EXPLORATION OF STRATO-VOLCANIC GEOTHERMAL SYSTEMS (PARADIGMS)

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Keywords: *Strato-volcanoes, conduits, acid magmatic condensates, rock dissolution, acidic and neutral pH fluids, advective flows, flank discharges, paradigms inferring thermal reservoirs, power potential estimates.*

ABSTRACT

Successful development of high-T volcanic geothermal systems in developing countries for electric power generation is often restricted by inadequate and even fictitious conceptual models used during early and follow-up exploration phases. Adherence to these models can lead to the development of paradigms that, in turn, lead to prediction of unrealistic and exaggerated power potential estimates, even if poor or no evidence for a high-T system has been found. Political pressure (energy supply planning) can be a reinforcing paradigm agent.

The exploration history of countries with volcanic systems, such as African Rift countries and Pacific rim countries, provides examples for the development of such paradigms. Exploration of strato-volcano prospects in these settings provides some warning examples. In Indonesia strato-volcanic geothermal prospects have been explored assuming that they host a high-T reservoir. An extreme paradigm developed in Rwanda where a huge strato-volcano without any manifestations was assumed to be associated with a large, concealed, high-T geothermal reservoir. The paradigm overcame all non-supportive exploration results and was used to drill two, up to 3 km deep wells into 'cold' granitic basement.

1. INTRODUCTION

Paradigms related to geothermal exploration can develop when high expectations are associated with the exploration of inferred high-T systems. The term 'geothermal paradigm' refers here to assumptions that support beliefs of scientific and planning groups involved in the assessment of the power potential of strato-volcanoes. The term 'strato-volcano' stands for 'young' volcanic edifices (active or inactive) that have suffered little erosion and exhibit a typical 'cone' structure with steep slopes around the summit. The exploration history of such prospects in Indonesia and Rwanda is used to draw attention to some paradigms.

Geothermal exploration of strato-volcano prospects in Indonesia involves at present c. 27 out of 42 prospects with development licenses (Petromindo.Com, 2012 map). Most of the 27 prospects exhibit some thermal manifestations over their flanks (mainly neutral pH bicarbonate springs). However, only 2 prospects with a productive thermal reservoir have been developed (Sibayak and Ulubelu prospects in Sumatra). In Rwanda, the lower flanks of inactive strato-volcanoes (without exposed thermal manifestations) have been explored. Deep exploratory wells of the main prospect (Karisimbi) were apparently located following a local paradigm.

2. CONCEPTUAL MODELS OF INDONESIAN STRATO_VOLCANIC SYSTEMS

Models of Indonesian strato-volcanic systems are shown in Fig.1 that updates an older model (Hochstein and Browne, 2000) and includes features that can be found over most explored strato-volcanoes.

Setting 1 in Fig.1 outlines a rare thermal reservoir, located adjacent to a quasi-vertical conduit zone that hosts neutral pH hot springs within a small caldera structure in the summit region. The setting applies to the small Sibayak (Sumatra) system (Hochstein and Sudarman, 2015).

Setting 2 shows systems with down-slope advective flows; these derive from condensation of magmatic gasses and vapour within the conduit zone. The acidic fluids can dissolve volcanic rocks near the conduit and move down-slope as diluted acidic sulphate thermal waters. Their cation ratios reflect the composition of the dissolved volcanic minerals. Rapid neutralization during the first stage of down-flow produces neutral pH bicarbonate waters, discharged by thermal springs over the flanks of the volcano ('advective flows'). The setting is typical for many Indonesian strato-volcanoes exhibiting thermal springs.

Setting 3 illustrates a fully convective high-T system that has developed beneath the middle slope region of a strato-volcano, a rare system in Indonesia. Its reservoir can discharge fully equilibrated NaCl – type, neutral pH fluids at the 'toe' of an outflow. At some level, advective flows can mix with high-T fluids. The Ulubelu thermal system, now under exploitation in Sumatra, is an example (Hochstein and Sudarman, 2015).

