

The Geology of Paka Volcano, and its Implication on Geothermal

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Paka Volcano, geothermal, heat source, structures

ABSTRACT

Paka is a complex multi vent low basalt-trachyte volcano dominated by a young central caldera at the summit, which is 1.5 km in diameter. It is situated 25 km north of Lake Baringo and 15 km east of Nginyang' Village. The volcanic complex is dotted with a number of smaller satellite volcanic centers, which are linked to the main volcano by linear zones of basalt and trachyte cones and eruptive fissures. The main heat source(s) for the Paka geothermal system are the trachyte-basalt intrusive or intrusion complexes underneath the volcano. These bodies are long-lived and are fed by up-welling from time to time of fresh magma from depth. Altered grounds, fumaroles and well-crystallized sulphur deposits along faults within the caldera and the Eastern crater indicate that the faults are deep-seated and are magmatic in provenance. At a local scale, the NNE-SSW and N-S trending faults and fractures are essential in enhancing permeability in the prospect area. The subsurface rocks of Paka prospect wherein the geothermal reservoir is expected to be situated are made up of mainly faulted Miocene lavas. The combination of local and regional structures has enabled fracturing in the reservoir rocks to allow for movement and retention of geothermal fluids. The cap rock for the system is expected to be the Plio-Pleistocene lavas and their associated pyroclastics.

Introduction

Paka is a complex multi vent low basalt-trachyte volcano located in the [Great Rift Valley, Kenya](#). The geothermal prospect is characterized by a well-defined volcano situated 25 km north of Lake Baringo (Figure 1) and 15 km east of Nginyang' Village. It is bound by the Latitude 00°55' East and Longitude 36°12'E and rises to a maximum altitude of 1697 m with an irregular outline covering an area of approximately 280 km² where geothermal activity is widespread.

The dominantly Pleistocene Paka shield volcano in the Gregory Rift contains a small 1.5-km-wide summit caldera. Eruption of large volumes of trachytic pyroclastic rocks around the end of the Pleistocene and the beginning of the Holocene(10ka) formed a NW-trending ridge of pyroclastic cones across the

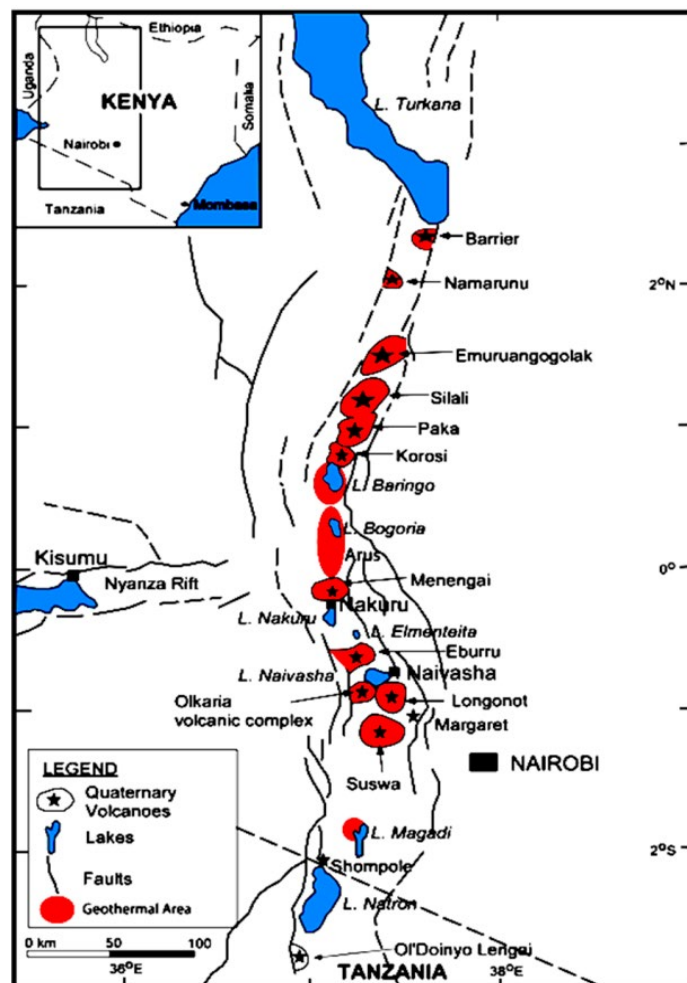


Figure.1 Location of Paka geothermal prospect on the Kenyan rift.

summit region; collapse of this area formed the summit caldera and associated craters. The volcanic complex is about 15 km in diameter. The volcano is cut on its eastern flanks by a swarm of NNE-SSW trending faults. Young pyroclastic deposits blanket a large part of the volcano.

