Update of the Conceptual Model of the Olkaria Geothermal System

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ABSTRACT

Many theories have been proposed regarding the conceptual model of Olkaria. Recent accelerated drilling has left many lessons in the hands of the developer regarding the *true* subsurface conditions in the field. Moreover, it has generated important data on the conditions of marginal areas that had not been drilled before. The Olkaria system remains a large and complex system with boundaries, at least of permeability beginning to be evident. However, these boundaries provide significant constraints to the development strategy of the field; but do not at all define the extent of the Olkaria geothermal system. Few interpretations have arisen recently that inform future development strategies of the area. This paper unifies all available data from different scientific disciplines as well as drilling data and well performance to provide an update of the field's conceptual model.

1. Introduction

Olkaria, a large volcanic complex, located at the axis of the Great East African Rift System, has been the focus of geothermal exploration in Kenya for many years. Reconnaissance studies were commissioned to explore the area for geothermal resources in the early fifties. Numerous surface manifestations prevalent in the area including fumaroles, altered grounds and sulphur deposits, are believed to have attracted initial explorers. It was however not until 1956, when drilling started in the area. Two wells, OW-X1 and OW-X2 were drilled to 950 m depth with no success. These wells were located close to an area which was most probably easily accessible and with greater surface activity. Their failure to sustain discharge discouraged further drilling activity until the oil crisis when exploration for alternative energy sources gathered momentum. By this time, the government and the United Nations Development Program had entered into a

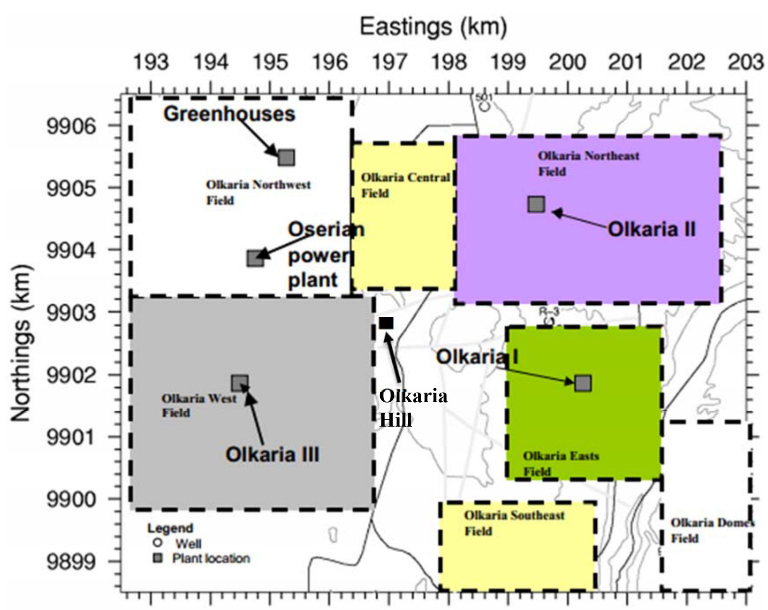

Figure 1. Olkaria geothermal field showing seven production sectors.

cooperation which supported additional exploration studies. Extensive geo-scientific studies were carried out and proved the existence of exploitable geothermal resources at Olkaria.

The next well was located south east of Olkaria hill and was drilled deeper to a kilometre depth. OW-1 was not artesian despite being located in a geologically plausible location at the intersection of two major faults. A decision was then made to concentrate drilling efforts eastwards near the most recent lava flow. OW-2 was drilled in that area in 1981 with great success at last. The well encountered temperature above 280°C and discharged high-enthalpy fluids. It is important to notice that this significant resource finding was realised about thirty years since initial drilling activities commenced. This success gathered impetuous for further drilling activity. Deep production wells were henceforth drilled near this well and culminated into commissioning of a 45 MWe plant at Olkaria 1 which became fully operational in 1985.

For further development in the area, the field was subdivided into seven sectors; Olkaria West (OWPF), Olkaria North West (ONWPF), Olkaria Central (OCPF), Olkaria North East (ONEPF), Olkaria East (OEPF), Olkaria South East (OSEPF) production fields and Olkaria Domes. (Fig. 1) The locations of the field sectors were decided relative to Olkaria Hill.

Later drilling activities concentrated at the Olkaria West and North East fields where power plants with 84 MWe and 105 MWe were subsequently built. Drilling at Olkaria Domes did not start until 1998 when the first well was drilled there. To date, many wells have been drilled in the Domes field and both large and wellhead plants have been producing for few years already. Olkaria fields are now significantly larger than previously estimated. An area of more than 200 square kilometres now has proven reserves close to 1GWe at wellhead. This places Olkaria as a significant player in the global energy mix.

Further drilling activity is ongoing both infield and on the margins of the proven field. This newly acquired data has become extremely useful in updating the existing conceptual model of Olkaria.

