IPA08-G-139

PROCEEDINGS, INDONESIAN PETROLEUM ASSOCIATION
Thirty-Second Annual Convention & Exhibition, May 2008

MUD DIAPIRS AND MUD VOLCANOES IN DEPRESSIONS OF JAVA TO MADURA : ORIGINS, NATURES, AND IMPLICATIONS TO PETROLEUM SYSTEM

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ABSTRACT

Mud diapir and mud volcano are piercement structures showing release of overpressured sediments piercing upward from subsurface to the Earth's surface due to buoyancy and differential pressure. These structures occur in "elisional" basin mainly characterized by rapid deposition of thick young sediments, presences of fluid overpressures, under-compacted sediments, and petroleum generation; and recently compressed.

The Bogor-North Serayu-Kendeng-Madura Strait Zone was an axial depression of Java to Madura Islands with elisional characteristics. The Mio-Pliocene and Pleistocene sediments were rapidly deposited into the depression and compressed since then due to the islands have been located frontal to the plate convergent boundary. Numerous mud diapirs and mud volcanoes are found along the zone.

We examined the origins and natures of mud diapirs and mud volcanoes found along the depression, they include : Ciuyah mud volcano (Kuningan, eastern West Java), North Serayu diapirs (northern Central Java), mud volcanoes of Bledug Kuwu, Bledung Kesongo, Bledug Kropak (to the south of Purwodadi, Central Java), mud diapir and mud volcano of Sangiran Dome (Central Java), LUSI (erupting mud volcano, Sidoarjo, East Java), Porong, Kalang Anyar, Pulungan (Sidoarjo), Gunung Anyar (Surabaya), Socah (Bangkalan, Madura), and submarine mud diapirs and mud volcanoes of the Madura Strait. The origins were basically same, relating to factors in elisional system. The surface morphologies of mud volcanoes include : swamp-like area, crater muddy lake, classic cone edifice, and collapsed synclinal depression. The development stages of the mud diapirs to mud volcanoes include stage-2 (pre-eruption –diapiric phase), stage-3 (syn-eruption), and stage-4 (post-eruption).

These mud diapirs and mud volcanoes apparently have spatial and genetic relationship with petroleum. Oil and gas seeps and producing oil and gas fields share the same places with the mud diapirs and mud volcanoes of the Bogor-North Serayu-Kendeng-Madura Strait Zone. It is considered that here mud diapirism and mud volcanism have implied the petroleum systems, especially in : maturing the source rocks generating petroleum, forming structural dips and faults for petroleum migration and generating diapiric structural traps at shallow horizons. Worldwide cases show that diapirism and mud volcanism have close relationship to petroleum and here in Java to Madura we have the same case.

INTRODUCTION

Mud volcanoes are worldwide phenomena. Milkov (2003) reported approximately 1,100 mud volcanoes have been documented onshore and in shallow water on continental shelves, and 1,000-100,000 mud volcanoes may exist on continental slopes and abyssal plains. These features are most common in areas of rapid sedimentation, lateral tectonic compression, and geologically recent magmatic activity. Mud volcanoes often occur at the surface and the seafloor as a result of migration of fluidized sediment along active faults due to overpressure, and may also form on top of seafloor-piercing shale diapirs. The study of mud volcanoes is important for a variety of reasons : indicator of active petroleum systems, a source of methane in the atmosphere and ocean, and a geohazard.

Depression of Java to Madura called the Bogor-North Serayu-Kendeng Trough or Zone which is presently compressed to become fold and thrust belt in the middle of the island was a site into which substantial sediments were rapidly deposited mainly during Mio-Pliocene and Pleistocene time. The site has been trending parallel with the tectonic compression due to subduction to the south of Java and sharing same place with coeval volcanic arcs.

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This condition has resulted in “elisional” system – sedimentary and tectonic regimes favorable for the occurrences of mud diapirs and mud volcanoes. Accordingly, mud diapirs and mud volcanoes commonly occur along the Bogor-North Serayu-Kendeng Zone from West Java to the Madura Strait.