Geology

Tectonic Setting

Paka is a shield volcanic complex located in the Kenya Rift which is an integral part of the East African Rift system which extends for over 3000km from southern Mozambique through Tanzania, Kenya and Ethiopia to join the Red Sea and the Gulf of Aden rifts at the Afar triple junction. Chorowicz (2005). The Kenya rift consists of a linear graben structure which extends for 900km from Turkana depression in the north to the central Tanzania plateau in the south. Its morphology is mainly due to tectonic events of the 1Ma. Widespread faulting is mainly due to tectonic and volcanic events of the last 1Ma. Widespread faulting accompanied the eruption of flood basalts and trachytes as the rift collapsed inwards to form the inner trough between 1.5 and 2.0Ma and was followed by the emplacement of large shield volcanoes along the central axis extending from Suswa to Barrier volcanic complex on the southern shores of Lake Turkana, most of these

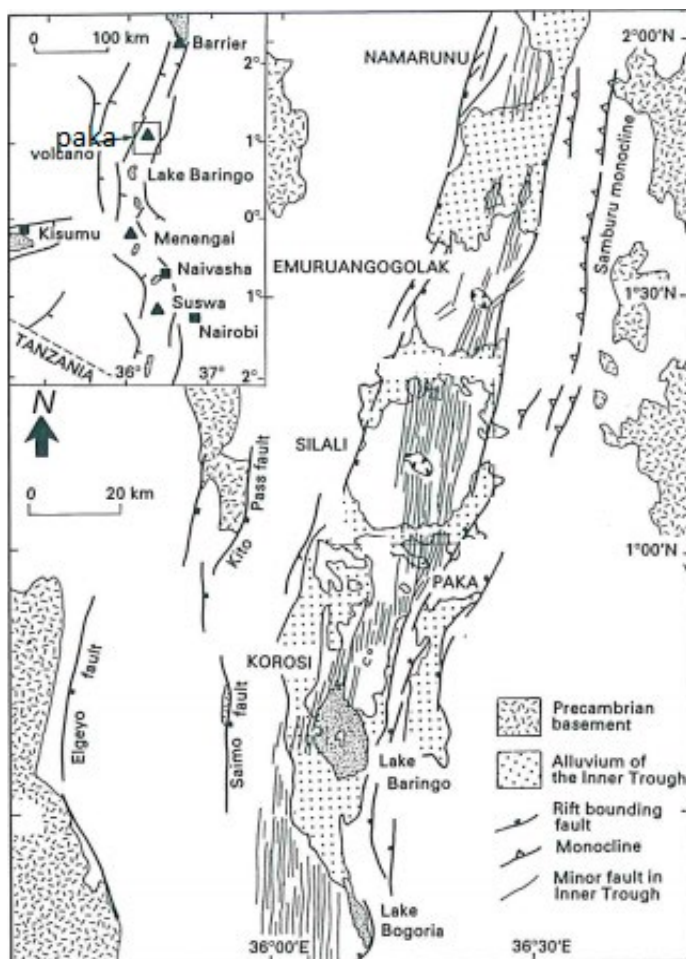


Figure 2. Tectonic Setting of Paka in relation to other Quaternary volcanoes in the northern Kenya rift; modified from (Smith et al., 1995).

are geothermal prospects, Paka volcano included.

Surface Geology

Paka is a shield volcano constructed largely by trachyte lavas and pyroclastic deposits. Basalt, hawaiite, mugearite, lavas were erupted from a series of fissure and fault zones located on the lower northeastern and southern flanks. Volcanic activity commenced by 390 Ka and has continued to within 10 Ka. The sequence of activities is summarized in Table.1 broadly speaking trachytic and basaltic activity occurred on a number of small satellite center's peripheral to the main volcanic edifice (Figure 3). The oldest exposed rocks are the Lower Trachytes, which constructed an early volcanic shield. Subsequent fracturing of the shield by the NNE-trending faults was accompanied by eruption of the Lower Basalts from fissures observed on the eastern flanks of the volcano.

