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https://doi.org/10.5109/5909074

出版情報：Proceedings of International Exchange and Innovation Conference on Engineering & Sciences (IEICES). 8, pp.108-113, 2022-10-20. Interdisciplinary Graduate School of Engineering Sciences, Kyushu University
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The Geyser Type Mud Volcano Eruption in Sidoarjo, East Java, Indonesia

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Abstract: *In 2006 a mud volcano eruption took place in Sidoarjo area about 20 km South of Surabaya, the capital city of East Java Province, Indonesia. The eruption caused heavy environmental impact due to the large amount of mud erupted. There were controversial opinions about the generation of the eruption. The first opinion suspected the oil exploration well drilled in the area as the prime trigger. In contrary, the second opinion pointed out the role of earthquake and the existence of Watukosek fault extending in the area. The present study aims to reveal the subsurface structural characteristics of the area including the confirmation of the existence of Watukosek fault which might be contributive to the settlement of the controvercy.. The methods applied in this study are surface conventional data collections and subsurface seismic surveys. The results showed that the eruption was generated and controlled by the reactivation of Watukosek fault which gave a passage for mud to pierce to the surface. The fault also connected the heat source of Penanggungan-Arjuno Welirang and the mud eruption system. It was concluded that the Sidoarjo mud eruption was a geothermal system occurred in clastic materials. The specific phenomenon was the geyser type of mud eruption rarely found in sedimentary host rocks.*

Keywords: Mud volcano; heavy environmental impact; geothermal system; geyser type.

1. INTRODUCTION

On May 29, 2006 a mud eruption occurred in Sidoarjo area about 20 km south of Kota Surabaya, the capital city of East Java Province (Fig. 1). The eruption produced the increasing amount of mud and water from 50,000 cu m per day in the beginning to 180,000 cu m per day in August of the same year. It continued for about five years with the fluctuating amount around 20,000 cu m per day. Finally it decreased to the amount of 12,000 which lasted for about 10 years.

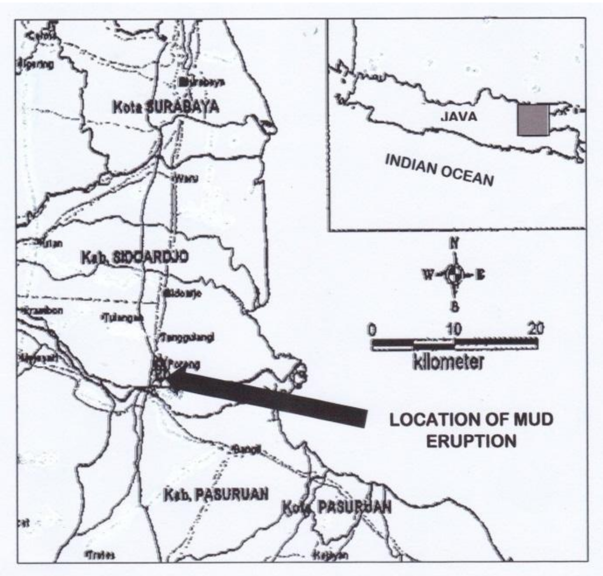

Fig. 1. The location of mud eruption in Sidoarjo area, East Java, Indonesia

The triggering factors of the eruption remained controversial (Sawolo, et al., 2009) [1]. The opinions focused on the human errors of the oil exploration drilling, and on the other hand the natural hazard related to the earthquake jolted a few days before in Yogyakarta (Davies, et al., 2008 [2]; Tingay, et al., 2008 [3]). The earthquake center of the 6.4 Richter scale was located in Yogyakarta area about 300 km SW of Sidoarjo. Combined with the existing Watukosek fault, the shaken mud squeezed up to the surface (Mazzini et al., 2009) [4]. The temperature ranged from 90^0 to 100^0C.

At the peak of the eruption, the materials consisted of 70% water and 30% mud (Safitri, 2009) [5]. The environmental impact covered the area about 840 ha. As many as 22 villages vanished and a number of factories located in the industrial estate were buried (Fig. 2).

Fig. 2. The impact of the eruption buried 22 villages and factories in the industrial estate (Zaennudin et al., 2010) [6].

The mud volcano eruption occurred at the overpressure sediments. Tanikawa et al., 2010 [7] discussed the fluid mechanism and simulation of overpressure at Sidoarjo mud eruption. The present study aims to contribute the subsurface information, to fulfil the gap generating the controversial opinion. The micro-seismic study outlined the configuration of reservoir being the source of erupted mud. The study also is aimed to reveal the nature of the geyserlike mud erupton rarely occurs.

