Field Trip Module

GEOCHEMISTRY FOR GEOTHERMAL DEVELOPMENT

Dieng, 24 August 2017

BPSDM, Ministry of Energy and Mineral Resources
in collaboration with
Universitas Gadjah Mada - Utrecht University - Geocap Capacity Building Programme

Geochemistry for Geothermal Development

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The Dieng Geothermal Field

1. Introduction

The Dieng geothermal field is located in Central Java, Indonesia, about 90 kilometers northwest of Yogyakarta and situated on a plateau at an elevation of about 2000 m above sea level (Figure 1). The fertile Dieng plateau is patched by agriculture plots. It is scattered with ancient Hindu temples as well as numerous surface manifestations of hydrothermal activity are found in this area.

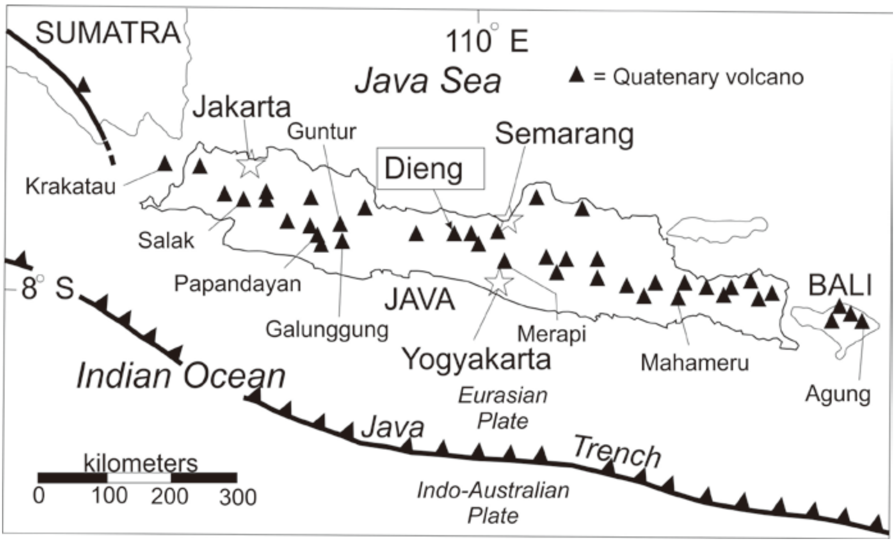


Figure 1. Map of location and regional geologic setting of the Dieng geothermal field in Central Java, Indonesia (Layman et al, 2002).

This fieldtrip guidebook is an achievement of the “Dieng Geothermal Fieldtrip Guidebook” developed by Utami et al, (2009) for the “World – Class Research University Program” sponsored by the Ministry of Education. This edition also includes the volcanic hazard potential of the Dieng Volcanic Area and the information of Kawah Timbang gas eruption that took place very recently.

2. Geology Setting

The Dieng Volcanic Complex (DVC) is characterized by a collapse structure containing 17 post intra-caldera eruptive centers with dimensions of about 14x6 km^2 (see Figure 2). This volcanic complex shows long-term volcanic activity of about 3 m.y. (Boedihardi, et al, 1991) and possibly record the long-term magma evolution at a single volcanic complex. The simplified geological map of Dieng Volcanic Centre is shown in Figure 3.

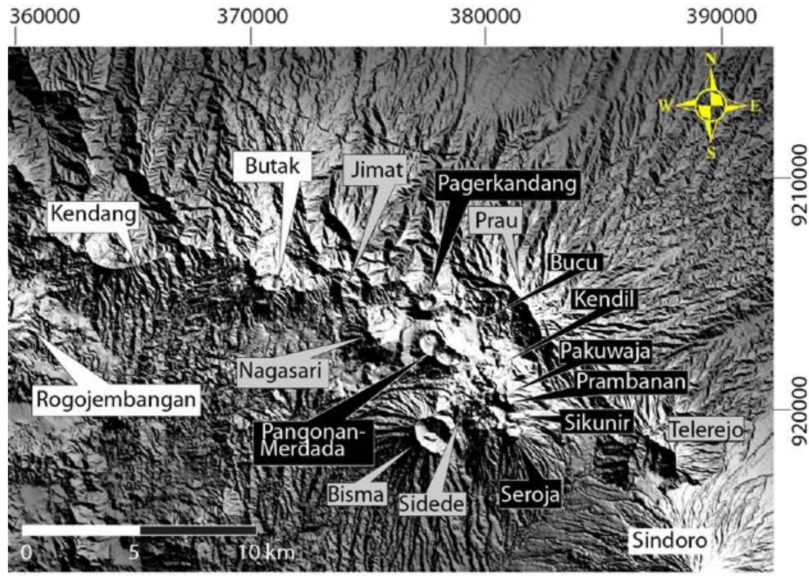


Fig 3

Figure 2. The DEM image which shows the distribution of volcanoes within and surrounding the DVC. Black labels represent volcanic edifices inside the caldera, gray labels represent those within the caldera boundary, and white labels represent those outside the DVC (Harijoko et al., 2015).

