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INFLUENCE OF HYDROTHERMAL ALTERATION IN PERMEABILITY OF OLKARIA NORTH EAST AND OLKARIA DOMES GEOTHERMAL RESERVOIRS.

A REPORT SUBMITTED TO THE DEPARTMENT OF GEOLOGY IN FULFILLMENT OF THE REQUIREMENTS FOR SGL 413 (PROJECT IN GEOLOGY).

JUNE 2011

DECLARATION AND APPROVAL

Declaration by student

I declare that this is my original work and has not been presented anywhere for examination.

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This proposal has not been submitted for examination with my approval as the official University Supervisor.

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ABSTRACT

The geothermal exploration well OW-701 and OW-709 are found in the Olkaria Northeast fields while OW-904 and OW-905A are found in the Olkaria Domes. Rocks encountered in the wells include pyroclastics, ryholite,tuff, trachyte and basalts. Fractures, vesicle, spaces between breccia fragments, glassy rocks and primary minerals exhibit little or no hydrothermal alteration in the upper parts of the wells. Fractures are mechanical breaks in rocks, they provide pathways for fluid flow. The intensity of veining varies with depth. They are most common in basalts and trachytes and less common in rhyolite and tuffs. The common vein filling minerals are calcite, quartz, pyrite, epidote and clays. The secondary mineralization results in decrease in permeability of reservoir rocks. The chemical composition of the host rock determines the availability of components to form alteration minerals as well as possible fugitive components from the presumed magmatic heat source. Temperature dictates the formation of hydrothermal minerals. Hydrothermal mineral deposition is mostly found in vesicles and vein fillings. The vesicles are filled, lined or unfilled by secondary minerals. Hydrothermal mineral deposition can be useful in measuring permeability.

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1. INTRODUCTION

The Greater Olkaria geothermal area is situated south of Lake Naivasha on the floor of the southern segment of the Kenya rift. The geology of the Olkaria Geothermal area is subdivided into seven fields for geothermal development purposes namely development purposes namely Olkaria East, Olkaria Northeast, Olkaria Central, Olkaria Northwest, Olkaria Southwest, Olkaria Southeast and Olkaria Domes.

Geothermal energy is a clean and reliable source for production of electricity, which is not affected by short-term fluctuations in the weather or world producer prices of oil. Once installed, maintenance costs are low and availability is high..

1.1 STATEMENT OF THE PROBLEM

In the Olkaria geothermal field, hydrothermal alteration minerals appear both as replacement of the primary minerals, as well as fillings in vesicles, vugs and fractures. Primary minerals usually tend to alter to hydrothermal alteration minerals that are either stable or at least metastable in these environments. Permeability of the rocks controls the access of thermal fluids, which cause hydrothermal alteration of the rocks and precipitation of secondary minerals in open spaces.

Hydrothermal minerals are deposited in the fissures and on wall linings of drilled wells, hence reducing permeability. The rate of deposition in rock voids during alteration is higher in rocks with high permeability. Scaling is a major challenge to already productive wells. Scaling is bottom hole formation of mineral deposits caused by change in temperature and pressure.

1.2 RESEARCH QUESTIONS

What is the occurrence of hydrothermal minerals in the Olkaria Northeast and Olkaria Domes geothermal reservoirs?

How do hydrothermal minerals influence permeability of rocks in the geothermal reservoirs?

How does permeability relate with hydrothermal alteration of rocks in Olkaria NE and Domes reservoirs?

1.3 OBJECTIVES

Identify the distribution of hydrothermal minerals in the Olkaria Northeast and Olkaria Domes reservoirs.

Establish how hydrothermal alteration of rocks has influenced permeability in both the Olkaria Northeast and Olkaria Domes.

Establish the relationship between hydrothermal alteration and permeability of rocks

1.4 OUTPUT

The intended output is to find out how hydrothermal alteration mineral deposition has occurred in the Olkaria NE and Domes reservoirs and how this relates to steam production used for power production.

1.5 METHODOLOGY

This work being a library research, an evaluation of the geological cross sections of the area and structural map of the area was done. Literature on the permeability patterns in the Olkaria geothermal field, petrographic studies of drill cuttings from wells and literature on the lithology and distribution of hydrothermal minerals was compiled.

1.6 JUSTIFICATION

Geothermal power is cheap, efficient and does not depend on climatic conditions. Olkaria Geothermal Project is aimed at exploiting this renewable energy source. Wells drilled in this area have reduced steam production which can be a result of resource depletion or sealing of the steam pathways. We know that well re-injection is done to prevent resource depletion, yet steam production has reduced over the years.

2. METHODOLOGY

2.1 LITERATURE REVIEW

Geothermal reservoir fluids are produced in important volumes only from zones containing fractures that are both open and well-connected hydraulically.

