Proceedings World Geothermal Congress 2015
Melbourne, Australia, 19-25 April 2015

Indonesian Volcanic Geothermal Systems

Manfred P.Hochstein[1] and Sayogi Sudarman[2]

[1]School of Environment and IESE, Univ. of Auckland, NZ; [2]GE Program, Univ. of Indonesia, Jakarta, Indonesia

[1]mp.hochstein@auckland.ac.nz; [2]ssudarman3@yahoo.com

Keywords: Volcanic geothermal systems, strato-volcano geothermal system, volcanic geothermal 'feeder' system, advective and convective fluid flow, potential estimate problems, geothermometry

ABSTRACT

Two groups of Indonesian volcanic geothermal systems have been recognised by using fluid analyses and volcanic (terrain) settings as discriminants. The larger group includes geothermal systems that are hosted by young strato-volcanoes. Their thermal manifestations are often sustained by advective flow of diluted condensates over the upper flanks and foothill region of volcanoes with high relief. A smaller group includes steeply dipping 'volcanic feeder (plug-type) systems' hosted by convective systems standing in moderate terrain. The feeders transfer acidic fluids to the surface and have affinity with 'vapour core' structures.

About 20 Indonesian strato-volcano prospects have been explored searching for high T prospects. Mixed neutral pH and acidic manifestations occur in one prospect (Sibayak), close to the summit sector. Prospects with acidic manifestations up-slope and minor neutral pH springs down-slope are common (K. Ijen, Tangkuban Perahu). Outflows of neutral and quasi-equilibrated thermal fluids in the foothills have been reported for a few strato-volcano prospects (Ulubelu). At least 5 volcanic acidic feeder (plug type) systems have been explored. These are hosted by liquid-dominated reservoirs (Dieng, Lahendong). Cation-based geothermometry can not be applied to infer reservoir equilibrium temperatures of volcanic geothermal systems using thermal spring analyses since cation compositions are un-equilibrated. With inferred reservoir dimensions, often reflecting incoherent geophysical anomaly areas and palaeo- resistivity structures, power potentials quoted in the past for accelerated developments of volcanic geothermal prospects are open to criticism.

1. INTRODUCTION

The term 'volcanic geothermal system' is used here to describe heat transfer systems hosted by young volcanic mountains that involve one or more of the following: some discharge of dominantly neutral (pH) fluids by advective flow on the flanks, some mixed upflow or outflow of neutral (pH) fluids from a convective high T reservoir, some discharge of magmatic and acidic fluids from conduits in a summit region or via steep feeder channels transferring acidic condensates and traces of magmatic fluids.

Volcanic geothermal systems are hosted by 'volcanic systems' whose heat transfer is associated with the production of magmatic fluids, pyroclastics, and lava flows from discharge centres near conduits and eruption craters.

Over 20 volcanic geothermal systems were explored in Indonesia between 1970 and 2000 (Hochstein and Sudarman, 2008). Most prospects are associated with volcanoes of high relief (mainly strato-volcanoes). Developed prospects of this type are Sibayak and Ulubelu (Sumatra). A smaller group of volcanic geothermal systems occur in moderate volcanic terrain where acidic condensates are discharged by feeders, hosted and surrounded by convective high T reservoirs. Examples of such systems are Lahendong (Sulawesi), Dieng and Patuha (Java) that have affinity with 'vapour-core' systems in the Philippines (Reyes et al., 1993).

Exploration of volcanic geothermal prospects was undertaken by VSI and Pertamina groups since the early 1970's. The likely extent of concealed thermally altered rocks could often not be defined because of incoherent survey data. By 2000, Pertamina returned most licenses of their volcanic geothermal prospects to the Ministry of Energy and Mineral Resources (MEMR). Other geothermal development concessions were renewed. A 2003 geothermal law requires that new licenses be issued by a bidding process. The bidding documents (Dokumen Lelang) were prepared by the new Geological Agency (Badan Geologi).

Since 2007, new exploration licenses (WKP) have been issued by MEMR and tendered by regional government offices for volcanic geothermal prospects which include areas with active volcanoes. Electrical power potentials (Pe) are quoted in each bidding document using inferred cross-sectional reservoir areas and equilibrium temperatures of reservoir fluids based on analyses of geophysical anomalies and surface fluids. Power potentials (Pe) of promising prospects were listed by the Geological Agency (Sukhyar, Ed., 2010) already together with capacity estimates of power plants. Bidders for exploration licenses have to estimate the price of electricity to be delivered for a total development scheme. Plant capacity estimates were adopted by the Government by an official decree (Permen-15/2010) which defines partial geothermal development targets for enhanced electricity production of c. 4,500 MWe from 47 geothermal prospects by the end of 2014. The targets also refer to the development of 22 volcanic geothermal systems with expected production reaching c. 2,600 MWe.

2. APPROACH AND METHODS

The aim of our study was to check whether the inferred potential of volcanic geothermal prospects is supported by the exploration results of similar prospects which already produce electric power. We had access to exploration studies of most volcanic geothermal prospects. Bidding documents (Dokumen Lelang) were inspected in 2010 at the MEMR to check the extent of later studies when compiling a review and an assessment of the limits of power potential estimates of Indonesian geothermal prospects (Hochstein and Crosetti, 2012). Most exploration results cited here were taken from the literature with some data provided by developers.

Field notes taken during our visits of the prospects were used to obtain order of magnitude assessments for heat losses related to discharges of acidic fluids versus those associated with neutral pH manifestations. Fluid flow characteristics and mixing were assessed by checking the degree of equilibration of constituents used for cation geothermometry and checking of isotope data following the approach by Reyes et al. (1993). For presentation of equilibration status, normalised Na/K versus Ca/Mg plots are used (Giggenbach, 1988), rather than normalised Na-K-Mg data in triangular plots We became aware that most Indonesian strato-volcanoes discharge gasses which originate from mantle wedge melts together with large discharges of CO_2 gasses of crustal origin (Halldorsson et al., 2013) which tend to disturb gas equilibria. Geophysical surveys which had been used to infer the extent of hot altered rocks were checked but only typical studies are cited. Exploration and drilling data have been used to construct simplified cross-sections which show inferred patterns of advective and convective fluid flows. The geometry and position of wells in these sections are condensed and simplified to present a cartoon-type conceptual model.