Lower Trachytes

The oldest exposed rocks in the Paka geothermal prospect are the Lower Trachytes, which constructed an early volcanic shield recognized by their eroded and faulted nature. The lava is exposed in a series of scattered outcrops peripheral to the lower flanks of the volcano at Kasakat. Tapough, Adomeyon, north of Komolwo, East of the Eastern Boundary fault, south of Muruase and around Orus. The flow to the south and to the southwest, which is exposed beneath the Upper Trachyte was dated by Dunkley et al., (1993) and yielded an age of 219 ± 4 Ka. The trachyte is fine grained with alkali feldspar phenocrysts up to 20 mm in length. The Lower Trachyte is generally altered and the rock is fissile and show breaking along thin parallel sheets

Lower Basalt

The Lower basalts are exposed in the lower plains to the southwest, southeast and on the eastern sides of Paka. The Lower Basalts are strongly faulted, eroded and thickly vegetated. Abundant spatter and scoria cones indicate most of the Lower Basalts were erupted from fissures. The formation is generally dark grey in color and consists of up to 5 mm plagioclase feldspars, augite and olivine phenocrysts. The groundmass is made up of mainly tiny plagioclase laths. The rock formation is in most cases vesicular with the vesicles being infilled by pneumatolitic calcite and secondary clays. The Formation is generally faulted and weathered.

Upper Trachyte

The Upper Trachyte is exposed on the southeast at Chebungus, on the western sector at Muruase, on the northern plains at Napokorian. The formation is vesicular to compact, fissile, fine grained and is porphyritic with alkali feldspars. The feldspar laths also show an aligned flow direction, a characteristic trachoid texture. Like the Lower Trachyte the Upper Trachyte consisted of alkali feldspars, pyroxenes, plagioclase, magnetite and to a small extent pyroxenes. To the northern plains, the Formation is underlying the pyroclastic deposits that have buried the lava exposing ribbon like outcrops marking flow fronts.

Upper Basalt

The Upper basalts occur northern and the southern plains and were erupted from NNE-trending fissures occurring both in the north and the south of the volcano. The matrix consists of feld-

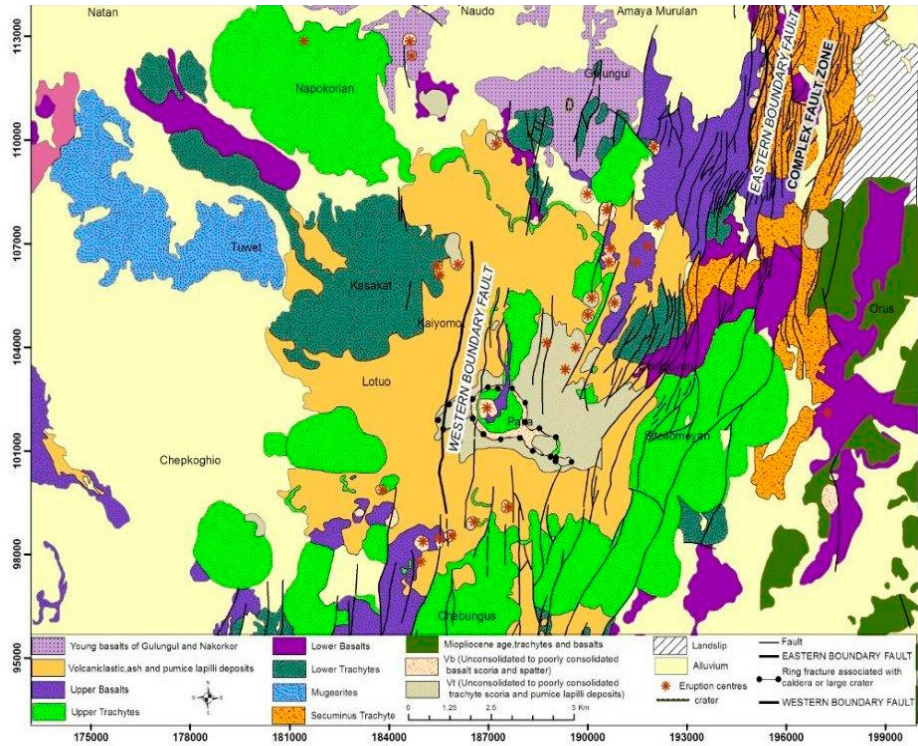


Figure 3. Geology Map of Paka Geothermal prospect. modified from Dunkley et al., 1993 with recent inclusions.

spar, augite and magnetite crystals as euhedral laths in a granular groundmass. The rock is vesicular, with the small rounded vesicles occasionally being in-filled with secondary calcite. The rock has been affected by later faulting forming a combination of horsts and grabens within the formation. The rock is generally less vegetated than the Lower Basalts.