According to Lagat (1995), the occurrences and distribution of these hydrothermal minerals indicate that the minerals in all the wells show prograde variation patterns. The correlation of between the formation, interpreted hydrothermal alteration and fluid inclusion temperatures indicate that there have been temporal changes in the Olkaria Domes systems with part of the field indicating cooling whereas other parts indicate heating.

Fractures, vesicles, spaces between breccias fragments, glassy rocks and primary minerals exhibit little or no hydrothermal alteration in the upper parts of the wells with mainly silica, calcite, zeolites, phyllosilicates, oxides and sulphides being the alteration minerals present. In deeper parts of the wells, however, hydrothermal alteration is ranged from high to extensive.

Structures in the greater Olkaria volcanic complex include; the ring structure, the Ol'Njorowa gorge, the ENE-WSW Olkaria fault and N-S, NNE-SSW, NW-SE and WNW-ESE trending faults. Subsurface faults have been encountered in most Olkaria wells (Odongo, 1982)

3. RESULTS

The Greater Olkaria geothermal area is situated south of Lake Naivasha on the floor of the southern segment of the Kenya rift. The Kenya rift is part of the east African rift system. The rift is part of a continental divergent zone where spreading occurs resulting to the thinning of the crust hence eruption of the lavas and associated volcanic activities. Figure 3.1 shows the geothermal prospects along the Kenya rift valley.

Figure 3-1 : Map of the Kenya rift showing the location of Olkaria geothermal field

(Karingithi, 2000)

The Olkaria geothermal area is within the Greater Olkaria volcanic complex. It is subdivided into seven fields for geothermal development purposes namely: Olkaria east, Olkaria northeast, Olkaria central, Olkaria northwest, Olkaria southwest, Olkaria southeast and Olkaria domes. (Fig 3.2)

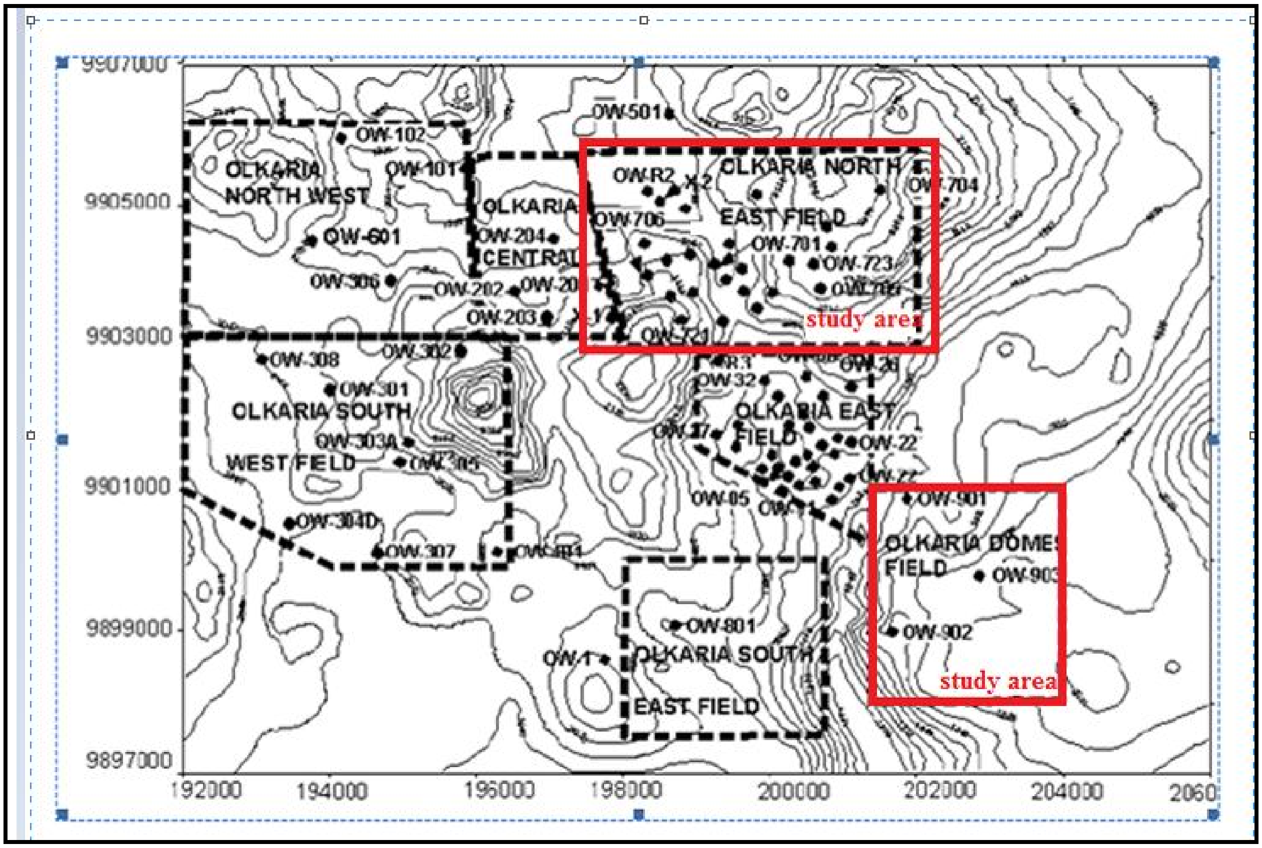

Figure 3-2 : Map of the Greater Olkaria geothermal areas showing the fields' location.