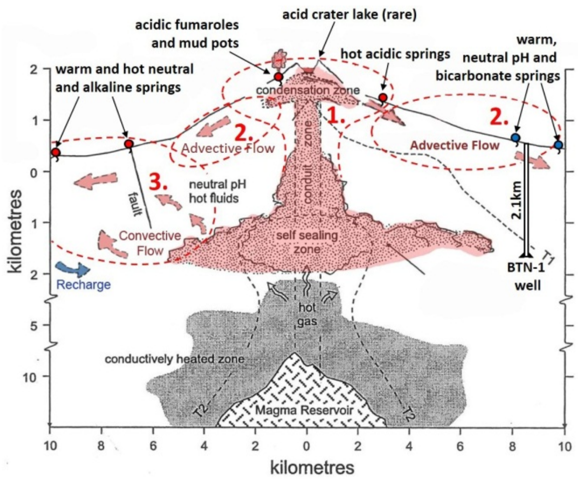

Figure 1: Conceptual model of strato-volcanic systems with three settings: 1. a summit system: 2. advective flow systems, 3. a convective high -T system beneath a flank.

3. EARLY EXPLORATION OF INDONESIAN STRATO-VOLVANOES

3.1 G. Karang

Exploration of geothermal systems in the Banten concession started in the 1970's (Hochstein and Sudarman, 2008). Beneath the S foothills of G. Karang (Fig.2), the exploration model indicated a high-T reservoir upstream of the Citaman springs (T c. 67 deg C, c. 7 MW natural heat loss). The model was based on DC resistivity surveys, T-gradients in 100 to 150 m deep holes, and seismic studies (Mulyadi, 1985, Sudarman, 1985). Standard geo-thermometers were used to predict high (c. 260 deg C) reservoir temperatures.

A deep (2.1 km) exploration well (BTN-1) was sited c. 3 km upstream from the N-most Citaman springs (Fig.2); an approximate terrain setting of the well is indicated in Fig.1. It was completed in 1985 and encountered several flows with Ts up to 120 deg C in the 1 to 2 km depth interval. The well could not be discharged.

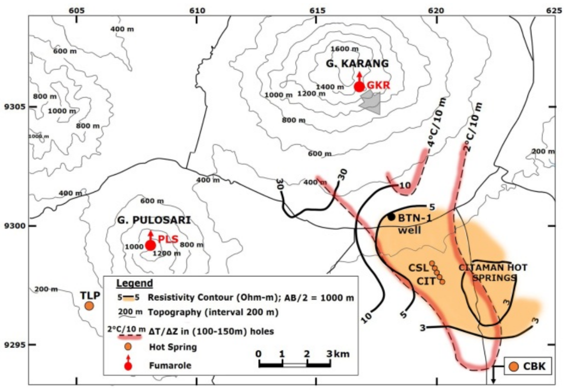

Figure 2: Exploration and drill-site selection of an advective flow system (G. Karang strato-volcano, Indonesia).

We can understand why the predicted high Ts could not be found since there is now good evidence that cation constituents of all advective flows from strato-volcanoes are un-equilibrated (Hochstein and Sudarman, 2015).

Thermal equilibrium Ts of cation constituents, involving plots of (K/Na) versus (Mg/Ca) ratios (Giggenbach, 1988), have been used for a re-assessment. Analyses of old and recent fluid samples (Mulyadi, 1985, Badan Tenaga, 2012) from the Banten prospect are shown in Fig.3. The clusters of acidic condensate data from summit fumaroles (G.Karang and G.Pulosari) and of down-slope thermal springs show that all fluids are un-equilibrated. Hence, Na/K and Na/K/Ca geo-thermometers could not be used to predict high fluid Ts.

The paradigm of predicting high-T reservoirs beneath or within strato-volcanoes by using not applicable geo-thermometers would affect assessment of power potentials of similar prospects during the next decades.