Pyroclastic and Volcanoclastic Deposits

The pyroclastic deposits form a large mantle averaging 30 m over the summit area and large parts of the western and the northern flanks of Paka. The distribution was greatly affected by the prevailing easterly wind direction flow. The deposits overlie the Upper Basalts and the Upper trachytes and are cut by the caldera. On the caldera walls, they overlie a thick (>30m) sequence of trachyte lavas. The deposits were erupted from large trachyte and pumice cones on the summit area and from smaller cones aligned in a N-S direction on the summit area and the upper northeastern flanks. The pyroclastics are trachytic in composition and consists of pumice, obsidian and lithics of trachyte lava and large blocks of syenite. On the eastern crater, the pyroclastic are extensively altered to reddish and white (kaolinite and alunite) clays.

Trachyte and Mugearite

Trachyte and Mugearite are post caldera eruptions and are mainly erupted within the caldera flowing northwards. The trachyte has pronounced concentric ridges and multi lobate flow fronts up to 40m high. The rock is fine grained and is porphyritic with feldspars, augite and tiny microphenocrysts of pyroxenes. The final stage of activity within the caldera was marked by the eruption of fluid mugearite from a scoria cone (plate 1) within the western half of the caldera. The lavas from this cone flowed

southwards and eastwards across the trachyte on the caldera floor before flowing out of the breach and down on the northern flanks.

Young Basalts

Occurrences of Young Basalts were observed west of Naudo and at Gulungul and from fissure trending NE-SE to the northeastern flanks of the volcano Young fissure-fed basalts were also erupted to the south, between Paka and Korosi volcanoes.

Like the post caldera Trachytes, the Young Basalts are less vegetated and still show the pristine flow morphology. The rock is fine grained to glassy and is vesicular at the edges and consists of phenocrysts of plagioclase, pyroxenes and tiny phenocrysts of augite.

Stratigraphy and Evolution of Paka Volcano

Eruptions began with the development of a lava shield 18-25 km diameter around 390Ka. Tuff cones were built on the western side of the shield. Large parts of the volcano were covered by pumice tuffs and intercalated agglomerates, followed by caldera formation.

The most recent eruption produced basalt eruptions in the caldera, a flow from a cone low on the SW flanks, and basalt lava flows on both sides volcano of the on a line running NNE through the caldera.

In an art shell evolution and history of Paka volcano may be broadly separated by two periods of trachytic volcanism separated by basaltic activity and faulting. The oldest exposed rocks are the shield trachytes (Lower Trachytes). Subsequent fracturing of the shield by the NNE-trending faults was accompanied by eruption of Lower Basalts from fissure sources on the eastern flanks of Paka. Faulting was followed by the eruption of Upper Trachytes around the flanks of the volcano. These lavas were erupted from cone structures located along N-trending and NNE-tending fissures on the upper flanks and the summit area. Repeated faulting and fracturing across the shield led to the formation of an axial rift zone defined by the Eastern and Western Boundary faults Dunkley et al., (1993). The Upper Basalt and the Upper Trachytes overlie the Lower Basalts and both are affected by the repeated faulting. At around 10ka, pyroclastic flows and deposits were

Table 1. Stratigraphic sequence of Paka.

| Formation | Age | Volcanic Activity |
|--------------------------|------------------------|---------------------|
| Young Basalt | 200BP | |
| Trachyte and Mugearite | 10±3Ka | Intra Caldera Lavas |
| Caldera Formation | | |
| Pyroclastic Deposits | 8±4Ka | |
| Upper Basalt | | |
| Upper Trachyte | | |
| Lower Basalts | | |
| Lower Trachyte | 219+/-6ka 390+/-6ka | Shield Formation |

erupted from a complex of cones on the upper northern flanks and summit area. Pyroclastic flows from the summit cones were topographically constrained by the rift volcanic zone and flowed down the northern flanks and locally Tuff cones were built on the western side of the shield. Large parts of the volcano were covered by pumice tuffs and intercalated agglomerates.