2. METHOD

To achieve the objective concerning the characteristic of the subsurface of the eruption, the first step was to collect the conventional surface information, consisting of geological and geochemical data. The ^{18}O and ^{2}D stable isotope analysis were done to reveal the source of water. The data of carbon isotope analysis $\partial^{13}(Cco_2)$ from gas emanation was also collected. The last two methods were done by the Geological Survey, and the data used in this paper are secondary published data (Zaennudin et al., 2010) [6]. The data obtained will be used to find out the general configuration of the mud and water source of the eruption.

Further, the existing seismic profiles were used as the main source of the secondary subsurface data. The analiysis outlined the subsurface structural condition leading to the information of the weak zones where mud pierced out (Burhannudinnur, 2019) [8].

Finally the tomography mapping was carried out in this research by collecting the micro seismic data. As many as 30 permanent seismographs and 47 temporary seismographs were installed in the area covering about 10 to 10 kilometers. Six of those seismographs were stationed around the eruption point to monitor the seismic wave of each eruption. These seismographs were computerized and connected to the camera to record the visual appearance of the eruptions. The method was applied to describe the characteristics of the rythmic eruption of the mud.

3. RESULTS

3.1 Surface data

The mud volcano is located in the Kendeng Zone of the back arc basin of Java. The northward moving Indo-Australian plate pushed the Eurasian continental plate resulting in the accumulation of pressure in the back arc basin. The North East Java Basin therefore, was controlled by the N-S stress field (Hall, Sevatjasnova, 2012) [9].

The basin is divided into Rembang and Kendeng Zones. The present volcanic arc and the ancient magmatic arc of Southern Mountain are located in the South (Fig. 3).

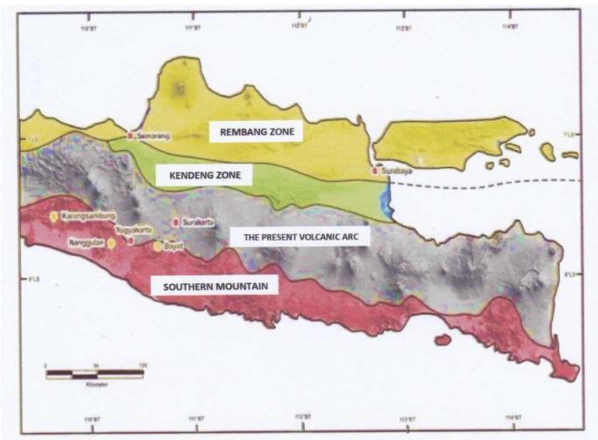

Fig. 3. The narrowly elongated E-W basin of North East Java consisting of Rembang Zone and Kendeng Zone.

The average width of the basin is about 25 kilometers, whereas the length is 350 kilometers and the depth is more than 8,000 meters. It resulted therefore, in an elongated and narrow E-W basin with sharp slopes.

Due to the continuing stress, the development of the basin was relatively rapid, producing clastic sediments of gravity slumping. The sediment consists of mud, shale, clays and sand. In places coral reefs developed.

The stratigraphy started with mudstones in the base at the depth of > 8,000 meters which is called Ngimbang with the age of Eocene. Tuban and Prupuh Formations both consisting of limestone, overlain Ngimbang Formation. The age of those formations is Oligocene to Miocene (De Genevraye and Samuel, 1972) [10].

These formations are overlain by Kalibeng Formation of Pliocene to Pleistocene age consisting of volcano clastics materials and bluish grey clay. Overlaying Kalibeng Formation is Pucangan Formation consisting of clay and silt deposits of Late Pleistocene (Fig. 4).