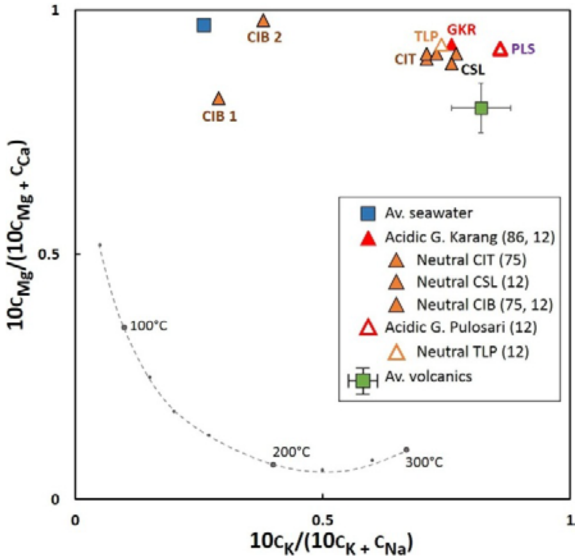

Figure 3: Normalized cation-ratio plot of thermal waters from the G. Karang and G. Pulosari strato- volcanic systems.

3.2 Exploration of the G. Salak and Sibayak strato-volcano systems

The G.Salak prospect is part of the greater Perbakti-G.Salak concession that had been explored since 1973. The prospect includes the partly eroded G.Perbakti volcano (named later Awibengkok) and a thermal area near K.Ratu on G.Salak, a historically active strato-volcano. (Hochstein and Sudarman, 2008).

After drilling the first exploratory wells at Awibengkok in 1983/4 with moderate success, drilling activity shifted to the G. Salak prospect in 1984. The first well (R-1) was drilled to 2.7 km depth and penetrated the entire volcanic sequence, encountering significant acid alteration. It bottomed in sediments with Ts of up to 300 deg C. The well could be discharged but produced some corrosive magmatic gasses. The other two wells were not productive thus exploration activity returned to the Perbakti prospect.

However, there was a successful development of a small strato- volcanic reservoir of the historically active Sibayak volcano. Geophysical surveys by Pertamina outlined in 1987 a low resistivity structure within a small summit caldera hosting significant thermal manifestations. The first 1.5 km deep exploration well (SBY-1) was drilled in 1992 and encountered a liquid-dominated reservoir with 225 deg C. Additional directional wells were drilled; one was drilled towards a conduit and encountered some magmatic gas that restricted further exploration. The presently installed plant had a running capacity of c. 10 MW before production was stopped by the nearby erupting Sinabung volcano. The fluid characteristics of the Sibayak prospect have been described by Hochstein and Sudarman (2015).

3.3 Development of geothermal paradigms

The third decade of Indonesian geothermal developments (1990-2000) saw many accelerated phases introduced by inviting foreign developers to participate in joint development and operation contracts (JOCs). Rapid exploration and deep drilling of many volcanic geothermal prospects occurred although after the Asian financial crisis (1997/8) a rapid decline in development activity happened.

During the third decade (1990-2000), assessments of the electric power potential (Pe) of geothermal prospects in volcanic terrain settings were undertaken by Pertamina using some of the following criteria and assumptions:

i: An attractive prospect exhibits thermal manifestations (active or inactive) .

ii. A suitable hydrological and permeable litho-stratigraphic setting is required.

iii. Low resistivity rocks at shallow and intermediate depths (say < 10 ohm m) are the result of ongoing thermal alteration processes and are associated with a deeper T-anomaly.

iv. Areas with low resistivity structures at shallow and/or intermediate depths outline a 'clay-cap' setting.

v. Deep seated high resistivity structures (MT surveys) beneath a low resistivity 'cap' indicate a reservoir with propylitic alteration.

vi. The constituents of thermal fluids (and gasses) can be used to estimate reservoir Ts.

vii. Thermal springs over the slopes of strato-volcanoes indicate a convective reservoir.

viii.. Convective geothermal reservoirs, hosted by strato-volcanoes, involve heat transfer via magmatic fluids in conduits and/or heat transfer from a hot substratum.

ix. An electric power potential Pe can be predicted from a cross-sectional area of a reservoir defined by its resistivity structure and the application of geothermometers.

x. Reservoir parameters of developed prospects can be used for Pe estimates.