This pyroclastic activity triggered the collapse of the summit to form a caldera at around 10ka. Post caldera activity comprised the eruption and subsequent ponding of trachytic lava within the caldera. The most recent eruption produced basalt eruptions in the caldera with flow from a cone (plate.1) in the SW edge within the caldera and the lower SW flanks basaltic lava flows on both sides volcano of the on a line running NNE through the caldera (Figure. 3 and 6).

age of these sequence ranges from early Pleistocene represented

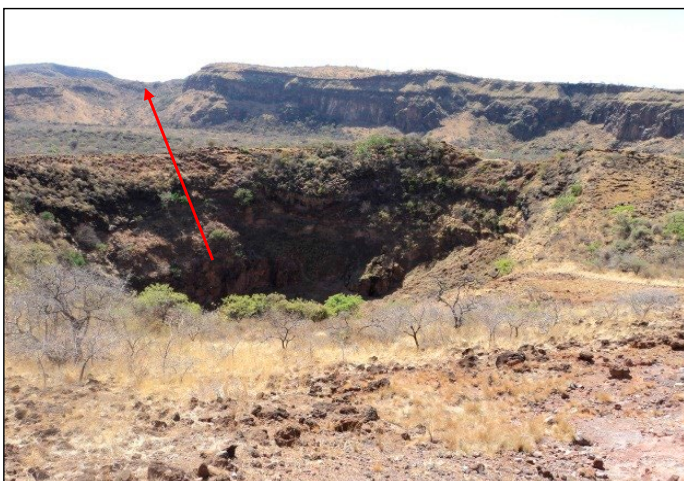


Plate 1. Cone that erupted in the caldera.

by shield formation to a few hundred years BP represented by the less vegetated Young Basalts. This is summarized in Table 1.

Structural Setup

The dominant structural setup of the northern sector wherein the Paka prospect is located is complex and it includes; the eastern rift flank, the rift proper, the caldera, NW, NNE and N-S trending faults. It's dominated by a broad zone of normal faulting 7.5km wide bounded by the eastern and the western boundaries respectively.

Field observations indicate that the main focus of faulting is generally restricted to this axial zone of rifting with displacements across individual faults being minor (~10m), although the cumulative displacement across the Boundary faults is considerable (up to 250 m at the Eastern Boundary Fault). On a regional scale the zone shows a right stepping en echelon pattern across the volcano, and even extends southwards to Chepchuk and northwards onto the southern flanks of Silali. On the southern flanks of the volcano, faults trend N-S but as they close Paka summit area, they show a deviation in the NNE to NE direction (Figure 4). This refraction and disappearance of faulting in the summit area implies that a magma body may have existed at a shallower depth within the volcanic centre at the time of faulting relative to regional subsidence echoed by Mahood (op. cit) in Dunkley et al. (1993) for deep magma chambers.

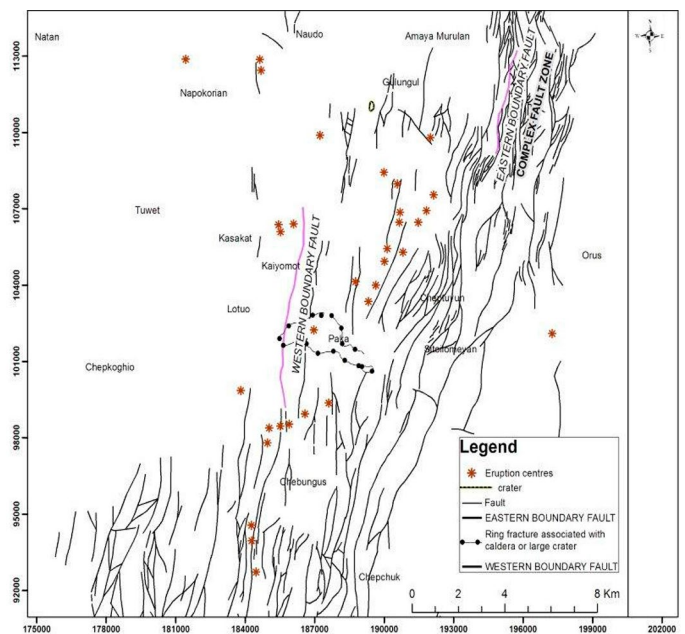


Figure 4. Structural Map of Paka modified from Dunkley with additions after field mapping.

