HYDROTHERMAL ALTERATION CHARACTERIZATION OF GEOTHERMAL FIELDS IN INDONESIA BY ROCK PETROLOGY AND MODELLING

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ABSTRACT

Indonesia with its large, but partially unexplored geothermal potential is one of the most interesting and suitable places in the world to conduct geothermal exploration research.

This study focuses on geothermal exploration based on fluid-rock geochemistry/geomechanics and aims to compile an overview on geochemical data-rock properties from important geothermal fields in Indonesia. The research carried out in the field and in the laboratory is performed in the framework of the GEOCAP cooperation (Geothermal Capacity Building program Indonesia- the Netherlands).

The application of petrology and geochemistry accounts to a better understanding of areas where operating power plants exist but also helps in the initial exploration stage of green areas. Because of their relevance and geological setting geothermal fields in Java (Wayang Windu, Tanguban Perahu) have been visited so far. Mount Salak, Gunung Slamet (Java) and Flores surveys are planned in the near future. Operators, universities and governmental agencies will benefit from this approach as it will be applied also to new green-field terrains.

By comparing the characteristics of the fluids, the alteration petrology and the rock geochemistry we also aim to compile an overview of the geochemistry of several geothermal fields in Indonesia. The gathering of this information is the base for the geomechanical experiments on-going at TUD.

At the same time the rock petrology and fluid geochemistry will be used as input data to model the reservoir fluid composition along with T-P parameters with the geochemical workbench PHREEQC. The field and laboratory data are mandatory for both the implementation and validation of the model results. If successful, this approach can be applied in many geothermal fields characterized by steep terrain and tropical vegetation, which hampers the classical seismic-geophysical exploration methods.

Keywords: geothermal exploration, capacity building, fluid chemistry and rock petrology

INTRODUCTION

In a conventional approach, several methods need to be adopted and integrated to understand the geochemical and geophysical signatures of active geothermal systems (e.g., Rybach and Muffler 1981). These methods also apply for green-field studies and include: (a) geochemical investigations (e.g., using chemical geo-thermometers to infer the temperature of the geothermal reservoir and measurements of gas isotopes, such as $^3He/^4He$, to constrain the origin (mantle or crust) of fluids; (b) drilling of exploration wells; (c) gravity measurements to map any negative anomaly associated with the steam fraction in high-porosity reservoir rocks or to locate zones of lowered density provoked by thermal expansion in magmatic bodies; (d) application of electrical methods such as resistivity to search for zones of higher-salinity fluids; (e) use of seismic methods for the determination of shallow intrusions and their vertical extension.

Young volcanic zones along convergent plate margins are prime targets for the exploration of geothermal-energy sources as active magma chambers have an intrinsically geothermal potential (Bogie et al. 2005). Heath transfer in those areas is dominated by circulating fluids and, in the case of two-phase systems, also by steam. Therefore, surface manifestations like hot springs and steam vents are indicators for geothermal activity. Prior to any geophysical surveying of geothermal systems, a field-based geological and geochemical reconnaissance is required to develop a conceptual model of a geothermal field. The exploration phase predating drilling of the first well is commonly termed Greenfield exploration, referring to the juvenile non-exploited condition of a geothermal reservoir (Hochstein, 1988). However, superficial geothermal manifestations are not manifested in all volcanic fields. Geological formations serving as barriers or seals for fluids may prevent discharge of up-flowing waters.

Java, i.e., is geologically associated with the magmatic arc of the Sunda subduction zone (Simkin and Siebert 1994). Here, geothermal waters were subject of exploration and utilization over several decades (Hochstein et al., 2000; Hochstein and Sundarman 2008). However, the efforts to explore and exploit geothermal prospects changed over the years and also with respect to their location along the island chain. For example, activities for exploitation of geothermal energy centered on vapor-dominated system in western and central Java (in Salak or Cisolok) at the end of the 1970ies, where the infrastructure was sufficiently developed. Efforts increased in the mid 1990ies, when the Indonesian government encouraged foreign investors to take part in the exploration. Recently, the main activities are focused on existing power plants at Kamojang**,** Wyang Windu and Djeng.