2. Geology and Structural Setting

Olkaria is located on the floor of the central Kenyan rift about 150 km to the North East of Nairobi. The area is both geologically and structurally complex. The volcanic system is associated with an old central volcano which collapsed leaving a large caldera of approximately 5 km diameter, defined in part, by a ring fracture and by rhyolite domes. Rocks occurring on the surface are predominantly Quaternary comendites, pumice fall and ash deposits of late Pliocene to Holocene. Some trachytic flows appear to the south of the geothermal area below thick pyroclastics commonly associated with the Longonot and Suswa eruptives. Minor volcanic glass material also appears in a few localities.

Volcanic centres are structurally controlled. The main eruptive centre is the Olkaria Hill with other major structural features also contributing significantly. The Ololbutot and Gorge Farm faults are such eruptive fissures. The most recent volcanic episode is associated with the Ololbutot fault which produced rhyolite flows dated about 250 years BP based on charred wood found under it (Clarke, et al 1990).

The litho-stratigraphic structure in the area is nearly horizontal (Muchemi, 1999; Brown, 1984). Based on rock cutting and cores, the general litho-stratigraphy of the greater Olkaria complex can be divided into two; with the axis separating the western sector from the eastern sector passing through the Olkaria Hill. Omenda (1998) discusses these formations and proposed nomenclature: Mau tuffs, Plateau trachytes, Olkaria basalts and Upper Olkaria volcanics. Mau tuffs were found to be unique to the western sector while the trachytes and basalts are unique to the eastern sector.

Geothermal manifestations are also structurally controlled. Hot

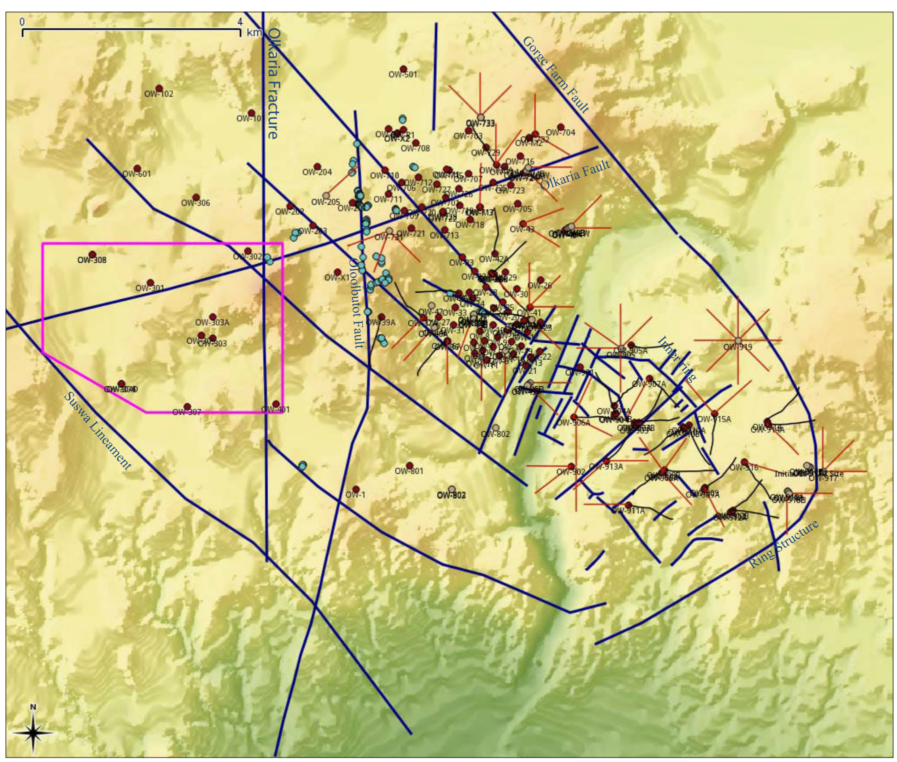

Figure 2. Structural map of the Olkaria geothermal field.

grounds and fumaroles are located along fractures with intense hydrothermal activity found at their intersections. Production wells cited at these intersections prove to be exceptionally good. This is a good indication of open fractures.

Olkaria is also quite complex structurally. The area is located at the vicinity of the western boundary faults of the rift system. Tectonic activity is associated with extensional rifting with consequent tension creating North-South faulting along the axis of the rift. The dominant structures at Olkaria are the Ololbutot fault (North-South), the Gorge Farm fault (North East-South West), the Olkaria Fault (East North East-West South West) and the Suswa fault (North East-South West). An alignment of eruptive domes is prominent to the east of the field probably demarcating a caldera rim which has been mapped elsewhere around the greater volcanic complex. Many other buried faults with similar trends have been inferred by analysis of drill cores and rock cuttings. (Muchemi, 1998; Omenda, 1998).

Micro-seismic monitoring of Olkaria geothermal field has shown lineaments of epicentres similar to mapped structures on surface (Simiyu and Keller, 1998). Intersections of these lineaments are associated with shallower and less prominent seismic events suspected to be consequent of fluid flow in the subsurface.

