mainly oriented in NW-SE, NNW-SSE, NNE-SSW. Aquifers occur in stratigraphic contacts, fracture and fault zones. The aquifer rock in Olkaria Domes is trachyte. Feed zones in Olkaria Domes have been observed at depths between 1000 to 2000 meters and 2000 to 3000 meters. The feed zones are aligned with stratigraphic contacts, intrusions and fractures oriented in NW-SE, N-S, and ENE-WSW direction. The injectivities of the wells vary widely with some as low as 50 lpm/bar while in others it is very high in the range of 450 lpm/bar. Wells with high injectivity index and high temperatures had also very high outputs while the converse was observed. Wells with high injectivity and lower temperatures and had low out put were converted to injector wells. These wells had varying degrees of injectivity capacities. Generally wells in Olkaria Domes have feed zones between 1000 to 2000 meters for shallow aquifers while deeper aquifers.

Production casing depths may not provide an obvious relationship with well output. A comparison made between well output and production well casing indicated generally that wells cased at ~ 1200 meters had relatively lower out put than wells that were cased at ~ 950 meters. There outputs ranged between 2.6 to 12.5 MWe and average ~ 5.4 MWe while those cased to ~ 950 of production casing range in out put between 4.6 MWe and the highest of 18.8 MWe with an average of ~ 10 MWe. This assessment indicates that there is no obvious advantage of setting the production casing at 1200 meters if other factors controlling well outputs are not considered.

In Olkaria Domes a mix of directional and vertical wells were drilled. Out puts from both sets of wells suggested that the median out put value was in the range of 5-10 MWe. Wells drilled directionally had some of the highest output wells with four wells with an output of > 15 MWe while two vertical wells had an output > 15MWe. Drilling of directional wells seems to have increased chances of intersecting fractures and faults thus contributing to higher out puts. Directional wells drilled inside the Olkaria ring and Gorge farm fault had higher outputs than wells that were drilled and intersected the ring structure and the gorge farm fault.

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