Over 20 accessible Indonesian strato-volcano prospects were explored by the Pertamina and VSI groups until the late 90's. Early deep exploratory drilling was replaced by drilling of intermediate depth TG (temperature gradient) wells. Between 1985 and 1995, a few c. 0.5 km deep TG wells were drilled to test inferred strato-volcanic systems at Ungaran, K. Ijen and at Rajabasa; none of the wells was successful. When the above listed criteria and assumptions were applied to 217 thermal prospects, a subtotal of 71 prospects were identified in 1999 as high-T systems with a total power potential of c. 9,000 MWe for reserves and c. 11,500 MWe for poorly known resources (Sudarman et al., 2000).

In 2003, Pertamina and the state electricity company PLN were reconstructed as limited liability companies. The new Geothermal Laws (22/2001 and 27/2003) shifted control of geothermal exploration and development from Pertamina and PLN to the Ministry of Energy and Mineral Resources (MEMR). The national Geological Agency (Badan Geologi) was given a key role in preparing selection of geothermal prospects to be developed which included prospects that had been returned by Pertamina and PLN. During the selection process much emphasis was attached to estimates of electric power potentials (Pe) and the electric power costs that in many cases had to be derived from poor data. Where data were sparse, the above cited assumptions were often used to obtain a result. Thus paradigms became attached to the new selection process. Existing exploration data were used to compile an assessment of prospects (Dokumen Lelang). Interested developers had to obtain licenses to explore and develop a prospect involving a bidding process. Over 25 new working permits were issued between 2003 and 2010. Revision of Indonesian geothermal prospects by the Badan Geologi listed for some 265 prospects an 'upgraded' total potential of c 13,500 MWe for reserves and c.15,000 MWe for resources (Sukhyar, 2010). The total of c. 28.5 GWe, however, has been quoted ever since to describe a total power potential.

3.4 Exploration of a well studied strato-volcanic prospect (Tangkuban Perahu).

Tangkuban Perahu (TBP) is an active strato-volcano with historic eruptions confined to a few summit craters in the centre of the c. 20 km large Sunda Caldera, a conceptual model (Hochstein et al. 2013) is shown in Fig.4. Acidic hot springs discharge c. 5 km to the NE from the summit area at Ciater (c.5 MW), and 6 km to the SW at Kancah (c.2 MW). The acidic sulphate/chloride waters (pH 2-3) derive from condensates of magmatic fluids, their cation content from acid dissolution of volcanic rocks near the summit (see Fig. 5). The shallow outflows undergo neutralization by fluid/rock interaction. Dilution with infiltrated surface waters and a regional CO2 flux change the composition of acidic fluids to that of neutral pH Na-HCO3 type fluids which move further down-slope beneath the S flanks and to Na-Cl/HCO3 type waters beneath the N flanks. These outward flows represent 'advective flows' as shown in Fig.1.

The TBP prospect had been explored by Pertamina, in the early 1980's. It involved detailed (DC-) resistivity surveys, an early MT study, and gravity and geochemistry surveys. The study outlined areas with intermediate resistivities (c. 50 ohm-m in the upper 300 m) around the Kancah and Ciater thermal springs covering c. 6 and c. 8 km2 respectively (Boedihardi, 1987). De-formation of the summit area was interpreted by Dvorak at al. (1990) as the result of some magma intrusion (see Fig.4). The prospect was found to be not viable for development and Pertamina returned the license to the Ministry in 2002. In 1997, a separate permit had already been issued for the Ciater prospect, covering an enclave of c. 20 km2 (WKP 1997).

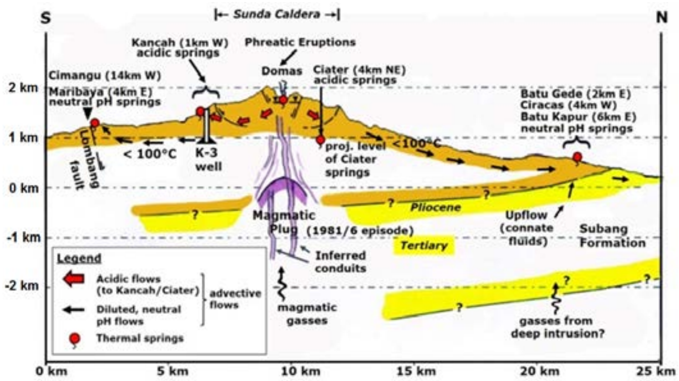

Figure 4: Conceptual model of Tangkuban Parahu strato-volcano system showing advective flow patterns of acidic and neutral pH fluids.