Based on well data (Layman et al, 2002), The Dieng Volcanic Complex (DVC) is composed by a sequence of interbedded lavas, tuffs and breccias, which extend from the surface to depths of 1500-2500 meters. Below the volcanic sequence is a fine-grained, micro-diorite intrusive (andesite complex), which is generally encountered at elevations between -300 to +600 meters a.s.l. The intrusive may represent the upper, solidified portions of the magmatic heat source for the Dieng geothermal system.

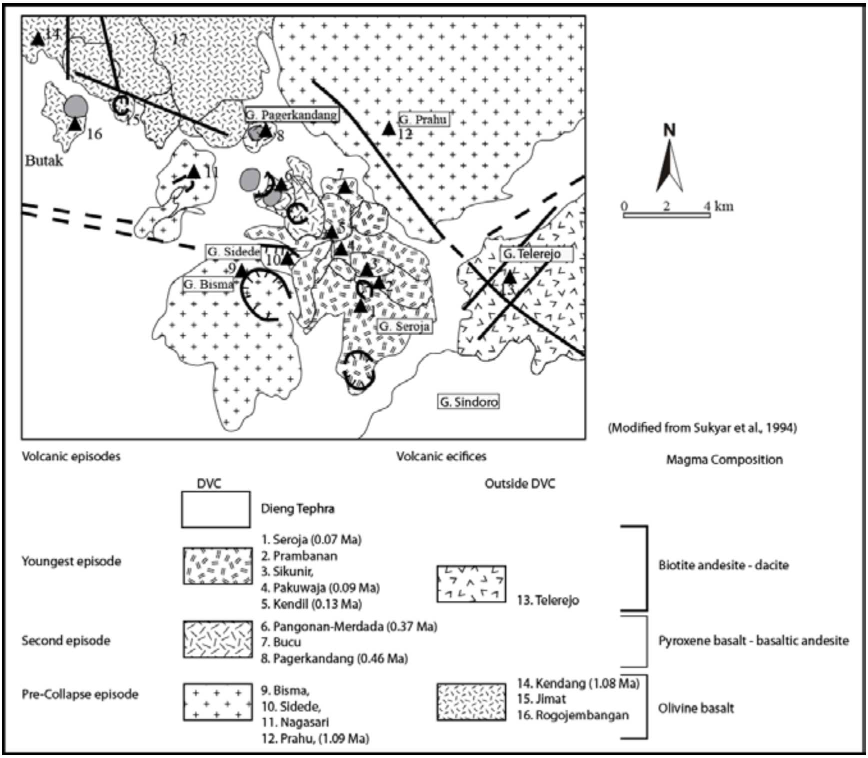


Figure 3. Geologic map of DVC, modified from Sukhyar et al. (1986). Modification is mainly to the stratigraphic order based on the radiometric age data of Boedihardi et al., (1991) and the new K – Ar and $^{40}Ar/^{39}Ar$ dating result of this study (Harijoko et al., 2015).

A system of northwest-trending fractures is inferred to control the intrusion of the magmatic hear source at depth, as well as the orientation of volcanic vents, the fumarolic discharges, the location of the geothermal reservoir. Plan view of the Dieng Volcanic Complex is shown in Figure 4.