Recent published works such as Deon et al. (2015) and Brehme et al. (2014, 2015, 2016) evidences the important of water and rock geochemistry when exploring tropical fields. Analyses on water and rocks deliver valuable information. An approach applied to a wider range of fields is still missing. By comparing the characteristic of the fluids, the alteration petrology and the rock we aim to contribute to compile an overview of the geochemistry in the important geothermal fields in Indonesia and to characterize the rocks for the geomechanical experiments on-going and planed at TUD. The goal is not only to obtain scientific results but also to deliver a reliable method to the governmental agencies, companies and academics.

Deon et al. (2016) describes the fluid-rock characteristics of Tanguban Perahu and Wayang Windu. (see Figure 1). In this paper we present a wider application method to detect hydrothermal alteration specifically looking at clays. A combination of X-ray Diffraction (XRD) technique accompanied by Electronmicroprobe analyzer (EMPA) has been chosed to determine if and in which extend the rocks are suitable for geomechaical experiments and further acizing tests. A first set of experiments involving temperature test are presented in Imaro et al (2017).

METHODS

Rock samples

The XRD analyses have been performed on the crushed and sieved samples using a Bruker D2 Phaser XRD installed in the laboratories of ITC, University of Twente. The rock powder has been placed on a XRD sample holder (amount approximately 1 gram) and analyzed. The patterns have been acquired from 6˚ to 80˚ (degrees 2θ). The interpretation has been carried out semi-quantitatively by using the program DIFFRAC.EVA (Brucker).

EMPA images have been collected with a JEOL JXA 8230 electron microprobe (15 kV accelerating voltage) at the Electron Microprobe Laboratory, Department of Inorganic and Isotope Geochemistry at the Helmholtz Centre Potsdam – German Research Centre for Geosciences (GFZ) in Potsdam, Germany. The measuring conditions are described in have described in Deon et al. (2016).

Water probes have been sampled in three locations as shown in Figure 2: Kawah Putih (acidic volcanic crater lake), Cimanggu (hot spring) and Cibolang (hot river). The water samples have been collected according to the procedure of Giggenbach & Gougel (1989) recommended for the quantitative analysis of the major ions. Water samples were filtrated using a 0.45 µm membrane filter to prevent the interaction of the fluid with suspended particles and algal growth. For the analysis of anions, water samples were untreated, while for cation analysis planed soon, the water samples will acidified with HNO_3. The on-site measurements covered pH, temperature (T) and carbonate content. The elements in the water samples have been measured at the University of Twente, Netherlands.

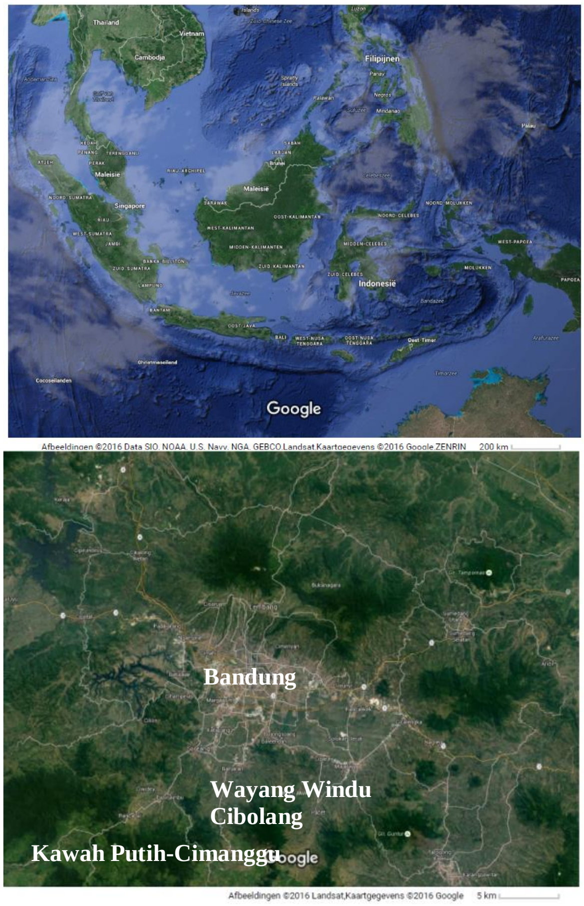

Figure 1: Map of Indonesia with the highlighted research areas. Detailed map of the fieldwork area in West Java in the proximity of Bandung. (Source Google Earth)

Figure 2: a) acidic volcanic lake crater Kawah Putih

Figure 2: b) hot spring Cimanggu

Figure 2: c) river in Cibolang.

