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RESERVOIR MODELS OF THE OLKARIA GEOTHERMAL PROJECT (1975 – 1985)

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ABSTRACT

Over most of the surface of the earth conductive heat flow from deep in the crust is normal, and on the average this heat flux is 60mW/msq and this maintains an average temperature gradient of 30^0 C/km. Both this heat flux and the temperature attained at reasonable depths are too low to have any economic value at present. However, in anomalous regions the local heat flux and geothermal gradient may be much higher than these values and there may be surface discharges of hot water and steam. These zones thus provide a source of energy (hot rock) and the transport medium (fluid) through which we may exploit this energy. Surface studies are thus usually made in the "steam seep" zones and exploratory wells are drilled. The potential of any "hot" anomaly, however, has to be evaluated before any development can be initiated and recently there have been efforts to apply the most modern geological and reservoir engineering principles in order to quantify the reservoir parameters, particularly those related to estimates of reserves and future productivity. This paper discusses the relation between geological, geochemical, geophysical prospecting and reservoir assessment during the exploration and development phase of a geothermal prospect. The Olkaria Geothermal Project in Kenya (45MWe) is cited as a case study.

Introduction

The sequence of activities undertaken during a geothermal exploration program have been reviewed by Ramey (1981) and are summarized in Fig. 1. The initial phase consists of conducting multi-disciplinary regional surveys to identify any promising prospects. In geological studies special emphasis is placed on the tectonic and stratigraphic setting of the area, including a study of recent faulting and the age distribution of young volcanic rocks. Hydrologic studies include the mapping of aquifers, aquicludes and the static groundwater flow pattern, and the measurements of surface discharge from springs. Temperature and discharge measurements of natural hot water and fumaroles provide information on heat flow from these sources which has to be added to the surface heat flux data in the determination of the total heat output from an area. Geochemical studies involve sampling water and gases from hot springs and fumaroles, and analysis of these samples provide information on the temperature to be expected at depth, the chemical nature of the fluids and the source of recharging water. Geophysical surveys are especially useful in delineating the boundaries of a prospect and for pinpointing targets for exploratory drilling. Electrical resistivity surveys are extremely useful as the resistivity of a porous medium containing brine or hot temperature fluid is extremely low.[1]

Seismic, gravimetric, magnetic and micro-earthquake surveys are also useful in defining reasonable conceptual models of a prospect. Shallow drill holes for the purpose of determining the geothermal gradient and the surface heat flux data are also useful to guide selection of a site for exploratory drilling. However, the acid test of any exploration program is the drilling of an exploratory well.

When and if a successful bore hole is drilled in a prospect the production engineer is responsible for the construction and maintenance of well head, steam collecting and separating equipment and allocating plant load to individual wells. He also has the main task of determining the yield characteristics, the potential and efficiency of the well, and analysis of the well test data to determine whether or not some remedial work is required to obtain optimum production from existing wells. The problems involve a low driving force moving the fluid into the well (low formation pressure), low formation permeability, or a damaged well bore condition. The reservoir engineer is interested in the long term behavior of the well and the reservoir. Important questions he must answer are: what is the optimum plan of development of the reservoir, how many wells and what sort of pattern of wells will be required for the optimum development of the reservoir, what sort of fluid will the reservoir produce throughout the production life of the reservoir, and what will be the future productivity of the wells.

This means that it is necessary for a reservoir engineer to estimate the areal extent, thickness, porosity and fluid content of the reservoir from early data obtained from geophysical measurements, geological information and quantitative analysis of core samples obtained from the reservoir. Core analysis involves the determination of storage capacity within the pore space by determination of the porosity of the rock samples from a bore-hole; whereas well testing is the most common and reliable technique for providing data on the in-situ reservoir parameters. The analysis of the data provides the first estimates of formation permeability and other important producing mechanisms and involves the interpretation of pressure-time information obtained following a specific schedule of production of a well or wells in a reservoir, while reservoir modeling provides quantitative estimates of future fluid flow from the reservoir as a whole. Mathematical reservoir modeling involves a developing conceptual model of the field under investigation, quantifying the model with data obtained from well testing (permeability, the volumetric extent of the reservoir, etc.) and calibrating it with the history of the field under exploitation.