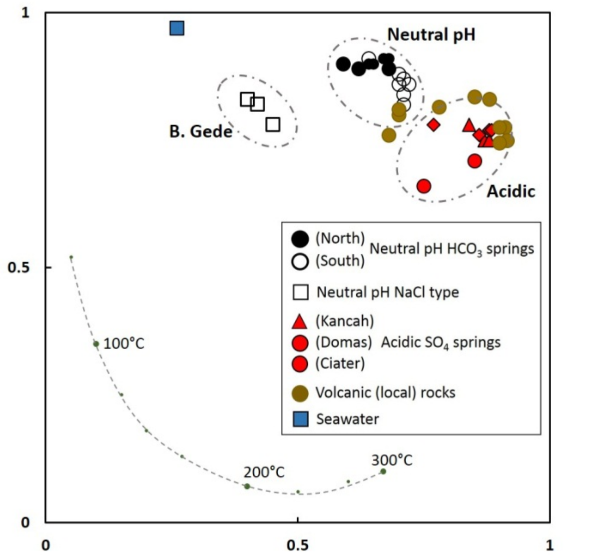

Figure 5: Normalized cation-ratio plot of thermal fluids from Tangkuban Parahu.

Only small surveys were undertaken between 2002 and 2008 by the Badan Geologi. The license area of the TBP prospect was reduced to 450 km2. Follow-up studies included a few geological, geochemical and geophysical surveys (Nasution et al., 2004). A bidding document (Dokumen Lelang) was prepared by the Provincial Government of W-Java and issued in May 2008. It postulates that two separate geothermal reservoirs occur at Kancah (8.5 km2) and at Ciater (10 km2) with inferred mean reservoir Ts of 250 deg C (supported by mis-interpreted geochemical data). The document quotes a power potential of c. 105 MWe and c. 120 MWe respectively.

Bidding for the Kancah prospect was won by PT Indonesian Power. In a government document (Permen 15/2010) targets were set for the development of 110 MWe at Kancah (TBP 1) and 60 MW (TBP 2) at Ciater by the end of 2014. The setting of such targets indicates the growing influence of geothermal paradigms since there was still no evidence that the targeted reservoirs did exist.

Additional exploration was conducted during 2010/11, assisted by a USTDA grant and a US exploration group. It involved geochemical and gas surveys and an extensive MT programme. Most of the results have been circulated (Triyono, 2013). Interpretation of the MT data indicates a c. 2 km thick, low resistivity layer (< 5 ohm m) that can be traced to outcropping, low resistivity claystones of the Subang Formation at the N boundary of the concession (Fig.4). The first exploration well (K-3 in Fig.4) was drilled in 2014 to c 0.62 km depth near the Kancah acidic springs and encountered 'cold' bottom-hole Ts of 50-60 deg C (S. Sudarman, pers.com.).

The failure can be seen as an outcome of the paradigm that led to the prediction of a high T reservoir to occur beneath the S flanks of the Tangkuban Perahu strato volcano. A low resistivity layer at c. 2 km depth beneath the Kancah area (Fig.4) has recently been used to propose future targets depths of 2.5 to 3 km for deep exploration holes (Ibrahim at al., 2015). The cation-ratio plot in Fig.5, however, shows that the acidic manifestations at Kancah and Ciater are not the result of convective flows of a deeper reservoir but are part of long-distance 'advective flows'.

4. GEOTHERMAL EXPLORATION OF A STRATO-VOLCANO IN RWANDA

4.1 The beginnings

The electricity supply in Rwanda is inadequate (only c. 110 MWe installed plant capacity). The possible geothermal potential of young, albeit inactive strato-volcanoes of the Virunga Range had been noticed by visiting experts. A Rwanda geothermal reconnaissance survey was supported by a German aid program in 2007 and provided an overview of prospective areas centred on the huge, 4,500 m high Karisimbi strato volcano (Jolie, 2010).

