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Revision of the Conceptual Model for the Olkaria Geothermal System, Kenya

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ABSTRACT

Olkaria is an unusually large and powerful geothermal system located inside the East African Rift Zone, about 100 km WNW of Nairobi, the capital of Kenya. It is situated inside a major volcanic complex that is associated with a buried caldera and cut by N-S trending normal rifting faults and other major faults and fractures. The Olkaria system is presently under intense development with the electrical generating capacity having increased from about 200 MW_e in 2010 to more than 670 MW_e at the end of 2016. This development has been dominated by Kenya Electric Generating Company (KenGen) in its 204 km^2 license area. Utilization in Olkaria started when the Olkaria I power station (45 MW_e) was commissioned in the 1980's, while the Olkaria II power station (105 MW_e) was not commissioned until the early 21st century. In 2007 drilling of deeper wells (to about 3000 m), in an extended area, identified a much larger and more widespread resource than was previously believed to exist. Extensive drilling since then (about 165 deep wells) has been the basis of the intense development for electricity generation in recent years. The conceptual model of the Olkaria geothermal system has been under constant revision in recent years based on available geological- and geophysical information, temperature- and pressure data, various reservoir testing and monitoring data as well as information on the chemical content of reservoir fluids. Most important are the comprehensive data from the new wells drilled in the area since 2007. At least three deep magmatic heat sources are assumed in the system with hot water up-flows into the four main well fields. Comprehensive management is essential for the successful future utilization of the Olkaria geothermal system; including monitoring, reinjection, research and modelling as well as environmental and social awareness. Further exploration of the parts of KenGen's license area where exploration has been limited is essential before they will be considered for further development.

1. INTRODUCTION

The Olkaria geothermal resource is located in the Kenya Rift valley, about 120 km from Nairobi. Geothermal activity is widespread in the Kenyan rift, with 14 major geothermal prospects having been identified (Fig. 1). The Olkaria geothermal field is inside a major volcanic complex cut by N-S trending normal rifting faults. It is characterized by numerous volcanic rhyolitic domes, some of which form a ring structure, which has been interpreted as indicating the presence of a buried volcanic caldera (Fig. 2). Olkaria is an unusually large and powerful geothermal system. It is surrounded by further geothermal prospects, as shown in Fig. 1.

Exploration of the Olkaria geothermal resource started in 1956 with deep drilling commencing in 1973. A feasibility study in 1976 indicated that development of the geothermal resource was feasible and consequently the 45 MW_e Olkaria I power plant was constructed (Ouma, 2010). It consists of three units commissioned between 1981 and 1985. The next 15 years development was limited, but it picked up pace after 2000 with the construction of Olkaria III and later Olkaria II. The development of Olkaria has been most intense after 2007, first through a major drilling campaign (about 165 wells) and later through the construction of more power plants. The drilling of deeper wells (to about 3000 m), in an extended area, has led to the identification of a much larger and more widespread resource than was previously believed to exist. Table 1 summarizes the development history of the Olkaria geothermal system.

Five power plants are currently installed in the field producing electricity; Olkaria I with 45 MW_e capacity, Olkaria II with 105 MW_e capacity, Olkaria III with 140 MW_e capacity, Olkaria IV with 150 MW_e capacity and a 150 MW_e expansion of Olkaria I (units 4 and 5), which recently came on line. Olkaria I, II, IV and units 4 and 5 of Olkaria I are operated by KenGen while Olkaria III is operated by OrPower-4 Inc. The parts of the Olkaria geothermal field being utilized or under development have been subdivided into sectors that include Olkaria East (Olkaria I), Olkaria Northeast (Olkaria II), Olkaria West (Olkaria III) and Olkaria Domes (Olkaria IV). Fig. 2 shows the location of the power plants and Fig. 3 shows the location of wells drilled in the field up to the middle of 2016. KenGen's licence area in Olkaria covers 204 km^2.

The Olkaria II power plant, consisting of three units, was commissioned between 2003 and 2010. The Olkaria III power plant was commissioned in two phases between 2000 and 2009 and has, furthermore, been under expansion since 2012. The Olkaria IV power plant was commissioned in September 2014, and the expansion of Olkaria I came on line in two steps, towards the end of 2014 and in early 2015. In addition, KenGen also operates several well-head units at a combined capacity of about 80 MW_e, having started their installation in 2011. The combined generation capacity in Olkaria is, therefore, a little over 670 MW_e at present. Finally, the geothermal resources of the NW part of the Olkaria area are utilized both for direct heat (50 hectares of greenhouses) and small-scale electricity generation by the Oserian flower farm.