3. CHARACTERISTICS OF GEOTHERMAL SYSTEMS ASSOCIATED WITH INDONESIAN STRATO-VOLCANOES

About 80 strato-volcanoes (active and non-active) occur in Indonesia with their centres lying almost parallel to active plate boundaries. A group of c. 20 geothermal system associated with strato-volcanoes has been explored until now. Three sub-groups are indicated. One involves a high standing, convective high-T reservoir beneath the summit region of a volcano (Sibayak type). Another sub-group is characterised by significant, often acidic advective flows beneath the upper flanks although a concealed convective high-T reservoir beneath the flanks or the summit region is not indicated (Kawah Ijen type). An active reservoir beneath the flanks is indicated for the third group of prospects that discharge neutral pH, NaCl-type thermal waters at the bottom section, representing outflows of a high-T reservoir (Ulubelu type).

3.1 The Sibayak System

The Sibayak volcanic geothermal reservoir occurs near the conduit(s) of two small strato-volcanoes (3.21° N, 98.47° E) in a partly infilled, small caldera. Both neutral pH SO_4-HCO_3- and acidic SO_4-type thermal waters discharge along the S margin; fumaroles discharge neutral and acidic steam up-slope. The natural heat discharge has been estimated to be > 30 MW. An area with significant thermal alteration was outlined by resistivity surveys (Mulyadi, 2000). Ten deep wells were drilled into the reservoir as outlined by geophysical surveys. The highest T and high productivity were encountered in the deviated well SBY-5, close to the inferred conduit zone (bottom T of c. 290 deg C). Gasses are dominantly CO_2 and H_2S. Some wells discharge minor magmatic gasses (HF, HCl). Recent surveys have shown that anomalous He (Ra) and ^{13}C (CO_2) isotope data occur at Sibayak in fumarole and soil gasses at stations over c. 4 km apart. The data point to upflow of gasses of mantle wedge origin (Halldorsson et al., 2013). A simplified pattern of fluid flow within the Sibayak reservoir is shown in Fig.1.1.

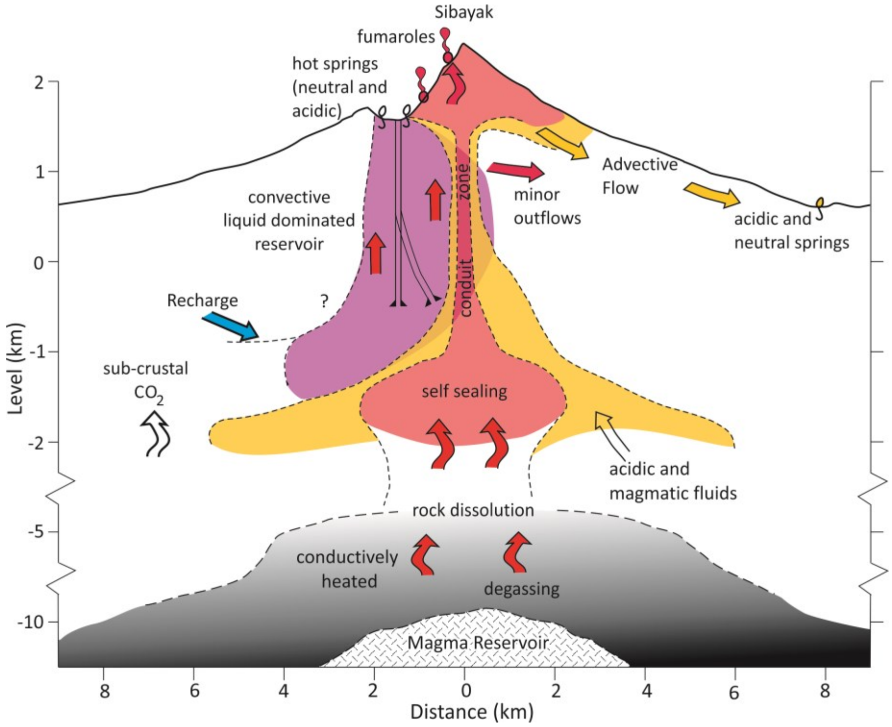

Figure 1.1: Conceptual model of the Sibayak volcanic geothermal system showing inferred fluid flow patterns along a schematic W-E section. Well location is reduced to that of two bunched wells. The lateral extent of the liquid dominated geothermal and volcanic conduit reservoirs is inferred.

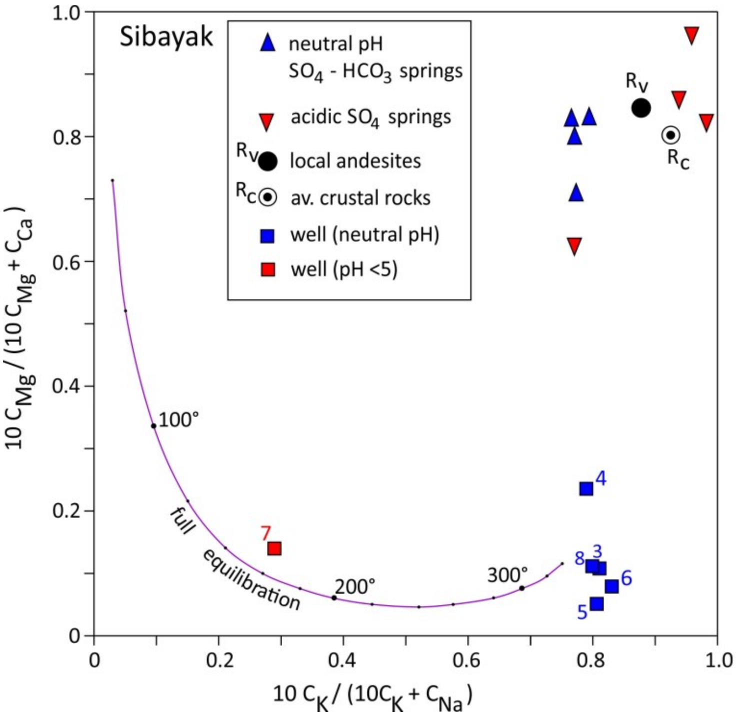

Figure 1.2: Cation ratio plot (Na/K versus Ca/Mg) of thermal spring and deep well samples from the Sibayak prospect.

The degree of fluid-rock interaction is indicated by data in Fig. 1.2 showing normalised Na/K versus Ca/Mg ratios of surface manifestations and well samples. The Na/K and Ca/Mg values of all springs cluster around that of rock minerals of local andesites and crustal rocks indicating that the cation constituents derive from rock dissolution. Assuming that adsorbtion of magmatic gasses by condensates is involved in the dissolution, this could occur both within the top condensate zone as well as at greater depths around the inferred, deep contact zone indicated in Fig. 1.1 (after Hochstein and Browne, 2000). Reservoir modelling by Atmojo et al. (2000) produced a similar conceptual model for the Sibayak reservoir whose power potential, Pe, has been listed as c. 30 MWe. The running capacity during the last decade was < 10 MWe. The prospect carries a significant volcanic risk for long- term developments (historic eruption in 1881).

