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Overpressured Structures and Their Releases in the Depression of Java to Madura: Origins and Natures of Mud Diapirs and Mud Volcanoes

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ABSTRACT

Deep depression trending west-east in axial position exist in Java to Madura Islands and the Madura Strait called regionally as the Depression of Bogor-North Serayu-Kendeng-Madura Strait (van Bemmelen, 1949). All of the overpressured structures and their releases in the forms of mud diapirs and mud volcanoes are located within this depression (Satyana and Asnidar, 2008). The depression occurs as "elisional" basin (Akhmanov and Mazzini, 2007) with characteristics of : thick and rapid deposition of young sediments, present as overpressure fluids, under-compacted fine- grained sediments, and tightly compressed.

This passage will discuss the origin and nature occurrence of the mud diapirs and mud volcanoes within depressional zone from west to east and northeast of Java to Madura as follows : Ciuyah mud volcano (at the border of Bogor-North Serayu depression), North Serayu diapirs and groups of mud volcanoes Bledug Kuwu, Bledung Kesongo, Bledug Kropak (in the north of Central Java), Sangiran Dome (in Central Java), Porong, LUSI (Recent mud volcano and still erupting, in Sidoarjo, East Java), Kalang Anyar, Pulungan (Sidoarjo), Gunung Anyar (Surabaya), Socah (Bangkalan, Madura), and subsea mud diapirs and mud volcanoes of the Madura Strait. These sedimentary deformation structures are originally similar in relation with the controlling factor of elisional system and surface morphologies of swamplike, collapse- synclinal depression, couple crater-muddy lake and classic cone edifice.

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Introduction

Mud diapirs and mud volcanoes are common structures in sedimentary basins with elisional characters. Milkov (2003) reported worldwide that around 1,100 mud volcanoes exist both onshore and offshore. In offshore this phenomenon exists within shallow and even more common at seafloor of deep-water basin. This structure generally found in rapid sedimentary basin with tectonically compressed and geologically related to recent magmatic activity. Hence, it is formed in relation with the overpressure release of fluidized sediment along the active faults.

According to the regional physiography of Java and Madura, the depression zone consists of the Bogor-North Serayu-Kendeng Trough (van Bemmelen, 1949) (Figure 1) and continues offshore to the Madura Strait was a deep which since Plio-Pleistocene time was compressed to become fold and thrust belt (called Bogor-North Serayu-Kendeng Anticlinorium – van Bemmelen, 1949) in the axial position of Java-Madura. Into the depression, substantial sediments, mostly volcaniclastic in natures and rapidly deposited during short period of Mio-Pliocene time. The depression has also been parallel, close to, and overlapping in some places with Mio-Pliocene to Quaternary volcanic arcs. Rapid deposition of thick and young sediments has generated undercompacted sediments and overpressuring, regionally high gradient geothermal in the depression due to close location with volcanism, and laterally compression have resulted in "elisional" system favorable for mud diapir and mud volcano occurrence. Accordingly, these sedimentary deformation structures commonly occur along the depression zones of Bogor-North Serayu-Kendeng-Madura Strait (Satyana and Asnidar, 2008).

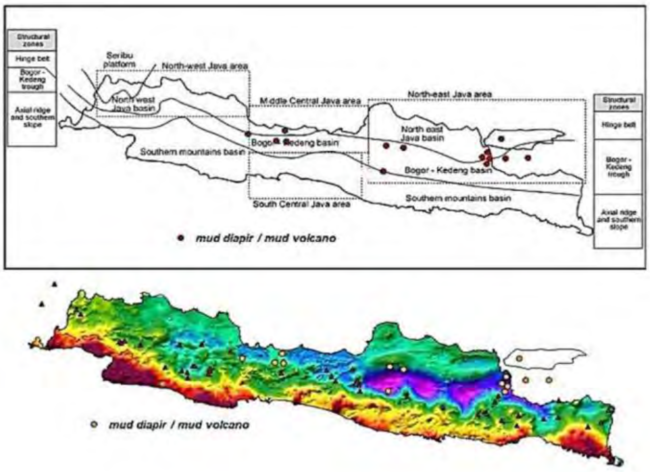

Figure 1. Several mud diapirs and mud volcanoes exist in the depression zone of Java to Madura (Bogor-North Serayu-Kendeng-Madura Strait) (Satyana and Asnidar, 2008).

Regional evaluation of Java to Madura depression area as site for mud diapirs and mud volcanoes was firstly conducted by and published in Satyana and Asnidar (2008). The present paper summarizes and updates the work of Satyana and Asnidar (2008).

Elisional Basin

As mentioned above, overpressured structures and their releases as mud diapirs and mud volcanoes occur in basin with elisional condition. Kholodov (1983) in Akhmanov and Mazzini (2007) was firstly discussing elisional condition of sedimentary basin (Figure 2).

Elisional basin is characterized by:

1. quick and stable tectonic submergence of basin,
2. deposition of ultrathick sedimentary series,
3. younger deposits entirely cover underlying series,
4. fluid overpressure and sediment undercompaction,
5. fine- grained clayey and clastic sediments present as the storage of gas and water, initial pore waters preservation and the formation of fluid diagenetic at depth, and
6. pressure gradient and fluid migration from the center part of basins to peripheral, and
7. deep-buried clayey sediments serve as the storage system of diagenetic fluids while sandy sediments present as passive repositories.