RESULTS

Rocks

The XRD semi-quantitative (Figure 3a and 3b) interpretation results of the analyzed rocks are listed in table 1. The samples from Tanguban Perahu (basalts) mostly contain plagioclase and feldspar (B2). BB, BC show small amounts of goethite whereas BD ilmenite. The pumice XRD pattern indicates a high amount of tridymite. Nearly 90 wt. % of quartz and 9 wt. % of sulfur form CB1. KB1 (Kawah Burung) shows almost only sulfur and KW1 has a smaller amount of sulfur (60 wt.%) along with 30 wt. % of trydimyte and pyroxene (7.2 wt.%). In Table 1 the crystallinity (%) has been calculated for each compound. The mineral structures adopted with the EVA program represent an ideal match with the measured patterns and are chosen on the base of the rock type analyzed.

The analyses performed at the EMPA show plagioclase crystals (Figure 4a and b) and quartz. The element distribution mapping refers to the Al concentration on a plagioclase crystal (see Figure 5a and b). The brighter the color appears the higher the element concentration occurs to be in the spot. The samples B2, BB, BC and BD are classified as basalts; CB1 and KW1 as a silica sinter (based on the quartz amount), KB1 sulfur and PM as a pumice. Because of the concentration below 1 wt.% the clay fraction could not be identified with XRD but has been observed at the EMPA scattered in the basalts. Kaolinite $AlSi_2O_5(OH)_4$ constitutes approximately 1 wt. % of the phases amount of the analyzed samples.

Table 1: Mineral composition of the rock samples and the calculated (semi-quantitatively) mineral fractions.

Sample	Cristallinity percentage	Compound name	Compound formula	Weight percent
B2	51,1	Oligoclase	$(Ca,Na)(Al,Si)_4O_8$	73,7
		Sanidine	$K(AlSi_3O_8)$	26,3
BB	64,1	Bytownite	$(Ca,Na)(Al,Si)_4O_8$	69,4
		Microcline	$K(AlSi_3O_8)$	29,2
		Goethite	$FeHO_2$	1,4
BC	62,0	Bytownite	$(Ca,Na)(Al,Si)_4O_8$	89,8
		Sulfur	S_8	8,8
		Goethite	$FeHO_2$	1,4
BD	80,3	Bytownite	$(Ca,Na)(Al,Si)_4O_8$	59,7
		Anorthoclase	$Na,K(AlSi_3O_8)$	36,4
		Ilmenite	$FeTiO_3$	3,9
CB1	85,7	Quartz	SiO_2	88,7
		Sulfur	S_8	9,9
		Anatase	TiO_2	0,8
		Cristobalite	SiO_2	0,6
KB1	85,4	Sulfur	S_8	94,3
		Cristobalite	SiO_2	5,7
KW1	52,2	Sulfur	S_8	60,4
		Tridimyte	SiO_2	32,4
		Diopside	$MgCaSi_2O_6$	7,2
PM	68,6	Tridimyte	SiO_2	65,6
		Biachellaite	$(Na,Ca,K)_8(Si_6Al_6O_{24})(SO_4)_2(OH)_2 \bullet H_2O$	26,2
		Anatase	TiO_2	8,2