3. Conceptual Model

Grant and Bixley, (2011) define conceptual models as descriptive models of geothermal systems incorporating, and unifying the essential parts of physical features of the system. Conceptual basis are constructed by unified interpretation of data available for a particular field. Incorporation of ideas and viewpoints from various disciplines and expertise are essential to corroborate findings into some meaningful interpretations. Variable datasets are used in the construction of these models depending on the phase of development. Fields under exploration rarely have any datasets beyond surface geo-scientific data. In the case of fields that have some or many drill holes, conceptual models involve interpretation of a lot more data and are therefore considerably more detailed.

The Olkaria geothermal field has been studied extensively over the decades. New information is increasingly acquired with drilling of additional and deeper wells all of which have increased the knowledge of the system. Down-hole data is of paramount importance in providing calibrations to models developed earlier with little or no information about the different sectors of the field, its geometry, nature and boundaries. With increased acquisition of these datasets, it has become necessary every so often to revise our conceptual understanding of the system. Too often discoveries previously not envisaged have been encountered mainly through bold drilling steps outside the traditional exploitation area.

The Olkaria conceptual model proposed by West-JEC (2009) and improved by Mannvit/ÍSOR/Vatnaskil/Verkís Consortium (2012) describes the heat source of the system as of magmatic origin lying at shallow (6 km) depths with dyke intrusions which in turn are responsible for at least four up flow areas; one below the Domes, another below the OEPF, another below ONEPF and another below OWPF. Meteoric water from the high rift scarps percolate via deep seated faults dipping into the centre of the rift are heated on their way down and up along permeable structures.

3.1 Temperature

The present work has found evidence for shallow intrusives that form heat sources and shows fluid paths forming the traditional mushroom of convection in the reservoir. Through corroboration of various datasets, we find structures responsible for these convective currents as well as additional upflow and downflow zones.

A very detailed 3D formation temperature and pressure model has been constructed for the field. 3D visualisation of the system using Petrel visualisation software has enhanced a great deal to the understanding of the distribution of both parameters. Figure 3 shows temperature distribution at one kilometre depth. Temperature is contoured in a color scale with blue being cold and red being hot (see the scale in the map) At this depth, about km^2 of area is above the 200 ^{O}C contour. Five upflow zones are prominent in the area separated in the uppermost parts by colder recharge sections mainly following known structural trends in the N-S (Oloolbutot), NNE-SSW (Gorge fissures) and partly NE-SW(Olkaria fault) directions.

The geometry of these upflows is somewhat very similar. Large circular tops are evident elongated in the direction of structures that increasingly broaden towards their bases. At shallow depths, these tops appear isolated from each other by some shallow recharge zones but eventually unify at depth. The bases of upflow zones occur at the vicinity of seismic S-wave shadows.

3.2 Alteration Mineralogy

To investigate temperature evolutions in the reservoir, mineral thermometers were compared to present conditions in the reservoir. The results of this works are considerably detailed and continuous calibration is ongoing as new data is acquired literally every day. Figure 4 is presented here to somewhat summarise the findings. In the figure, first occurrences of epidote are plotted for all wells and a surface is generated from the data. Comparisons with formation temperature reveal interesting details not only about the present conditions in the reservoir but also how temperature has evolved. Regions of recent heating in the reservoir appear with the light green color while regions of cooling appear in green. It is immediately apparent here that regions with known upflow zones have been heating more recently but also quite interestingly it is also apparent that some structures are controlling new heating activity in the reservoir. The structures that significantly contribute to this heating are the Olkaria fault (striking NE) and the fissures swarm defining the Gorge (striking NNE) and to some extend the Oloolbutot fault (striking N-S). Few other isolated hotspots exists in the margins of the densely explored areas. These areas should be prime targets for further drilling activities.

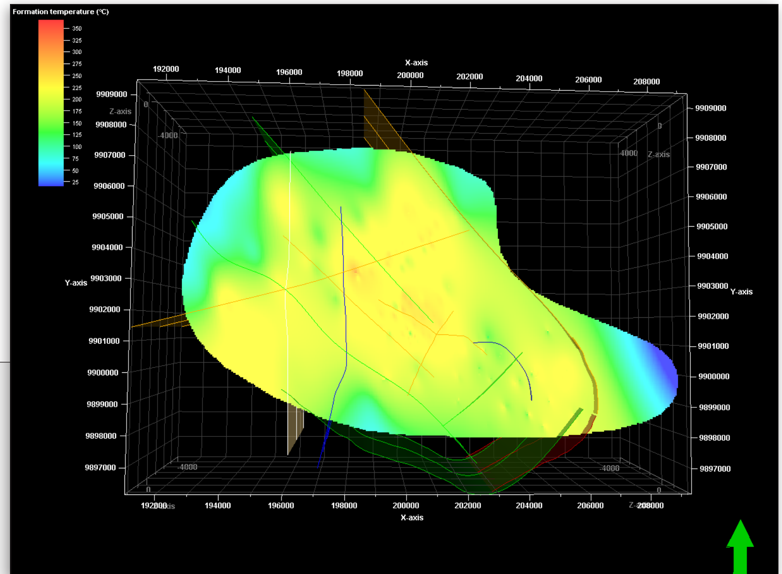

Figure 3. Temperature distribution at one kilometre depth.