3.2 Strato-volcanic systems with advective flow

A group of strato-volcano systems exhibits significant advective flow beneath the flanks but without typical manifestations showing that an active high-T system exists beneath the flanks. Two examples of this group are shown together in Fig. 2.1. Each prospect is in a half-section with reference to an active conduit-crater zone in the centre where meteoric and magmatic vapours discharge. Condensation in the summit region produces acidic thermal waters which by advective sub-surface flow can discharge via acidic springs over the flanks. Infiltration and fluid-rock interaction affect the subsurface flows downstream which become neutral (pH) waters discharging at minor springs over the lower flank section.

3.2.1 The Kawah Ijen System

The K. Ijen system is dominated by the degassing Ijen strato-volcano (8.06° N, 114.24° E), located at the SE rim of the old Ijen caldera. Hot magmatic gasses discharge around and at the bottom of a large (0.44 km^2) acid (pH < 1) crater lake near the summit, increasing its annual av. surface T to c. 35 deg C. Heat is mainly discharged by evaporation (c. 1,000 MW). Subsurface leakage from the acid lake enters an acid creek and is channelled across the whole width (c. 12 km) of the caldera to its N rim. Here the Blawan springs discharge neutral (pH) bicarbonate waters, with up to 50 deg C and c. 2 MW anomalous heat (Hochstein et al., 2013). Other active thermal manifestations have not been found although low resistivity and demagnetised structures were detected inside the caldera. Detailed geophysical surveys by Pertamina included gravity, airborne magnetic, and resistivity surveys (DC and MT) and drilling of several T-gradient wells. A deep slim hole (SH-01) in the centre of a poorly defined resistivity structure inside the caldera encountered up to 80 deg C at 0.5 km depth. At the same depth, traces of alteration minerals (epidote) were found pointing to an extinct thermal reservoir associated with the subdued low resistivity structure. Evidence for another palaeo-reservoir is indicated by a de-magnetised volcanic dome inside the caldera (see L-half of Fig. 2.1).

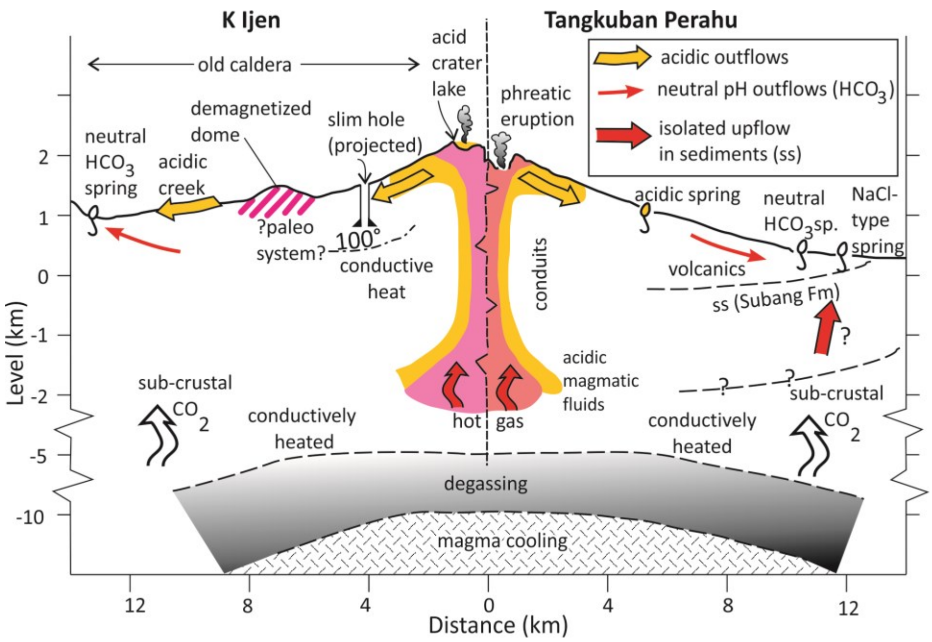

Figure 2.1: Conceptual models of a N half section of the K. Ijen prospect (left) and another N half section of the Tangkuban Perahu prospect (right) showing advective flow patterns. The central vertical axis in the figure coincides with the axis of their conduits.

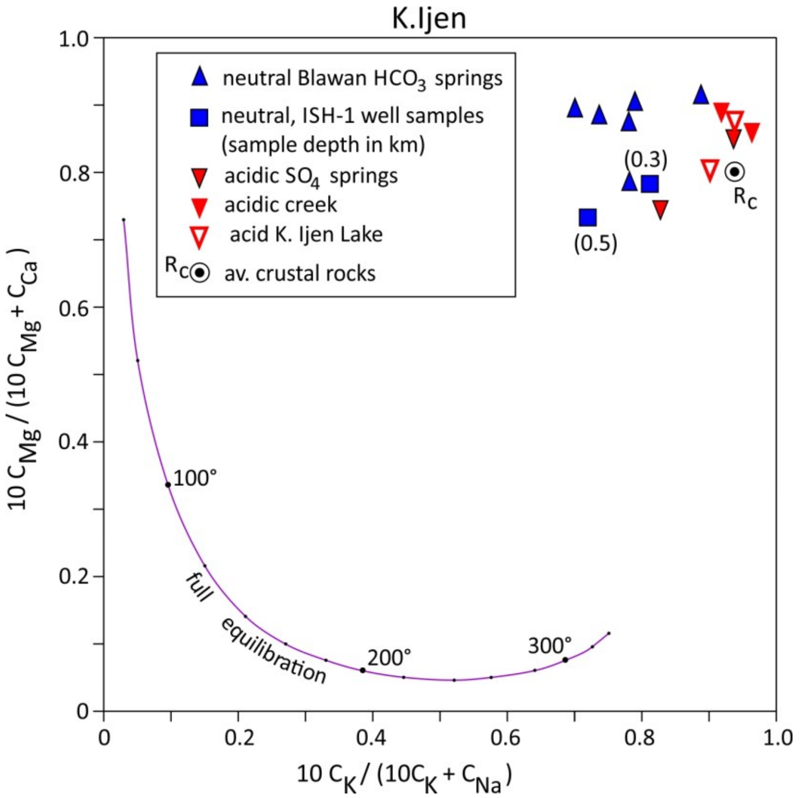

Figure 2.2: Cation ratio plot of the acid lake, acid creek, distant neutral (pH) springs and well samples of the K. Ijen prospect.