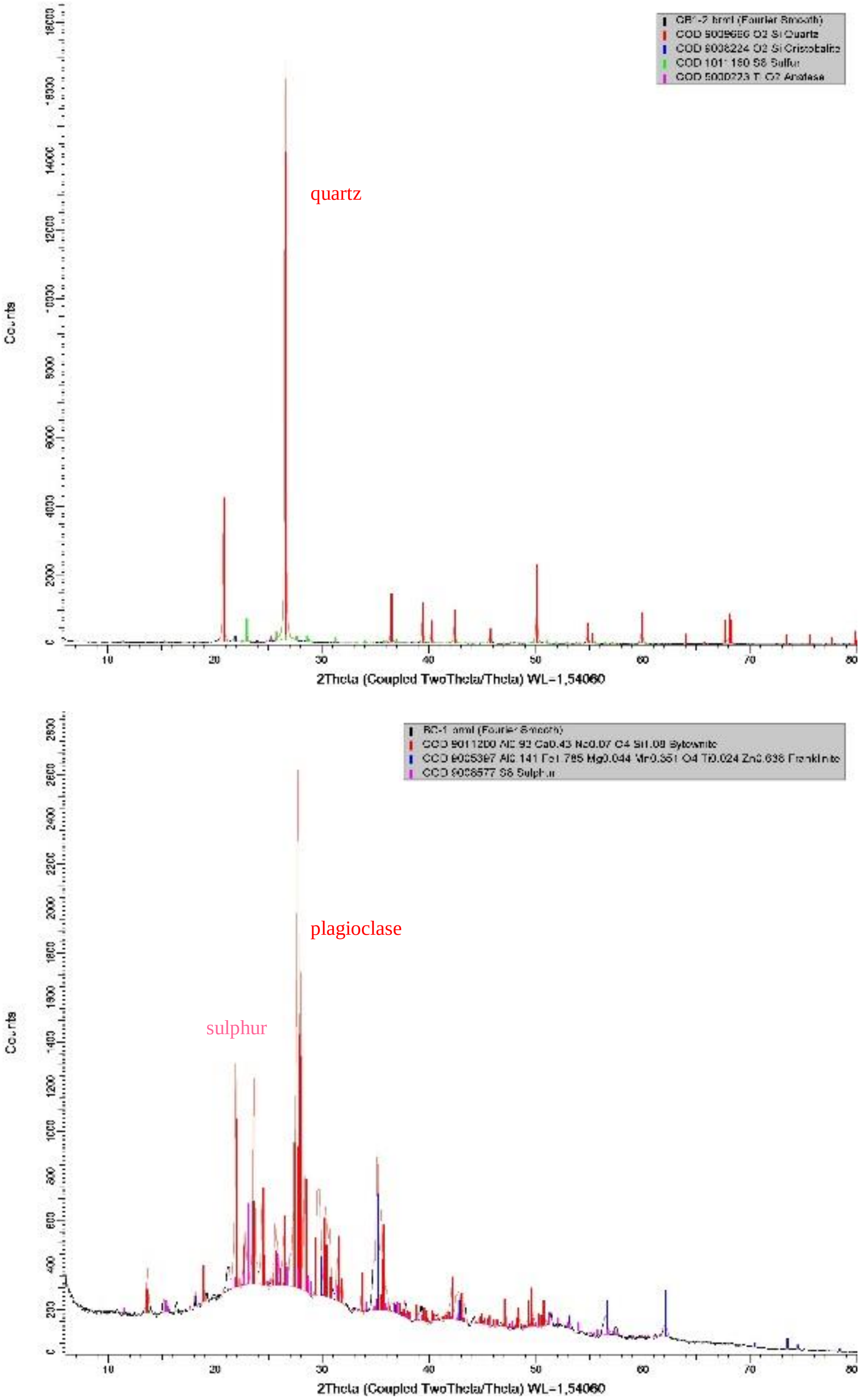

Figure 3: XRD patterns with the peak match and identification. a) sample CB1 where the intense high red peaks have been assigned to quartz (top figure). b) BC 1 where the most intense peaks belong to plagioclase (bottom figure). The bumps indicate the amorphous fraction.

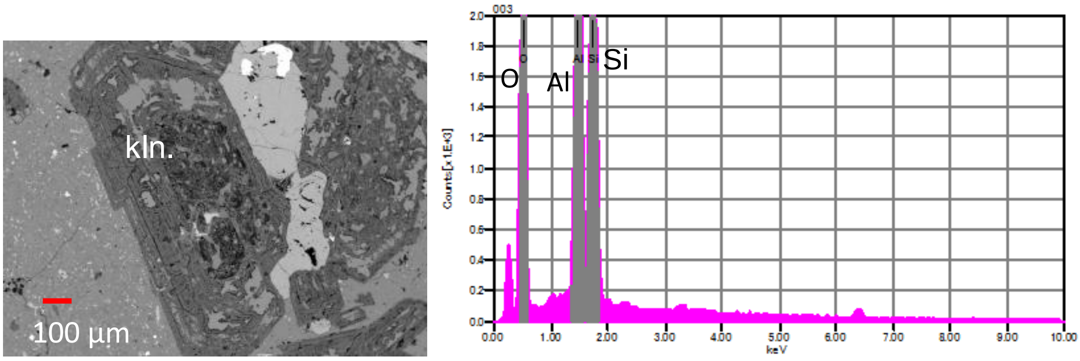

*Figure 4: a) EMP image aquired on a plagioclase crystal where **the alteration patterns** are clearly visible in the plagioclase grain (left). b) EBS sprectum aquired on the alteration rims showing **kaolinite** occurrence (right).*