(Karingithi, 2000)

This report covers the zones affected by hydrothermal alteration minerals filling fractures, fissures, cavities and vugs. From the Olkaria Domes field, the wells put into consideration are wells OW-904 and OW-905A. The well OW-904 is a directional well that is drilled to a depth of 2793m total depth, which is approximately 2660m vertical depth. From Olkaria North East, we consider the wells 701 and 702, (Ryder, 1986).

2.1 GEOLOGY OF THE OLKARIA DOMES AND OLKARIA NE RESERVOIRS

The Olkaria volcanic complex is one of several major volcanic centers in the Central Kenya Rift of the East African Rift system, associated with an area of Quaternary silicic volcanism. A structural N-S running boundary passes through the Olkaria Hill that divides the Greater Olkaria area into east and west stratigraphic zones. In the Olkaria area the surface to about 1400 m a.s.l. is covered by Quaternary comendites and pantellerites and an extensive cover of pyroclastic fall from Longonot and Suswa. Volcanic eruption centers are structurally controlled.

The main centers are the Olkaria Hill, Ololbutot fault zone and the Gorge Farm area. The most recent volcanism is associated with the Ololbutot fracture zone. The youngest lava is the Ololbutot rhyolite flow, which is about 250 ±100 years BP (Karingithi, 2000)

Structurally the Rift Valley can be divided into the Northern, Central and Southern parts. The geothermal field is associated with the Olkaria volcanic centre. The reservoir appears bounded by faults forming a ring structure. Fractures also contribute to well discharge, the hydrology of the reservoir is controlled by the Olkaria fault (Odongo, 1982)

The major rocks found in the reservoirs are unconsolidated pyroclastics that are dominant in the shallow levels, overlying a volcanic sequence whose lithological composition is dominated by comenditic rhyolite, trachyte, basalt and tuff.

Pyroclastics

The pyroclastics are yellow to brown and form the upper part of the reservoirs. The rock is unindurated and consists of lithic fragments of rhyolite, trachyte and syenite. The matrix is dominated by ash size particles, crystals of glass, quartz, feldspars, amphiboles, obsidian and pumice.

Tuff

The tuff is brownish grey, grey to white in color and occurs in two types; the glassy and fragmental tuff. The glassy tuff is wholly glassy whereas the fragmental tuff is made up of lithics of lava fragments as well as subhedral to anhedral crystals lithics of quartz and feldspars.

Rhyolites

The rock occurs in two types

- Non porphyritic to weakly porphyritic type
- The quartz and feldspar porphyritic with abundant riebeckite and occasional hornblende

The rock is grey, greenish grey to brownish grey in color. The porphyritic type consists of phenocrysts of quartz and sanidine and arfvedsonite-riebeckite. The non porphyritic type consists of minor sanidine and quartz phenocrysts.

Trachytes

This is the most abundant rock in the area and occurs alternating with tuff, basalt and rhyolite. The rock is grey to brownish grey, fine grained and is composed of phenocrysts of feldspars. The matrix consists of flow oriented feldspar microlites in a fine grained to glassy groundmass. Sanidine crystals are the most common phenocrysts and occur in crystals

Basalts

They alternate with other rocks. The rock is light greenish grey to black, with holocrystalline groundmass composed of plagioclase laths and anhedral clinopyroxene and magnetite. It is porphyritic with plagioclase and pyroxene phenocrysts.

2.2 PERMEABILITY

Permeability is a measure of the ease with which fluid will flow through a porous medium under a specified hydraulic gradient.

The bulk permeability of volcanic rocks of Olkaria NE and Olkaria Domes is a function of primary and secondary permeability. **Primary permeability/ formation permeability**: develops from the original texture of the rock (for example, interconnected pores and vesicles and grain boundaries).

Secondary permeability/ fracture permeability: is promoted by rock fracture where it occurs, it is generally the dominant type of permeability in Olkaria NE and Okaria Domes. Fractured zones act as high permeability conduits for both vertical and horizontal flows. (Lagat, 2008)

Extraneous fluid enters the fractures, where it becomes supersaturated with respect to the rock composition. The presence of fractures thus allows fluid to flow over long distances and, in the process, become oversaturated in its solute, primarily due to changes in pressure and temperature. This causes minerals to precipitate in veins; the most common precipitated minerals the reservoirs are silica and quartz.