In Java, petroleum has been discovered and produced for more than 100 years in areas where diapirs and mud volcanoes occur. Oil and gas seeps and minor fields have been discovered and produced in the eastern part of the Bogor Zone and the North Serayu Zone. The Rembang-Kendeng Zone, which is part of the East Java Basin, is one of the oldest and richest petroleum areas in Indonesia. Recent discoveries and production of petroleum have also taken place in the Madura Strait. The sharing of places between petroleum and diapirs and mud volcanoes therefore, is interesting to examine.

The paper will discuss firstly in general about mud diapirsm and mud volcanism. Following this is the discussion on the axial depression/zone of Java called the Bogor-North Serayu-Kendeng-Madura Strait, examining its conditions to form diapirs and mud volcanoes. The origins and natures of individual existing mud diapirs and mud volcanoes observed along this zone will be addressed. The discussion on how these piercement structures have implied petroleum system in Java to Madura will end the paper.

MUD DIAPIRS AND MUD VOLCANOES

A diapir is an intrusion of relatively mobile mass that intrudes into preexisting strata caused by buoyancy and differential pressure. The mobile mass is either mud/shale or salt. Diapir relates to creation of overpressure in deep strata. In a broader sense there are numerous ways to create anomalous subsurface pressure. They include : non-equilibrium compaction, tectonic compression, aquathermal pressuring, transformation of smectite to illite, and hydrocarbon generation. *Non-equilibrium compaction* is believed to be the dominant mechanism in formation of overpressured sediments. During burial and compaction, water is physically expelled from sediments. In thick, rapidly deposited fine- grained sections reductions in porosity and permeability related to compaction inhibit the flow of water out of the shale. As burial continues, fluid pressure increases in response to bearing the increasing weight of the overburden. *Tectonic compression* creates abnormal pressure similar to the nonequilibrium compaction mechanism. *Aquathermal pressuring* occurs when increasing temperature with depth of burial causes pore waters to expand at a greater rate than the rock. *Transformation of smectite to illite* refers to the fact that at a temperature of about 221º F, smectite begins altering to illite and expels a large volume of water. *Hydrocarbon generation* is thought to be the next major contributor after compaction forces to the pressure increase in the formation rocks. The generation of hydrocarbons involves the transformation of kerogen in organic matter into liquid and gaseous phases. This transformation results in an increase in fluid volume of the organic matter that will lead to the growth of formation pressure.

An undercompacted mud or shale is a body out of pressure and gravity equilibrium with its surroundings (Hedberg, 1974). It is also a plastic body of relatively low viscosity which will flow relative to its surroundings. It thus is not surprising that undercompacted shales frequently should be the source of diapirism. As has been suggested above, it seems not improbable that internal pressure caused by gas generation may be a strong contributing factor to shale diapirism.

Diapirs commonly intrude vertically upward along fractures or zones of structural weakness through more dense overlying rocks because of density contrast between a less dense, lower rock mass and overlying denser rocks. The density contrast manifests as a force of buoyancy. The process is known as diapirism. The resulting structures are also referred to as piercement structures. In the process, segments of the existing strata can be disconnected and pushed upwards. While moving higher, they retain much of their original properties such as pressure, which can be significantly different from that of the shallower strata they get pushed into. Rock types such as evaporitic salt deposits and gas charged muds are potential sources of diapir.

When diapir breaches the surface, it becomes mud volcano. The term "mud-volcano" generally is applied to a more or less violent eruption or surface extrusion of watery mud or clay which almost invariably is accompanied by methane gas, and which commonly tends to build up a solid mud or clay deposit around its orifice which may have a conical or volcano-like shape (Hedberg, 1974). The source of a mud volcano commonly may be traced to a substantial subsurface layer or diapir of highly plastic, and probably undercompacted, mud or shale. Mud volcanoes also commonly appear to be related to lines of fracture, faulting, or sharp folding. There appears to be a close inter-relation between undercompacted (overpressured) muds or shale bodies, mud or shale diapirs, mud lumps, and mud volcanoes; and all degrees of gradation from one to another.

In this case, when diapirs usually have rather intrusive nature, whereas mud volcanoes are characterized by the extrusive nature. In addition, mud diapirism is described mainly as a slow process of a movement of a plastic rock while mud volcano is an instantaneous event. Faults associated with shale diapirism processes strongly influence mud volcanoes occurrence (Giovanni, 2003). Extrusion products are clay muds, connate salty waters and gases (mainly methane). Mud is driven upward by buoyancy forces arising from the bulk density contrast between an over pressured muddy mass and an overburden of greater density.