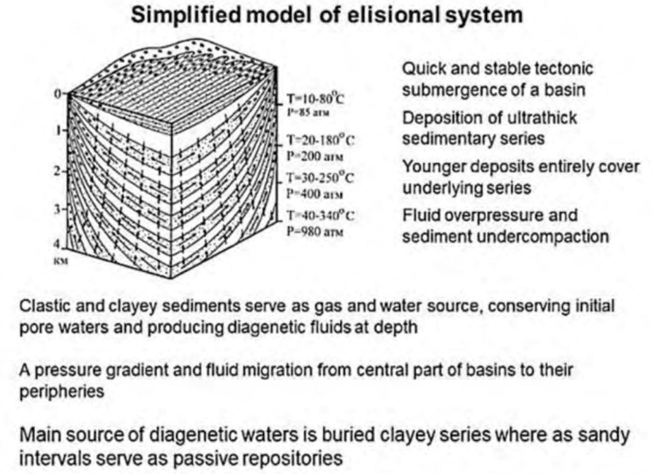

Figure 2*. Sedimentary, tectonic-structural, and hydro-dynamic natures of basin with elisional system (Kholodov 1983 in Akhmanov and Mazzini, 2007).*

Related to elisional system, Milkov (2000) discussed conditions important for mud volcano formation, as follow:

1. rate of rapid sedimentation,
2. thick overburden,
3. presence of subsurface plastic stratum,
4. sufficient supply of gas and high potential hydrocarbon,
5. abnormally high formation pressure,
6. compressional settings,
7. high seismicity, and
8. fault occurrence

There are numerous ways creating overpressure. They include: non-equilibrium compaction, tectonic compression, aquathermal pressuring, transformation of smectite to illite, and hydrocarbon generation (Satyana and Asnidar, 2008). The predominant mechanism of overpressure generation occurs through non-equilibrium compaction. Immediately after deposition, rock undergoes burial and compaction with progressive process of physical water expulsion from sediments. The thick and rapid deposition of fine-grained sediments has low porosity and poor permeability in relation with the compaction process which inhibits the pore fluid flow of shale. With the increasing burial, pressurized fluid increases in correspond with the increasing weight of overburden.

Tectonic compression able to creates abnormal pressure which is similar to the mechanism of non-equilibrium compaction. Burial process causes temperature increased with depth and produce thermal fluid. The burial also causes pore water expansion greater than the rock. During burial, diagenesis occurred in the form of smectite transformation to illite at temperature of 100° C. The alteration of smectite to illite will expel a large volume of water. The next contributor is hydrocarbon generation that occurs after compaction and increase the pressure of rock formation. The subsequent process of hydrocarbon generation includes the kerogen transformation to liquid and gaseous phases. As a result, the increasing of fluid volume leads to the growth of formation pressure.

Mud Diapirs and Mud Volcanoes

Diapir is an intrusion/ piercement structure of relatively mobile mass intruding into preexisting strata caused by buoyancy and differential pressure (Hedberg, 1974). The mobile mass is either mud/shale or salt. Overpressuring and undercompacted shales frequently source diapirism. Diapirism occurs when there is release of overpressure. The release of overpressure is often caused by faulting. Diapirs commonly intrude vertically upward along faults or zones of structural weakness. Density reversal between deeper less dense undercompacted source of diapirs and shallower denser overlying sediments drive diapirs move vertically when faulting release the overpressure. This density reversal drives force of buoyancy for moving diapirs.

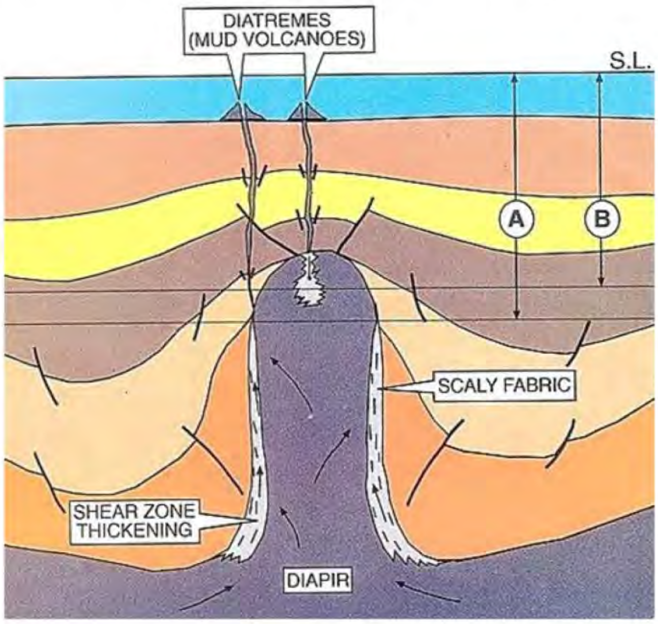

Figure 3*. Relation between diapir and mud volcano, pipe of diatreme, connecting diapir to mud volcano is not a requirement for mud volcano, diapir which intrudes to surface becomes mud volcano. A-interval depth for strain softening, B-interval depth for methane expansion (Ware and Ichram, 1997).*

When diapir breaches the surface, it becomes mud volcano (Figure 3). Mud volcano is an instantaneous event. The terminology of "mud-volcano" is generally applied to a greater or lesser scale of mud eruption. In other word, this term is also used for surface extrusion of invariably watery mud or clay which contained methane gas and tend to create a conical or volcano-like mud (Hedberg, 1974).

The source of a mud volcano is subjected to a substantial subsurface or diapiric layer of highly plastic, and undercompacted mud or shale. It also presents in relation with fracture, fault, or sharp fold tectonic structures. The fault structure is associated with shale diapirism which strongly influences the occurrence of mud volcanoes (Giovanni, 2003). Extrusion products are clay muds, connate salty waters and gases (mainly methane). Mud is squeezed upward by buoyancy forces which arise from the contrast of bulk density between over-pressured muddy mass and greater density of overburden.

As a closed system, the source of mud volcano can be disclosed through natural faulting or cracking of deep-seated over-pressured mud to the surface. This process produces phase differentiation followed by rapid migration of large volume materials from source and eruption to the surface. Following this, a large volume of water escaped, causes material deficiency at depth and leads to the formation of collapse caldera around mud volcano. Post formation stage includes channel sealing of dehydrated and degassed of the erupted materials.