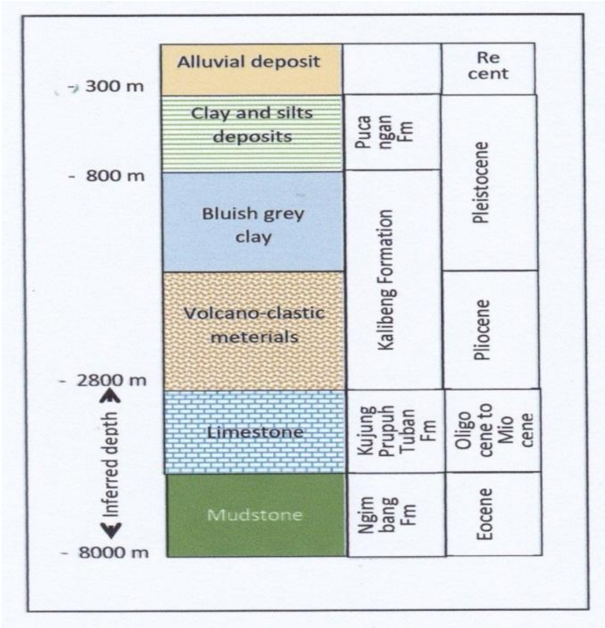

Fig. 4. The general stratigraphy of the area (modified from Genevraye and Samuel, 1972) [10]

The surface investigation concerning physical and chemical characteristics of the erupted mud and water showed the following data (Table 1).

Table 1. The chemical and mineral composition of erupted mud (Zaennudin et al., 2010 [6], Burhannudinnur, 2020 [11])

Chemical		Mineral	
Elements	%-weight	Elements	Ppm
SiO_2	44.49 – 53.25	Cu	22.49
Al_2O_3	17.22 -19.96	Pb	49.40
$Fe_2\,O_3$	4.95	Zn	96.29
CaO	1.78	Mn	653.78
MgO	0.10	Ag	0.95
Na_2O	1.99	Fe	3.55
K_2O	0.52	Cd	6.01
S	0.31	As	3.46
Salt	0.05 – 0.70	Sb	4.13
Water	22.84-70.00	Se	83.528
		Hg	20.41
		B	trace

3.2. Subsurface data

The seismic data showed the diapiric structure below Sidoarjo area. It involved both Tuban and Kalibeng Formations, where the latter became the core of the dome. Pucangan Formation overlaying those formations is slightly involved.

At the crest of the dome the polygonal valve fault system developed. The faults released the pressure accmulated by the up doming. The plastic materials of volcanoclastic and bluish clays strongly involved in the mechanism. The faults intensively took place in this formation.

The polygonal valve faulting structure might develop solely or in combination. There are five types of faulting structure, namely dendritic, multiple dendritic, single and double oblique and piercing faults. These types of faultings indicate the weak zones where mud would be able to squeeze through to the surface (Fig. 5).

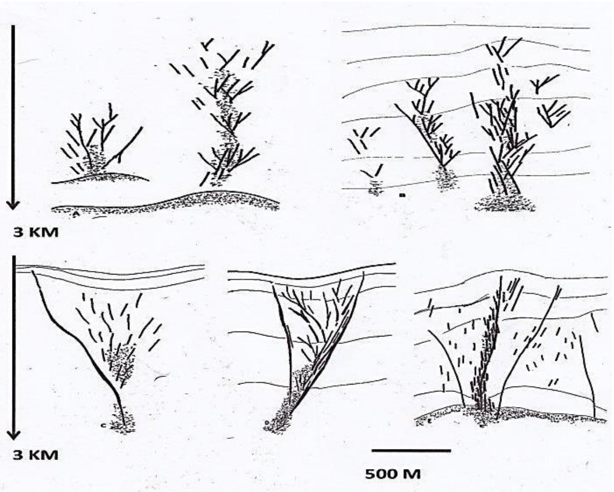

Fig. 5. The valve faults developed at the dome structure identified from the seismic profile. Upper left the dendritic structure, upper right the multiple dendritic, lower left single oblique, lower middle double oblique and lower right piercing fault.

The seismic signatures show bright appearance produced by the chaotic signals. This phenomenon indicates the high plasticity related to the accumulation of pressure. The bright appearance occurs in the crest of the diapiric structure at the lithologic boundary contact. The bright appearance was accompanied by the presence of the faulting structure. The less solid materials absorb the seismic wave, resulting in the bright appearance. The configurations of the appearance were mostly ellipsoidal with vertical long axis.

The bright structure located at the crest of the dome was connected with faults to other bright one in the upper lithological layers. Finally the fault reached the surface where the eruption occurred.

The embryo of the chaotic signatures might also take place without the valve faulting or piercing materials. This phenomenon indicates the potential mud volcano eruption in the future. The seismic records therefore might give the information for the preparation of mud eruption danger zoning.

The micro seismic investigation recorded the earthquakes with the epicenters distributed at the depth between 10 to 20 kilometers. Laterally the epicenters accumulated in NE-SW line indicating the presence of the weak zones of Watukosek fault (Fig. 6).