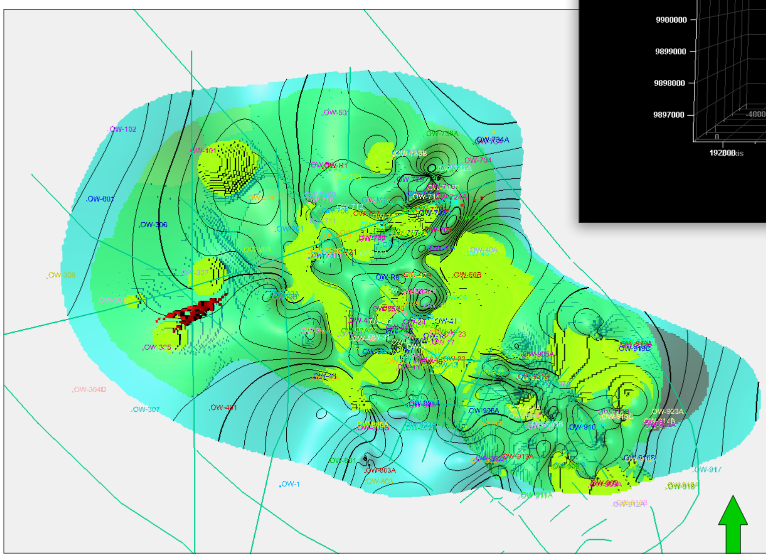

Figure 4. Comparison between formation temperature and epidote occurrence.

3.3 Permeability

Further to this, feed zones in individual wells were identified and classified in a relative scale of minor, average and major feed points. The same is plotted in Figure 5. The relative strength of the feed zone relates to the size of the symbol representing it in the figure. Lineations of feed zones are associated with known structural trends in the field. Major fault zones such as the Olkaria, NW-SE faults and inner and outer ring structures correlate very well with major permeability zones. It is also apparent that these faults are near vertical. An attempt is also made to relate the vertical spread of the feed points to the deliverability of intersecting wells. We find wells with major feed points at depth tend to be hotter and more productive than those with shallower feed points. Figure 6 relates the temperatures in the reservoir and corresponding feeder zones in the wells.

It can be deduced here that permeability is zoned similar to characteristics of wells in each field zone. The Domes field has the majority of major feed zones near the bottom of wells, while those wells in the East have their feed zones mainly in the middle of their trajectories. In the north-east fields wells have variable distribution of permeability with no clearly mapped consistency. In this field, minor feed zones and wells as major ones are found from shallower to deeper levels. The same applies to the south-east where no real major feed zones comparable to the

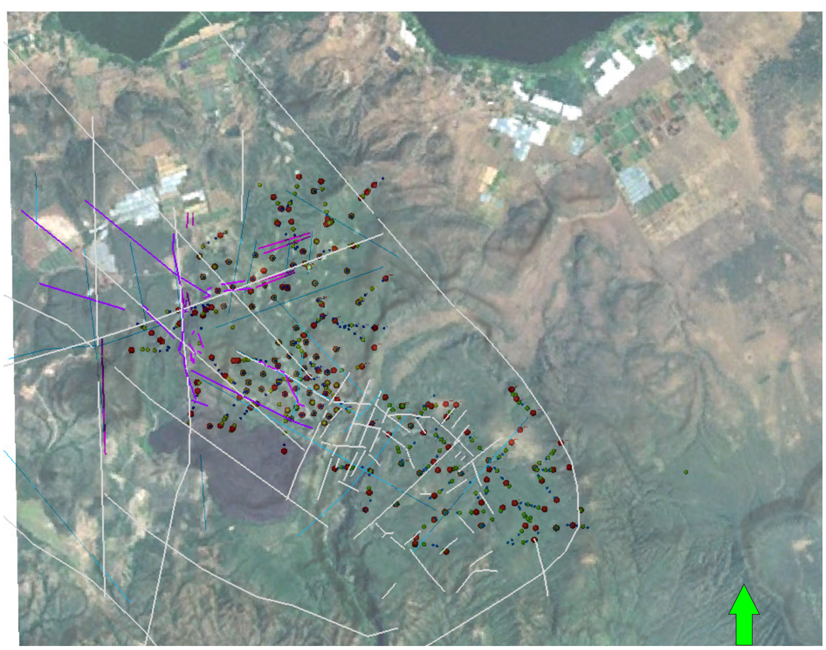

Figure 5. Map of well feed points and their relative sizes (Major-Red, Average-Green and Minor-Blue).

rest of the wells were observed. Well deliverability in this field is also smaller compared to the rest of the fields. In siting future wells, these characteristics may be considered to enhance well targeting.