The relationship between diapir and mud volcano can be obviously seen on the stages of formation of diapir to mud volcano. Waluyo (2007 in Satyana and Asnidar, 2008) proposed the following stages from mud diapirism to mud volcano eruption (Figures 4, 5):

- Stage 1: embryonic, early stage of shale deformation at weak zones
- Stage 2: shale move upwards approaching the surface (shale diapirism phase)
- Stage 3: shale flows out on the surface (mud volcano phase)
- Stage 4: end of shale-flow period due to decrease in subsurface pressures, indicated by partial subsidence beneath the mud volcanoes

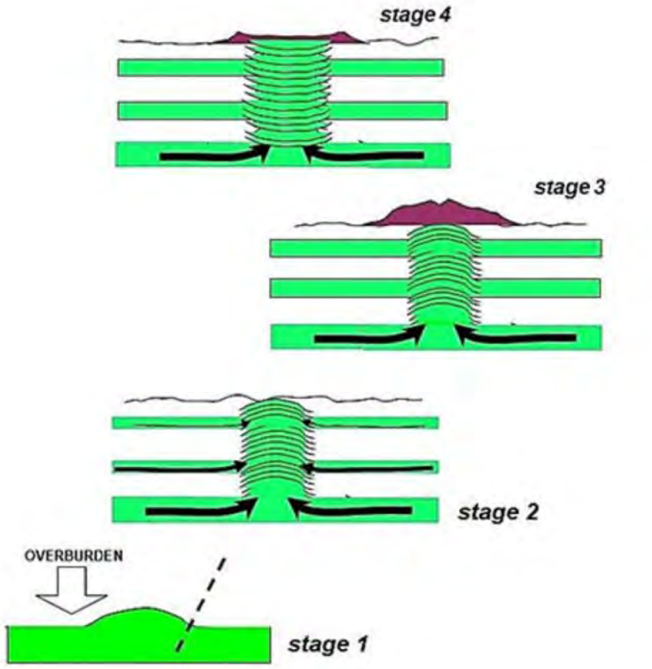

***Figure 4**. Stages of development from diapir to mud volcano, dash line –fault. Stage 1 and 2 diapirism, stage 3 mud volcanism, stage 4 post mud volcanism – formation of subsidence (Waluyo, 2007 in Satyana and Asnidar, 2008).*

Temperatures of erupted materials of mud volcano are much cooler than magmatic volcano and the ejected materials may be equal to the low level of freezing point, particularly occurred when venting site is associated with hydrocarbon clathrate hydrate deposits. However, the occurrence of mud volcanoes in volcanic area may have higher temperatures than average. Slurry of the fine solids is generally found as ejected materials that occurred in liquid phase as comprises of acidic or salty water and hydrocarbon fluids. Rocks of various sizes from granule to boulder can also be erupted in explosive mud volcano. Gases are commonly emitted in mud volcano eruption. About 86% of methane gas released together with lesser amount of carbon dioxide, hydrogen sulphide, and nitrogen. In volcanic area, they are also often associated with magmatic sills or dikes; while if mud volcanoes have proximity with volcanic area they will emit magmatic sourced- water and incombustible gases of helium.

Akhmanov and Mazzini (2007) proposed a variety of mud volcano morphology (Figure 6). This various morphology may also have relation with the different stages of its development. The types include:

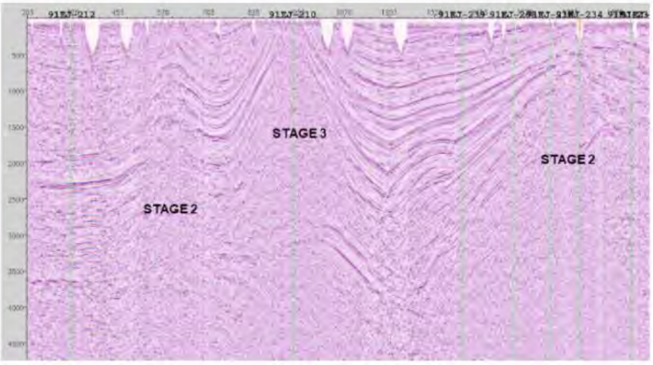

Figure 5. A seismic section in North Serayu-Kendeng Deep showing stages of development from diapiric structures to mud volcano.

1. "classic" conical-shaped of volcanic edifice equipped with crater and the stratification of mud flow which represents a periodical eruption;
2. large territory of swamp-like area;
3. sticky mud neck protrusion;
4. "collapsed synclinal" depression;
5. Crater muddy lake.

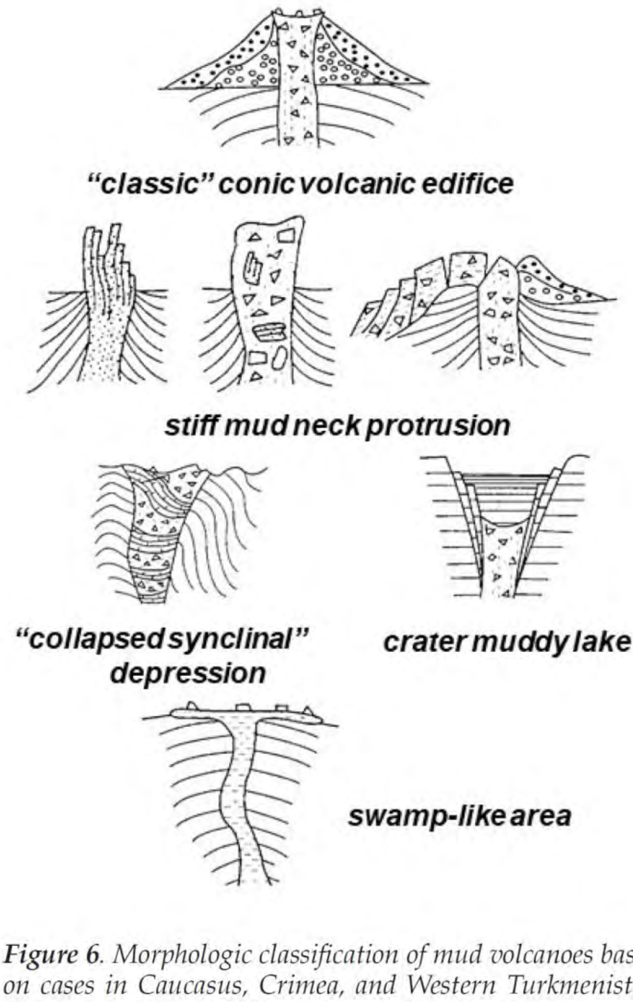

Figure 6. Morphologic classification of mud volcanoes based on cases in Caucasus, Crimea, and Western Turkmenistan (Kholodov, 2002 in Akhmanov and Mazzini, 2007)