The caldera is circular in plan with a diameter of 1.5km this suggests that there is magma chamber below and it was breached on the northern side as lava flowed. Caldera formation involved subsidence of the floor by 200 m. On regional scale and just like other calderas in the north such as Silali, Paka displays a NW-SE elongation, which is taken to imply a regional stress control on the shape and emplacement of the underlying magma body. On either side of the caldera are two craters each between 500-1000 m, also a 1 km diameter explosion crater is located on the outer SE edge of the caldera. The location the caldera and craters right in the central part of the volcanic complex is strategic it enhances the permeability and effectively increases the hydraulic gradient so that fluids percolate into the reservoir.

Faulting and subsidence continued during the eruption of pyroclastic deposits and some movements along the Western Boundary Fault occurred during post-dated caldera construction. The occurrence of eruption centers and thermal manifestations along the NE and NNE trending faults suggest that geothermal activity is structurally controlled. Some of the fissures are still open and are associated with thermal activity. Extensive hydrothermal alteration, geothermal grass and a swarm of fumaroles within a fault zone at the eastern crater, sulphur deposition and H₂S gas is linked to magmatic activity.

Petrogenesis

Analyses for oxides of major and trace elements of samples obtained from the Paka volcano were carried out by use of Atomic Absorption Spectroscopy (AAS). These results were graphically plotted on total alkali versus silica (TAS) diagrams so as to classify the rocks (Figure.5) These were then compared with data from Olkaria. Based these, Paka volcano is widely covered by rocks that are basaltic and trachytic in composition. While the Olkaria samples tend to be rhyolitic and trachytic in composition.

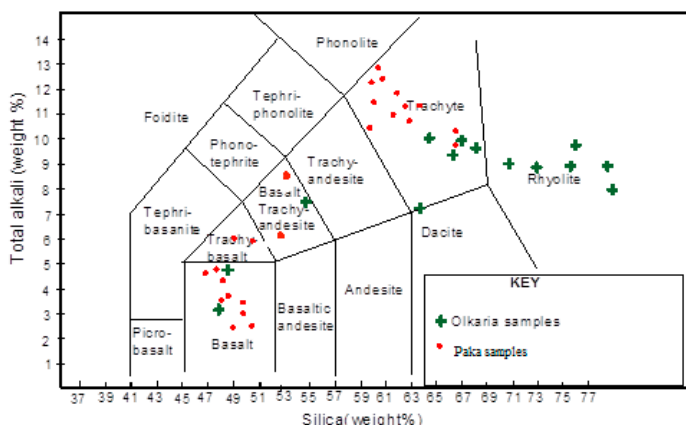


Figure 5. Paka Vs Olkaria Tas Diagram.

On Paka it appears that there is no systematic compositional variation between the lower, upper and post caldera trachytes. As a single group they are critically undersaturated with respect to Silica compared to the Olkaria trachytes (Figure 5). In Olkaria we have basaltic lava evolving to trachytes and then to peralkaline rhyolites (Marshall et al., 2009). This is supported by Macdonald et al., 2008 who calculated that the more evolved Olkaria trachytes formed by 92% crystallization of parental basaltic magmas, a further 26.5% by (volume) crystallization of trachyte which generated peralkaline rhyolitic melt. There it seems that there are no distinct intermediates however in Paka for intermediate lavas; we have mugearites which very much resemble basalts. Therefore we can hypothesize that replenishment of mafic magma caused pressurization of the magma chamber and injection into the surrounding tensile fissures, resulting in basaltic satellite eruptions of Paka, this explains why trachytic rocks have been erupted from the summit area but the basaltic lavas were mainly erupted from fissures on the flanks. Also Basalts have only been erupted in the summit area at a later stage following caldera formation.

In this field I would propose a shallow trachyte magma reservoirs where after caldera collapse we have many small partially interconnected reservoirs rather than having one major chamber and that the location of these reservoirs is guided is by post-caldera trachytic chambers supported by the fact that we have several eruptions on the summit area of Paka.