3.4 Joint Interpretation

Joint interpretation of data acquired in drill holes is a reliable method to infer on the characteristics of geothermal systems. Initially, before much drilling is done, surface exploration data such as resistivity surveys formed the principal data sources for such interpretations. Later as drilling increased, subsurface data measured directly in drill holes become available. This datasets become the most important constraints to initial ideas and should be used to develop hypothesis on the nature and characteristics of the system. Olkaria now has more than 300 drilled wells spread all over the field. The data collected from this drilling activity is considerably large, and therefore a lot more precision and accuracy is expected on the hypothesis made.

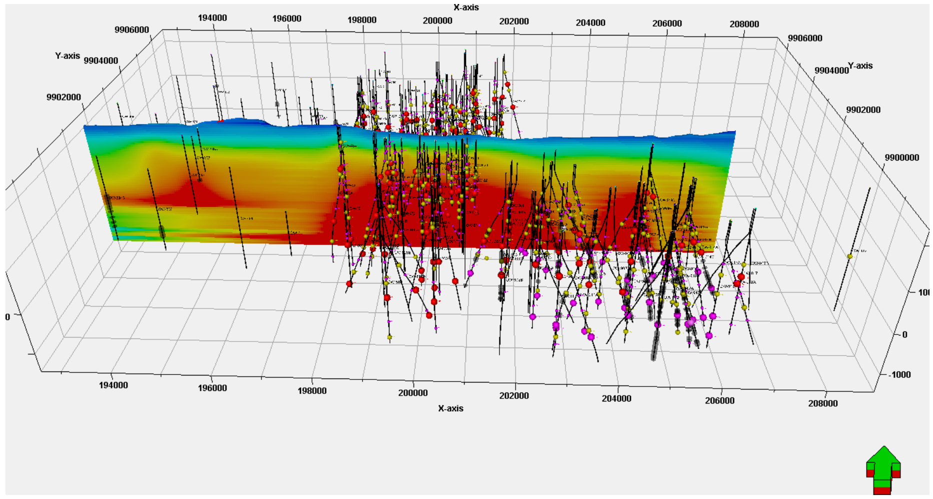

Figure 6. A typical temperature section and well feed points proportional to symbol sizes.

In this work emphasis is made on the interpretation of direct measurements with comparisons to inferences made from surface data. In most cases there are quite good corroborations between these datasets as may be expected in many high temperature fields around the world. There may be occasions where surface data points to one direction but drilling those prospects proves otherwise. Care is therefore necessary when interpreting these datasets. Figure 7 is a good example of joint interpretation of data interpreted separately by different scientists that somewhat corroborate. Figure 7 shows deep resistivity with epidote and actinolite surfaces to the top left, to the top right is the stratigraphy of the area superimposed again on the two mentioned alteration surfaces and structures, middle right is the temperature with the 250 °C isotherm