Dilution, neutralisation and mixing of the original magmatic fluids with meteoric waters are indicated by the cation ratio plot in Fig. 2.2. This shows that the acid lake waters, the acidic creek, and the distant neutralised bicarbonate waters all exhibit similar Na/K and Ca/Mg ratios, thus indicating their composition by acid dissolution of volcanic rocks (Delmelle et al., 2000) and later dilution by meteoric waters. The same applies to stronly diluted fluids sampled at the bottom of the SH-01 well. The Blawan spring waters, however, underwent some shallow 'heat sweep' which raised their temperatures. The results in Fig. 2.2 show that, despite neutralization upstream, the cation composition of the Blawan springs has remained unequilibrated and cannot be used to estimate equilibrium temperatures of an inferred high T reservoir upstream. The return of the exploration license in 2000 by Pertamina was justified. The prediction of high reservoir T beneath the Ijen caldera in the 2010 MEMR bidding document, however, was misleading.

3.2.2 The Tangkuban Perahu system

Advective flow of diluted acidic condensates occurs beneath the upper flanks of Tangkuban Perahu, an active strato-volcano (6.77° N, 107.60° E) producing intermittent phreatic eruptions (Simkin and Siebert, 1994). Acidic condensates are discharged by springs with flow rates of the order of 50 l/s over the NE and S slopes at Ciater and Kancah respectively. Minor springs discharge neutral (pH) bicarbonate waters further downstream. Their anomalous heat discharge rate is moderate (c. 5 to 10 MW and 2 MW for all acidic and neutral springs respectively). A small distant thermal spring, discharging NaCl water, occurs near the contact with thick Tertiary sediments and indicates a small upflow of thermal fluids from the underlying sediment whose discharge is not connected with a volcanic reservoir. Both the Tangkuban Perahu and Ijen craters discharge some magmatic water through fumaroles as indicated by the isotope plot shown in Fig. 2.3, a magmatic mix of up to c. 30 % and c.70 % respectively is indicated.

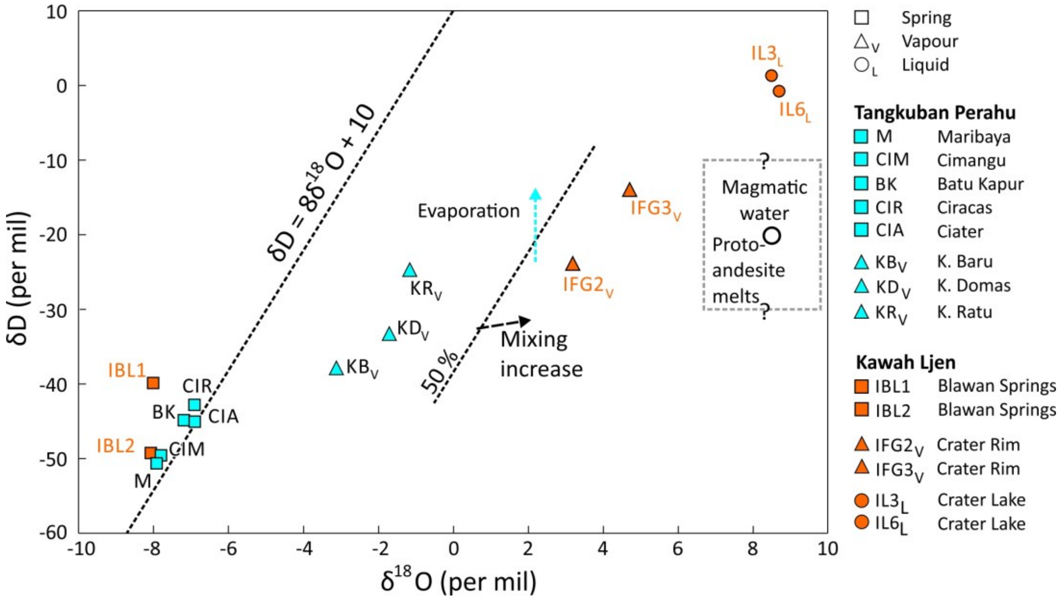

Figure 2.3: δ O^{18} versus δ D isotope data of water and vapour samples from the K. Ijen and the Tangkuban Perahu geothermal prospects.

Geological and geophysical surveys of the Tangkuban Perahu prospect were undertaken by Pertamina in the 1970's (Boedihardi, 1987). The geochemical characteristics of the thermal fluids have been described by Nasution et al. (2004). A concealed high T reservoir within the volcanic massif is not supported by the un-equilibrated status of the thermal spring constituents. The cation ratio plot of all springs is similar to that shown in Fig. 2.2. The Tangkuban Perahu license, except for the Ciater enclave license of 1997, was also returned in 2000 by Pertamina to the government. It has been re-issued by the W- Java regional office in 2007 – the prospect is under investigation.

3.3 Ulubelu – volcanic geothermal system with a large outflow structure

The manifestations of the Ulubelu geothermal prospect occur over moderate terrain, down-slope and to the S from the dormant G.Rendigan strato-volcano (5.35° N, 104.60° E). The manifestations show some zonation of acidic SO_4 springs upstream to neutral SO_4-HCO_3 springs mid- downstream to neutral Cl-SO_4-HCO_3 springs at the bottom where travertine has deposited (Kusnadi, 1993). The prospect was classified as a caldera type volcano or a volcano in a volcano-tectonic depression (Neumann van Padang, 1951). That model was still used when detailed exploration surveys were started 1990 (using gravity, magnetic, DC- and MT resistivity methods), followed in 1995 by drilling 3 deep (c. 1.2 km) slim holes. SL-3 (Fig.3.1). was thought to be near the centre of a volcano-tectonic depression reservoir (Mulyadi, 2000). Heat loss surveys were not undertaken. However, the bottom hole Ts in SL-3, with an inverse profile and c. 200 deg C at 0.95 km, did not support an 'upflow structure' of a high-T reservoir. Its centre has to occur somewhere nearer the Rendigan strato-volcano.