Mud volcano morphology commonly shows types combination as described above.

There is an interesting relationship between mud volcano morphology and characteristics of the erupted materials. The morphology types of mud volcano could be explained by distinguish the physical properties of supplied materials, the eruption frequency or based on the different stages of mud volcano development. The different shapes of mud volcanoes are applied using simple rules as follow : the greater pore-fluid pressure, the more violent of mud eruption; the larger structure, the more frequent eruption activity; the lower the viscosity, the larger and flatter the body. It can be inferred that the size of mud volcano indicates the size of the conduit and the driving mechanism of the mud volcano.

Depression of Java to Madura

The zone of depression has been called the Bogor—North Serayu—Kendeng Zone (van Bemmelen, 1949). As the depression zone has been uplifted and deformed significantly since the Plio-Pleistocene, the depression is called also the Bogor – North Serayu – Kendeng Anticlinorium and form one of the physiographic zones of Java (Figure 7). The depression continues into the Madura Strait until the area to the north of Bali, making a zone of around 1000km long and 60 km wide from Banten area at the westernmost part of Java to the offshore areas to the east of the Madura Strait. The zone dips to the east making offshore Madura Strait although it was also deformed.

The Bogor-North Serayu-Kendeng Depression has positioned at back-arc basin since its formation in early Neogene. The depression developed as an isostatic subsidence compensated the uplift of the southern Oligo-Miocene volcanic arcs. The depression subsided by overburden sediments. The central part of the depression also subsided due to thrust loading when the southern part of the depression was uplifted in Plio-Pleistocene time.

The Bogor-North Serayu-Kendeng-Madura Strait Depression received sediments from the two provenances: southern and northern uplifted areas. The southern provenance was mostly volcanic terrain with some siliciclastic and carbonate deposits.

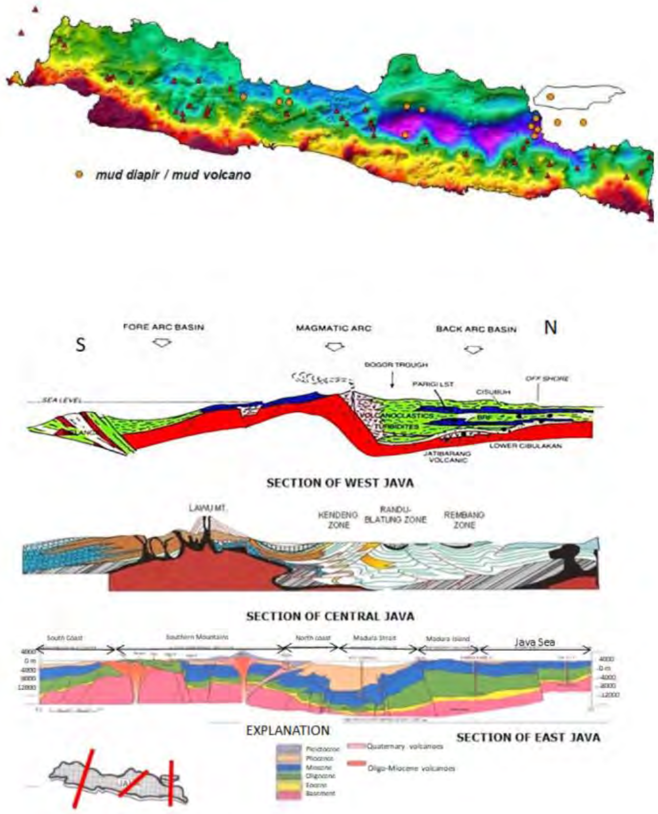

Figure 7. Above. Regional Bouguer gravity map of Java Island (dark red: high to purple: low). Bogor-North Serayu – Kendeng depression areas are blue to purple in colors, showing gravity low. Below. A series of geologic sections of West, Central, East Java (lines of sections are indicated), each show the presence of depression areas in the middle. Mud diapirism and mud volcanoes have occurred here.

The northern provenance was dominantly non-marine to shallow marine rock assemblages, composing the reservoirs of Northwest Java and Northeast Java Basins. Most of the sediments filling the depression were volcanic-clastic sediments eroded from the southern volcanic arcs. Very thick sediments were rapidly deposited mostly as turbiditic deposits. Rapid sedimentation generated elisional condition within the depression of Java to Madura. Volcanic sediments rapidly deposited into deep basin changed diagenetically to become clays, undercompaction and overpressuring were resulted in within the depression. When later it was compressed, faulting occur everywhere and overpressured structures released through the faults and pierced upward in many places forming mud diapirs and mud volcanoes.

The following parts discuss the main mud diapirs and mud volcanoes in the depression of Java to Madura, summarized and updated from Satyana and Asnidar (2008). They include: Ciuyah, North Serayu, Bledug Kuwu complex, Sangiran, LUSI, East Kendeng complex (Figure 8).