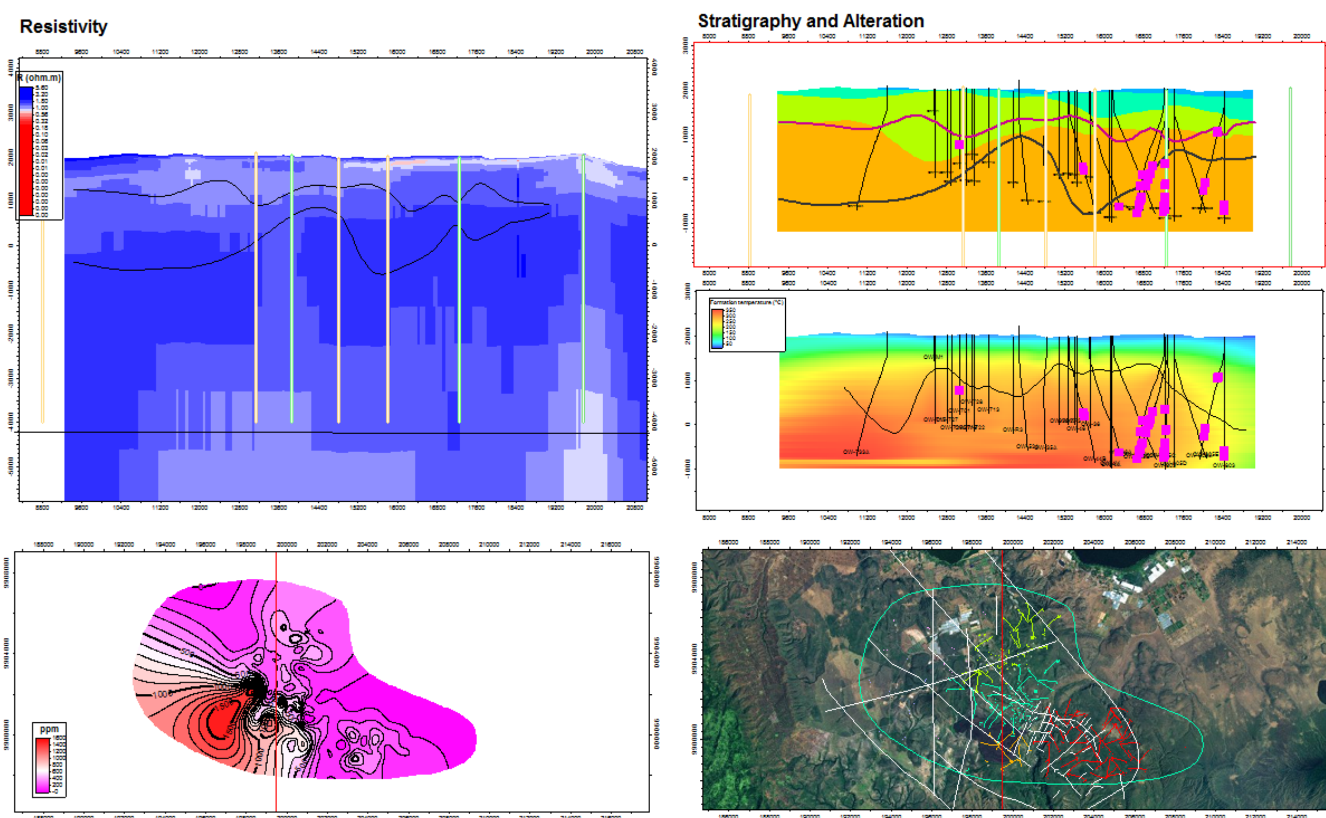

Figure 7a. Joint Interpretation Viewport 1.

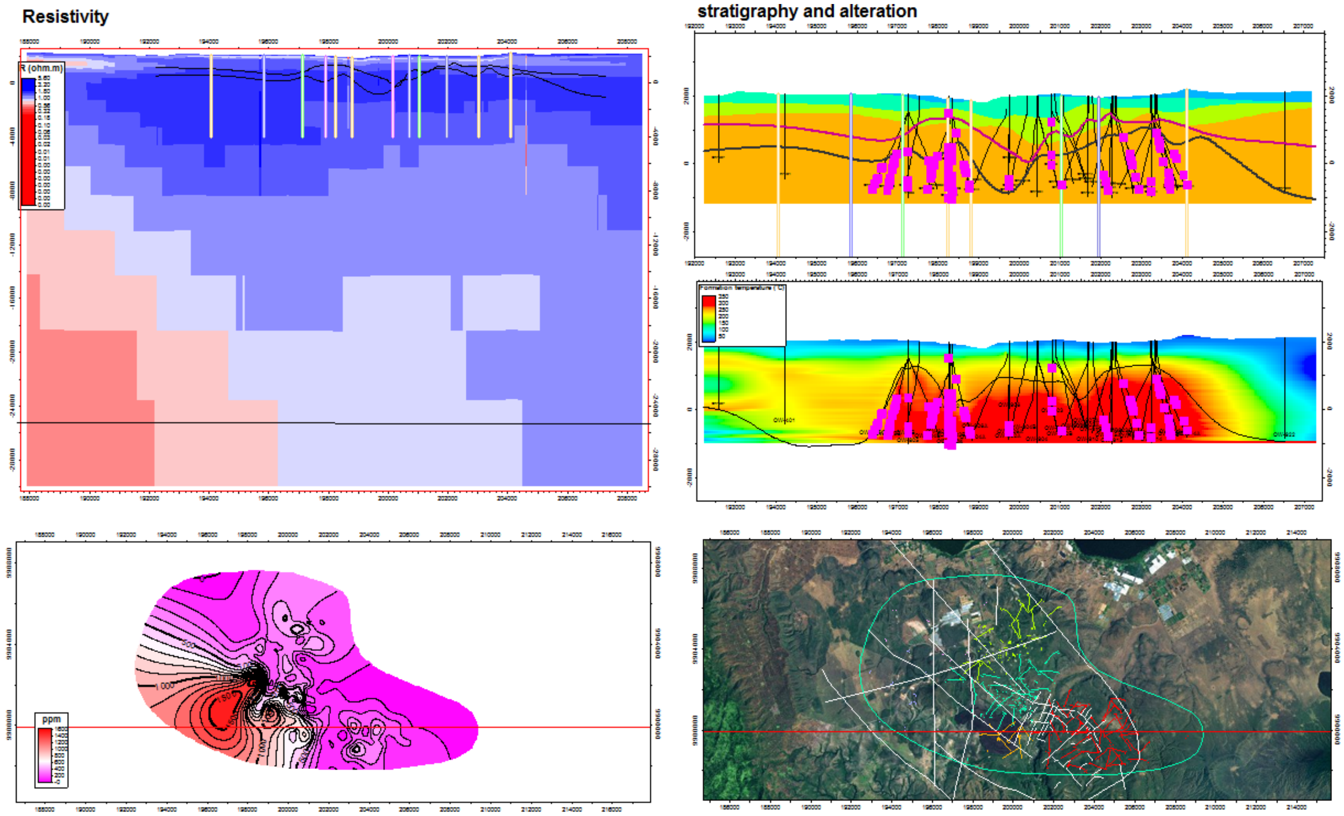

Figure 7b. Joint Interpretation viewport 2.

(purple dots are feed points), bottom left is the chloride discharge map and to the bottom right is the picture of the field. There is clear agreement in all datasets where resources are abundant, upflow zones and downflow recharges zones.