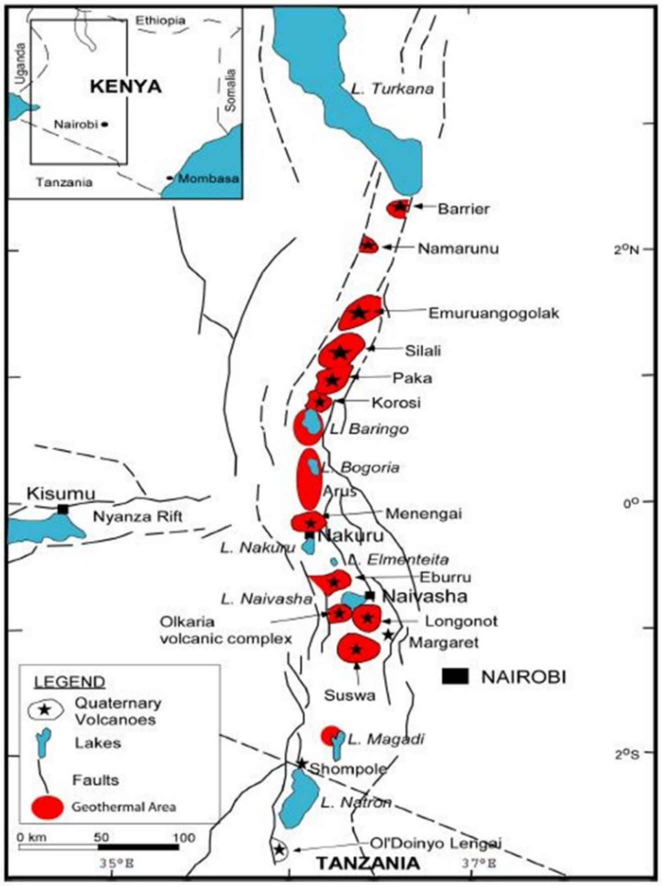

Figure 1: Map showing the location of the Greater Olkaria Geothermal Area within the Great Rift Valley of Kenya. Also shown are other volcanic and geothermal centres (Ofwona, 2010).

The development ongoing the last decade has mainly been based on KenGen's assessment of the capacity of the Olkaria geothermal resources, which in turn is based on the success of drilling operations since 2007, as well as on independent assessments performed by KenGen's advisors. These include work conducted by an Icelandic consortium composed of Mannvit hf, ÍSOR, Vatnaskil ehf and Verkís hf. Firstly, a comprehensive optimization study performed during 2011 – 2012 and, secondly, a model maintenance project carried out during 2014 – 2017. Both of these projects have involved the development or revision of the conceptual model of the Olkaria geothermal system, followed by the assessment of the system's capacity through the development of a complex numerical model of the system.

Table 1: Development history of the Olkaria geothermal resources.

Year		Capacity (MW_e)	Operator
1956	Exploration starts		
1973	Deep drilling starts		
1976	Favourable feasibility study		
1981-1985	Olkaria I (East)	45	KenGen
2000-present	Olkaria III (West)	139	OrPower-4
2003-2010	Olkaria II (Northeast)	105	KenGen
2007-present	About 165 deep wells drilled		
2014	Olkaria IV (Domes)	150	KenGen
2014-2015	Olkaria I additional units 4 and 5	150	KenGen
2010-2016	Well-head units	81	KenGen
2004	Direct use + small scale electrical generation	4	Oserian
	Total	674 MW_e	

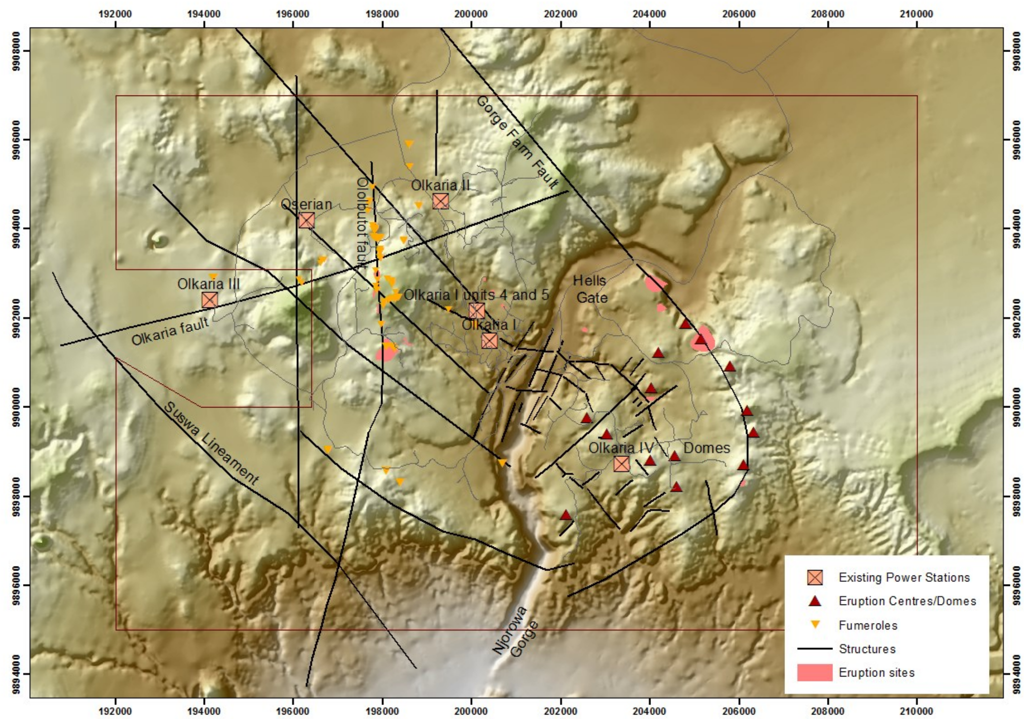

Figure 2: Map showing KenGen's geothermal concession area in the Olkaria volcanic complex, extending up to Lake Naivasha. The map also shows some of the main geological features of the area and the power plants in operation today.