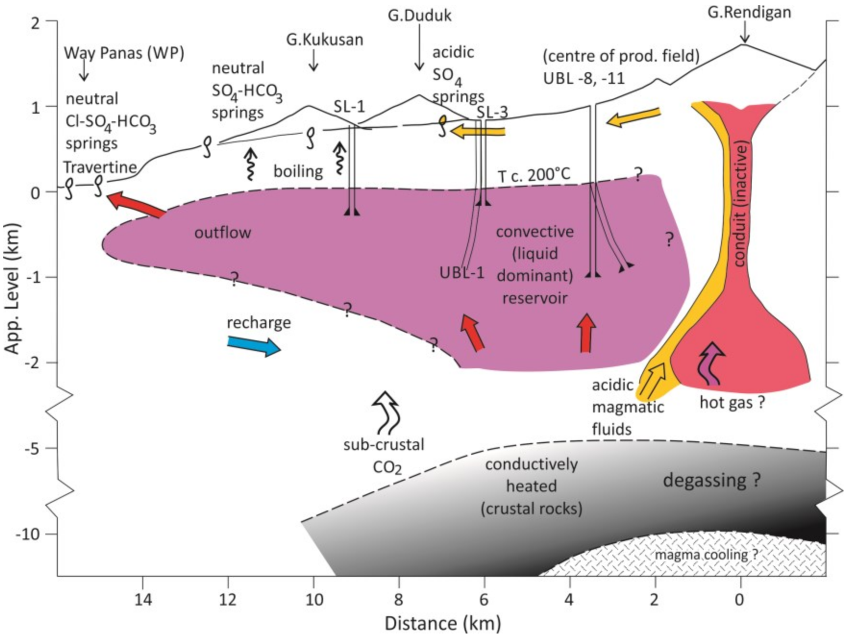

Figure 3.1: Conceptual model of the Ulubelu system along a simplified S-N profile; wells are shown with simplified projection; production wells are reduced to two bunched wells.

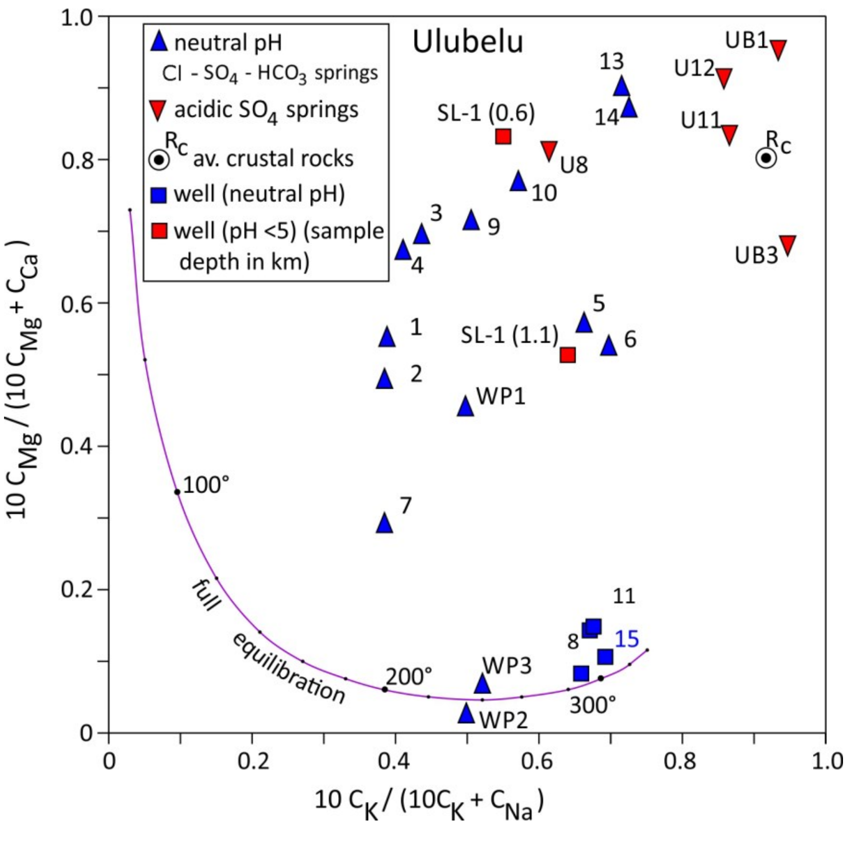

Figure 3.2: Cation ratio plot of spring and well samples from the Ulubelu Field.

Analyses of micro-earthquakes (MEQ) indicated swarm activity beneath G.Rendigan and its S flanks where no manifestations occur (Suharno et al., 2001). The first deep exploration well UBL-1 (1.7 km depth) was drilled near the SL-3 well in 2006. It encountered moderately higher Ts (c. 225 deg C). True high Ts were measured in the next wells with sites up the slopes of G. Rendigan. The well depths (all wells were now deviated) increased to > 2.3 km with bottom hole Ts also increasing to c. 280 deg C. The results led to a revision of the earlier conceptual model: Ulubelu is now seen as a volcanic geothermal system associated with an inactive strato-volcano and a large concealed outflow. Origin and mixing patterns are indicated in Fig.3.2. There is good evidence that all surface springs discharge non- equilibrated fluids except for the Way Panas springs at the toe of the outflow. Advective flow of acidic SO4 waters points to ascent of acidic fluids, the high T reservoir might extend up to a dormant conduit. The productivity of the deep discovery wells allowed planning of two power plants (the first phase of 2 x 55 MWe was commissioned in 2013).

4. VOLCANIC GEOTHERMAL SYSTEMS ASSOCIATED WITH ACIDIC FEEDERS

A few Indonesian volcanic geothermal systems have been explored where acidic fluids are discharged via steep feeder structures which are hosted by a liquid-dominated reservoir. The prospects stand in moderate volcanic terrain. Two sub-groups are indicated, namely single-feeder type systems, such as Lahendong and Patuha, and multiple feeders (Dieng).

4.1 The Lahendong system

The Lahendong prospect (5.35° N, 104.60° E) exhibits an acidic feeder structure, outlined at the surface by Lake Linau (0.44 km^2, pH c. 2.7) within a large crater, a strato-volcanic relict according to Neumann van Padang (1951). Acid and neutral pH manifestations occur around the lake and outline the N sector of the field where exploration was started in 1980; it was followed by exploratory drilling (Sudarman et al, 1996). Drilling was shifted to the S sector where 9 wells were drilled whose output has been used to start a 20 MWe modular plant in 2001. Development of the S sector continued and lead to the commissioning of three additional 20 MWe plants until 2014. Attention then shifted to the N sector where several deviated wells were drilled to intersect structures beneath Lake Linau. Some wells encountered acidic fluids within the feeder zone (pH 2.7 - 3.2, Brehme et al., 2014). One well encountered a micro-diorite (Koestono et al., 2010). Drilling at Lahendong has confirmed the existence of a deep reaching acidic feeder. It is likely that the acidic fluids encountered at 0.6 km depth in the first well (LHD-01) also derive from the Linau feeder. Observations of Lake Linau surface and outflow Ts (Brehme, pers.com. 2014) point to a heat loss of the order of c. 100 MW. Simplified sections of the Lahendong system are shown in Fig. 4.1.