2.3 HYDROTHERMAL ALTERATION

Rock alteration is a change in the textural, mineralogical and chemical composition of the host rock brought about by the action of hydrothermal fluids, steam and gas. The primary minerals are replaced by the secondary minerals because there has been a change in the prevailing conditions subjected to the rock. These changes could be changes in temperature, pressure, or chemical conditions or any combination of these. Hydrothermal alteration is a change in the mineralogy as a result of interaction of the rock with hot water fluids called hydrothermal fluids. The fluids carry metals in solution, either from a nearby igneous source, or from leaching out of some nearby rocks. (Evans, 1993)

Hydrothermal fluids cause hydrothermal alteration of rocks by passing hot water fluids through the rocks and changing their composition by adding or removing or redistributing components.

Temperatures can range from weakly elevated to boiling. Fluid composition is extremely variable. They may contain various types of gases, salts (briny fluids), water, and metals. The metals are carried as different complexes, thought to involve mainly sulphur and chlorine.

Meteoric water is possibly the main source of hydrothermal fluids, which percolates down to the faults. Such fluid transfers in the permeable system consist of a set of fissures generated during micro-seismic events in the Olkaria region.

Another source can be the magmatic rocks themselves, which exsolve water (called “juvenile” water) during the final stages of cooling.

Hydrothermal fluids circulate along fractures and faults. A formation, which has a well-developed fracture system, may serve as an excellent host rock. Veins form where the fluids flow through larger, open space fractures and precipitate minerals along the walls of the fracture, eventually filling it completely. Fault zones are excellent places for fluids to circulate and precipitate mineralization. Faulting may develop breccia and gouge, which is often a good candidate for replacement style mineralization. The form of mineralization and alteration associated with faults is highly variable, and may include massive to fine-grained, networks of veinlets, and occasionally vugy textures in some breccias.

Permeability of rocks controls the access of thermal fluids which cause hydrothermal alteration of rocks and precipitation of secondary minerals in open spaces. The degree of permeability is directly related to the intensity of the rock.

Hydrothermal mineral deposition is mostly found in vesicles and vein fillings. These voids form much of the porosity and permeability of the geothermal system. The vesicles are filled, lined or filled by secondary minerals (Koestono, 2007). Hydrothermal alteration in the geothermal system is a product of water-rock interaction. Hydrothermal deposition can be useful in measuring permeability.

The chemical composition of the host rock determines the availability of components to form alteration minerals as well as possible fugitive components from the presumed magmatic heat source. Temperature dictates the formation of hydrothermal minerals because most of the chemical reactions require elevated temperatures and also minerals are thermodynamically stable at high temperatures.

2.3.1 ALTERATION TYPES

There are as many alteration types as there minerals in the Olkaria North east and Olkaria Domes. According to Lagat, 1995, the following are the most common types of alteration:

a. Propylitic: (Chlorite and epidote)

Propylitic alteration turns rocks green, because the new minerals formed are green. These minerals include chlorite and epidote. They usually form from the decomposition of Fe-Mg-bearing minerals, such as biotite, amphibole or pyroxene, although they can also replace feldspars. Propylitic alteration occurs at high temperatures. Propylitic alteration will generally form in a distal setting relative to other alteration types. Presence of chlorite and epidote indicate temperatures of 220-340ºC.

b. Potassic: (K-feldspar and adularia)

Potassic alteration is a relatively high temperature type of alteration, which results from potassium enrichment. This style of alteration can form before complete crystallization of magma, as evidenced by the typically sinuous and rather discontinuous vein patterns. Potassic alteration can occur in deeper plutonic environments, where orthoclase will be formed, or in shallow, volcanic environments where adularia is formed.

c. Silicification: (Quartz)

Silicification is the addition of secondary silica (SiO_2). Silicification is one of the most common types of alteration, and it occurs in many different styles. One of the most common styles is called “silica flooding”, which results form replacement of the rock with microcrystalline quartz (chalcedony). Greater porosity of a rock will facilitate this process. Another common style of silicification is the formation of close-spaced fractures in a network, which are filled with quartz. Silica flooding is sometimes present in the wall rock along the margins of quartz veins. Silicification can occur over a wide range of temperatures.

d. Carbonatization: (Carbonate minerals)

Carbonitization is a general term for the addition of any type of carbonate mineral. The most common is calcite.

e. Argillic: (Clay minerals)

Argillic alteration is that which introduces any one of a wide variety of clay minerals, including kaolinite, smectite and illite. Argillic alteration is generally a low temperature event, and some may occur in atmospheric conditions. The earliest signs of argillic alteration include the bleaching out of feldspars.

f. Zeolitic: (Zeolite minerals)

Zeolitic alteration is often associated with volcanic environments, but it can occur at considerable distances from these. In volcanic environments, the zeolite minerals replace the glass matrix. Zeolite minerals are low temperature minerals, so they are generally formed during the waning stages of volcanic activity, in near-surface environments. Zeolitization occurs at over $<220^{\circ}C$.

g. Oxidation: (Oxide minerals)

Oxidation is simply the formation of any type of oxide mineral. The most common ones to form are hematite and limonite (iron oxides), but many different types can form, depending on the metals, which are present. Sulfide minerals often weather easily because they are susceptible to oxidation and replacement by iron oxides. Oxides form most easily in the surface or near surface environment, where oxygen from the atmosphere is more readily available. The temperature range for oxidation is variable. It can occur at surface or atmospheric conditions, or it can occur as a result of having low to moderate fluid temperatures.