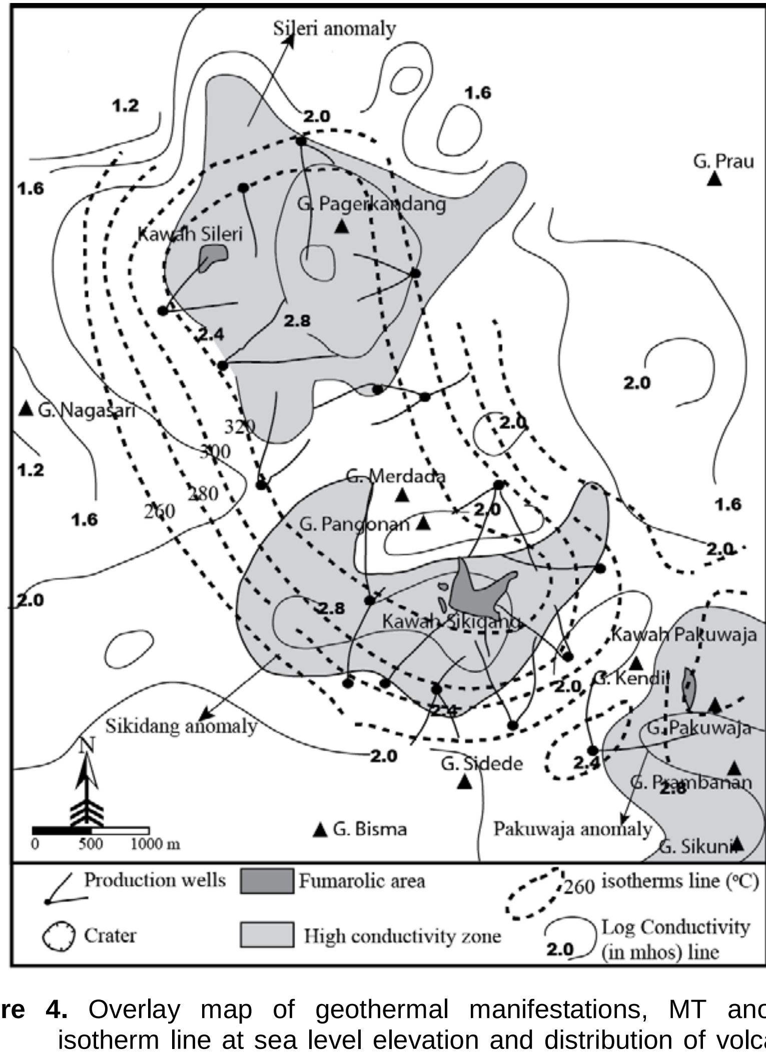


Figure 4. Overlay map of geothermal manifestations, MT anomaly, isotherm line at sea level elevation and distribution of volcanoes in the DVC. There is close spatial relationship between the fumarolic area, high conductivity zone and production zone of the

Dieng Geothermal Field. The production zone is situated beneath the G. Pangonan-Merdada and G. Pagerkandang. Conductivity map, isotherm line, and productivity zone are from Layman et al. (2002). (Harijoko et al., 2015).

Sukhyar (1994 vide Van Bergen et al, 2000) mentioned that there were 3 episodes of Quartenary mayor volcanism activities and Harijoko et al (2010) grouped the volcanic edifices in Dieng Volcanic Complex into three stages (Harijoko et al, 2010), namely pre-caldera (~3 Ma), post-caldera I (~2 to 1 Ma) and post- caldera II (< 1 Ma), based on their relationship to the caldera structure and their distribution and radiometric ages (see Figure 3). The radiometric age data were determined by K-Ar dating method (Boedihardi et al, 1991).

a. Pre-Collapse Episode (Lower Quarternary), which formed the boundary of northern part and southern part of Dieng Plateau, such as products of stratovolcanic Prau (3.6 Ma), Tlerep, and Rogojembangan (see Figure 2). The peak of the magma evolution is the explosive eruption of Prahu forming Dieng Plateau which being interpreted as caldera structure. The Nagasari volcanic cone is thought to be the western boundary of the plateau.
b. Second episode or intermediate episode, which produced some stratovolcanoes inside the depression (such as Mt. Bisma (2.53 Ma), Mt. Nagasari, Mt. Sidede, Mt. Bucu, and Mt. Jimat), with products,

such as basalt, basaltic andesite, and pyroxene andesite (see Figure 2). Pyroclastic fall deposits from all those volcanoes covered Dieng and Batur Depression, known as “Dieng Tephra”. Based on radiometric dating, it showed that this deposit is 16770 years old. The Nagasari volcanic cone (2.99 Ma) is thought to be the western boundary of the plateau. The last products of this episode is scoria fall, which estimated derived from Strombolian-type eruption.

c. Youngest Episode or Post – Caldera II, which which produced some stratovolcanoes inside the depression (such as Mt. Pagerkandang (0.46 Ma), Mt. Pangonan - Merdada (0.37 Ma), Mt. Butak, Mt. Kendil (0.19 Ma), Mt. Pakuwaja (0.09 Ma), Mt. Prambanan, Mt. Seroja (0.07 Ma), and Mt. Sikunir, with products, such as viscous olivine – biotite lava andesite and derived as pyroclastic fall products from 9 centers of eruption in the southern part of Dieng depression. The youngest lava is 8540 years old and separated from “Dieng Tephra” by paleosol layer.

   The process in this youngest episode formed some morphologies, such as Lake Menjer (derived from Mt. Seroja eruption crater), Lake Merdada (derived from Mt. Merdada eruption crater), and Lake Warna (Igir Binem eruption crater, which is the most eastern volcano in area, originated from youngest episode activities).

Boedihardi et al. (1991) mentioned that the Dieng geothermal field comprises 10 lithological units (see Geologic map on Figure 3). The dominant structural controls are faults with general trending of (from the oldest to the youngest) E – W, NW – SE, and N – S. The other significant structures are circular features which are thought to be crater rims. K/Ar age dating suggested that the magmatic activity in Dieng migrated in a NE - SE direction (see also Figure 4).

3. Geothermal system model

The geothermal system in Dieng Volcanic Complex (DVC) reported by Boedihardi et al. (1941) and Layman (2002) is summarized in this section.

Magneto-Telluric (MT) surveys indicates that geothermal resources in Dieng Volcanic Complex are divided into three potential areas namely Sileri, Sikidang, and Pakuwaja Blocks based on the occurence of a highly conductive zone (>1,000 Mhos) at 1 km (Figure 4). At the surface of those potential areas are occupied by fumarolic complex of Sileri, Sikidang, and Pakuwaja Craters. The blocks are separated from each other by a high resistivity zone identified by MT survey. The three blocks are related to Pagerkandang, Pangonan – Merdada, and Pakuwaja volcanoes. Driiling has confirmed that the productive area are Sileri and Sikidang Blocks. The Pakuwaja block has not been drilled, however.