However, detailed geological, geochemical and geophysical surveys did not find any evidence for a geothermal system. Thermal springs closest to Karisimbi volcano (KAR, MBO) occur c. 30 km away to the S and more than 40 km to the SW (GI springs) (Fig.6). The S springs discharge in Protozoic granites. Thermally altered rocks were not found and temperature surveys in 3 m deep holes around the Karisimbi periphery did not encounter any thermal ground. There was almost no seismic activity along the whole Virunga Range apart from that beneath two active volcanoes near the E boundary of the adjacent DR of Congo.

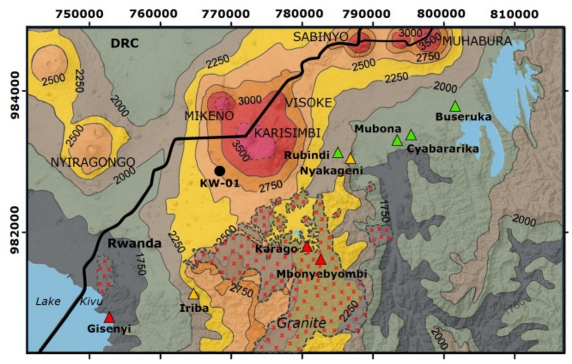

Figure 6: Topography of the Virunga Volcanic Range; thermal springs in the Rwanda sector are indicated by red and yellow triangles, cold CO2-rich springs by a green triangle.

A normalized plot of cation-ratios of spring waters, following Giggenbach (1988), is shown in Fig.7. The data show that all cation constituents are un-equilibrated (with respect to the T-controlled solubility of minerals during fluid/rock interaction). The samples do not allow any assessment of deep equilibrium Ts by geothermometry.

Cold Mg-bicarbonate springs in the NW quarter (i.e. RU, BU, MUB in Fig.6) discharge CO2 and deposit travertine; diffusive CO2 degassing is widespread. Gas analyses indicate minor mantle gasses. The lavas from Karisimbi have been classified as ranging from tephrite basanites to trachy-andesites; they are products of differentiation within the crust. The SW slopes of Karisimbi are covered by basanite debris and young basalt scoria cones.

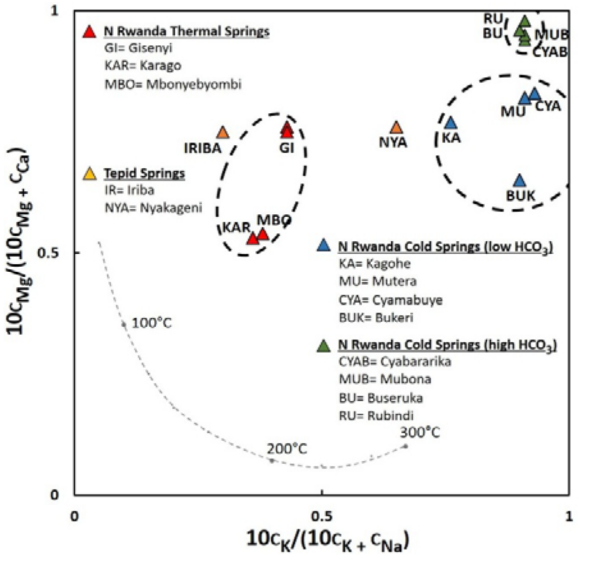

Figure 7: Normalized cation-ratio plot of thermal and cold springs shown in Fig. 6.

4.2 MT surveys of the Karisimbi prospect

A reconnaissance MT survey with widely spaced stations was undertaken in 2008, sponsored by the German aid program. Selected preliminary results of the first 2008 survey (Shalev et al.,2012) indicated a deep seated, low resistivity structure beneath the SW foothills of Karisimbi (Fig.8). Results of the same survey, based on a single MT sounding (GMT 12), were interpreted in terms of a deep geothermal system (Rutagarama, 2009).