Disclosure of mud volcanic source through faulting or crack system progradation to the surface leads to closed system opening. This results in phase differentiation, fast migration of large volume of the material from source and its erupting on the surface. Large amount of escaped water can form a material deficiency at the depth and lead to formation of collapse caldera around mud volcano. These processes complete an eruption phase with channel sealing by dehydrated and degassed erupted material.

Recent investigations based on numerous data demonstrated that strong earthquakes (M>4) "initiate" paroxysms of mud volcanoes eruptions, i.e. the latter should be considered as earthquakes consequences (Aliyev *et al.*, 2003). Correlation of data about earthquakes and recorded eruptions of mud volcanoes which have taken place in Azerbaijan for the last two centuries allowed expressing opinion about genetic linkage between activation of mud-volcanic activity and seismicity because these natural phenomena are due to tectonic tension accumulated in the earth crust. With account of magnitude of the earthquake, depth of the source, energetic class, distance between epicenter and location of volcanoes it was determined that strong earthquakes, as a rule, played a role of "a trigger" in the mud-volcanic process. The cause is determined most clearly when the earthquake source and volcano are located within one fault structure subject to the volcano has been calm for a long time (Lokbatan erupted in 11 years, Durandag – in 42 years, etc.) and accumulated enough energy for paroxysm of eruption.

There are several important conditions that are necessary for mud volcano formation (Milkov, 2000) :

1. rapid sedimentation rate,
2. thick sedimentary cover,
3. presence of plastic stratum in the subsurface,
4. enough gas supply and high hydrocarbon potential,
5. abnormally high formation pressure,
6. compressional settings,
7. high seismicity,
8. occurrence of faults,

Such condition is called “elisional” condition, basin which have these conditions is called elisional basin (Kholodov, 1983). An elisional basin is characterized by (*Figure 1*) :

1. quick and stable tectonic submergence of a basin,
2. deposition of ultrathick sedimentary series,
3. younger deposits entirely cover underlying series,
4. fluid overpressure and sediment undercompaction,
5. clastic and clayey sediments serve as gas and water source, conserving initial pore waters and producing diagenetic fluids at depth,
6. a pressure gradient and fluid migration from central part of basins to their peripheries, and
7. main source of diagenetic waters is buried clayey series where as sandy intervals serve as passive repositories.

Temperatures of erupted materials are much cooler than magmatic volcano and may be as low as the freezing point of ejected materials, particularly when venting is associated with the creation of hydrocarbon clathrate hydrate deposits. However, mud volcanoes occurring in volcanic area may have higher temperatures than average. Ejected materials often are slurry of fine solids suspended in liquids which may include water (frequently acidic or salty) and hydrocarbon fluids. About 86% of released gases are methane, with much less carbon dioxide, hydrogen sulphide, and nitrogen emitted. In volcanic area, they are also often associated with lava volcanoes; in the case of such close proximity, mud volcanoes emit incombustible gases including helium

The relationship between diapir and mud volcano can be obviously seen on the stages of formation of diapir to mud volcano. Waluyo (2007 -*unpublished*) proposed the following stages (*Figure 2*) :

- 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

A variety of morphology of mud volcanic edifices was proposed by Akhmanov and Mazzini (2007) (*Figure 2*). The different morphology of the mud volcanoes may also be related to the different stages in its development. The types include : (1) "classic" conic volcanic edifice with main crater and mud flow stratification reflecting periodical eruption; (2) swamp-like area extending sometime for large territory; (3) sticky mud neck protrusion; (4) "collapsed synclinal" depression; and (5) crater muddy lake. It is often that mud volcano morphology shows a combination of the common types described above.

An interesting relationship has been found between the shape of the mud volcano and the material erupted. The different morphology of mud volcanoes could be explained by differences in physical properties of material supplied, by the frequency of eruptions or it could represent different stages of mud volcano development. Simple rules appear to apply to the formation of different shapes of the mud volcanoes. The higher the pore-fluid pressure, the more violent the eruption; the more frequent the activity, the larger the structure; the lower the viscosity, the larger and flatter the body. It is possible to conclude that the size of mud volcano is mainly a function of the size of the conduit and the driving force of the mud volcanism in the area.