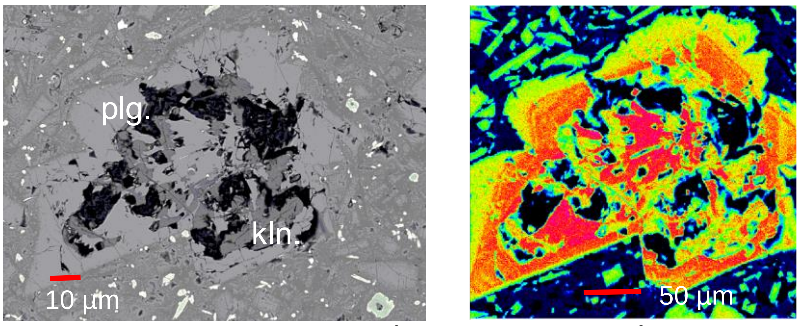

Figure 5: a) BSE image of a plagioclase crystal (left).
b) related Al distribution mapping on the altered plagioclase crystal (right).

Fluids

All the water samples have failed the bicarbonate test in the field due to the weather conditions (heavy rain) and / or absence of bicarbonate. The major anions are listed in Table 2. The temperature measured on-site ranges from 29.3 ˚C (KP1 Fig. 2a) to 90.3 ˚ C (CB1 Fig 2c). The pH of KP1 0.8 is more acidic than the other two springs CB1 (2.5) and CM1 (5.1). High sulfate concentration characterize both KP1 and CB1. A considerable amount of chlorine (˜ 600 ppm) has been detected on KP1 whereas the other two samples show no chlorine (CB1) and a smaller amount (˜40 ppm). Major cations have not been measured yet because the springs will be monitored and re- sampled in summer/fall 2017 during the dry season.

Table 2: Field parameter and water chemistry.

Sample	T(˚C)	pH	HCO_3^- (ppm)	SO_4^{2-} (ppm)	Cl^- (ppm)
KP1	29.3	0.8	n.d.	310	595
CB1	90.3	2.5	n.d.	474	-
CM1	64.6	5.1	n.d.	40	44

DISCUSSION

Rocks

The XRD patterns in Figure 3a and b show the peak interpretation of the samples CB1 (3a) and BC (3b). The two diffractograms have been selected based on the mineralogy of the rocks and the relevance applied to the Indonesian geothermal fields. CB1 is a typical silica sinter which can be often found in several geothermal fields such as Wayang Windu (this study) but also in other locations with hydrothermally altered outcrops. Intense and sharp quartz peaks can be observed in Figure 3a. Their intensity corresponds to the highest concentration (quartz) as shown in Table 1. Generally when the peak appears so sharp and high one can rely on the semi-quantitative interpretation. An absolute quantification of the mineral phases in the probes investigated in this paper could not be performed because of the amorphous fraction characterizing them. Manifestations such as silica sinters are often found near volcanic craters or high temperature hot springs (Deon et al. 2016). BC, basalt from the Tangkuban Perhau area, is characterized by a high amount of plagioclase in our XRD interpretation identified as bytownite. The bumps, visible in the pattern, are caused by the amorphous fraction detected in the samples as the crystallinity % (see Table 1) have been estimated to be 62 %. Basalts with this composition not only characterize many geothermal areas in Java but are often classified as the reservoir rock. It is therefore very important to gather as many details as possible on the samples (or cores whenever available) in order to determine the rock properties. The response to the temperature of these rocks and the variation of properties such as permeability-porosity is described in Imaro et al. (2017). Geomechanical experiments with acidizing are planned at TUD with the goal to test these rock types in order to improve the production in several active fields in Indonesia with already operating plants.

The clay fraction plays a very important role in the rock's response to temperature and stress but also on properties such as permeability, porosity and swelling. The amount could not be identified with the XRD due to the extremely limited amount lying below the detection limit (˜1 wt.%). This is why we have conducted detailed image acquiring and chemical analyses at the EMPA.

Selected well-formed plagioclase crystals have been chosen for the images acquirement at the EMPA as shown in Figure 4. Clear alteration rims spreading towards the inner part of the grain can be observed on the grain (Figure 4a). The chemical analyses (Figure 4b) indicates kaolinite as alteration phase. This rock have been collected in the Wayang Windu crater and therefore we relate the kaolinite occurrence to the hydrothermal alteration on going in the crater caused by high temperature steam and bubbling hot springs (see Deon et al. 2016).