3.5 Revised Conceptual Model

The updates of the Olkaria geothermal system conceptual model can be summarised as follows:

1. Considerable data has now been collected in the presumed less-explored areas to make the picture a lot better. Particularly, recent drillings of areas to the northeast and to the north as well as the areas adjacent to Olkaria hill has provided more clarity on the "presumed extension of the geothermal resource" outside the densely explored area. Geophysical data has now covered a greater area. The results of those studies show prospective areas extending further to the north, to the southeast, east and to the northwest.
2. Though three major intrusive are evident in the areas, more up flow areas (six) are evident from the temperature data. These mature up flows are seemingly separated by areas of colder flow commonly along major structural trends. The up flows are in the East, North-East, Domes, South-East, West field sectors and below well OW-101. The caldera ring fault continues to play a major role as a hydrological barrier at least in the uppermost parts with some wells crossing it at depth being productive. This suggests the fault is closed at depth and possibly transport hotter fluids. Care must however be taken in assuming the entire ring structure behaves this way as this is not true in some instances, especially south of the Domes field.
3. Recharge to the field follows known structural trends. For instance the fissure swarm defining the gorge is cold and provides the barrier between the domes field and the east. This swarms seemingly recharges the two areas while the Oloolbutot and Olkaria fault recharges the rest of the system. Evidences for these hypothesis are based on chemical analysis and formation temperatures. The ring structure acts as the source for recharge as well all around the field and more so to the east. Recharge from the south is not evident.
4. The resource distribution is on a SE-NW trend which follows the main strike of hot structures. These structures should therefore play an important role in future well siting and precise mapping should henceforth be emphasised. The intersection of this fault and those carrying the recharge fluids (often strike opposite) such as the N-S ololbutot and NE-SW Olkaria fault, and others in the south east often creates plausible conditions for convective reservoirs. This grid faulting is evident in the north east, south east and east fields.

5. The bottom of the permeable reservoir has not yet been reached. This is evident by permeability distribution in major feed zones and circulation losses extending deep into the bottom of a majority of wells. Permeability extends deepest in the domes area.

Figure 8 summarizes these findings. Upflow and down flow zones are shown by the temperature section taken approximately along the trend of regional structures. Arrows are used to distinguish these flow regimes. Also shown are the structures that play a major role in the fluid movements as discussed in this paper.

The purple domes show the shape of shear wave shadows which arguably correspond very closely with identified upflow zones. The use of several independent datasets that corroborate each other to delineate the resource creates greater confidence in the model. These datasets are jointly used to generate the Olkaria conceptual model.

4.0 Volumetric Assessment and Resource Update

The updated temperature model is used here as the basis for the areal extends of exploitable geothermal resources. The estimate is carried out by filtering the temperature at one kilometre depth so that only temperatures above 200 ^{O}C are considered. This criterion is considered quite strict, but ensures that convectional currents are not only feasible, but ensures artesian wells can be achieved in those localities. While this strict criterion is considered reasonable, it must be considered that it only considered the area covered by the wells. For Olkaria this is not too pessimistic as it may be in other geothermal fields since the well field covers most of the area already. While some areas may be covered more sparsely, the important aspect here is that drill holes extended over more than 90% of the area. More step-out wells drilled in recent months considerably increase the certainty of this hypothesis. The resultant areal extent for the 90th percentile becomes 78.75 Km^2. The simple Monte Carlo model variables are set such that:

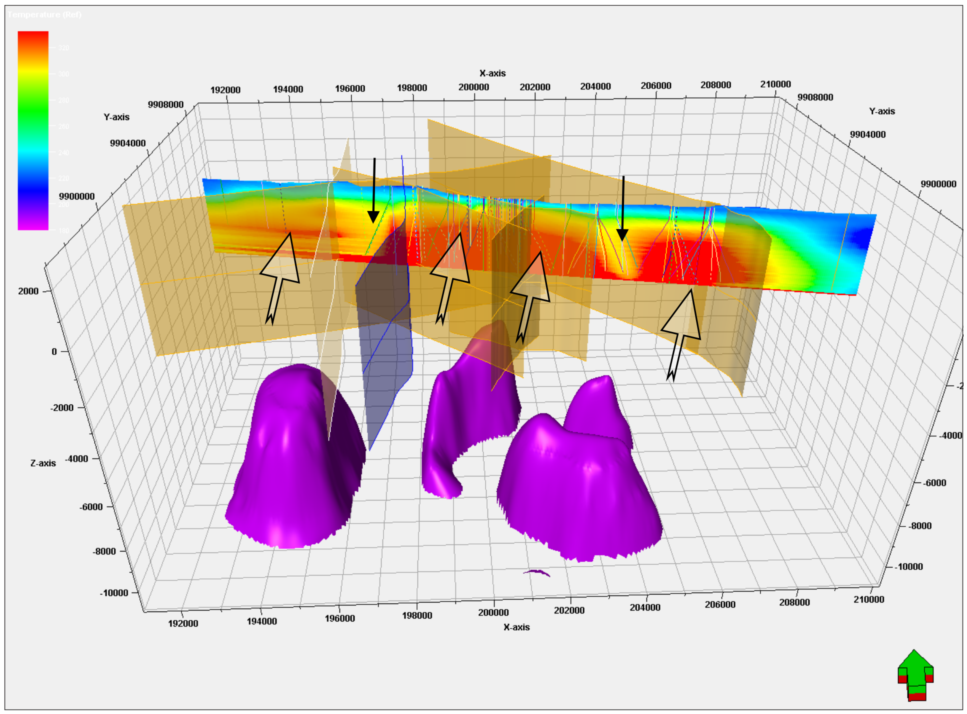

Figure 8. Updated Conceptual Model.