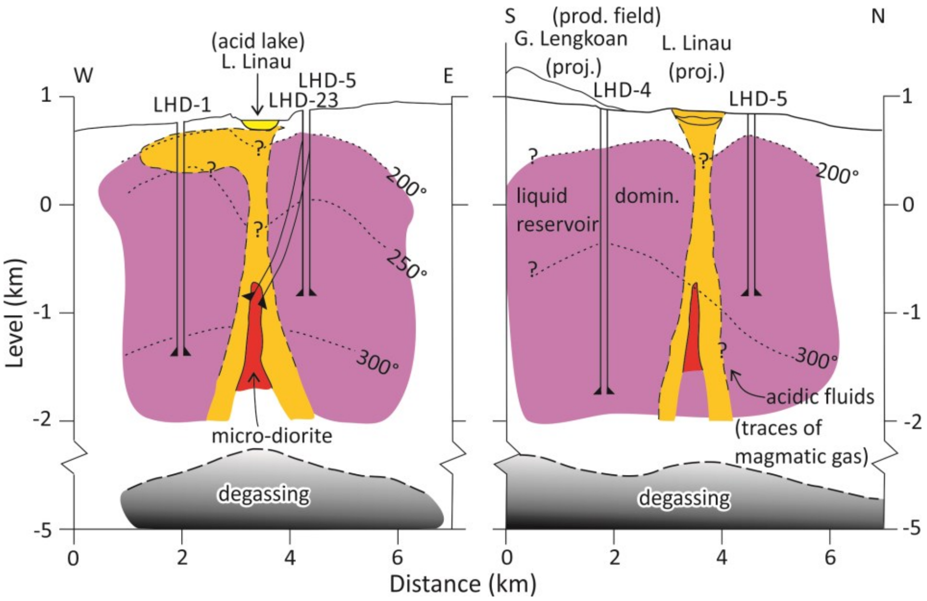

Figure 4.1: Conceptual model of the Lahendong system along schematic W-E and S-N sections. The vertical T fields are only an approximate representation.

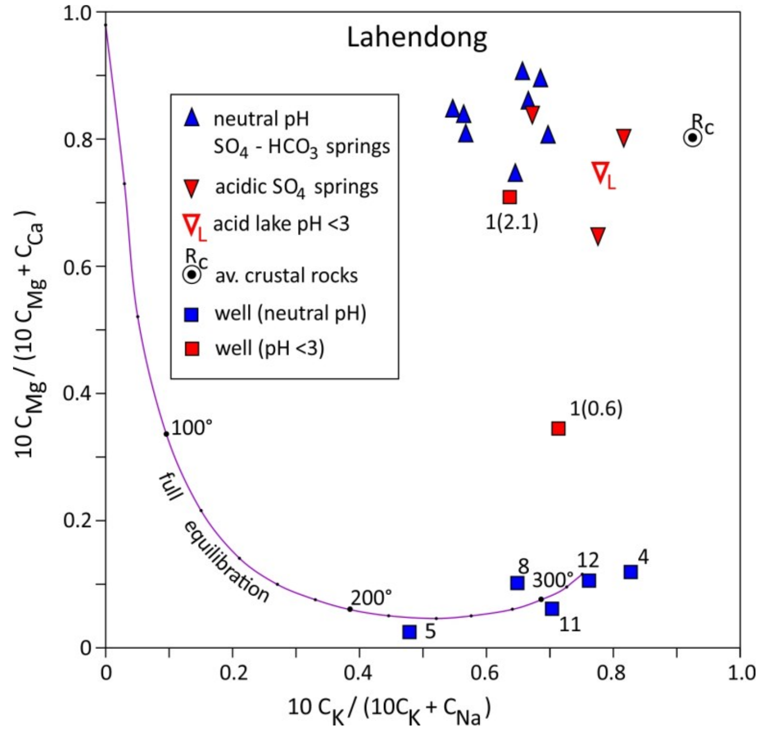

Figure 4.2: Cation ratio plot of spring and well samples from the Lahendong prospect.

Characteristics of fluids discharged at the surface and moving within the Lahendong reservoir are indicated by the cation ratio plot in Fig. 4.2. The cation composition of surface springs show that these waters have not equilibrated with respect to T-controlled fluid/ rock exchange processes and can not be used to infer equilibrium Ts of deeper fluids. Their composition also derives from acidic rock dissolution of volcanic and probably deeper crustal rocks. Acidic fluids sampled in well LHD-01 are un-equilibrated throughout. However, fluids from producing wells in the southern sector are fully equilibrated (i.e. LHD-04, -08, -11, and -12) ; their deep equilibrium T (c. 300 deg C) agrees with measured bottom hole Ts. Efforts to produce acidic fluids from wells intersecting the Linau feeder appear futile

4.2 The G. Patuha system

G. Patuha is a strato-volcano (7.15° N, 107.37° E) with a pronounced near surface, acid feeder structure which discharges acid waters (pH < 1) into a c. 0.07 km^2 large crater lake (Kawah Puti) near the summit. Its heat loss by evaporation is about 120 MW. This is similar in magnitude to that of the acidic lake at Lahendong. The system has been described by Layman and Soemarinda (2003). The feeder is hosted by a liquid dominated reservoir containing a well defined, thick vapour layer . A simple model of the reservoir has been presented (Hochstein and Sudarman, 2008). Productive wells drilled since 1995 now supply steam to a 55 MWe plant that should start production in 2014. Published geochemical analyses for Patuha are sparse and do not allow compilation of a cation ratio plot.

4.3 The Dieng system

The Dieng prospect (7.20° N, 109.92° E) is dominated by three major, historically active phreatic explosion centres on the Dieng Plateau (Simkin and Siebert, 1994). The centres (Sileri, Sikidang, and Pakuwaju) exhibit active surface manifestations (fumaroles, steaming ground, thermal pools and springs). Early exploration started in the 1970's and was followed by exploration drilling (Pertamina) until 1993, mainly in the greater Sikidang field (Boedihardi et al., 1991). A second phase of drilling was conducted by a US group (HCE) from 1995 to 1998, concentrating on the development of the adjacent Sileri field (Layman et al., 2002). Acidic (SO_4-type) fluids had been encountered in some Sikidang wells (DNG-1), along its NE boundary (DNG- 6, -23,-24), and SW boundary (DNG-9,-13); the term 'boundary' refers to resistivity and T anomaly patterns in maps by Layman et al. (2002). Acidic (pH 2.9) SO_4-Cl waters enter the 0.13 km^2 large Lake Warna at the NE boundary; its estimated evaporation heat loss is c. 85 MW. It is likely that shallow acidic corrosion affected most of the 21 Sikidang wells whose casings had collapsed by 1995. This caused a change in strategy which led to an enforced development of the Sileri Field and resulted in the construction of a 60 MWe plant, commissioned in 2002, now taken over by GeoDipa. Its running capacity declined until it was closed due to plant failure in 2013.