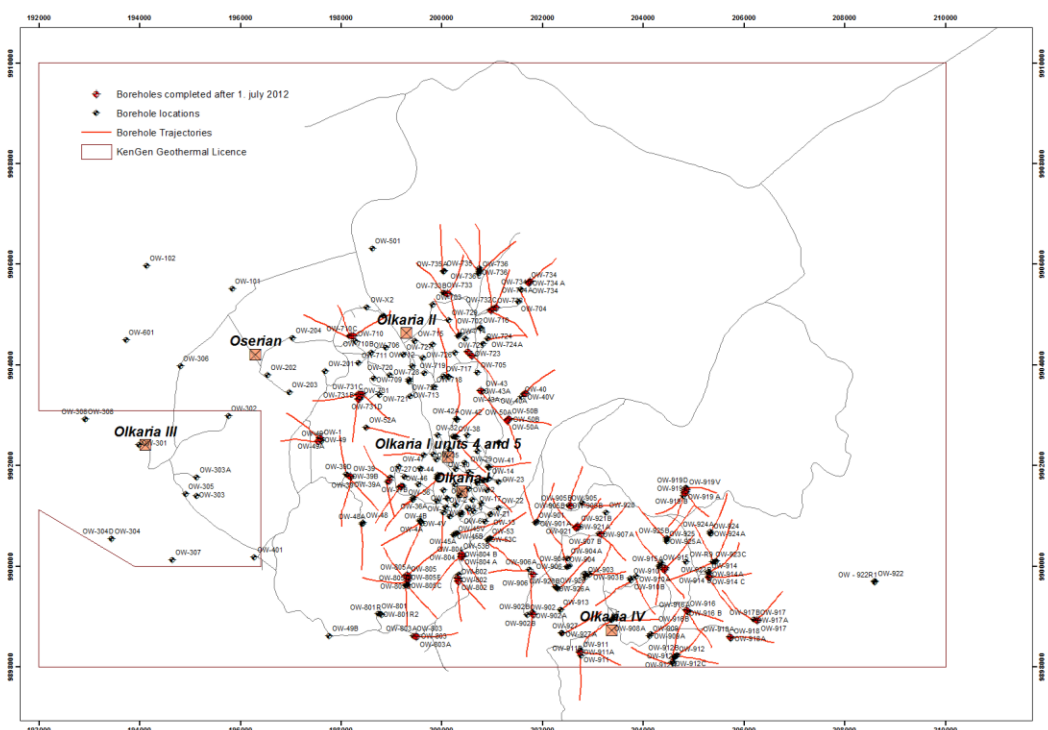

Figure 3: Map showing the location of wells in Olkaria drilled by KenGen up to mid 2016, horizontal trajectories of directionally drilled wells shown by red lines. The map covers KenGen's concession area, whilst OrPower-4's concession can be seen on the left (Olkaria III). Only wells drilled by KenGen are shown, but not a number of wells drilled in recent years by OrPower-4 Inc.

Axelsson et al. (2013) describe the conceptual model of the Olkaria geothermal system developed during the 2011 – 2012 optimization study referred to above. They, furthermore, present the results of different assessments made of the electrical generation capacity in the same study, including the outcome of numerical modelling. The numerical model involved is the largest, and most comprehensive numerical model developed for the Olkaria geothermal system up to now. The present paper is a follow-up to that paper presenting the results of the revision of the conceptual model during the 2014 – 2017 model maintenance project. That project also involved a revision of the earlier numerical model, the results of which await later publication. The data and results presented below largely stem from internal KenGen reports published by the Icelandic consortium. It should also be noted that this work has relied on data collected by KenGen, whilst data collected by OrPower-4 Inc. has not been incorporated.

2. THE OLKARIA CONCEPTUAL MODEL

2.1 General

Reliable conceptual models of geothermal systems are the key to successful development of all geothermal resources and emphasis is increasingly being put on the development of such models, especially during geothermal exploration and development, as well as their revision during long-term utilization and resource management. Conceptual model revision is obviously vital during expansion of geothermal operations, as is on-going in Olkaria. Conceptual models are descriptive or qualitative models incorporating, and unifying, the essential physical features of the systems in question (Grant et al., 1982). They are based on a unifying interpretation of data from all the relevant earth-science disciplines involved, bolstering the reliability and comprehensiveness of the outcome.

Conceptual models are mainly based on analysis of geological and geophysical information, temperature and pressure log data from wells as well as information on the chemical content of reservoir fluids. Monitoring data reflecting reservoir changes during long-term exploitation, furthermore, aid in revising conceptual models once these data become available (Axelsson, 2013). Conceptual models should explain the heat source for the reservoir in question and the location of recharge zones as well as the location of the main flow channels and the general flow patterns within the reservoir. A comprehensive conceptual model should, furthermore, provide an estimate of the size of the reservoir involved. Conceptual models are ultimately the foundation for all geothermal resource assessments, particularly volumetric assessments and geothermal reservoir modelling. In addition, conceptual models provide an important basis of field development plans, i.e. in selecting locations and targets of wells to be drilled.