The Pakuwaja is separated from Sikidang Block by high resistivity zone that is thought to have a low temperature.

There are barriers (rocks with low permeability and low temperature) separate the Sikidang – Merdada from the Sileri and Pakuwaja blocks (see Figure 5). The extent of the Kendil Block is controlled by NE – SW trending faults. This model indicates the presence of separate upflow zones which are probably interconnected at greater depths. Pudjijanto et al (1995) recognized that the three prosepcts areas coincide with the occurrence of anomaly of hydrocarbon gases (C_{7+} paraffin and C_{8+} aromatic) concentration in the soil.

Based on the host rock and the reservoir fluid characteristics as well as resistivity anomalies, the Dieng geothermal system has three separate prospect blocks based on MT sounding (see Figure 4), namely:

- Sileri prospect spatially associated with the 460.000-year old Mt. Pagerkandang in the Northwest
- Sikidang – Merdada prospect, spatially associated with the 370.000 year old Mt. Pangonan in the center
- Pakuwaja prospect spatially associated with the 90.000-year old Mt. Pakuwaja in the Southeast.

The geothermal potential of the Dieng field was estimated by Boedihardi et al. (1991). The energy potentials stored by fluid and rocks are 185 MWe and 355 MWe, respectively.

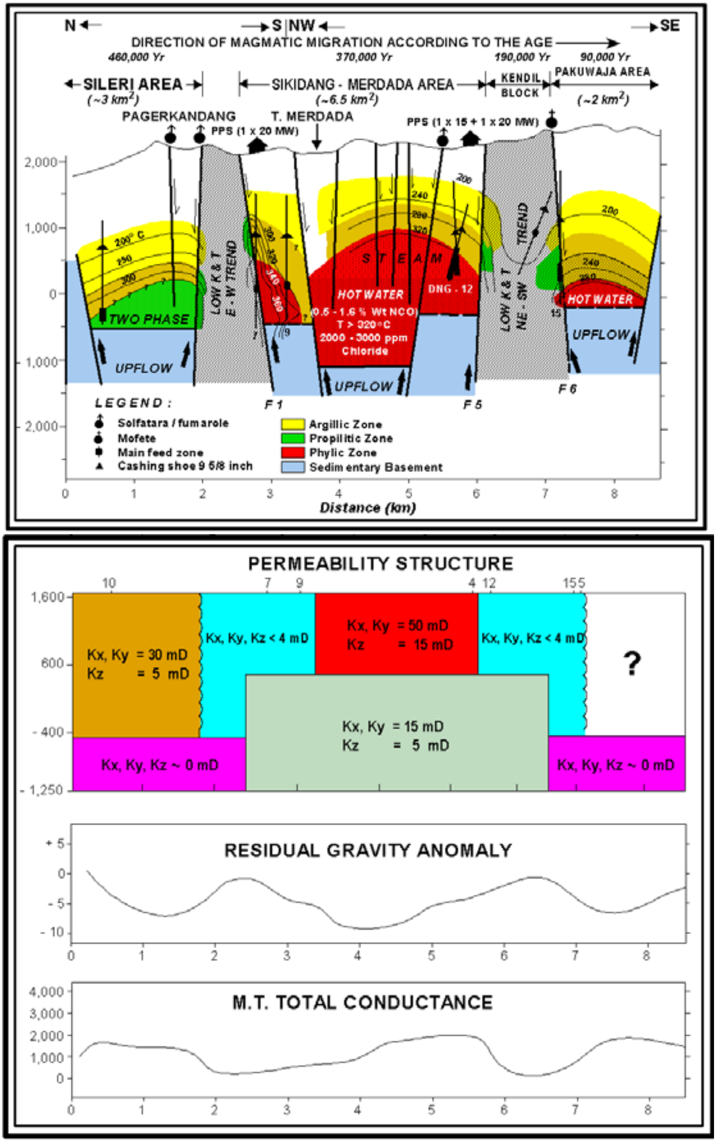


Figure 5. Integrated geothermal system model (Boedihardi et al., 1991).

4. Thermal manifestations

There are three main thermal manifestation areas in Dieng, namely:

1. The Batur Village – Dringo Lake – Mt. Butak – Sidongkal Village area, which consists of phreatic eruption vents, solfatara, and acid hot springs. The latest known and phenomenal phreatic eruption occurred in 20th February 1979 in Kawah Sinila. It released CO_2 gas in a lethal amount, killing 182 people ("Sinar Harapan" Daily, 23rd February 1979).
2. Mt. Pagerkandang – Siglagah and Bitingan area, which consists of fumaroles, acid hot pool and springs. The largest pool occupies the Kawah Sileri. The last eruption of the Kawah Sileri took place in 13th December 1954 ejecting mud and ash up to about 500 m high for 2 – 3 minutes. The ash spread within a radius of 1 km (Hadikusumo, 1961 in Wintolo, 1979).
3. Mt. Pangonan – Mt. Pakuwaja area, which consists of:
   - Phreatic eruption vents, mostly located in the eastern flank of the Kendill Hill, north of the Sikunang Village
   - Mud pools and gas discharge in Kawah Sikidang, which itself was thought to be a cluster of phreatic eruption craters; according to Bemmelen (1949) their last activity took place in 1934. A landslide-induced eruption occurred near Kawah Sikidang on January 2009, and the opening is named Kawah Sibanteng.