Hydrogeology

In hydrogeological terms the axial fault structure influences the geothermal system of the Paka volcano by acting as conduits if they are permeable, or by inhibiting lateral flow if they are of low permeability. Hydrogeology of the area is characterized by recharge mainly from the intensely faulted east rift shoulder and to some extent from Lake Baringo in the south via axial faults. The interaction between lateral and axial flows is modified by faults and dykes trending along the rift. These cause lateral flows to flow longer and deeper paths, and to align with axial flow paths within the rift floor. The NNE, N-S trending faults play an important role in the recharge of the Paka geothermal system. The Western Boundary fault acts as a major hydrogeological barrier in the prospect whereby to the west of the fault there are no surface manifestations. While the broad 7.5km rift which is composed

of echelon steps and fissure ensures that there is deep recharge to the geothermal system.

Geothermal Manifestations

Surficial geothermal activity is widespread at Paka both within the summit caldera and on extensive portions of the northern flank. Geothermal activity in the prospect are in the surface manifested in the form of hot and steaming grounds, and fumaroles, associated with hydrothermal alteration, widely developed on and within the summit craters in particular the northern flanks (Figure 6). The geothermal activity at these sites is locally characterized by well-crystallized sulphur deposits associated with geothermal grass and intense hydrothermal alteration. In many of these areas maximum temperatures are at or slightly exceed the local boiling point.

The maximum temperature recorded is about 97.8°C. The highest temperatures are found within areas of steaming grounds, often characterized by white, purple and red clays. Areas of extinct activity are indicated by hydrothermally altered ground with ambient temperatures.

Geothermal activity in Paka is dispersed over a broad NNE-trending zone extending from high on the southern flanks across the summit area and down the northern flanks. There is also an isolated occurrence to the north east but which is strongly controlled by NNE-trending faults and locally associated with

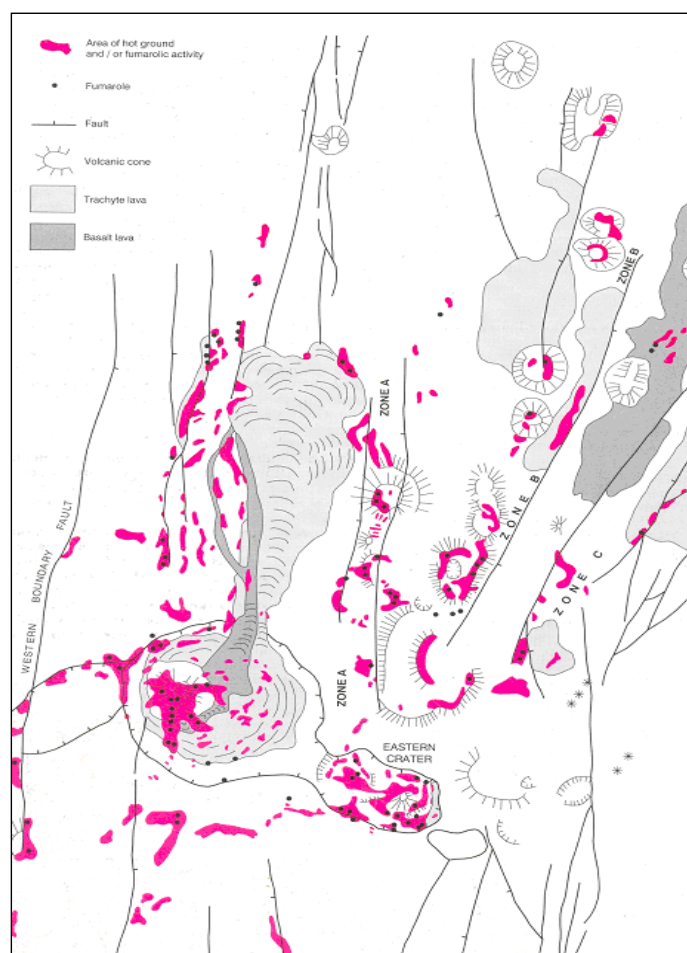


Figure 6. Map of Paka showing areas of thermal manifestations in relation to structures (after Dunkley et al., 1993).

trachytic scoria cones aligned along these faults. The activity is bounded on the west by the Western Boundary fault and on the east by the west-facing faults cutting northeast flanks of Paka. There are no manifestations beyond the two extremes (Figure 6).