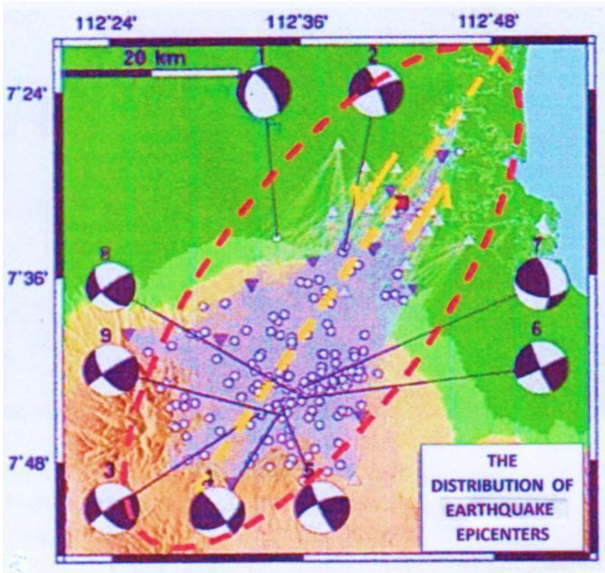

Fig. 6. The earthquake epicenters distribution showing the accumulation along the weak zone extending SW-NE where Sidoarjo mud eruption took place. Arrows indicate the left lateral movement of Watukosek Fault based on the focal mechanism analysis.

The line extended from Sidoarjo to Penanggungan volcano complex. Focal mechanism analysis of the earthquake showed the left lateral movement indicating the strike slip fault. The evidence was in line with the regional stress analysis.

The seismic records based on the earthquake monitoring confirmed the existence of Watukosek fault previously indicated from the geomorphologic features appeared at the surface. This fault is supposed to be the main cause of the eruption providing the weak zone for mud to pierce out, in contrary to the opinion that the mud eruption was caused by human error of oil exploration drilling.

The tomography map obtained by comparing the velocity of P and S waves (v_p/v_s) showed the configuration of mud reservoir beneath and under the eruption center. The reservoir composed of two zones namely a pocket at the depth of four kilometers up to the surface and a chamber with the depth from seven to 20 kilometers.

A conduit connected those two mud accumulations. The pressure release might be influenced by the condition of those accumulations. The depth of those pockets was respectively two and five kilometers.

The pocket located beneath the eruption center seemed to connect in SW direction to Pananggungan volcano complex. The eruption monitoring combined with the continuing visual observation, gave the close relationship between the seismicity and the eruption. The uprising mud and steam in the conduit were detected by short period seismographs. The shape of the pocket was elongated with the long axis extended about five kilometers in NE-SW direction.

The configuration of the chamber was cylindrical with the diameter about 10 kilometers distributed symmetrically under the eruption point. The core extended to 10 kilometer diameter (Fig. 7).

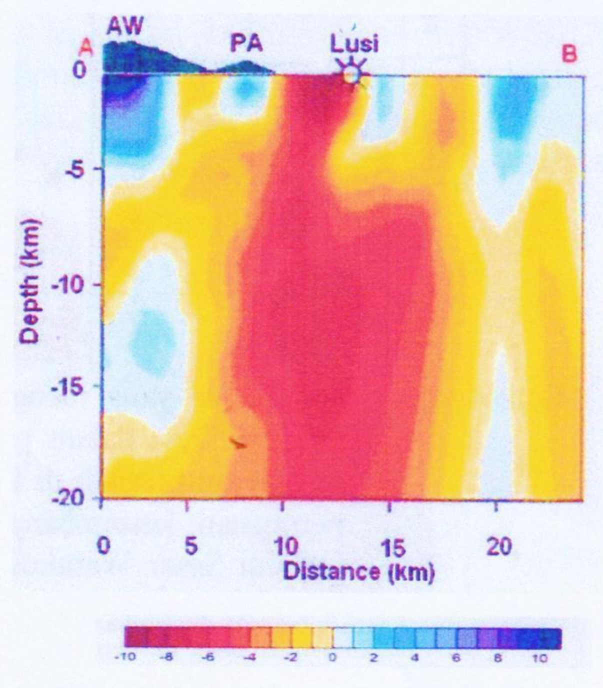

Fig. 7. Seismic wave anomalies show the distribution of mud accumulations and the differential temperatures under the eruption center (Lusi), Penanggungan (PA) and Arjuno-Welirang (AW). The bar below shows the scale of anomaly. A-B represents the section of NE-SW line.