- Acid lake with gas emanations occupies a large, elongated depression of Telaga Warna.
- Acid hot springs in Pulosari.

5. Production Characteristics from Field Sectors

Drilling at Dieng has defined a total proven of approximately 11.5 km^2 (see Figure 4). The productive parts of the field are thought in two main sectors, namely Sileri and Sikidang since the Pakuwaja prospect has not been drilled yet (figure 3, 4, 5). Production characteristics for representative wells from Sileri and Sikidang sectors are summarized as follows (Layman et al, 2002), summarized in Table 1

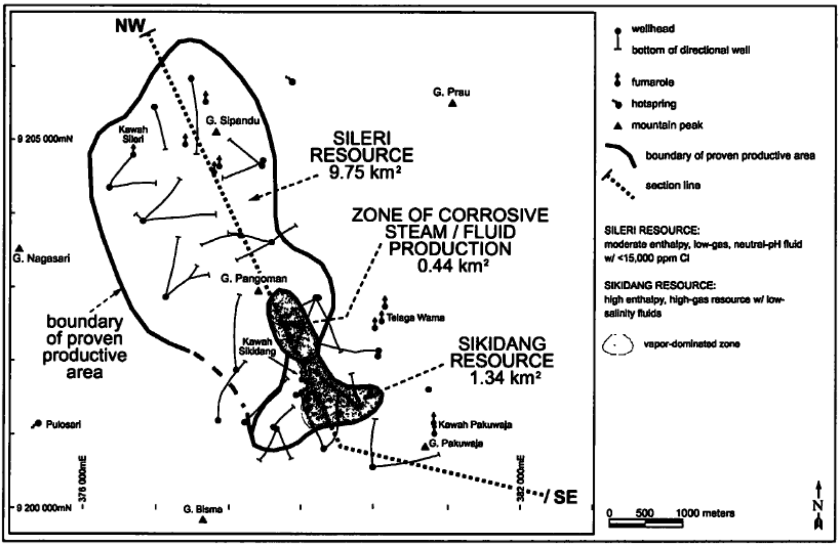


Figure 6. Map of proven productive area of Dieng geothermal field with resource sectors identified (Layman et al, 2002)

A. The Sileri sectors

The Sileri sector is characterized by relatively deep, high-temperature production. Reservoir temperatures range from 300-335 deg C, with first production typically encountered or below sea level, at depths between 2000-2300 meters.

Table 1. Production characteristics of representative wells, Sileri and Sikidang sectors, Dieng Geothermal Field (Layman et al, 2002).

Well Name	**HCE-9B**	**HCE-30**	**DNG-13**	**DNG-19**
Field Sector	**Sileri**	**Sileri**	**Sikidang**	**Sikidang**
Well Depth (m)	2366	2591	1853	2176
Slotted liner diameter (inches)	7	9 5/8	7	7
Depth to first major permeability (m)	2187	2096	1475	1450
Elevation of first major permeability (m)	+26	+62	+680	+750
Maximum temperature (^oC)	325	326	275	285
Steam flow rate @200 psig WHP (kph)	235	350	84	77
Brine flow rate @200 psig WHP (kph)	265	860	17	0
Discharge enthalpy (BTU/lb)	750	600	1044	1197
Power output (MWe)	15	23	5	5
Total gas in produced steam (wt.%)	0.7	0.4	15-20	6-8

Chloride in total well discharge (ppm)	8.500	13.400	4.000	Dry steam

Reservoir permeability in Sileri is rather high, allowing average well power outputs of about 13 MWe. Wells produce a moderate enthalpy (500-800 Btu/lb) two-phase discharge, with steam fractions at the wellhead ranging from 30-50%. Reservoir water are moderate salinity, neutral-pH Na-CI fluids with low gas content. Chloride content in total well discharges ranges from 7500-14,000 ppm, while gas contents in produced steam range from 0.3-2.3 weight %.

Downhole surveys indicate Sileri wells when shut-in stand with a water column across the depth interval of the reservoir production zones, indicating a liquid-dominated resource. Upward projection of hydrostatic pressure gradients measured in the reservoir zone indicate the regional deep water table lies at a depth of approximately 400 meters below the surface in the Sileri area, or about +1600 meters a.s.l. Reservoir boiling is indicated in some central Sileri wells at elevations of approximately 500-1000 meters a.s.l. Most shut-in wells develop a gas cap, with wellhead pressure between 500-1300 psig. Safety procedure must be carefully followed during initial well openings, due to high H_2S concentrations in this dead gas, which accumulates in the shut-in well bore.