Geothermal activity is widespread and most intense within the summit area but localized mainly around the basaltic scoria cone in the western part of the caldera floor. Hot grounds and weak fumaroles were found restricted to post caldera trachytic and basaltic lavas within the caldera. These lavas have blanketed the faults along its flow path down the northern flanks and consequently concealed most manifestations.

Intense geothermal activity occurs in the eastern crater (Figure 6) along the southern and south eastern walls. Manifestations here include hot ground, fumaroles and steaming ground, hosted in trachytic scree which are intensely altered to white and red kaolinitic clays. Patches of hot ground, some of which are associated with weak fumaroles, are found scattered over the upper flanks of the southern flanks of Paka. All these are developed upon the upper the upper trachytes which are altered in some places to red and/or whitish clays. Several of the patches here are linearly disposed.

Discussion

The apparent indicators for essential features for development of a geothermal system in Paka prospect are:

Heat Source

The continued eruptions (pre and post caldera) indicates that the magma chamber/s below the system is still active. The magmatic activity is indicated by the Quaternary eruption of Young Basalt lavas extending northwards from within the caldera and in the flanks along the NNE-trending fissures. At a larger scale, Paka volcano is predominantly of trachytic volcanism. Trachytes are derivatives of fractionation of silica under saturated magmas. Occurrences of shallow intrusives is evidenced by the presence of stratified micro-syenite bearing pyroclastic deposits exposed in the caldera walls appearing to overly trachytic lavas and lithic breccias. The main heat source(s) for the Paka geothermal system are the trachyte-basalt intrusives or intrusion complexes underneath the volcano. These bodies are long-lived and are fed by up-welling from time to time of fresh magma. Altered grounds, fumaroles and well-crystallized sulphur deposits along faults within the caldera and the Eastern crater indicate that the faults are deep-seated and are magmatic in provenance.

Additional evidence of a magma chamber is provided by fracture patterns in Paka; the intensity of faulting decreases on the western boundary fault but fault trends are refracted on the summit area. That's why we have so many ridges on the summit area.

Recharge and Permeability

Hydrogeology of the area is characterized by recharge mainly from the intensely faulted Laikipia escarpment to the east and Baringo ranges to the west, and to some extent from Lake Baringo in the south via axial faults. Lake Baringo is probably recharging the prospect Lagat (2007). The interaction between lateral and axial flows is augmented by faults and dykes trending NNE-SSW and N-S along the rift. These cause lateral flows to flow longer and deeper paths, and to align with axial flow paths within the rift floor.

Meteoric water from wetter and higher areas also recharges the system. At a local scale, the NNE-SSW and N-S trending faults and fractures are essential in enhancing permeability in the prospect area. The main focus of faulting generally restricted to this axial zone of rifting with displacements across individual faults being minor (~10 m), with considerable cumulative displacement across the Boundary faults (up to 250m at the Eastern Boundary Fault) effectively increase the hydraulic gradient.

Based on borehole data on drillers logs, Dunkley et al., (1993) has observed that aquifers in the area though discrete locally and hydraulically connected regionally, they are made up of fractured volcanic, sediments and weathered contacts between different lithological units. If further extrapolated this could be the scenario for the geothermal reservoir at depth.

Reservoir and System Capping

The subsurface rocks of Paka prospect wherein the geothermal reservoir is expected to be situated are made up of mainly faulted Miocene lavas. The combination of local and regional structures has enabled fracturing in the reservoir rocks to allow for movement and retention of geothermal fluids. The cap rock for the system is expected to be the Plio-Pleistocene lavas and their associated pyroclastics.

Conclusions

Strong manifestations in the prospect, continued eruptions (pre and post caldera) indicate that the magma chamber below the system is still active and that there is a geothermal system comprising (i) recharge and permeability, (ii) heat source (augmented by crystallised sulphur and highly altered grounds) (iii) reservoir & system capping and (iv) return path to the surface through the NNE fissures and fractures. Lateral recharge is from Laikipia Escarpment and Baringo Ranges and axial recharge is from Lake Baringo. These fluids will then circulate deep through the reservoir rocks and heated up in the vicinity of shallow intrusives. The hot fluids being less dense upflows but are stopped from escaping by Plio-Pleistocene lavas and pyroclastics that act as system capping.

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