The conceptual model of the Olkaria geothermal system has, of course, evolved through time (more than 40 years) as more information has been accumulated through surface exploration, drilling, utilization and reservoir engineering work. The first published version of the conceptual model was presented by SWECO and Virkir (1976). It was very simple due to the limited drilling done at the time. Later revisions saw the model expanding to cover more of the Olkaria area and include several zones of hot up-flow, first in the East and West sectors and later in the Northeast sector as well. Ofwona (2002) presented an updated version of the conceptual model. According to his revised model the hydrothermal systems of western and eastern Olkaria are clearly separated by the low temperature zone of central Olkaria. He postulated two possible up-flow zones in Olkaria Northeast and one up-flow zone in Olkaria East, with a down-flow separating Olkaria Northeast and Olkaria East. Extensive boiling also takes place in the up-flow zones to form steam caps below the cap rock, according to this revision. Cold water recharge into the Olkaria geothermal system is assumed to occur from all directions in that model. The latest version of the Olkaria conceptual model, prior to the one presented here, is the one developed by West Japan Engineering Consultants Inc. and subcontractors from 2005 to 2009 (KenGen in-house report). This model was quite comprehensive and appears to be still valid to some extent.

The extensive new data that have become available since 2007, however, mostly through the intensive drilling program KenGen has conducted, has prompted the updating of the Olkaria conceptual model, first the 2011 – 2012 revision presented by Axelsson et al. (2013) and later the 2014 – 2017 revision, which is presented here.

2.2 The Data

Axelsson et al. (2013) review the data available, which were used in the 2011 – 2012 revision of the conceptual model of the Olkaria geothermal system. Here the emphasis is on new data that has become available since that time as well as the model revision conducted during 2014 – 2017. For more detail on the data in general, the reader is referred to Axelsson et al. (2013).

The principal new data collected, analysed and incorporated into the conceptual model are data collected in association with the drilling, completion and testing of the 105 deep wells drilled since 2012 up to the middle of 2016 (25 – 30 wells per year). These include the following:

a) Borehole geology including stratigraphy, loss zone location and rock alteration.
b) Inter-well stratigraphic correlation resulting in the delineation of fault location and displacement.
c) Formation temperature and initial pressure profiles for wells, based on temperature and pressure recovery logs.
d) Injection and discharge test results.
e) Monitoring data from wells utilized, including mass flow, enthalpy and chemical content.

In addition, some more surface exploration data have been collected and analysed, or older data analysed, including:

f) Additional resistivity surveying data including TEM and MT data.
g) Some additional geological mapping data, focussing on faults, fractures and other related structures.

h) Additional analysis of isotope data from wells.

The new data have all been incorporated into an already existing database associated with a 3D visualization software, which has aided the revision of the conceptual model greatly.

The most important components of the conceptual model of the Olkaria geothermal system as a whole are still indications of the main heat sources of the system as well as the temperature model of the system, which by now is extremely detailed in the heavily drilled parts of the system. Micro-seismic data collected in the Olkaria area from 1996 to 1998 provides highly valuable data for the conceptual model of the Olkaria geothermal system. This includes both location of the seismic events as well as information on S-wave attenuation derived from the data, which has been interpreted as reflecting volumes of partially molten material (Fig. 4). The largest of these are found below the Olkaria Domes, Northeast and West production fields, with other smaller attenuating bodies possibly indicating further undiscovered geothermal resources. The conceptual model shows that these potential heat sources are linked with the temperature distribution, reflecting possible zones of hot up-flow. The temperature model for the geothermal system is presented in four horizontal views in figures 5 – 8, while NW-SE temperature and pressure cross-sections are presented in Fig. 9.