Primary minerals, order of replacement and alteration products of Olkaria NE and Olkaria Domes. (Table 3.1)

Table 3-1 : Order of replacement and alteration products in Olkaria

Order of replacement	Primary phases	Alteration products
↑ Increasing order	Volcanic glass	Zeolites, clays, quartz, calcite
	Olivine	Chlorite, actinolite, hematite, clay minerals
	Pyroxenes, amphiboles	Chlorite, illite, quartz, pyrite, calcite
	Ca-plagioclase	Calcite, albite, adularia, quartz, illite, epidote sphene
	Sanidine, orthoclase, microcline	Adularia
	Magnetite	Pyrite, sphene, haematite
	Quartz	No alteration

2.3.2 DISTRIBUTION AND DESCRIPTION OF HYDROTHERMAL MINERALS

The main hydrothermal minerals in Olkaria Domes and Olkaria North east are calcite, chlorite, chalcedony, epidote, secondary Fe-Ti oxides, pyrite and quartz, (Lagat, 2007). Mineral associations in vesicles are common and consist of two or more of the following minerals; calcite, quartz, epidote and pyrite with the paragenetic sequence varying with depth.

Calcite

It is encountered in trachytes, basalts and tuffs and becomes abundant in greater depths in all rock types it is encountered. It replaces primary plagioclase phenocrysts, pyroxenes and volcanic glass. Vesicles fractures and veins contain white massive or colorless crystalline calcite deposits. Crystal morphology of calcite is variable and ranges from individual thin bladed crystals to equant to needle like crystals.

Chalcedony

This mineral occurs in shallow depths. Colorless, white or bluish grey cryptocrystalline chalcedony lines vesicles and coat fractures and veins. At greater depth where temperatures are high, chalcedony in vesicles is seen transforming or is completely transformed into quartz but chalcedonic outline is preserved.

Chlorite

Chlorite is found in the lower parts of the wells. It varies in color from light to dark green, has low birefringence and occasionally shows anomalously blue, brown or purple interference colors and presents two different forms. In the upper levels of volcanic sequences, chlorite appears in small intergranular patches whereas at the deepest levels, chlorite is idiomorphic, forming radial aggregates in vein lets and vugs in association with quartz, calcite epidote and pyrite. Within veins, chlorite occurs as microspherules enclosed within epidote, but it may also replace primary pyroxene and the matrix.

Epidote

Epidote is found in the lower depths of the wells. Epidote shows a systematic textural development with increasing depth. First crystals are anhedral and form fine grained aggregates and in deeper zones they are idiomorphic, tabular, radiated or fibrous. Epidote is found filling fractures, vesicles and replacing primary plagioclase and pyroxene and in most cases forms mineral association with mainly quartz, chlorite and sometimes calcite and chlorite.

Oxides

Oxidation is the formation of any type of oxide mineral. The most common ones to form are mainly iron oxides, but other types form depending on the metal cations present. Sulfide minerals often weather easily because they are susceptible to oxidation and replacement by iron oxides. Hematite is a common oxide in the Olkaria NE reservoirs.

Pyrite

Pyrite crystals are distributed throughout the wells. It occurs as euhedral cubic crystals with brassy yellow luster in reflected light. Tiny cubic pyrite crystals were deposited in fractures, vesicles and veins and as disseminations in the groundmass.

Quartz

Quartz is a colorless to white in color and occurs in euhedral to subhedral crystals. It is identified both as vesicle fillings and vein filling mineral. The rock appears virtually throughout the wells with varying intensities. Most of these quartz deposits consist of tiny euhedral to anhedral crystals that formed in vesicles, veins and fractures.

Illite

Illite is detected from the surface to the bottom of the wells. The mineral is light green to white in color, replaces K-feldspars and occurs as a vein and vesicle filling mineral. At some depths illite occurs interlayered with smectite.

Smectite

Smectite is detected at the shallow depths of the rocks. The clay is bright green in color and alters mainly the feldspar phenocrysts and also occurs as deposits in veins and vesicles.

4. DISCUSSION

A hydrothermal system can be divided into 3 zones: recharge zone at the top, reaction zone at the bottom and discharge zone at the top which are dependent on the permeability of the reservoir.