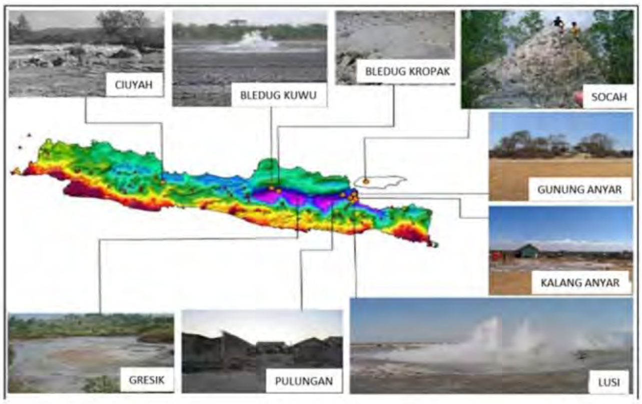

Figure 8. Locations of mud diapirs and mud volcanoes distribution along Java and Madura (Satyana and Asnidar, 2008).

Ciuyah Mud Volcano, Kuningan Area

Ciuyah means salted water. Ciuyah is located 5 km to the south of Kuningan area in the district of Ciniru. Geologically, it is the eastern part of the Bogor Depression. Here, hot salted mud and water flows continuously from several edifices (Figure 9). The local people called the edifices as Ciuyahleutik and Ciuyahgede, relative to the size of water flow coverage ("leutik" is small, "gede" is big). As water evaporated, salt crystals are deposited. The Ciuyah complex of salted mud flow and hot water is considered as mud volcano of post-eruptive phase. It represents the stage-4 mud volcano due to decrease in subsurface pressures, indicated by partial subsidence beneath the mud volcanoes. The surface morphology is a combination of swamp-like area and crater muddy lake.

The eastern part of the Bogor depression is slightly convex to the north, with intensive folding and northward upthrusts. The core of the anticlinorium consists of Miocene strata and its flanks are composed of Pliocene and Lower Pliocene deposits. The total thickness of the Neogene sediments in this depression is more than 6000 meters (van Bemmelen, 1949).

Figure 9. Ciuyah mud volcano, Kuningan area (Satyana and Asnidar, 2008).

The sediments are dominated by turbiditic volcanic-clastic sediments rapidly deposited into the depression (Miocene-Pliocene aged Rambatan, Halang, Pemali, Kumbang formations). To the northwest of Ciuyah area is Quaternary Mount Ceremai magmatic volcano. The north and west flanks of the volcano are slightly bulged due to draping overlying the diapiric structure subsurface made of plastic Pemali clay-shales and Early Pliocene plastic Kaliwangu clay marls.

North Serayu Diapirs

In the North Serayu Depression thick succession of the turbiditic deposits of the Early to Middle Miocene marly clays, quartz sandstones and tuff-sandstones were deposited rapidly. This flysch-like series comprise the Merawu and Penyatan formations in the central and eastern section, and Pemali Formation in the western section of the North Serayu Depression. The uplift of the southern Central Java in the Middle-Late Miocene was volumetrically compensated by a sudden increase of subsidence of the floor of the North Serayu Depression (van Bemmelen, 1949; Satyana and Armandita, 2004). The Mio-Pliocene succession of strata filled the subsiding trough of the North Serayu Zone, began with volcanic deposits, alternated with conglomerates, and ended with the soft clay marls and tuffaceous sandstones of the Kalibiuk Formation.

Gravitational sliding movements from south to north in the North Serayu Depression and rapid deposition of volcanic-clastic sediments during Mio-Pliocene coeval with compressional tectonics had resulted in formation of diapirs in this area. Seismic data acquired to the south of Tegal show the presences of these diapirs (Figure 10, called as "Tegal disturb zone" - Kartanegara et al., 1987). The presences of these diapirs may affect the formation of folds and thrusts in this area. These diapirs represent stage-2 of the development of diapir to mud volcano.

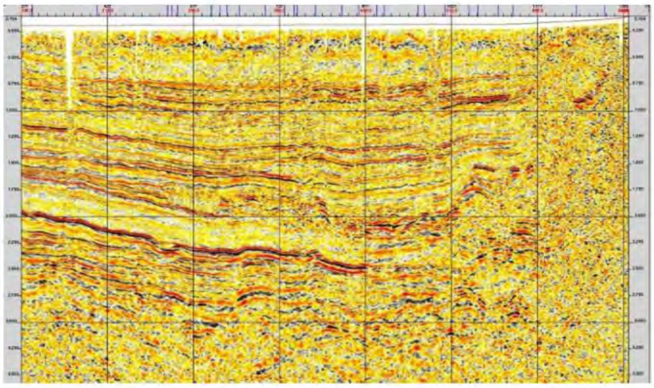

Figure 10. Right side of the seismic section is free of reflector or chaotic, showing the Tegal diapir.

The plastic Merawu flysch pierced as diapirs and were intensively folded. At the end of the Neogene, the subsidence of depression came to an end. The Neogene formations, thousands of meters thick and partly consisting of plastic, unconsolidated clays and marls, were arched up by diapirism.

Bledug Kuwu Mud Volcano Complex

"Bledug" means the sound like cannon-fire. Complex of Bledug Kuwu mud volcanoes are

located to the east of Semarang city and 20 km to south of Purwodadi town, Central Java. Geologically, they are situated at the border between North Serayu and Kendeng Depressions. There are some mud volcanoes in this area (such as Bledug Kuwu, Bledug Kesongo, Bledug Kropak, and several others, Figures 11-15). Kuwu is the largest mud volcano in the area (Figures 11, 12). The morphology is a set of vents in a flat area which contain quick- dry sand, with a dried mud crust. The eruption emerges like a burst of warm gas and mud while it occurs for more than one but vary in frequency. It can be assumed that mud flows gradually and relatively slowly, but it keeps liquefied by the escaping fluids and gases (Burgon et al., 2002). The morphology type is a combination of swamp like area extending for large coverage and crater muddy lake. The phase of mud volcano is eruptive to post-eruptive (stage 3 to 4).