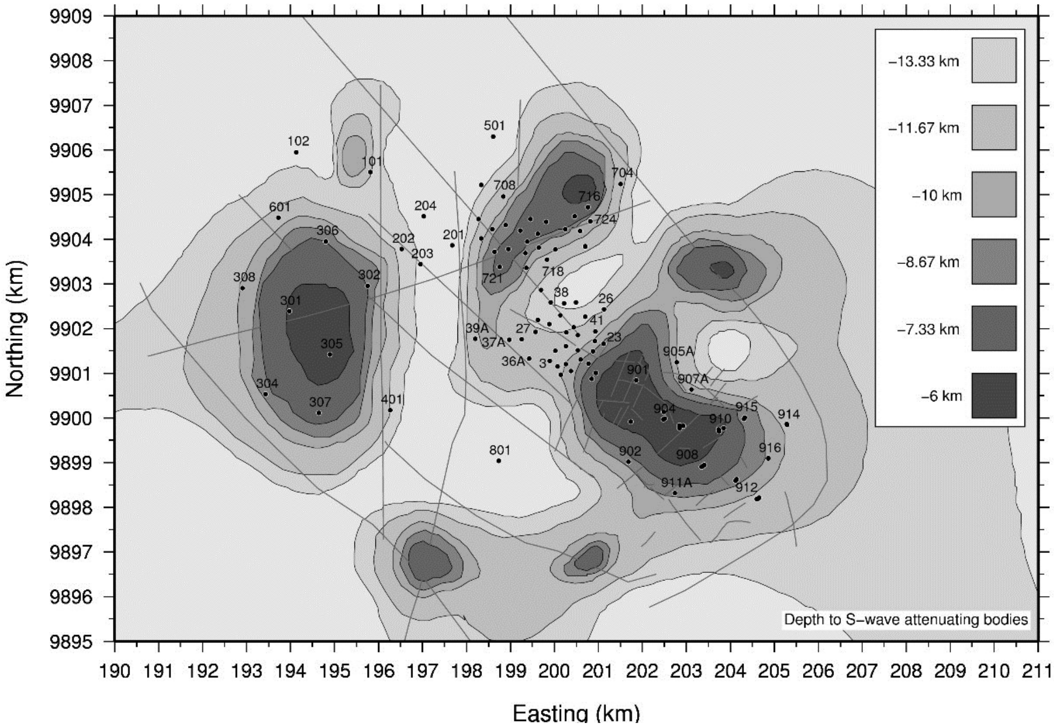

Figure 4: Contour map of the depth to the top of S-wave attenuating bodies beneath the Olkaria geothermal field along with structural features in the area and well location. Based on in-house KenGen reports and Simiyu (2000).

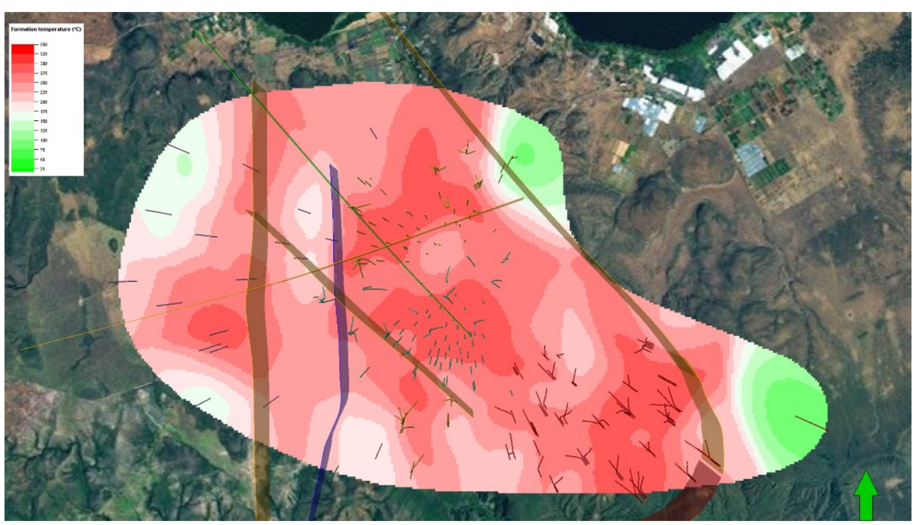

Figure 5: Horizontal view of the temperature distribution at 800 m a.s.l. (~1200 m depth) in the revised temperature model of the Olkaria geothermal system. Also shown are the main faults/fractures of the system.

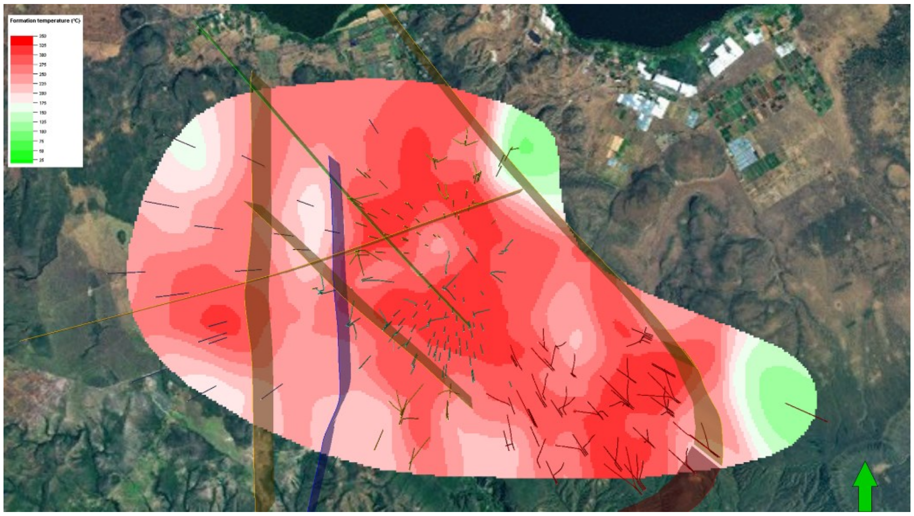

Figure 6: Horizontal view of the temperature distribution at 400 m a.s.l. (~1600 m depth) in the revised temperature model of the Olkaria geothermal system. Also shown are the main faults/fractures of the system.