The eruption clearly demonstrated the rhythmic periodicity of the average 10 seconds. The trains of micro tremors were detected from the depth of 30 meters, where the accumulation of steam begun. The dominated steam saturated water brought along mud. The characteristics of the eruption resembled that of geyser.

4. DISCUSSION

The mud volcano eruption in Sidoarjo is complicated because of the following reasons:

1) The eruption occurred when the oil exploration program was underway in the area;
2) The location of the eruption center was close by to the exploration drilling point. The first eruption took place at a distance of 100 meters from the site;
3) The exploration activity was located at the densely populated area including the industrial estate, infra structure facilities, toll road and intercity railway;
4) A few days earlier, an earthquake jolted Yogyakarta area, about 300 kilometers SW of the drilling location;
5) The exploration area was closely located to the range of active volcanoes, namely Penanggungan and Arjuno-Welirang complex. The closest distance was about less than five kilometers to Penanggungan parasitic volcano of the volcano complex;
6) The extraordinary amount of mud and water erupted which was very unusual. At the peak of the eruption period, water content exceeded 70% of the total volume of the erupted materials (Safitri, 2009) [5]. The accumulation of mud therefore, resembled the flood containing mud which expanded very quickly to the surrounding area. Topographically the volcano did not exist, the large pond instead was formed.

The discussion on the genesis of the mud volcano eruption became very delicate because of the large impact of the eruption concerning the responsibility to recover the environment. The first group questioned the role of the earthquake of 6.4 Richter scale occurred a few days earlier in Yogyakarta about 300 kilometers SW of Sidoarjo, as the trigger to the mud eruption (Davies, et al., 2008 [2]; Tingay, et al., 2008 [3]). This group argued that the wave might not have sufficient amplifying effect to the saturated mud at the drilling location.

Sawolo et al., (2009) [1] supported this opinion and pointed out the human errors as the cause of the hazard. The operating company therefore should bear the responsibility on the disaster.

The second group presented the data on instability of the area based on the earthquake record (Mazzini et al., 2009) [4]. Moreover a weak zone called Watukosek fault might have been reactivated by the Yogyakarta earthquake. The fault gave way for the saturated mud to pierce up to the surface. This opinion brought the case into the natural hazard that fell into government responsibility.

The present study gave a detailed information on the characteristics of faulting structure beneath the mud volcanoes in Kendeng Zone including Sidoarjo area. Based on the earthquake monitoring, it was confirmed that Watukosek fault was reactivated as an active strike slip fault. It extended to the heat source of Arjuno-Welirang and Pananggungan volcano complex and provided the passage of heat transfer to Sidoarjo mud system.

The research concluded that the mud system originated from three formations consisting of high plasticity clays. The role of heat, water, Watukosek fault and the earthquake might have been the main trigger of the eruption. The high content of water combined with the heat transfer from the volcano system resulted in the eruption caharacteritics of geyser type hosted by sedimentary rocks (Fig. 8).

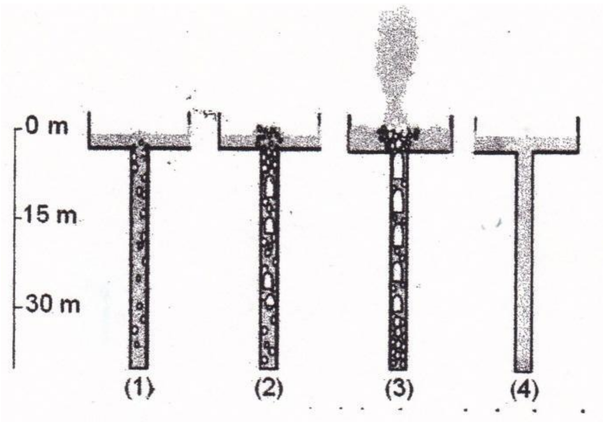

Fig. 8. The unique geyser type mud volcano eruption containing predominantly hot water in Sidoarjo mud volcano eruption. The phenomenon of geyser in geothermal system hosted by clastic sediments rarely found. For explanation, see the text.