A more detailed and precise technique to map the alteration has been applied to a second crystal (Figure 5). The grain has been selected and chemically analysed to confirm the alteration. Al has been chosen as element for the mapping because its different occurrence (concentration) in plagioclase and kaolinite. Thus, the identification of clay is supported by the Al different concentration in the grain. By looking at the different intensity of the colours related to Al in the image one can distinguish between the areas with high Al concentration (yellow) and lower (green). The regions with smaller Al content are those where kaolinite can be detected as alteration of the plagioclase shown in the Figure 5a.

Commonly the clay fraction is determined with XRD on a separated portion of the sample. This technique is reliable but very time–consuming and bounded to the available amount of clay. Very small fractions (below 1 wt. %) can hardly be identified and quantified. The EMPA, if available, allows a "relatively" quick and reliable determination of the clay type (based on the chemistry) directly on the thin section.

Fluids

The sampled springs have been analyzed only in terms of two major anions (sulfate and chlorine). The results have been plotted in the Giggenbach ternary diagram in Figure 6. The concentration of the major anion allows to classify the water samples in terms of vicinity to reservoir. However, without cation concentration it is not possible to estimate the reservoir temperature and apply the geothermometers. More sampling and monitoring are planed on those springs. Sample KP1 plots in the mature water field whereas CB1 in the steam heated water. The high concentration of Cl (˜600 ppm) in KP1 is likely to be expected because of the very acidic pH of the volcanic crater lake Kawah Putih. The samples CM1 is most likely chracterized by a high concentration of bicarbonate because of the very low measured concentration of sulfate and chlorine. More sampling and analyses are needed in order to better investigate this springs and their geochemistry.

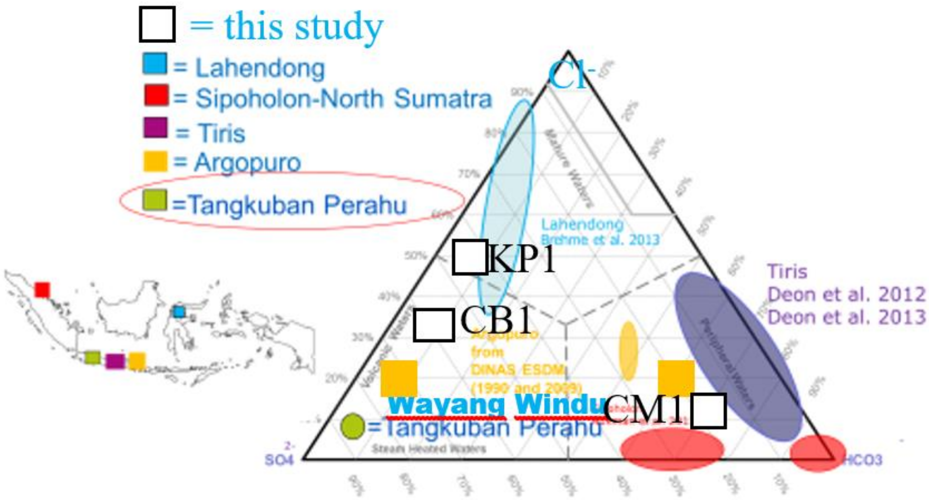

Figure 6: Ternary diagram of the major anions Cl^{-}, SO_4^{2-}, HCO_3^{-}. Data from the literature show significant differences in the geochemistry from different fields and are included for comparison.

CONCLUSION AND OUTLOOK

The additional data presented in the work complete those included in Deon et al. (2016). We aim to apply this approach to other fields in Java: Mount Salak and Mount Slamet. By sampling water and rocks additional information will be gathered on theses areas. The data will be implemented in the PHREEQC geochemical workbench in order to simulate the reservoir fluid composition. The novely in this study is the binary appproach which is followed: not only we are going to test PHREEQC with data from green fields but also with data from areas where plants are already operating. This will allow to verify whether the reservoir temperatures-composition estimation for the areas under exploration is correct by validating the results on already explored and known areas.

This paper is the follow up of the paper presented at the IGCE 2016. More steps and field campaigns are planed with our Indonesian partners along with capacity building activities within the Dutch-Indonesian cooperation GEOCAP (Geothermal Capacity Building Program the Netherlands-Indonesia).

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