DEPRESSIONS OF JAVA – MADURA

Java Island, located at the southern part of the Sundaland, was formed by rock assemblages associated with an active margin of plate convergence. The island has recorded plate convergence between the Indian oceanic crust and the Sundaland continental fragment since Late Cretaceous time. Therefore, the island is made up of complex of plutonic-volcanic arcs, accretionary prisms, subduction zones, and related sedimentary rocks (Satyana and Armandita, 2004) (*Figure 3*).

Three basic geologic provinces trending east-west parallel with the long axis of the island can be outlined in Java from north to south (*Figures 3, 4*) : (1) uplifted nonmarine to shallow marine sediments in the north, (2) subsided volcaniclastic sediments in the middle, and (3) uplifted volcanic and carbonate sediments in the south. The depression of Java to Madura relates to the province number two. This province has been significantly uplifted since the Plio-Pleistocene.

The zone of depression has been called the Bogor-North Serayu-Kendeng (van Bemmelen, 1949). Due to the depression has been uplifted and deformed significantly since the Plio-Pleistocene, the depression has been termed the Bogor-North Serayu-Kendeng Anticlinorium and form one of the physiographic zones of Java. This zone is 1000 kms long and 60 kms wide from Rangkasbitung area at the western part of West Java to the offshore areas to the east of the Madura Strait. At the eastern part of the depression, along the Madura Strait and to the north of Bali, the depression has not been uplifted, instead deepwater sedimentation is still taking place.

The Bogor-North Serayu-Kendeng Depression has positioned at back-arc basin since its formation in early Neogene. The depression developed as a response to the isostatic compensation of the uplift of the southern Oligo-Miocene volcanic arcs. Volcanic-clastic sediments eroded from the southern volcanic arcs mostly were deposited into the depression and causing the depression subsided. The central part of the depression also subsided due to thrust loading mainly in Plio-Pleistocene, but its southern and northern margins were uplifted to become fold and thrust belts.

The Bogor-North Serayu-Kendeng Depression received sediments from the two provenances : northern and southern uplifted areas. The northern provenance was dominantly non-marine to shallow marine rock assemblages, composing the reservoirs of Northwest Java and Northeast Java Basins. The southern provenance was mostly volcanic terrain with some siliciclastic and carbonate deposits. Very thick sediments from the two provenances were deposited rapidly into the Bogor-North Serayu-Kendeng Depression mostly as turbiditic deposits and later were compressed and pierced in many places to become mud diapirs and mud volcanoes discussed below.

Due to its tectonic position which is frontal to the subduction of Indian oceanic crust to the south, Java has been active in seismicity. The presence of active faults identified onshore at Java Island sharing the same place with the depression of Bogor-North Serayu-Kendeng making the tripartite requirements favoring the presences of mud volcanoes : presence of active faults, presence of depression, and presence of active earthquakes (*Figure 5*).

DIAPIRS AND MUD VOLCANOES OF JAVA TO MADURA

Mud diapirs and mud volcanoes are found along the depressions of Java to Madura in Bogor-North Serayu-Kendeng-Strait of Madura Zone (*Figures 4, 6, 7*) Several of them are: Ciuyah in Kuningan area, North Serayu, Bledug Kuwu & nearby mud volcanoes, Sangiran Dome, LUSI, Porong, Pulungan, Gunung Anyar, Kalang Anyar and submarine mud diapirs and mud volcanoes beneath the Madura Strait.

Ciuyah Mud Volcano, Kuningan Area

Ciuyah means salted water. Ciuyah is located 5 kms to the south of Kuningan area in the district of Ciniru (*Figures 4, 6*). Geologically, it is the eastern part of the Bogor Depression. Here, hot salted mud and water flows continuously from several springs. The local people called the springs as Ciuyahleutik and Ciuyahgede, relative to the size of water flow coverage ("leutik" is small, "gede" is big). As water evaporated, salt crystalls are deposited. The Ciuyah complex of salted mud flow and hot water springs is considered as mud volcano of post-eruptive phase or called as dormant and "gryphon-salsa" periods (Akhmanov and Mazzini, 2007). 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 formed by Pliocene and Lower Pliocene deposits. The total thickness of the Neogene sediments in this depression is more than 6000 meters (van Bemmelen, 1949). 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 Ciremai magmatic volcano. The north and west flanks of the volcano are slightly bulged due to draping overlying the diapirs made of plastic Pemali clay-shales and Early Pliocene plastic Kaliwangu clay marls.