A conceptual model of a geothermal system is a qualitative or a descriptive model of the system or part of it that incorporates the essential physical features of the reservoir under development. It should describe the source of water, mechanisms of water transport to depth, the process of heating the deeper sections of the system, the subsequent rise of buoyant hot liquid, its dispersion into chargeable aquifers, the cooling of aquifer liquids by near surface effects and all impervious boundaries that might affect future production. To construct and correctly interpret such a detailed conceptual model requires input data from a wide spectrum of geological, hydrological, geochemical and geophysical measurements as well as a profound understanding of the hydrological, geochemical and geophysical measurements as well as understanding the hydrodynamics of liquids convecting in rock formations. Vigorous convection will occur only in geological formations having adequate permeability derived from inter-granular spaces and fracture distribution.

Before any field developments take place it is necessary that the conceptual model of the field be quantified by drilling bore-holes, and carrying out temperature, pressure logs, well testing and core analysis to obtain data to give a preliminary estimate of the resource quality and quantity so that the model's predictive value can be judged.

An Example of Reservoir Modelling

Modelling studies of the Olkaria geothermal field illustrate very well the relationship of earth sciences, well test analysis and reservoir physics in building an initial working conceptual model and refining it as more and more data becomes available. Geothermal exploration in the Rift Valley of Kenya started in 1970. At the three prospects shown in Fig. 2, geological, hydrological, geochemical and geophysical surveys ware carried out to delineate the geothermal reservoirs responsible for the intense surface thermal manifestations in these area in the form of hot water springs, fumaroles and geysers. In 1972 it was decided to concentrate drilling the Olkaria prospect (Noble et al. 1976). An infra-red imagery of the area showed that the thermal activity in the form of fumaroles and hot ground is scattered over an area of 50km^2 and is typically associated with N-S trending faults.[2] Geological surveys indicated that the area is underlain by volcanic rock with basalt dominating below a depth of 500m which would act as a caprock to the system and underlying zone of rocks mainly consisting of tuffs.

Hydrological surveys showed that the general groundwater movement is into the Rift Valley from the Mau and Aberdares Range of mountains and southwards from Lake Naivasha, and the former areas were assumed to supply deep recharge tot he system. Geochemical analysis of gas compositions in steam from fumaroles suggested that underground temperatures exceeded 300^{o}C near the OLK2 well (Fig. 3). Geophysical resistivity surveys showed four areas of less than 20 Ohm-m, and seismic surveys indicated that the basement rocks reside approximately 1600 mbsl (Bhogal, 1980)[3]

The first conceptual model of the system (not shown) was largely based on the interpretation of electrical resistivity data on the premises that since the electrical resistivity of a porous medium containing dry steam can be very high, electrical resistivity surveys could discriminate between dry steam and the underlying hot water reservoir. The model conceived a dry steam reservoir occurring in patches in the areas above depressed water level. Well OLK1 was sited to exploit dry steam. The well gave negative results, with a temperature of 126^{o}C at 1000 m depth, but the water level, was found to be very low. The steam zone was not established, and a new conceptual model of the field had to be built. Although another four cellars had been constructed in the vicinity of OLK1, it was decided to drill in the area which showed low 20 ohm-m resistivity and favorable gas chemistry. Well OLK2 gave positive results penetrating a 100m thick steam zone below 650 m depth. Aquifers where encountered at greater depths but the well was drilled to 1350m and the maximum down-hole temperatures were about 280^{o}C. Another five wells were drilled as offsets before a feasibility study to harness the steam was carried out by SWECO (1976).

Figure 4 shows the conceptual model and the processes operating the reservoir around Well OLK6. It incorporates all the geological, lithological and down-hole pressure and temperature information available in 1976. Circulating groundwater attains a high temperature of 320^{o}C at 1600 mbs under the area and due to the density difference between the hot fluid and colder water in surrounding regions the fluid rises under a buoyancy force. About sea level the water has reached the saturation pressure at 320^{o}C and boiling initiates steam bubbles in the water. The rising fluid becomes a mixture of steam and water and the temperatures of the mixture follows the boiling curve of water as pressure decreases upward. The upward migration of the steam mixture is influenced by relative permeabilities of the rock for each phase but these depend in turn on the relative volumes of each phase in the permeable volume of rock. At low steam saturation, the relative permeability for steam is so low that the steam is practically stagnant or carried with the water as small bubbles. As the steam saturation increases at lower pressures, the relative permeability of steam increases and separate movement or the steam bubbles become possible. The steam then rises faster than the water and gradually dominates in the largest channels where resistance to flow is lowest. The water lags behind and the loss of steam with time builds up a concentration gradient of increasing salinity. At 1200-1250 masl, the impermeable caprock prevents further rising of the steam and the low piezometric head of the reservoir water allows the steam to accumulate under the caprock at a pressure of 35-38 bars absolute. Although steam is dominating in this zone, water is also present as condensed porewater and this flows downwards. With rapid development and exploitation (45 MWe in April 1985) and the increasing amount of data being gathered at Olkaria the reservoir model has been refined. Drilling and reinterpretation of resistivity data indicate that there is a lens of saline water overlying the steam reservoir and well test analysis indicates that the steam zone thickens eastwards. [4]