Figure 11. *Bledug Kuwu mud volcano, to the south of Purwodadi, Central Java (Satyana and Asnidar, 2008).*

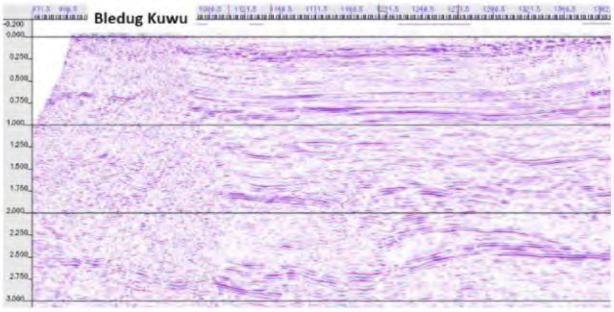

Figure 12. *Left side of the seismic section is free of reflector or chaotic, showing the diapir that connects to Bledug Kuwu mud volcano.*

The presence of quick-dry sand indicates the subsidence of mud volcano area. The Kuwu mud volcano complex extends for about 45 hectares. The biggest vent has diameter of 9 meters and able to erupt mud materials as high as 5.3 meters. In the main site of Bledug Kuwu, the main volcano usually erupts four or five times a minute. With regards to the salinity and turbidity of the mud volcanoes, there is no vegetation or animal life in the eruption area. However, local people utilize the expelled water to extract salt as cooking ingredient. The expelled gasses of CO2 and traces of H2S are nonflammable. In addition, the mud sometimes carries rock fragments and fossils without any detail documentation.

The big mud volcano has temperature ranges from 28-30° C, while the small mud volcano has only 15-16° C. Small mud volcano has more water content (lower density), which might account for its more frequent eruptions and lower temperature.

Figure 13. *Bledug Kropak, small vents of mud volcano still bubbling methane gas, south of Purwodadi area.*

According to the seismic image that across these mud volcanoes indicate disturbed zones from top of the Kujung Formation up section through the top of Wonocolo Formation to the surface. Bledug Kesongo is obviously characterized by collapse structure with upward concave horizons (Figure 15) along the disturbed zone indicates the stage-4 of mud volcano subsidence. The disturbed zone of Bledug Kuwu is represented by a chaotic mixture of upward convex and concave reflectors indicating stage-3 to stage-4.

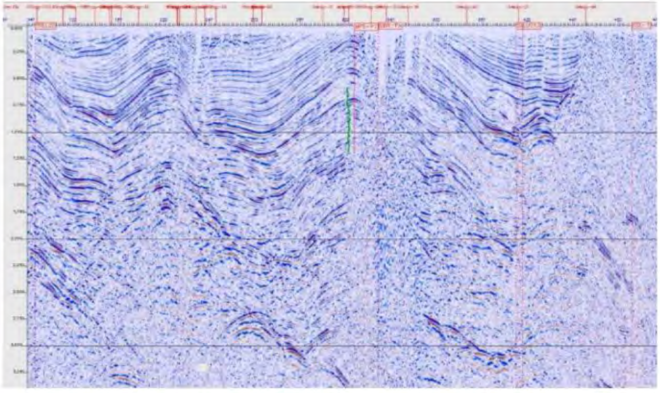

Figure 14. *Complex of mud diapirs and mud volcanoes of south Purwodadi, Central Java in the border of North Serayu and Kendeng depression. Free reflectors and chaotic internal characters indicate the diapirism.*

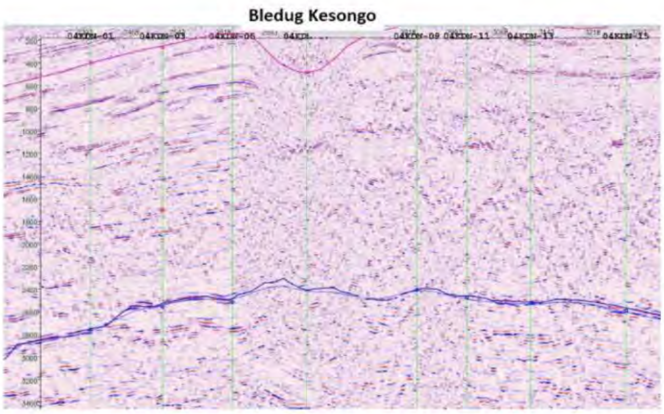

Figure 15. Collapse structure of Bleduk Kesongo, south Purwodadi area, Central Java, showing post-mud volcanism (stage 4), indicated by sinking reflectors.

The sources of diapirs and mud volcanoes are considered the lower shale interval of Late Miocene Wonocolo. This is confirmed by fossil content of mud materials. However, the seismic image shows that the mud source is derived from shales of Early Miocene Tuban Formation. Some diapirs also exist in this area, particularly found below the top of Wonocolo Formation. Meanwhile, the fold formation underlies the diapirs as suggested by some seismic sections.

Sangiran Dome

Sangiran Dome is located 12 km to the north of Surakarta/ Solo city (Central Java). Geologically, it is located between the Zone of Central Depression and the southern border of the Kendeng Zone (van Bemmelen,1949). The Solo Zone is a generally low, flat area in which the oldest outcropping beds are Late Pliocene (Sangiran Dome). Most of the zone is covered by young volcanics. Subsurface geology is poorly known. The thickness of the sedimentary section may reach 9000 meters (Kadar et al., 1989).

A unique natural feature of Sangiran Dome is observed throughout the geology of Java. This feature is situated in the southern margin of the Kendeng zone with intense folding and faulting structures of E-W trend orientation and elongation, yet slightly northern elongation (Lunt et al., 1989).

The features of geological interest are its structural expression, mud volcanoes (with exotic blocks of Miocene, Eocene and basement rock). The area has been famous since 1930's for its rich hominid and vertebrate fossil faunas. The location of Sangiran was the second site of *Homo erectus* fossils discovery in the eastern Java. This site is located after the river section of Trinil, about 50 kilometers to the east.