In recharge zones, meteoritic water penetrates the crust and is warmed during its descent. At first the meteoritic water and the host rock interact chemically under oxidizing conditions and at low temperatures (50˚C). Then the resultant fluid reacts with the wall in a reductive environment and at low temperatures. The chemical reactions in recharge zones are: alkaline earth fixation in the crust, calcite/aragonite precipitation, and anhydrite precipitation. Then the circulation develops in the reaction zones where high-temperature (350-400˚C) processes develop. If the hydrothermal fluid is sufficiently channeled to exit the crust at the discharge zone with a low cooling rate, all the hydrothermal mineral content precipitates on the earth's surface. If the fluid cools inside the crust before exiting, pyrite and chalcopyrite are precipitated.

Geothermal waters of Olkaria NE and Domes are saturated with silica and are frequently close to saturation with calcite, calcium sulphate and calcium fluoride. Changes in temperature and pressure disturb the equilibrium and will lead to precipitation of minerals. Calcite and silica deposits are the most frequent scale formation materials. Silica is found in virtually all geothermal brine and its concentration is directly proportional to the temperature of the brine. As brine flows through the well to the surface, the temperature of the brine decreases, silica solubility decreases and deposition begins.

Water from OW-709 are slightly supersaturated with calcite, highly supersaturated with epidote, the concentrations of bicarbonate are generally high in water discharged from Olkaria wells. The fluids discharged in this wells are pyrite supersaturated. If heat flow from the aquifer rock to the supersaturated fluids in the aquifer contributed to vaporization of the water, then minerals are precipitated. OW-903 is drilled through a fault and waters of different properties get into the well changing the bottom hole temperatures and pressure that leads to formation of mineral deposits.

Sources of permeability of Olkaria Domes and Olkaria Northeast geothermal reservoirs include fractures, fissures, joints, lithological contacts, clast matrix or fragment contacts in some breccias. Fractures are the conduits for fluid movement in geothermal reservoir. The effects of water rock reaction and fracturing on permeability vary during the lifetime of the geothermal system. Figure 4.1.

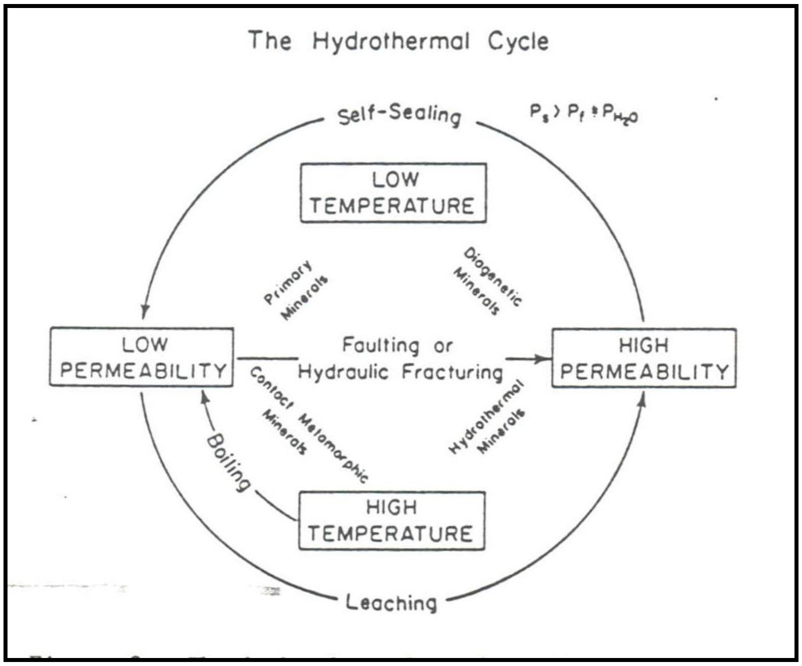

Figure 4-1: The hydrothermal cycle (Elders, 1982).

Changes in permeability due to mineral reactions and fracturing of rocks

The diagenetic processes are triggered by surrounding reactions between the circulating fluids and the rock walls. They are controlled by diffusion of species through the fissures. Precipitation in the faults and fissures is triggered when concentration exceeds equilibrium value. The concentration depends on both temperature and pressure.

Precipitation of minerals leads to the increase in density and reduction in permeability and porosity of rocks. Initially, leaching can increase permeability and porosity but prolonged leaching or incongruent solution decreases permeability. This is because pore spaces in rocks tend to compact under the overlying load as solution occurs at grain to grain contacts, reducing porosity. Sulfides are the dominant prograde minerals filling the fissures while the fluid is cooling at 350-250˚C. The sulfides are mainly pyrite and chalcopyrite. The sulfides precipitate in the fissure network. The basaltic rock of Olkaria NE and Olkaria Domes contains small quantities of magnetite which react during the hydrothermal alteration with the fluid (HS3) to produce pyrite.