The diapiric structure of the sediments provided space for steam accumulation. The rhythmic mud and steam eruptions with about 10 second intervals resembled the geyser characteristics (Karyono et al., 2016) [12].
The mechanism of geyser begun with the accumulation of steam at the depth of 30 meters clearly depicted in the microseismic record. The 30 meter heated water column mixed with mud, pressed down the uprising steam. The mechanism were divided into four phases, namely (1) hot water dominated, (2) opening steam explosion (3) geysering when steam pressure exceeded the weight of water column, and finally the column refilled with the uprising water.
The hydrologic system in the basin and the heat supply from the volcano created the unique geothermal system rarely found. However the elements of the system such as the cap rock and the configuration of the reservoir were not revealed. The geomagnetic survey unable to detect the deep layers. The magnetotelluric method, on the other hand, might be able to reveal the deeper layers in geothermal exploration (Saibi, 2021) [13].
The environmental impact was severe because both mud and water contained poissonous elements, among others boron. However boron can be separated from aqueous solutions using Mg-Al composition (Alkhudhayri et al., 2018) [14].
Analyzing the seismic records, it appeared the bright features produced by the chaotic seismic signatures indicated the accumulation of pressured mud. Two generative locations and two migration subsystems were detected (Fig. 9).

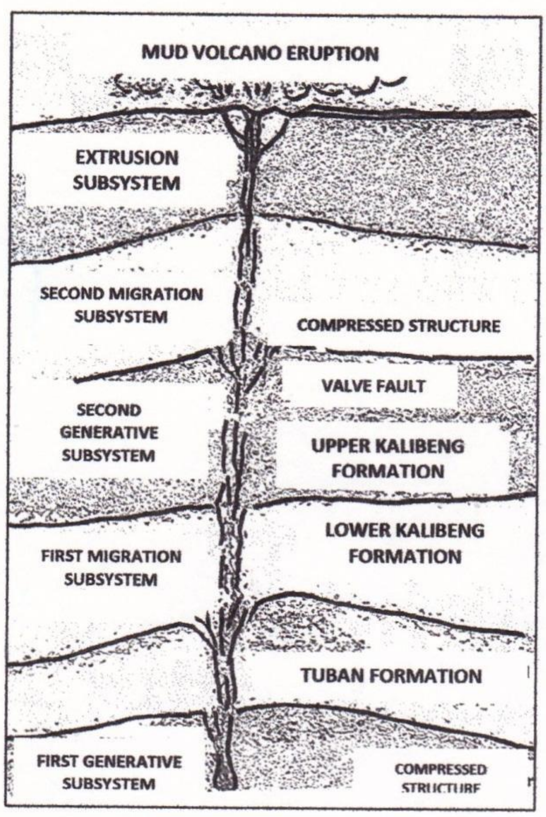

Fig. 9. The graphic model of Sidoarjo mud eruption shows the generative and migration subsystems occurred in Tuban and Kalibeng Formation.

The diapiric structure shown by seismic record clearly identified the location of the eruption point. The polygonal valve fractures and faulting created a weak zone where mud squeezed and piercing up to the surface. The generative subsystem took place in Tuban and Kalibeng Formations. The deepest generation subsystem was located in Tuban Formation at the depth of approximately 3,000 meters. The generated mud migrated to the upper level in the base of Kalibeng Formation and at the intra formation between Tuban and Kalibeng.
In the upper part, the second generative subsystem took place at Lower Kalibeng Formation joining the piercing mud from the first migration. Further, the second generation together with the migrated mud from the first generation moved to Upper Kalibeng in the second migration subsystem. Finally the mud extrusion took place in Pucangan Formation at the depth of 800 meters. Based on the ^{18}O and ^{2}D stable isotope analysis it was concluded that water originated from connate water,

5. CONCLUSIONS

The Sidoarjo mud volcano eruption might have been triggered by the reactivation of Watukosek fault related to the earthquake occurred earlier in Yogyakarta. The oversaturated mud and the passage provided by Watukosek fault resulted in the geyser type mud volcano eruption. The accumulated pressure might relate to the compression due to the northward moving Indo-Australian tectonic plate. The volcanic heat system located South of the area, supplied heat to the hydrologic system through the weak zone of Watukosek fault. The condition resulted in the development of geothermal system in the clastic sediment. The Sidoarjo mud eruption showed very rare phenomena of geyser characteristics occurring in clastic sediments host.

ACKNOWLEDGMENT

The authors wish to express their gratitude to Trisakti University, Universitas Padjadjaran and Meteorology and Geophysics Agency for the support and financial funding of the research. Vote of thanks is also due to Merapi volcano geochemical laboratory in Yogyakarta for the geochemical analysis. The authors deeply indebted to the Center for Earth Evolution and Dynamics, University of Oslo, Norway and also to Genève University, Swisserland, and to Geophysics Institute of FTH, Zurich, Swisserland for the scientific discussions.

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