Most of the 46 deep wells had encountered high-T, neutral pH fluids. Feeder channels, shown in Fig.5.1, are indicated by fluid constituents for the centre of the Sikidang field (DNG-1), for Lake Warna, and for a cluster of wells on the DNG -6 pad where DNG -23 and DNG-24 discharged acidic steam. Two other feeders were assumed to occur beneath, or near to the Sileri and Pakuwaja phreatic craters. Fig. 5.1 updates an older conceptual Dieng model (Fig. 6b in Hochstein and Sudarman, 2008).

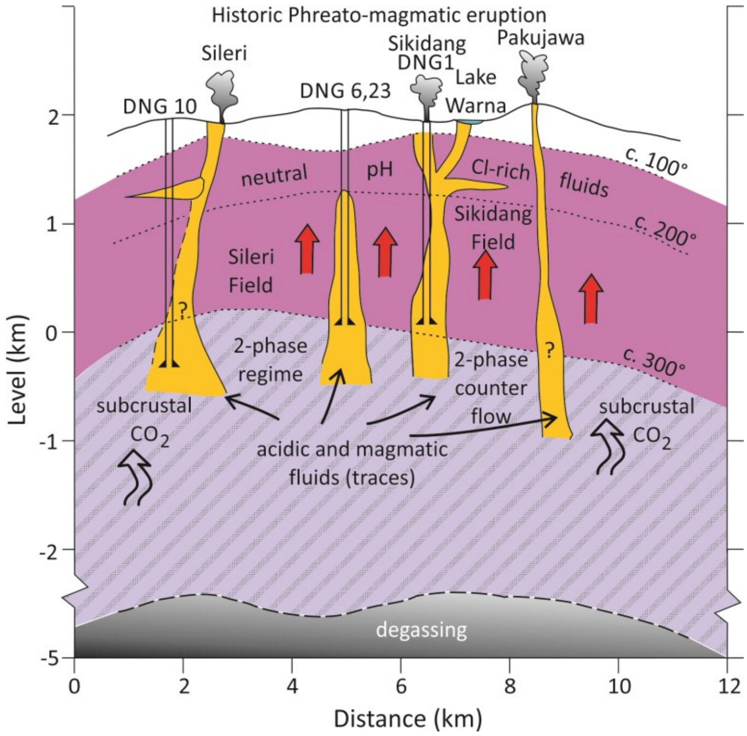

Figure 5.1: Conceptual model of the Dieng system with observed and inferred acidic 'feeder' structures projected on to a central NW-SE section; contours of the T-field are only approximate.

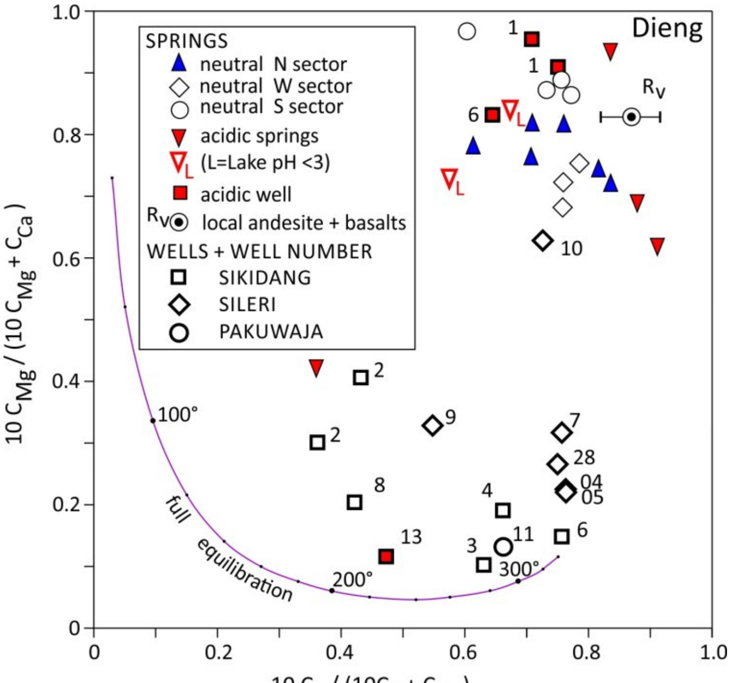

Figure 5.2: Cation ratio plot of springs and well samples for different sectors of the Dieng.

Cation ratios of a few published analyses of Dieng manifestations and of well samples are shown in Fig. 5.2. All spring samples show non-equilibrated cation compositions pointing to dissolution of local volcanic rocks by acidic fluids. A few acidic well samples show up with un-equilibrated fluids (DNG -1 and DNG -6, but also DNG -10), other samples show partial equilibration pointing to disturbances which prevent full re-equilibration (effect of deep crustal fluids?).

5. SUMMARY AND CONCLUSIONS

The existence of a concealed high–T geothermal reservoir has been inferred in the past for most explored volcanic geothermal volcanic prospects in Indonesia that exhibit active thermal manifestations. For prospects associated with single strato-volcanoes, we found that thermal discharges over the flanks are often the result of advective downflows of acidic condensates that downstream are progressively neutralised by rock interactions and dilution with groundwater. Studies of advective flows at K. Ijen, for example, have shown that acid and later diluted neutralised waters from a high-standing source (lake) can flow large distances (>10 km) but still retain the un-equilibrated composition of the parent water.

Thermal springs over liquid dominated geothermal reservoirs studied elsewhere often discharge fully equilibrated fluids reflecting convective up-flow patterns (Giggenbach and Glover, 1992). A characteristic feature of thermal waters discharged over Indonesian volcanic geothermal prospects is the un-equilibrated status of their cation compositions. This also applies to thermal springs discharging over liquid dominated systems in moderate volcanic terrain which host acidic feeder structures. Deep equilibrium Ts can not be assessed from un-equilibrated fluids which therefore can not be used to predict the existence of a high-T reservoir for volcanic geothermal systems. There is, however, one setting where fully equilibrated deep fluids discharge at the surface, namely that of a strato-volcano prospect whose high-T reservoir can discharge thermal water over long distance at the toe of an outflow (the Ulubelu setting).