The solubility of silica is prograde at temperatures between 25 and 320˚C and retrograde above 320˚C. Consequently, silica precipitates in the deep part of the Olkaria wells where the fluid is heating and in shallow depths of the wells where the fluid is cooling. Silica precipitation occurs in the form of quartz veins.

Incongruent solution by hot solution leaves behind high temperature phases denser than the phases which are dissolved. Therefore, both solution and precipitation of minerals tend to be self limiting. Both processes tend to reduce permeability by self sealing and therefore reduce fluid flow (Elders 1982).

Fracture sealing driven by stress with mass transfer from solution cleavage to fracture. It is observed in the fault zones. The characteristic times of sealing range from years to centuries. Fracture sealing in the Olkaria NE and Olkaria domes is takes place in the following mechanisms: silicification, carbonitization, zeolitization, argillization and oxidation.

The figure 4.2 shows the process of fracture sealing over time, time in Ma. The mineral deposits form as a result of wall rock alteration.

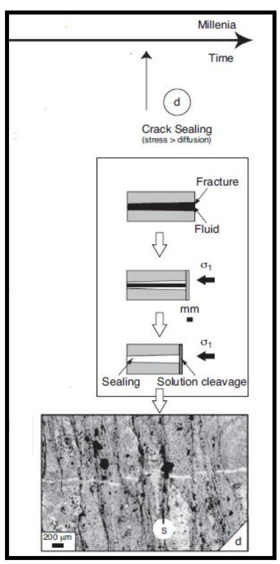

Figure 4-2: Fracture sealing process in Olkaria NE and Domes (Gratier, 2011)

The permeability of these reservoirs is not controlled by the mean width of the fissures, but by the effective width of the micro-fissures allowing percolation of hydrothermal fluids from one large fissure to the micro-fissures. Mineral precipitation is controlled by surface reactions between rock and hydrothermal fluid, especially for sulfides which form in the walls of the fissures. Sulfides precipitate preferentially in constricted zones where the ratio of water to rock is high, thus in the micro-fissures. This localized precipitation hardly affects the large fissures but seals the micro-fissures (Fontaine et. al., 2001). Such a process reduces permeability fast. Super saturation localizes precipitation in narrow temperature domains. It likely accelerates the obstruction of the permeable network, and thus favors the rapid sealing of the system. A possibility is that the precipitation triggered by super saturation occurs as clots which occlude the micro-fissures, that local seismic events can create a new permeable system allowing fluid circulation. Such seismic events in the vicinity of a sealed hydrothermal system may be responsible for the permeability recovery.

5. CONCLUSION

In this study, it is evident that the permeability decrease of Olkaria NE and Domes result from the precipitation in the fissure network. Well productivity is affected both by inflow performance that is greatly influenced by permeability. Olkaria wells have low productivity because of the low permeabilities.

The figure 5.1 illustrates upflow of boiling water until steam is discharged. It is also evident that down flow of cooled water along the faults, due to the temperature drop at the bottom of the well, it causes precipitation of minerals. This same phenomenon is what happens at the well OW-903 since the well cuts a fault.

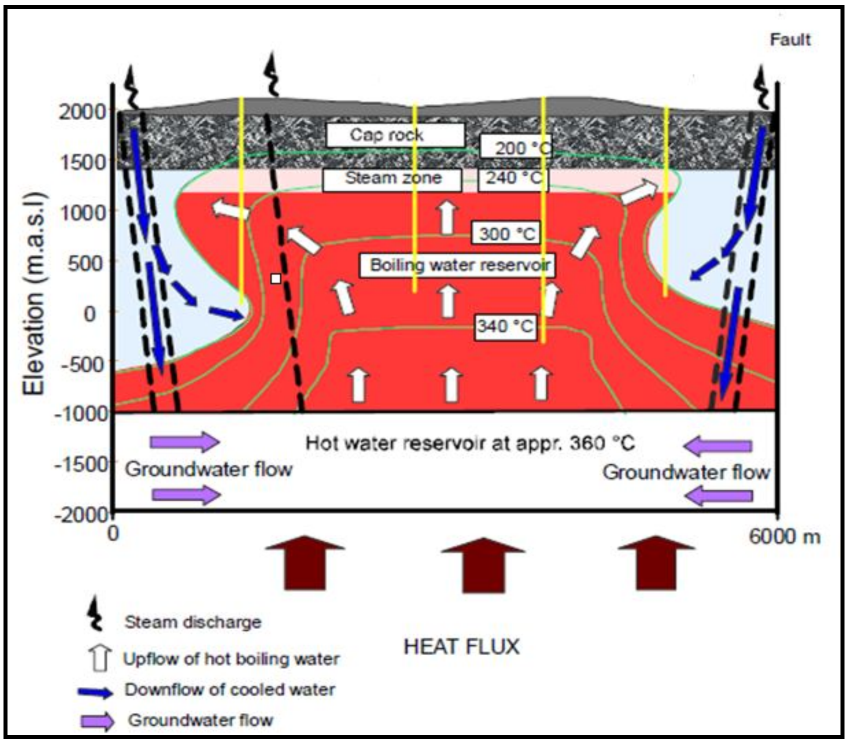

Figure 5-1: A model of steam flow in Olkaria reservoir (Ofwona, 2002)

RECCOMENDATION

More elaborate studies should be done on the extent of mineralization along the steam pathways and drilled wells.