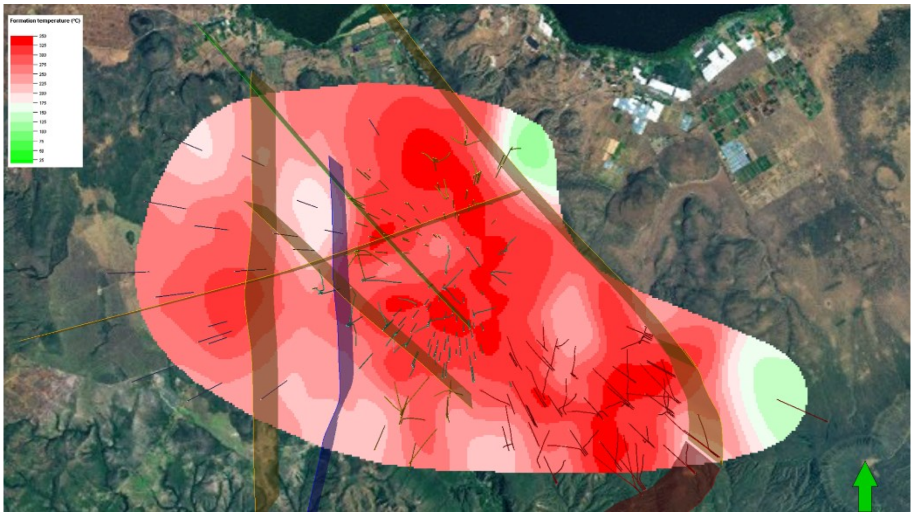

Figure 7: Horizontal view of the temperature distribution at 0 m a.s.l. (~2000 m depth) in the revised temperature model of the Olkaria geothermal system. Also shown are the main faults/fractures of the system.

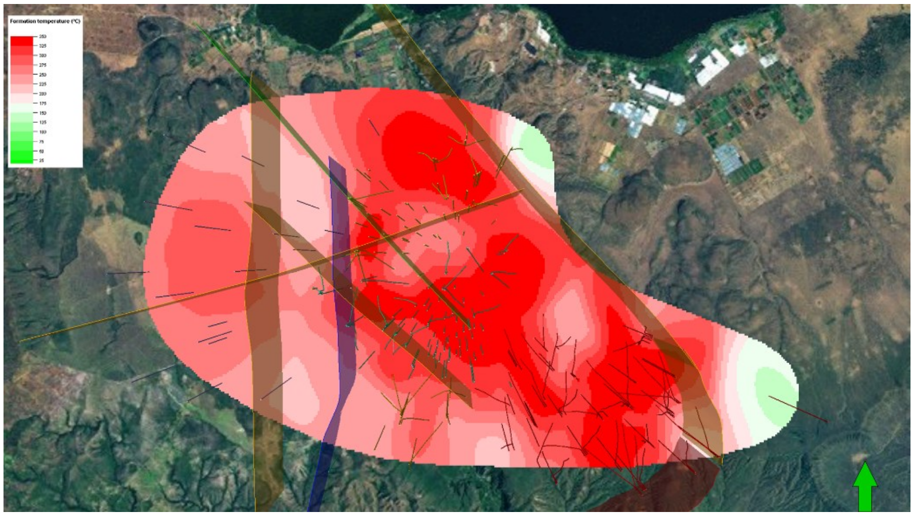

Figure 8: Horizontal view of the temperature distribution at -400 m a.s.l. (~2400 m depth) in the revised temperature model of the Olkaria geothermal system. Also shown are the main faults/fractures of the system.