The assumption that low resistivity structures over volcanic geothermal prospects can be associated with the presence of certain conductive clay minerals, caused by recent thermal alteration, should be applied with caution. The exploration of the Ijen caldera prospect (see 3.2.1) has shown that low resistivity structures can still be observed over an extinct system; another extinct reservoir is indicated at Ijen by the de-magnetisation of a volcanic dome inside the caldera which requires de-magnetisation by rising and condensing vapour. Hence, it is appropriate to assume that geophysical anomalies over inferred active geothermal systems are controlled by the cummulative effect of thermal rock alteration, including palaeo alteration.

With the basic uncertainties of using an inferred reservoir T and an inferred extent of a possible reservoir, and without evidence that such reservoir exists, the prediction of the likely volume of any reservoir and its stored anomalous heat is highly speculative. To extend the speculation to predict power potential of volcanic geothermal prospects has probably become an exercise in optimism. Exploration and development of volcanic geothermal prospects as envisaged in the Permen 15/2010 directive appear to have reached only about 10 % of the target figure predicted for these resources at the end of 2014.

REFERENCES

Atmoyo, J.P., Itoi, R., Tanaka, T., Fukuda, M. Sudarman, S., Widjarso, A.: Modelling studies of Sibayak geothermal reservoir, Northern Sumatra, Indonesia, Proceedings, World Geothermal Congress Kyushu-Tohoku, Japan (2000), 2037-2043.

Boedihardi, M.R.: Interpretation of Tangkuban Perahu geophysical data, Geotherm. Diploma Report 87.04, Engineering Library, Univ. of Auckland (1987), 1-55.

Boedihardi, M., Suranto, Sudarman, S.: Evaluation of the Dieng Geothermal Field; review of development strategy, Proceedings Indonesian Petroleum Assoc. (Oct. 1991), 347-351.

Brehme, M., Moeck, I., Kamah,Y., Zimmermann, G., Sauter, S.: A hydrotectonic model of a geothermal reservoir – a study in Lahendong, Indonesia, Geothermics, 51, (2014), 228-239.

Delmelle, P., Bernard, A., Kukusabe, M., Fischer, T.P., Takano, B.: Geochemistry of the magmatic-hydrothermal system of Kawah Ijen volcano, East Java, Indonesia, Journ. Volcanology Geotherm. Research, 97, (2000), 31-53.

Giggenbach, W.F.: Geothermal solute equilibria, derivation of Na-K-Mg-Ca indicators, Geochimica Cosmochim. Acta, 32, (1988), 2749-2765.

Gigenbach, W.F., Glover, R.B.: Tectonic regime and major processes governing the chemistry of water and gas discharges from the Rotorua Geothermal Field, Geothermics, 21, (1992), 121-140.

Halldorsson, S.A., Hilton, D.R.,Troll,V.R., Fischer, T.P.: Resolving volatile sources along the western Sunda arc, Indonesia, Chemical Geology, 339, (2013), 263-282.

Hochstein, M.P., Browne, P.R.L.: Surface manifestations of geothermal systems with volcanic heat sources, In: Sigurdson (Ed.), Encyclopedia of Volcanoes, Academic Press, (2000), 835-855.

Hochstein, M.P., Sudarman, S.: History of geothermal exploration in Indonesia from 1970 to 2000, Geothermics, 37, (2008), 220-266.

Hochstein, M.P., Crosetti, M.: Ranking of Indonesian geothermal prospects (known reserves), Proceedings NZ Geothermal Workshop 2012, Auckland, (2012).

Hochstein, M.P., Zheng, K., Pasvanoglu, S., Vivian-Neal, P.: Advective (Heat Sweep) geothermal systems, Proceedings, 38th Workshop on Geothermal Reservoir Engineering, Stanford University, (2013).

Koestono, H., Siahaan, E.E., Silaban, M., Franzson, H.: Geothermal model of the Lahendong Geothermal Field, Indonesia, Proceedings World Geothermal Congress, Bali, Indonesia (2010).

Kusnadi, D.: Application of geothermometry to geothermal fluids: examples from Broadlands - Ohaaki, NZ, and Ulubelu, Indonesia, Geotherm. Diploma Report 93.13, Engineering Library, Univ. of Auckland (1993), 1- 60.

Layman, E.B., Agus, I., Warsa, S.: The Dieng geothermal resource, Central Java, Indonesia, Geothermal Resources Council Transactions, 26, (2002), 573-579.

Layman, E.B., Soemarinda, S.: The Patua vapour-dominated resource West Java, Indonesia, Proceedings, 28th Workshop on Geothermal Reservoir Engineering, Stanford University, (2003)

Mulyadi, R.: Magneto-telluric method applied for geothermal exploration in Sibayak, North Sumatra, Proceedings, World Geothermal Congress Kyushu-Tohoku, Japan (2000a), 1469-1472.

Mulyadi, R.: Ulubelu, the most developed geothermal area in South Sumatra, Proceedings, World Geothermal Congress Kyushu-Tohoku, Japan (2000b), 1463-1468.

Neumann van Padang, M.: Catalogue of the active volcanoes of the world including solfatara fields, part I, Indonesia, International Volcanological Association, Naples (1951), 1-271.

Nasution, A., Kartadinata, M. N., Kobayashi, T., Siregar, D., Sitaningsih, E., Hadisantono, R., Kadarstia, E.: Geology, Age dating and Geochemistry of the Tangkuban Perahu geothermal area, West Java, Indonesia, Journal Geothermal Research Soc. Japan, 26, (2004), 265-303.

Reyes, A.G., Gigenbach, W.F., Saleras, J.R.M., Salonga, N.D., Vergara, M,: Petrology and Geochemistry of Alto Peak, a vapour-cored hydrothermal system, Leyte Province, Philippines, Geothermics, 22, (1993), 479-519.

Simkin, T., and Siebert, L.: Volcanoes of the World, Geoscience Press, Tucson, US, (1994), 64-79.

Suharno, Soengkono, S., Sudarman, S.: Microearthquake activity in Rendigan-Ulubelu-Waypanas (RUW) geothermal field, Lampung, Indonesia, Proceedings, 23rd NZ Geothermal Workshop, (2001), 85 – 89.

Sudarman, S., Sumintadineja, P., Ushijima, K,: Exploration of geothermal resources in Lahendong area, North Sulawesi, Indonesia, Memoirs of the Faculty of Engineering, Kyushu University, 56, (1996), 171-186.