B. The Sikidang Sector

Production from the Sikidang sector is at shallower depth and at lower temperature than at Sileri. Reservoir temperature range from 240-300 deg C, with first production in most wells encountered at depths of of 1400-1500 meters, or about +500 to +750 meters a.s.l. elevation. Reservoir permeability is low to moderate, resulting in average well outputs of about 5-6 MWe. Wells produce high enthalpy discharge (1000-1200 Btu/lb) of either dry steam or steam with a small water fraction of up 15% at the wellhead.

An accurate chloride measurements in produced liquids are often difficult to obtain in high enthalpy wells due to evaporative concentration. However, chloride levels in total flow appear range from 800 to 4500 ppm for liquid-producing wells. This is significantly lower than chloride level in the Sileri sector.

Gas concentrations in steam produced by Sikidang wells are very high. Their stabilized values after sustained flow in the range of 4-18 weight *%.* In the early stage of testing, gas levels of over 30 % of weight *have* been measured in some wells. After long-term tests and production during the I980's, through 1994, gas levels generally declined. However, after testing was initiated on two Sikidang wells after about a 2-year shut-in period, gas levels had returned to initial high levels. One Sikidang well (DNG-20J provides an exception, in that stabilized gas level in produced steam is 1.6 weight *%.* This appears to be of the result of the 2100 meter depth lo first production for this well, which is unusually deep for the Sikidang sector.

Downhole surveys indicat several wells in the eastern portion of the Sikidang sector stand when shut-in with a vapor column across the interval of the reservoir production zones, indicating a vapor-dominated resource. These same wells produce dry steam discharges. Pressures in the vapor-dominated zone range from 1000-1800 psig, generally decreasing to the south. Pressure profiles indicate this vapor zone extends to a depth of at least 2200 meters, or -200 meters a,s,l.

The westernmost wells in the Sikidang sector stand with a water column across the depth interval of most or the entire production zone. This is consistent with lower production enthalpies.

5. Volcanic Hazards

The prominent volcanic hazards in Dieng Volcanic Complex are phreatic eruptions. In some cases, the eruptions were accompanied by the formation of gas plume composed of nearly pure CO_2 and subordinate of methane and sulphur compounds (Allard et al, 1989). Within the historical time at least nine eruptions were recorded, namely those took place at Sileri, Timbang, Candradimuka, Pakuwaja, and Sibanteng craters (see Figure 7). The most catastrophic was the eruption followed by CO_2 gas emission occurred at Timbang/Sinila Crater in 1979, killing more than 140 people (Table 2).

On 15th January, 2009, a phreatic eruption occurred at Sibanteng crater. Though there was no casualty the pile of eruption materials destroyed some infrastructures along the nearby section of the Tulis River.

Recently (from 29th May 2011, 20:45 to 10th June 2011, 18:45 local time) the Center of Volcanology and Geohazards Mitigation announced the third level alert to Dieng Complex, due to the increase in CO_2 gas concentration emitted by the Timbang Crater. The highest concentration was 2,2 volume%, exceeding the tolerable level for human and animal. Similar phenomenon took place in 1979 when a lethal concentration of CO_2 gas emitted from Timbang/Sinila Crater. Based on the carbon isotope analysis Allard et al (1989) identified that the gas emitted from Timbang/Sinila crater in 1979 was of magmatic origin.

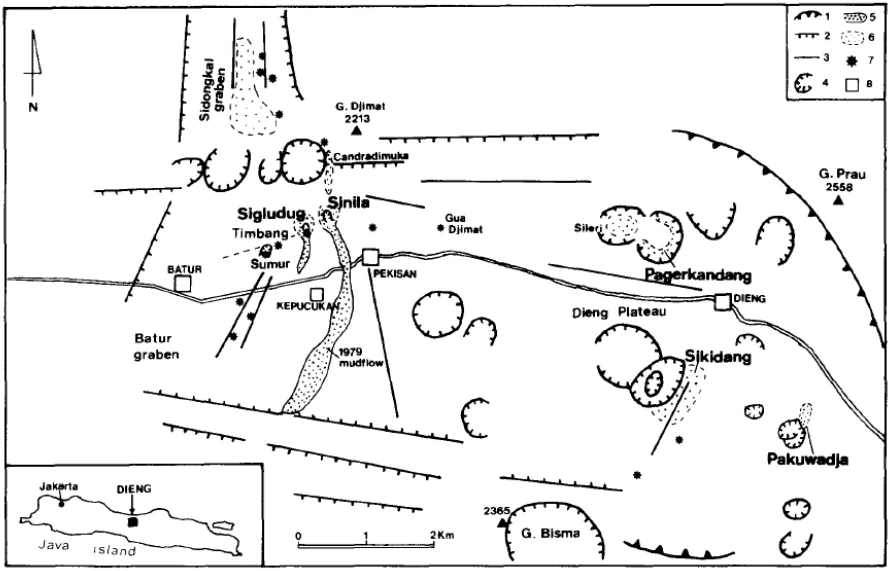


Figure 7. A schematic map of Dieng Volcanic Complex showing the location of Sinila and Timbang craters that erupted CO_2 gas (Allard et al, 1989)

Table 2. Historical phreatic eruption at DVC (Stehn, 1932, 1939 ; Zen, 1971 ; Delarue, 1982 vide Allard et al., 1989 and compiled from Global Volcanism Program Smithsonian Institute, and PVMBG DVC Monitoring Office).