Structurally the area is a dome, somewhat elongated in NNE-SSW direction. Structuring is very young (between 0.7 and 0.5 Ma - middle Pleistocene and could repeat until 0.12 Ma - base late Pleistocene – Kadar et al., 1989). The origin of Sangiran Dome was interpreted in various ways. Van Bemmelen (1949) considered its origin as compressive structure related to volcano-tectonic collapse of the Old Lawu volcano; other opinions are diapiric shale flow, a wrench-related fold, an incipient volcano, or due to a basement related fault.

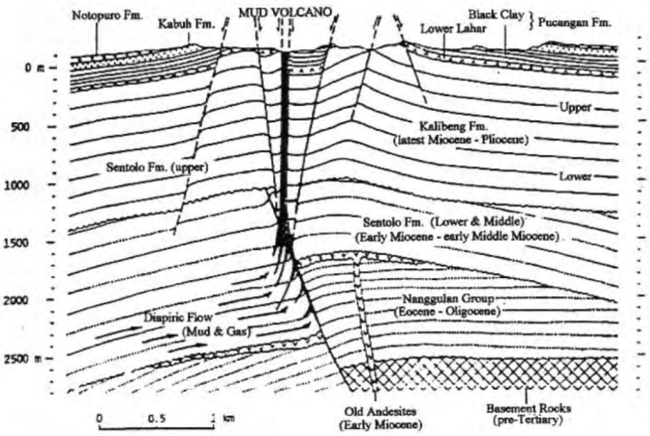

Figure 16. Schematic section of Sangiran Dome, representing mud volcano (Itihara et al., 1985).

Itihara et al. (1985) interpreted that the Sangiran Dome is an expression of mud volcano (Figure 16). They explained that Sangiran Dome related to basement involved fault, perhaps with a north - south orientation, occurred first and produced a fold perpendicular to the regional orientation. This fault acted as a focus for overpressured Early Miocene muds which could then rise and, along with overthrusted, fractured rock from the fault plane, escape to the surface as mud volcano. The shape of dome and presence of several spots of saline water, bubbles of methane gas, and erupted materials of fossils, exotic blocks of various rocks may confirm that the Sangiran Dome is an extinct mud volcano (Lunt et al., 1998). All exotic blocks are thought to have come from subsurface as a result of explosion.

The oldest beds in the center of the dome are relatively soft clays and now form a topographic depression, surrounded by a ring of hills composed of the harder sands and conglomerates of the Kabuh and Notopuro Formations. The oldest beds are a shallowing-upward marine sequence

(Kalibeng Formation, Late Pliocene), successively overlain by brackish bay to fresh water lacustrine black clays (Pucangan Formation), fluviatile sandy beds (Kabuh Formation) and "cold lahars" (Notopuro Formation). Thin tuff beds are found throughout the section.

Based on the schematic profile of the Sangiran Dome mud volcano (Watanabe and Kadar, 1985), the mud volcano morphology type of the Sangiran Dome is collapsed synclinal depression. Stage-4 consists of some subsidence underlying the mud volcano and known as the development stage of mud volcano.

Satyana (2008) proposed that mud volcano eruption in Sangiran area had affected the demise and evolution of hominids here and its surrounding areas. In the Sangiran dome, the sub-species of *Homo erectus erectus* lived, particularly in the Pleistocene ages (1.3-0.5 Ma). This sub-species was known as hominid or the early human. Their fossils were found in the upper part of Pucangan and lower part of Kabuh Formations. This sub-species extinct between 0.7-0.5 Ma due to contemporaneous eruption of the Sangiran mud volcanoes. The eruption caused the area became in-habitable, thus, later hominid of sub-species *Homo erectus ngandongensis / soloensis* were migrated eastward downstream of the Solo River. This sub-species lived until the latest Pleistocene (0.05 Ma) in Sambungmacan, Ngawi, and Ngandong areas.

LUSI and Other Mud Volcanoes in East Kendeng Zone

On 29th May 2006, an unexpected mud eruption occurred in the Porong area, Sidoarjo, East Java. The location of eruption was then named as LUSI (the abbreviation of "Lumpur Sidoarjo" or Sidoarjo mud) (Figure 17).

Based on the characteristics of eruption and related geologic data, LUSI was concluded as evolved from mud volcano eruption to sediment-hosted hydrothermal system (Mazzini et al., 2012). The eruption is still occurring today (July 2019) after it erupted for more than thirteen years. The volumes of erupted mud and fluid in early periods were between 100,000 to 150,000 m3/day (maximum level was 180,000 m3/day at December 2006 –Mazzini et al., 2007) with erupted materials 80% solid and 20% fluid (gas and water). Recently, the volume decreased to 30,000 to 50,000 m3/day with 80% fluid and 20% solid (Figure 18).

***Figure 17**. Eruption of LUSI (Lumpur Sidoarjo) mud volcano in April 2007, almost one year after the beginning of the eruption (29th May 2006).*

***Figure 18**. Eruption of LUSI, part of hot water becomes steam when it exposes to air, condition in 2014, The man is Prof. Dr. Hardi Prasetyo, vice chairman of BPLS –governmental body for managing impact of LUSI.*

The temperature of erupted water has remained constant at about 100°C (Handoko Wibowo, personal communication). The mud flooded areas of 824 hectares, consisting of 16 villages and more than 10,400 houses. Factories, infrastructures of transportation and power transmission were damaged. It is expected that the mud eruption will last for years. Erupted materials of LUSI are now mostly associated with magmatic fluids, it has relation with volcanic complex to the south. The origin of LUSI eruption has been a matter of debate. Two trigger mechanisms were: (1) underground blowout of Banjar Panji-1 well drilled by Lapindo Brantas at the time mud eruption occurred, (2) tectonic re-activation of the Watukosek Fault (a regional fault in this area) to overpressured structure by the Yogyakarta earthquake on May 27th 2006. The origin of LUSI and its debates is discussed by Satyana (2019b, this volume).