These observations have been incorporated in the new model shown in Figure 5.[5]

New exploration wells OW101 to OW106, continued geological and geophysical exploration, and reinterpretation of previous data with the experience gained over the last ten years have also led to refinements of the original conceptual model of the Olkaria geothermal system. Lithological and well test data from the new wells has provided spatial information about the subsurface geology, the depth to steam zone and the underlying boiling reservoir. The geological model incorporating all this information is shown in Figure 6. The reinterpretation of geophysical data has redefined the up-flow zone in a different area, has demarcated the areal extent of the saline aquifer and positive suggestions regarding the recharge and outflow areas from the system have been made (Fig. 7). Well test data indicates anomalously high pressures in OW301 compared to the present production area around OLK2. At present, one of the important question about the Olkaria resource is whether the OLK2 east reservoir and the OW301 west reservoir are hydrologically connected or whether two separate resources are present (KPC, 1984). Study of the chemistry of fluids is expected to provide an answer. If they are separate, a new conceptual model will have to be formulated. It will provide detail to the original model.[6]

The development of the quantification processes of the Olkaria field follows a trend parallel to the conceptual models discussed above. The first study of Sweco (1976) used the models shown in Figures 3 and 4 to estimate the resource energy of the reservoir. Using an areal extent of 12 km^2 for the low resistivity zone around OLK2 and a thickness of 2.8 km for the reservoir, porosity of 10%, recovery factor of 10% a resource of 170 MWe for 25 years on the assumption that it had a constant thickness and similar areal extent as the underlying water reservoir. The probable resource for the whole area was estimated to be 218 MWe for 25 years assuming that the other low resistivity areas have a reservoir similar to the one discussed above. Simulation studies by Bodvarsson (1980), and Bodvarsson and Pruess (1981) have used numerical modeling techniques to investigate the effects of vertical and horizontal permeabilities on the generating capacity of the Olkaria field, and also have investigated the effects of exploiting aquifers at different depths. The results of these simulation studies indicated that the well field (East of Olkaria) was capable of providing steam for 45 MWe power production and the field was developed to that capacity by April 1985. The conceptual model of the field shown in Figure 5 with twenty two producing wells has been used to develop a well by well (distributed) three dimensional numerical model of the field that can be used to predict with confidence the future behavior of the wells, the effects of re-injection, and the overall depletion of the reservoir (Bordvarsson et al., 1985). The surface locations of wells are used as nodal points to develop a grid and the other elements without any wells are assumed to provide recharge to the well field. To determine the vertical dimension of the model the locations and relative strengths of feed zones for all wells are considered. The model matches reasonably well the flow rate and enthalpy history of all the Olkaria wells. The main conclusions from the study are that 60% of the production fluid comes from liquid zone and the rest from the steam zone, and the present East Olkaria area can apparently easily handle power production of 45 MWe for the next 30 years.[7]

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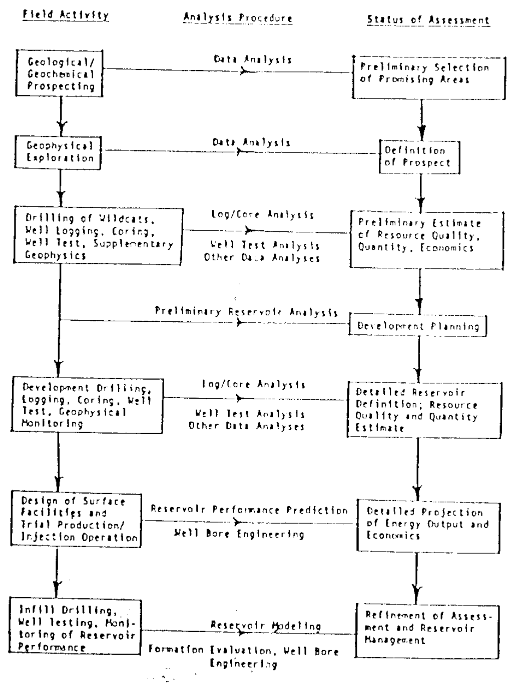

Figure 1. Flow chart of geothermal reservoir assessment (from Ramey, 1981).