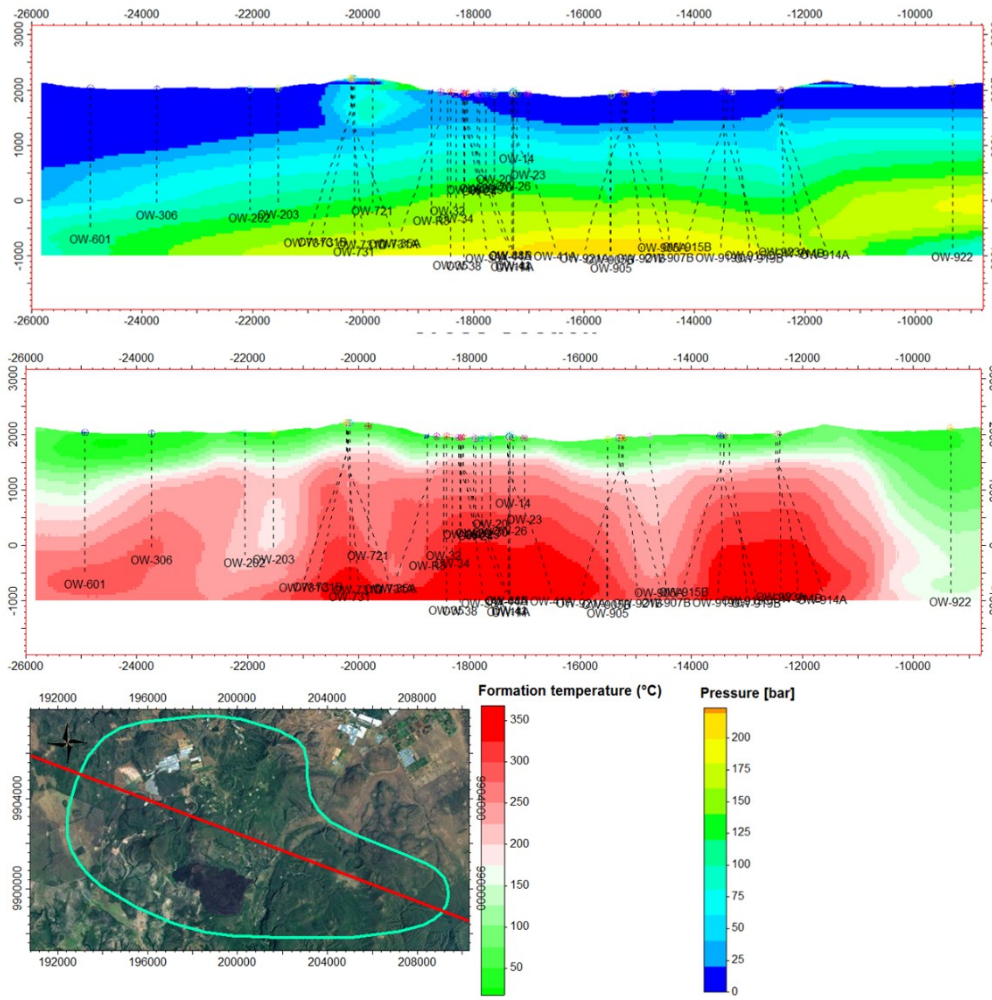

Figure 9: A view of the temperature and pressure distribution in a NW-SE cross section through the Olkaria geothermal system.

A good correlation between the deep-seated heat-source bodies proposed and the temperature conditions above 3 km depth can be seen in the above figures. It should, however, be noted that the micro-seismic study was conducted some 20 years ago. Thus a a repetition of that study, with more up-to-date analysis, would be highly beneficial. The revised temperature model also indicates that some sort of boundaries have been delinated in the Northeast and Domes fields with the wells drilled. These boundaries appear to be linked with with the Gorge Farm fault and the ring structure in the Domes (see Fig. 2), respectively. This was not seen before the 2014 – 2017 conceptual model revision.

The cross-sections presented in Fig. 9 indicate a general pressure- and temperature decline towards the NW. This can be interpreted as indicating a general flow from the center of the system towards NW, with an outflow in that region. The outflow may be delineated, or controlled, by the two NW-striking faults in the north part of the area (see Fig. 2).

2.3 The 2014-17 Model Revision

The revision of the conceptual model for the Olkaria geothermal system presented here has emphasised (a) interpretation of data not available during development of previous conceptual models, (b) development of a new temperature and pressure model for the system, (c) analysis of the permeability structure and structural control of the geothermal system as well as (d) presentation of principal aspects of the conceptual model by a three-dimensional visualization software. The main results of the 2011 – 2012 model revision are still valid and the reader is referred to details presented by Axelsson et al. (2013).

The main aspects of this most recent (2014 – 2017) revision of the conceptual model are the following:

(1) During the 2011 – 2012 conceptual model development the Olkaria geothermal resources were split in two; a heavily explored part where extensive drilling, testing and/or utilization had taken place and a less explored part where limited exploration had taken place, apart from some surface exploration. Since then the heavily explored area has expanded and the less explored area shrunk correspondingly through intense production well drilling. A peripheral zone defined on the edge of the heavily explored part in 2012 (Axelsson et al., 2013) has now been drilled and become part of the heavily explored part.

(2) The heat source of the geothermal system is assumed to be a deep-seated magma chamber or chambers, as in the 2011 version of the conceptual model. Three main intrusions are believed to extend up from the magma chamber(s) to shallower depths of 6 – 8 km. These heat source bodies (possibly partially molten) are proposed to lie beneath Olkaria Hill (Olkaria West), in the northeast beneath the Gorge Farm (Olkaria East and Northeast) volcanic centre, and in the Domes area.

(3) Several major up-flow zones related to these heat sources can be identified from the temperature model, while their number (at least four) cannot be ascertained exactly. The existence of the most prominent up-flow zones is supported by chemical data.

(4) The extent of the Olkaria geothermal resources is now better defined than before, clear boundaries have now been delineated, e.g. along the Gorge Farm fault in the Northeast area and along the ring structure on the southeast edge of the Domes area. These boundaries need to be explored further through additional drilling, as their nature may vary with depth (barriers at shallower levels, perhaps not so at greater depth). The extent of the resources has still not been delineated in other parts of the Olkaria area, such as in the north central part, the northwest part and the south-southwest part. This also applies to the far northeast corner of KenGen's concession area as well as the Hell's Gate area, where no drilling has been undertaken yet.

(5) The recharge to the Olkaria system appears to be controlled by the main structural trends of the system, with the basic flow, especially at depth, being part of the deep Rift Valley ground-water current. At the flanks and in shallower parts it is to a differing extent mixed with water from the Rift Valley escarpments, most evidently in the Western field. Colder in-flow appears to be commonly occurring along major structural trends, e.g. the ring structure in the Domes, the Gorge Farm fault in the Northeast field and the central Ololbutot fault (see Fig. 2).

(6) Understanding of the permeability structure of the Olkaria system has improved considerably in recent years, mainly through the intense drilling that has taken place. The permeability appears to be mainly controlled by predominantly NW-SE and NE-SW faults as well as the ring structure. It also appears to be quite significantly controlled by intersections of these structures. The main resource distribution, furthermore, follows a NW-SE trend, and the temperature and pressure model indicates general flow in that direction in the upper part of the system, including an outflow to the NW.