LUSI is one of numerous mud eruption in the east Kendeng Depression. Some mud volcano phenomena are found close to LUSI. Their feature occurs variably whether in active, extinct, or dormant condition as observed in the Kalang Anyar and Pulungan - Sidoarjo, Gunung Anyar-Surabaya, Wringin Anom – Gresik and Socah - Bangkalan, Madura (Figures 19, 20).

Figure 19. *Mud volcano of Socah, Bangkalan, Madura.*

Figure 20. *Mud volcano of Kalang Anyar (upper left, dormant), Gunung Anyar (upper right, extinct), Pulungan (lower, extinct), to the north of LUSI, Sidoarjo area (Mazzini et al, 2007).*

With regards to the historical chronicles, folklore, and geological data, Satyana (2007, 2019) elaborated the Javanese history with the presence of complex mud volcanoes during the periods of Jenggala and Majapahit Kingdom (12th-15th century). He indicated the presence of mud volcanoes in this period in a zone called Tunggorono–Jombatan–Segunung–Canggu-Bangsal in Jombang–Tarik, mostly in Sidoarjo area, as long as 25 km.

Subsea Mud Volcanoes at the Madura Strait

The Madura Strait is basically known as one of the deepest and thickest basins in Indonesia which occurred as the offshore extension of the Kendeng Depression. The western basinal area experienced a very rapid sedimentation since the late Miocene. As a result, more than 3000 meters of Plio-Peistocene section were deposited in this basin. Although the eastern basin has similar deposition to the western one, but this basin underwent an earlier subside during the late Oligocene-early Miocene.

In the late Pliocene time, rapid subsidence took place and characterized by the deposition of overpressured thick clays. In the Madura Strait, a lateral left wrench fault of E - W trending triggered the mobilization of Miocene basinal shales. This event took place during the Plio-Pleistocene and generated a series of shale diapirs. To the south, the on-going subduction along the Java trench has a strong impact toward the formation of several structures such as predominant north-directed thrusting that dependent on the basement faulting.

Very thick young sediments were rapidly deposited and compressed within elisional system of the Madura Strait depression. Mud diapirs and mud volcanoes occur numerously in the basin. Seismic data in the area obviously show the presences of mud diapirs and subsea mud volcanoes in Pliocene to Pleistocene sections. Classic conic volcanic edifice type subsea mud volcanoes of stage-3 development (eruptive-phase) are observed in the seismic sections. The relationship between mud diapirs of stage-2 development and later stage mud volcanoes can also be observed in some seismic sections (Figure 21).

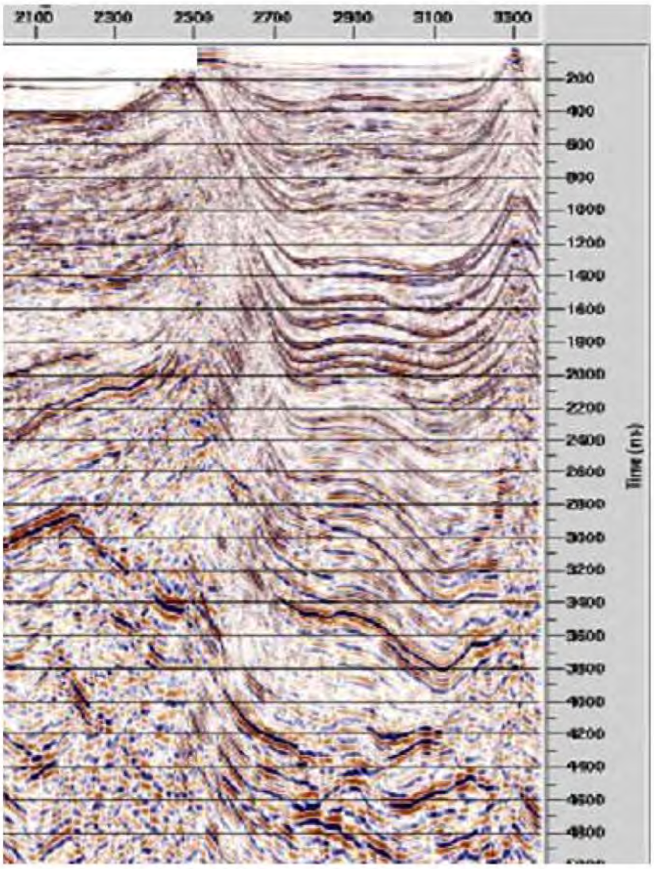

Figure 21. *Seismic section in Madura Strait, showing the presence of two diapiric structures which intrude to surface become two subsea mud volcanoes (Satyana and Asnidar, 2008).*

Conclusions

Mud diapir and mud volcano occur in "elisional" basin where the following factors exist: stable tectonic submergence, rapid deposition of thick young sediments, the presence of subsurface plastic strata, over-pressured fluid overpressure and under-compacted sediments, enough gas supply and high hydrocarbon potential, the formation of diagenetic fluids from buried clayey intervals, compressional setting, numerous faults-high seismicity, and also high geothermal gradient.

The Bogor-North Serayu-Kendeng-Madura Strait Zone represents good elisional basin with numerous mud diapirs and mud volcanoes. The location of their distribution includes : Ciuyah mud volcano in Kuningan, eastern West Java; North Serayu diapirs in northern Central Java; mud volcano complex of Bledug Kuwu, Bledug Kesongo and Bledug Kropak which are located to the south of Purwodadi, Central Java; mud diapir and mud volcano of Sangiran Dome in Central Java, LUSI (mud volcano eruption) Pulungan and Kalang Anyar in Sidoarjo, East Java, Gunung Anyar in Surabaya, East Java, Socah mud volcano in Bangkalan, Madura and subsea mud diapirs and mud volcanoes in the Madura Strait.

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