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APPENDICES

OCCURRENCE OF ALTERATION MINERALS OF OW-701

Depth (m)	Occurrence of hydrothermal minerals	Deposited minerals	Filling type
257-260	Vesicles in rhyolite are either completely in filled with reddish-brown clays or lined with dull green chlorite. Some vesicles have bladed calcite and pyrite is present lining some vesicles.	Chlorite, calcite, pyrite	Vesicle
660-664	Altered feldspar phenocrysts in trachyte rock are set in a uniformly dull green chloritic, aphanitic groundmass with clots of chlorite possibly altered from ferromagnesian minerals. Irregular veining and fracturing is noted and most of the veins and fractures are filled with quartz and calcite. The near vertical fracture surface show finely bladed calcite displaying an almost pearly luster overlying moderately coarse quartz vein mineral. Pyrite is weakly disseminated as scattered euhedral crystals and patchy infillings in cavities.	Chlorite, calcite, quartz, pyrite	Vein, vesicle
1051-1053	There are minor thin fractures sealed with chlorite.	Chlorite	Vein
1450-1560	The brecciated trachyte is partially silicified, oxidized and of pyritic matrix. The fractures present are sealed with pyrite.	Oxides, pyrite	Vein

1803	The chloritic groundmass of rhyolite has disseminated tiny anhedral cubes of clustered pyrite. The pyrite is also present in joint/fracture surfaces associated with chlorite.	Chlorite, pyrite	Vein, vesicle

OCCURRENCE OF ALTERATION MINERALS OF OW-709

Depth (m)	Occurrence of hydrothermal minerals	Deposited minerals	Filling type
201-209	The intensely altered rhyolitic lithic tuff is clay rich. Pyrite is widely disseminated throughout the silicified material and occasionally lines cavities.	Pyrite, smectite	Vein, vesicles
648-656	Feldspar phenocrysts insipient chlorite and clay alteration. Chlorite is also present within the groundmass as poorly defined clots and patches while pyrite is scattered throughout the matrix.	Chlorite, pyrite	Vesicle
1351-1360	The basalt rock has partially to extensively altered feldspar with the vertical fracture showing brecciated fragments cemented with silica, Elsewhere, interlacing hairline fractures have been sealed with silica and chlorite	Quartz, chlorite	Vein

OCCURRENCE OF ALTERATION MINERALS OF OW-904A

Depth (m)	Occurrence of hydrothermal minerals	Deposited mineral	Filling type
516-548	Moderately altered rhyolite rock and silicified lava has large pyrite cubes and smectite clays.	Pyrite, smectite	Vein
624-684	The trachyte rock is medium to highly altered vesicular rock has the vesicles filled with calcite, some of which are pneumatolic. Smectite and chlorite are also present.	Calcite, smectite, chlorite	Vesicle
1264-1314	Fractures present in the trachyte rock are filled with chlorite and pyrite.	Chlorite, pyrite	Vein
2440-2452	Rhyolite rock is moderately to highly altered to chlorite and epidote in veins.	Chlorite, pyrite	Vein
2452-2476	Basalt shows high intensity of alteration by the moderate degree of silicification and the well crystallized epidote in veins.	Quartz, epidote	Veins

OCCURRENCE OF ALTERATION MINERALS OF OW-905A

Depth (m)	Occurrence of hydrothermal minerals	Rock type
532-572	The greenish rock is altered completely to smectite. Crystals of riebeckite show slight alteration to clays The rock shows moderate alteration and has fine pyrite cubes disseminated in the veins as well as in veins Calcite and quartz occurs as veins	Rhyolite
644-666	Plagioclase phenocrysts show replacement by calcite and albite along edges, the rock is highly altered to greenish and bluish clays. Calcite is abundant in veins and vesicles	Basalt
1090-1110	The rock is highly altered to clays and pyrite is deposited in veins as well as disseminated in the groundmass	Tuff
1488-1496	Plagioclase phenocrysts show alteration to chlorite and metasomatism by calcite along the edges Abundant calcite occurs as vein fillings in association with quartz and epidote. It occurs in veins and vugs	Basalts
1496-1610	Fractures are filled with chlorite	Trachyte
2248-2362	The rock is high in silica and is weakly altered to dark green clays. Minor epidote and quartz occur in veins	Trachyte
2726-2770	Feldspar phenocrysts show moderate to complete alteration to greenish clays Pyrite is disseminated in the groundmass and deposited in veins	Trachyte