(7) Recent deep drilling, e.g. in the centre of the geothermal system indicates that the Olkaria geothermal resources may extend to greater depth than explored through drilling so far. The base of the permeable part of the geothermal system has thus not been delineated yet. Deep roots research in other parts of the world (see e.g. http://georg.hi.is/efni/geothermal-deep-roots) may hint at the way forward for geothermal utilization in Olkaria.

2.4 Capacity Assessments

Axelsson et al. (2013) review previous assessments of the production capacity of the Olkaria geothermal system. These mainly include several numerical modelling studies as well as volumetric and lumped parameter modelling studies. The first numerical model was e.g. developed in the 1980's (Bödvarsson et al., 1990). Yet the 2011 – 2012 optimization study involved the most comprehensive assessment of the Olkaria geothermal resources conducted to date.

During the 2011 – 2012 study the electrical generation capacity of the heavily explored part of KenGen's concession area in Olkaria, at that time, was estimated to be about 630 MW_e based on a volumetric resource assessment, lumped parameter pressure response modelling and detailed numerical modelling (Axelsson et al., 2013). This included 150 MW_e already installed and 280 MW_e under construction, at the time. The results of the three different assessment methods were quite comparable, which added confidence to the results. The electrical generation capacity of the less explored part was estimated to be about 300 MW_e based on a Monte Carlo volumetric assessment, an estimate that had to be confirmed through comprehensive exploration and drilling. Today (end of 2016) the capacity installed in KenGen's concession area corresponds to 530 MW_e. It should be noted that in addition 140 MW_e are installed in Olkaria West (Olkaria III) by OrPower-4.

The numerical model set up in 2011 – 2012 has been revised and updated during the 2014 – 2017 model maintenance project. At the writing of this paper its revision is being finalized, and future predictions being calculated for different utilization scenarios. Preliminary results indicate a capacity of at least 800 MW_e, but with quite a large pressure draw-down in some sectors. Yet the results for some parts of the system are uncertain because of limited testing and production experience; these sectors may also require more reinjection than modelled to manage pressure draw-down. Recent Monte Carlo volumetric assessments, of approximately half of what is now the less explored area, yield a P90 estimate of approximately 140 MW_e, while the southwest and northeast corners of the concession area have not been assessed specifically during the 2014 – 2017 project.

3. CONCLUSIONS

This paper has described the principal aspects of the most up-to-date version of the conceptual model of the Olkaria geothermal system in Kenya. The model has been evolving concurrently with the development of the system for electrical energy generation, with the earliest version dating back to the 1970's. The present version is the product of a comprehensive optimization study carried out during 2011 – 2012 and a follow-up model maintenance project that started in 2014, and is now coming to an end. The present version is quite comprehensive and detailed for a large part of the geothermal system, mainly because of the extensive data collected through the roughly 165 deep production and exploration wells drilled in KenGen's licence area in the Olkaria field. The basis of the conceptual model is a comprehensive database incorporating almost all available Olkaria exploration-, well- and monitoring data, linked to a 3-D visualization software. Accompanying the conceptual model development has been the construction and revision of the largest and most comprehensive and detailed numerical model of the geothermal system set up to date.

The conceptual model of the Olkaria geothermal system can be considered a living entity, which requires constant updating in order for it to be effective as a key tool in well-targeting and long-term management. It should, therefore, be updated regularly both on basis of new exploration data, data from new wells as they are drilled and tested, and very importantly on basis of constantly collected monitoring data. As the geothermal system is very large and complex, and parts of it have not been thoroughly explored yet, variable research remains to be conducted. This will not be listed here, but we would like to point out the possibility that productive resources may still remain to be discovered at depth below the present maximum drilling depth of 3000 m, as the base of the permeable part of the geothermal system has not been delineated yet. Deep roots research, such as ongoing in Iceland, Italy and Japan may to some extent be the way forward for geothermal utilization in Olkaria.

The Olkaria system is an unusually large and powerful geothermal system. During the last decade, its development and consequent expansion of power-plant capacity has been very rapid. This makes the need for comprehensive and efficient management extremely important, including large-scale reinjection, which by now has increased to almost 50%. Essential components of such management also include comprehensive and effective monitoring of the geothermal system's response to the large-scale utilization (e.g. accurate monitoring of its pressure decline) and the maintaining and application of the conceptual and numerical models. The present utilization and future development will be extremely important for Kenya as a country, and are expected to be accompanied by rapid economic, environmental and social benefits, in line with Kenya Vision 2030 (http://www.vision2030.go.ke/).

The work presented here focusses on KenGen's licence area in Olkaria, while OrPower-4 also runs a sizable operation in their concession. Interference between the two concessions was not considered as being significant in the past, when both operations were much smaller in terms of capacity. This has now changed and we recommend that some sort of common management be set up for the whole Olkaria area, including the union of conceptual models and the construction of a common numerical model for both of KenGen's and OrPower-4's concessions, in the near future. This also applies to other concessions, such as to the south and southeast of Olkaria, as their development is about to start to some extent.

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