Surface Area – 78.5 min (90%) and 183.6 max; most likely 87.5 (100%)

Thickness – 1000 m-3500 m; most likely 2000 m

Porosity – 5%-15%; most likely 10%

Recovery Factor – 12%-32%; most likely 25%

The parameters are selected based on the arguments that:

a) Surface area – since the established resource extend is known based on the estimate described earlier in this section, it is assumed that the extent is 90% certain. However, the fact that not all the area is uniformly covered with drill holes means there are possibilities that newer areas may be discovered with step-out drilling. Resistivity studies show prospects in a total area slightly above 240 km^2. However of this area only 204 km^2 is available for KenGen's activities. The upper limit is therefore set to be the 90th percentile of the available area. The likely estimate is reasonably set at 100/90% of the proven area.

b) The bottom of the reservoir is yet to be reached. With the majority of the wells drilled to 3 km, a 2 km thickness has been already established. Rare drilling below this depth show that permeability probably extends deeper.

c) Porosity and permeability are set following the linear relationship proposed by Muffler (1977, 1979) and do compare closely with those of Williams, 2007.

The results of the Monte Carlo simulations yield a generating capacity of 1256 MWe, 2422 MWe and 4252 MWe for the 10th, 50th and 90th percentile respectively for Olkaria (see cumulative probability curve in Figure 9). It has been argued that the 10th percentile which represents the highest confidence level is perhaps the proven resource capacity only, while the 90th represents the maximum capacity including proven, probable and possible reserves.

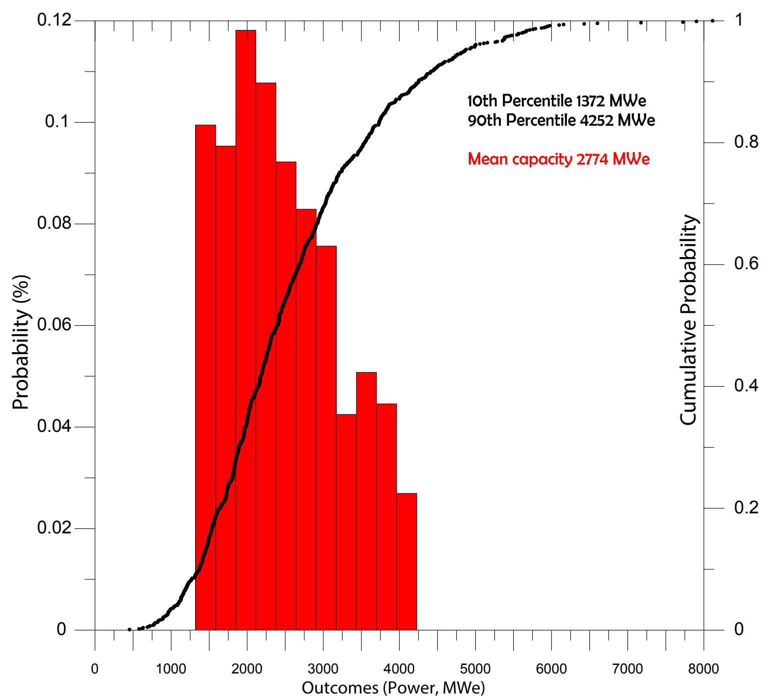

Figure 9. Results of Monte Carlo simulation.

5.0 Conclusions

Olkaria geothermal system is heated by shallow magmatic intrusives. The flow of hot geothermal fluids are controlled by permeable structures creating mushroom structures. Multiple upflows are evident in the area, reaching five in number, separated by regions of colder fluid incursions along known structures. The system is large and complex. Drilling activities have been undertaken in a large area making it possible to achieve more certainty in the Olkaria field.

In this update of the model, data directly measured in boreholes has been used to both constrain surface data as well as being the main input for subsequent modelling work. Unlike at the exploration stage where less certain data is used for volumetric capacity estimates, temperature data directly measured in boreholes and modelled in a precise grid populated by thousands of data points is used to constrain resource extend. For this tasks, more spread step-out drilling activity greatly assisted to delineate apparent resource boundaries.

Recent volumetric capacity estimates revises Olkaria's electrical generating capacity to 1372 MWe (proven capacity), 2774 MWe (mean capacity) and 4252 MWe (proven, possible and probable) reserves.

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