In the post-eruptive phase of mud volcano, fluid migration through more permeable zones in the channel constructs small seeping features at the mud volcano surface. Sealed pathways to the surface turn the system back from open to closed physicochemical condition. This phase follows an eruptive phase and starts preparation for new paroxysm. In closed environment the elisional processes regenerate high water-saturation and overpressure of deep strata. Delicate equilibrium can be broken and new eruptive phase can be triggered by earthquake or tectonic reactivation, being followed with new cycle.

North Serayu Diapirs

North Serayu Depression is an eastward continuation of the Bogor Depression. It has been uplifted to become the North Serayu Anticlinorium/ Range. Geology of the North Serayu Range records the history of basin subsidence with deepwater sedimentation and ended with uplift (Satyana and Armandita, 2004).

The Eocene Worowari siliciclastic beds are the oldest sedimentary rocks in this area. These were transgressively covered by Early Miocene coarse conglomerates and quartzitic sandstones of the Lutut Beds and reef limestones called Sigugur Beds. Significant subsidence of the North Serayu Basin started thereafter. 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; Satyana, 2007). This sudden increase of orogenic relief has not only caused the gravitational sliding movements from south to north, but caused also that portions of the northern flank of the basin slid down toward the deepest part. The Mio-Pliocene succession of strata, filling the 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 (*Figures 4, 7*) show the presences of these diapirs (called as "Tegal disturb zone" by 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.

The North Serayu Zone is a good example of development of a depressional trough into a fold and thrust belt. The elevation of the depressional deposits caused gravitational reactions and the crest of the fold and thrust belt was pierced by diapirs and also volcanic magma. Gravitational tectogenesis interrupted the subsidence of the North Serayu depression at the end of Miocene by a revolutionary phase of gravitational tectogenesis. It is possible that this gravitational settling was promoted by an impulse of uplift of the adjacent belt (South Serayu Range), and concomitant further subsidence of the depression. This tectogenesis gave rise to the overthrusts converging towards the axis of subsiding trough. 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 kms to south of Purwodadi town, Central Java (*Figures 4, 6, 7*). Geologically, they are located at the boundary area between North Serayu and Kendeng Depressions.

There are some mud volcanoes in this area (Bledug Kuwu, Bledug Kesongo, Bledug Kropak, and several others). Kuwu is the largest of a number of active mud volcanoes in the area. The morphology is a set of vents in a flat area of quick-sand like clay, with a dried mud crust. Eruptions vary in frequency but generally occur more than once a minute, as a burst of warm gas spraying mud in all directions. It is assumed that mud flows more slowly and gradually, but is kept liquefied by the escaping fluids and gases (Burgon *et al*., 2002).

The morphology type is a combination of swamp-like area extending for large territory and crater muddy lake. The phase of mud volcano is eruptive to post-eruptive (stage 3 to 4). The presence of quick-sand indicates the subsidence of mud volcano area. The Kuwu mud volcano cluster covers about 45 hectares. The biggest vent can erupt materials as high as 5.3 meters with expelled mud reaching out for a diameter of about 9 meters. At the main Kuwu site the big mud volcano usually erupts four or five times a minute.

The salinity and turbidity of the mud volcanoes mean that there is no vegetation or animal life in the area of the eruptions. The gas expelled is non-flammable, reported as CO_2, with traces of H_2S. Local people commercially process the expelled water to extract salt for cooking. It is also reported that the mud sometimes carries rock fragments and fossils, but no details are available. Samples of the mud taken by Burgon *et al*. (2002) proved to be barren of any calcareous micro or nannofossils suggesting mildly acidic conditions.