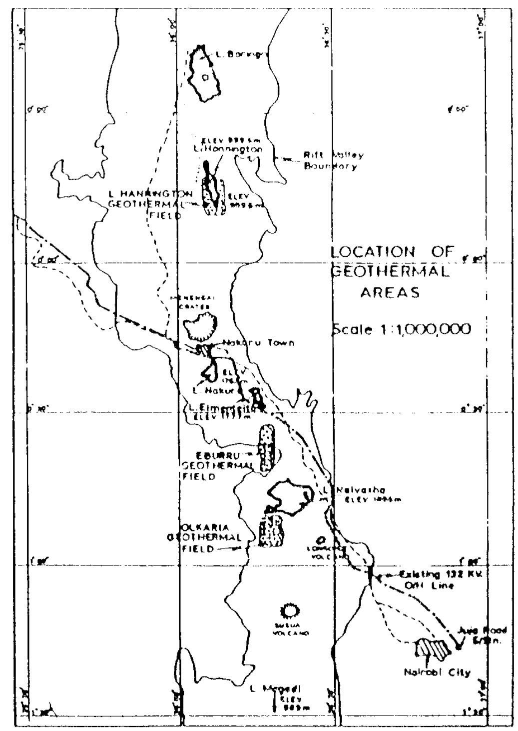

Figure 2. Location of geothermal areas in the Rift Valley of Kenya (from Noble *et al.*, 1976).

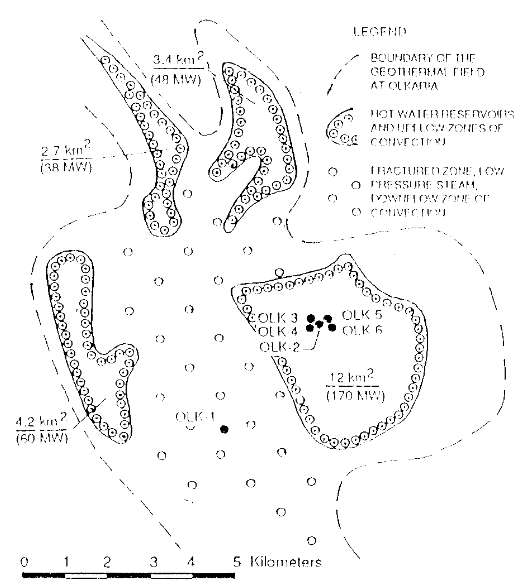

Figure 3. Potential hot water reservoirs at Olkaria (modified after Bhogal, 1978).

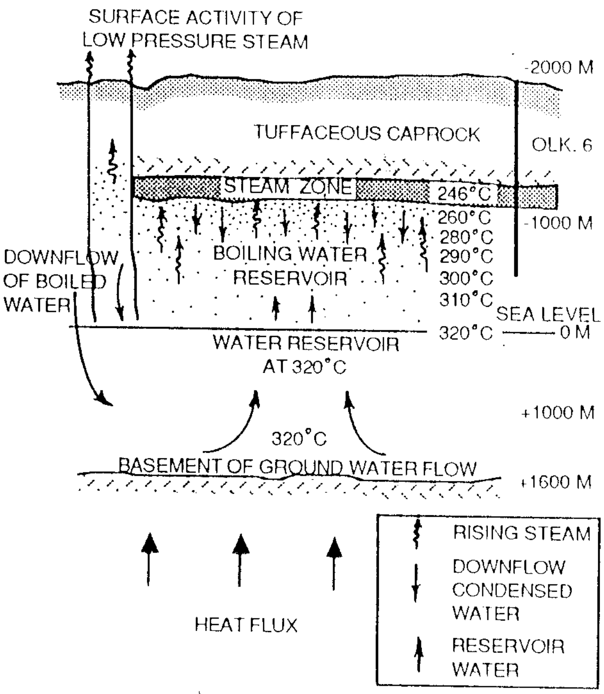

Figure 4. Schematic cross section through Olkaria resservoir (from SWECO, 1976)