Regional tectonic deformation arguments were also used to predict a heat source beneath the S flanks of Karisimbi volcano and beneath the protected Volcanoes National Park area. The prediction was adopted by Jolie (2010) to outline a fictitious low resistivity anomaly at 6 km depth (also shown Fig.8). Although information about an actual thermal reservoir could not be produced, a power potential of the order of 120 MWe was quoted by Rutagarama (2009) using complex arguments. The obvious argument, that there was no evidence to infer the existence of such a resource, was refuted. Instead an argument was used during sessions of the Rwanda EWSA authority to promote drilling at Karisimbi that became the 'Karisimbi paradigm':

"Karisimbi is the 2nd largest strato-volcano in Africa; its large volume of extruded volcanic rocks indicates a large crustal magma chamber where differentiation of mafic magma has occurred. From the top of that chamber, heat has always been transferred by conduction and/or fluids to the Karisimbi pedestal, a process that must have produced large geothermal systems."

The search for concealed low resistivity basement structures as indicator for the elusive drilling target was continued and by 2012/13 some 75 MT stations had been occupied in a c. 6 km wide strip outside the National Park boundary fence around Karisimbi Volcano. All together, c. 160 MT stations were occupied between 2008 and 2013 within the greater project area. New 3-D interpretations, presented recently by Irabaruta and Wameyo (2015), do not support the low resistivity structure in Fig.8 based mainly on 1-D interpretations of the 2008 survey.data..

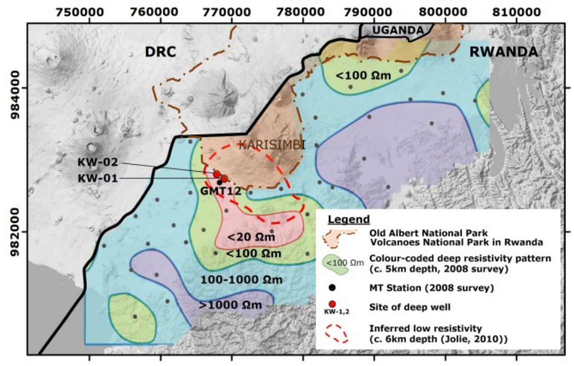

Figure 8: Deep resistivity patterns based on 2009 interpretation of MT soundings in the greater Karisimbi area (2008 survey); the old (1925) Albert National Park area is shown that includes the Rwanda Volcanoes Park (in light brown) and Park boundaries.

A local low resistivity anomaly at the border of the National Park (close to the old GMT 12 site) was selected in 2013 as target for deep exploratory wells. Two wells were drilled during 2013/14; the first one (KW-01) went down to 3 km depth after reaching the top of the granites at c. 1 km depth; the bottom-hole T was 72 deg C. Drilling of the second well (KW-02) was stopped in March 2014 at a depth of 1.37 km after results of well KW-01 became known. Despite the failure of the Karisimbi project, future deep drilling near another strato-volcano in the NE (Kinigi-) sector of Karisimbi is being considered (Rutagarama, 2015).

5. CONCLUSIONS

* Exploration of strato-volcanoes in Indonesia and Rwanda were based on the tacit assumption that they host high-T reservoirs. In Indonesia, the occurrence of active thermal manifestations over the flanks was used to support such a paradigm. In Rwanda, the huge (rock) volume of a strato-volcano with no thermal manifestations became the key part of a paradigm to infer the existence of a high-T resource (in the absence of manifestations).

* Normalized cation-ratio diagrams show that the constituents of thermal springs of explored Indonesian strato-volcanoes derive from acid dissolution of host rocks near the summit and conduits. The original acidic fluids move down-slope and become neutral pH bicarbonate waters. This down-slope flow of thermal fluids constitutes an 'advective flow' that can follow multiple down-flow directions during past flows. The cation composition of advective flows is not equilibrated and can not be used to predict the equilibrium Ts of deep fluids.

* Advective flows cause thermal alteration that produces shallow to intermediate depth resistivity structures which have been used to infer a cross-sectional area of deeper thermal structures. Such resistivity flank anomalies and mis-interpreted fluid equilibria have been used, in the absence of any drill hole data, to predict the electric power potential of many Indonesian strato-volcano prospects. Since these prospects constitute the majority of all presently licensed geothermal developments (27 out of c. 42), their inferred total power potential and associated time lines of development should be reviewed.

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