Date	Eruption Site	Phenomena	Precursors	Casualties
1786	Candradimuka	a, b, c, d	g	n.d
1826	Pakuwaja	a, b, c, d	?	n.d
1928 (05/13)	Timbang	a, b, c, d, e, f	g, h	n.d
1939 (10/13)	Timbang	a, b, c, d, e, f	g, h	5

1944 (12/04)	Sileri	a, b, c, d	h	117
1945 (04/12)	Candradimuka	a, b	No	n.d
1956 (12/13)	Sileri	a, b, c	No	n.d
1964 (12/13)	Sileri	a, b, c, d	No	114
1979 (02/20)	Timbang	a, b, c, d, e, f	g, h	149
1986 (08/06)	Sileri	a, b, c, d, e, f	g, h	n.d
1992 (03/18)	Sikidang	a, b	No	3
1998 (July)	Sileri	a, b	No	n.d
2002 (April)	Sileri	a, b, c, d	g	n.d
2002 (May – July)	Sileri, Sikidang	a, b, c, d, e,	g, h	n.d
2003 (July – Aug)	Sileri	a, b, c, d, e,	g, h	n.d
2009	Sibanteng	a, b, c, d, e,	g, h	n.d
2011 (May – Jun)	Timbang, Sileri, Sikidang	a, b, c, d, e, f	g, h	Birds, vegetation, 1200

				people evacuated.
2013 (Mar – May)	Timbang	a, f	g	animals
2013 (April-May)	Sileri	a, b, c, d, e, f	g, h	1000 people evacuated
2017 (07/02)	Sileri	a, b, c, d, e,	g, h	17 people hurted

Note :
a : gas plume; b : block projection; c : ashfall; d : crater formation; e : mudflows; f : CO2 outflow; g : felt seismicity; h : fissure opening; n.d : no data

6. Phreatic Eruption Chronology of Sileri Crater (on 2nd July, 2017)

6.1. Visual of Last Month.

During June 2017, the weather was sunny – cloudy, rains happened 12 times, in the form of drizzle – medium rain, with rainfall reached 57 mm. Compare with last month, rainfall rate was declining this month. Rainfall with gust happened from morning to evening. The gust was low to intermediate, happened from south, east, west, and north direction. The minimum temperature in the morning was 11^{o}C and the maximum temperature in the afternoon was 25^{o}C.

On 1st and 2nd July, 2017, the weather was sunny and cloudy. The gust was low, blow to North and North-East direction. The temperature was 11-19^{o}C, white thick fume with approximately high 40 m above the crater.

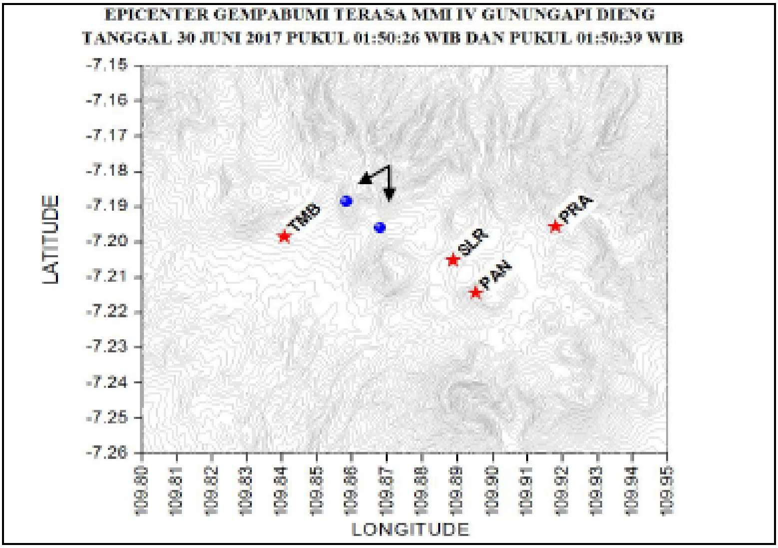
Figure 8. (a) Landscape photograph of Sileri Crater on 30th of June, 2017. (b) Landscape photograph of Sileri Crater on 1st of July, 2017.