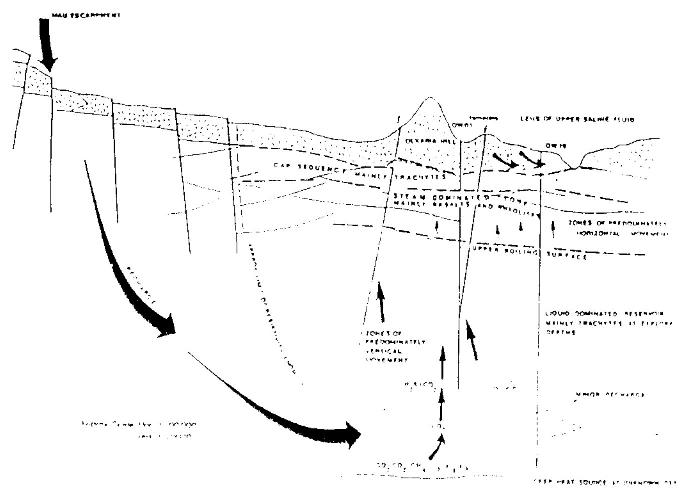

Figure 6. Schematic cross-section through Olkaria reservoir (from Kenya Power Company, KPC, 1984).

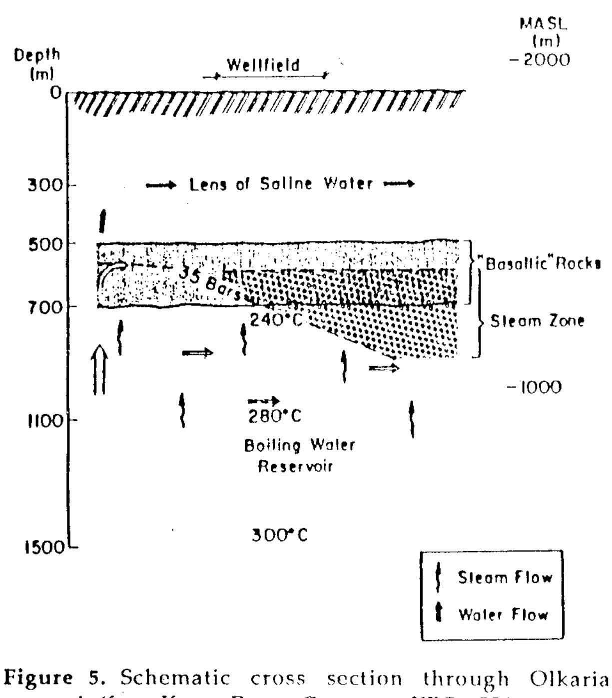

Figure 5. Schematic cross section through Olkaria reservoir (from Kenya Power Company, KPC, 1984).

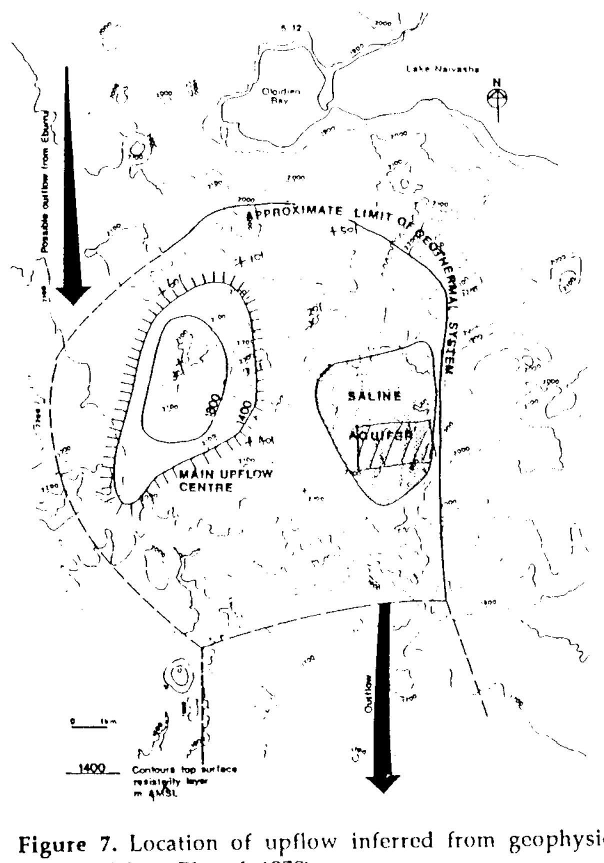

Figure 7. Location of upflow inferred from geophysics (modified from Bhogal, 1978).