(c) Photograph of Sileri Crater after eruption on 2nd of July, 2017. (source : Badan Geologi)

6.2. Seismicity of Last Month.

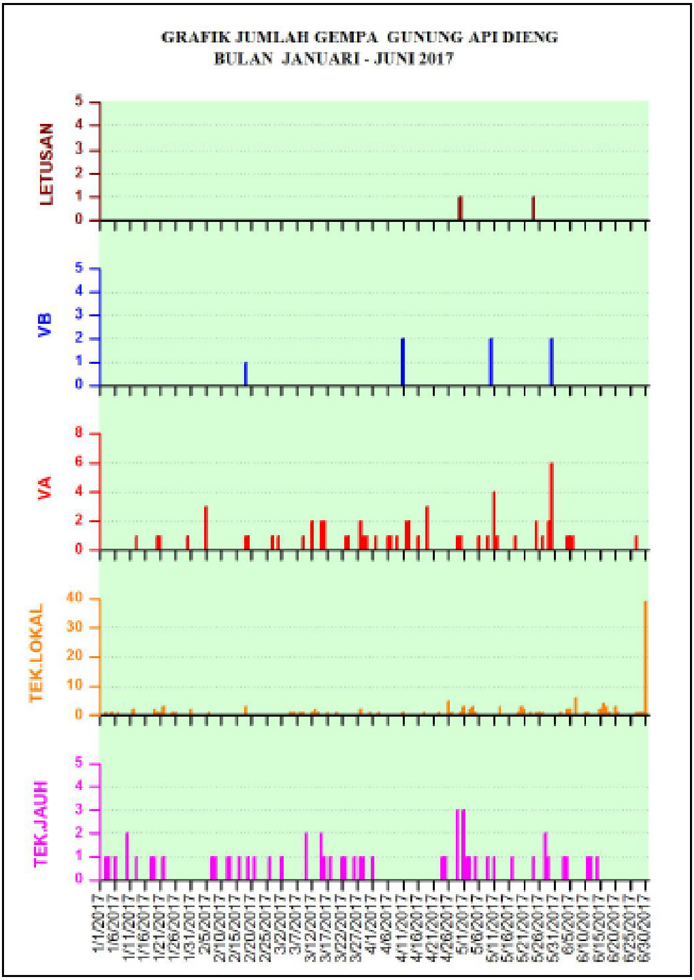
During June 2017, seismograph recorded 78 times seismicity, with details, e.g. :

- 5 times Distant Tectonic Earthquake (unfelt)
- 69 times Local Tectonic Earthquake (twice recorded in MMI IV)
- 4 times Deep Vulcanic Earthquake (VA)



On 30th June 2017, Local Tectonic Earthquake recorded 37 times, with 3-68 mm amplitude, S-P : 0,4 – 0,28 seconds, duration of earthquake : 3,6 – 11,4 seconds. The example of epicenter showed by the arrow sign in the map above, the red star sign showed the location of earthquake monitoring tools, SLR = Sileri.

On 1st – 2nd July, 2017 (until 11.30 am), earthquake not detected and recorded.



6.3. The Hazard Mitigation Survey of Dieng Volcanic Complex Eruption (before eruption on 2nd July, 2017)

a. Sikidang Crater (on 29th June 2017)

- Temperature of Crater 84,2^oC
- pH of Crater 2,62
- Ambient Temperature 21,2^oC

Toxic Gas in Atmosphere.

- CO_2 0,06 % Vol
- SO_2 0
- H_2S > 100 Ppm

Notes : Sunny – cloudy weather, the gust is medium, blow to south direction.

b. Sibanteng Crater (on 29th June 2017)

- Temperature of Crater 90,1^oC
- pH of Crater 2,56
- Ambient Temperature 21,2^oC

Toxic Gas in Atmosphere.

- CO_2 0,04 % Vol
- SO_2 0,4 Ppm
- H_2S > 49,8 Ppm

Notes : Sunny – cloudy weather, the gust is medium, blow to south direction.

c. Candradimuka Crater (on 29th June 2017)

- Temperature of Crater 86,9^oC
- pH of Crater 7,25
- Ambient Temperature 21^oC

Toxic Gas in Atmosphere.

- CO_2 0,35 % Vol

- SO_2 0,1 Ppm
- H_2S 98,5 Ppm

Notes : Sunny – overcast weather, the gust is medium, blow to north direction.

d. Sileri Crater (on 29th June 2017)

- Temperature of Crater 58,8^oC
- pH of Crater 5,98
- Ambient Temperature 23,3^oC

Toxic Gas in Atmosphere.

- CO_2 0,05 % Vol
- SO_2 0
- H_2S 0,5 Ppm

Notes : Overcast weather, the gust is low, blow to west direction

e. Sileri Crater (on 29th June 2017)

- Temperature of Crater 58,6^oC
- pH of Crater 5,82
- Ambient Temperature 24^oC

Toxic Gas in Atmosphere.

- CO_2 0,04 % Vol
- SO_2 2,25 Ppm
- H_2S 2,3 Ppm

Notes : Overcast weather, the gust is low, blow to west direction. White thick fume, low pressure, with approximately high to 20 m

From the visual observation, instrumental, data, seismicity, gas data of Timbang Crater, Sileri Crater, Sikidang Crater, Candradimuka Crater, and Sibanteng Crater during June 2017, especially from the last 2 days (29th and 30th June 2017), overall there were no increasing activities from all crater in Dieng Volcanic Complex.

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