The temperature of the big mud volcano ranges from 28-30ºC, while the small mud volcano is reported to have a temperature of only 15-16ºC, a surprising feature hard to explain or verify. Small mud volcano has more water content (lower density), which might account for its more frequent eruptions and lower temperature.

Seismic sections across these mud volcanoes show 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 along the disturbed zone indicating the stage-4 of mud volcano subsidence. The Bledug Kuwu disturbed zone is chaotic mixture of upward convex and concave reflectors indicating stage-3 to stage-4. The mother beds of diapirs and mud volcanoes are considered the lower part of Late Miocene Wonocolo shales. This is confirmed by fossil content of mud materials. However, seismic sections show that the source of mud may also come from Early Miocene Tuban shales. Some diapirs also occur in this area, they are generally below the top of Wonocolo Formation. Folds in this area are considered to form relating to underlying diapirs as suggested by some seismic sections (*Figure 7*).

Sangiran Dome

Sangiran Dome is located 12 kms to the north of Surakarta/ Solo city (Central Java) (*Figures 4, 7*). 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). Almost all modern (Pleistocene-Recent) subduction-related andesitic volcanoes are situated in this zone. Average height of the major peaks is 3000 meters.

The Sangiran Dome is a unique feature in Javanese geology. It is set on the southern margin of an area of intense folding and faulting (the Kendeng Zone) where structures are dominantly east-west in orientation and elongation, yet it is a dome with, if anything, slightly northern elongation (Lunt *et al*., 1989).

The hilly area around Sangiran exhibits some excellent outcrops of the Late Pliocene and Pleistocene of the so- called Central Depression (Solo zone, Ngawi Subzone) of Java. Good examples of young shallow marine, lacustrine, fluvial and volcanic deposits like lahars and tuffs can be studied. Other 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 early of 1900s for its rich hominid and vertebrate fossil faunas. The Sangiran location was the second site where Homo erectus fossils were found in the eastern Java, after the river section at Trinil, 50 kilometers to the east. It remains one of the most active sites for Plio-Pleistocene research and is also an excellent location to study fluvial and volcanic sedimentation.

Structurally the area is a dome, somewhat elongated in NNE-SSW direction. Structuring is very young (0.5 Ma or younger – Kadar *et al*., 1989). Van Bemmelen (1949) considered its origin as compressive 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. Itihara *in* Watanabe & Kadar (1985) 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 dome shape and presence of several small saline seeps 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 the upward piercement.

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. Reworked Pliocene deep-water marine microfauna are locally abundant in the non-marine Pucangan and Kabuh Formations, probably Kendeng zone erosional products. The andesitic volcanic clasts in the Kabuh and Notopuro Formations must have had a southern origin.

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

LUSI and Other Mud Volcanoes in East Kendeng Zone

An unexpected eruption of mud and fluids took place on 29th May 2006 in the Porong area, Sidoarjo, East Java (*Figures 4, 6, 7*). The eruption site was named LUSI (abbreviation of “Lumpur Sidoarjo” or Sidoarjo mud). Based on the characteristics of eruption and related geologic data, LUSI was concluded as eruption of mud volcano. The eruption is still taking place at the time of this writing (March 2008). The volumes of erupted mud increased from the initial 5000 m^3/day in early stage to 120,000 m^3/day in August 2006 and peaked to 170,000 m^3/day in September 2006 and reached the record-high level of 180,000 m^3/day in December 2006 (Mazzini *et al.*, 2007). LUSI was still active in

December 2007 expelling more than 80,000 m^3/day. As of December 2007 the total volume of expelled mud was estimated at 1 billion cubic feet, covering an area of 2.5 square miles, burying eleven villages and displacing at least 16,000 people. Transportation and power transmission infrastructure has been damaged extensively in the area. It is expected that the mud eruption will last for years to come and the area will experience a significant depression, forming a large caldera.

LUSI is one of numerous mud volcanoes in the eastern part of the Kendeng Zone/Depression. Mud volcanoes occur at many locations in the Kendeng Zone from Bledug Kuwu at the western border of the zone to the submarine mud volcanoes in the Madura Strait. Other recognized mud volcanoes close to LUSI (variably active, extinct, or dormant) are Porong, Kalang Anyar (Sidoarjo), Gunung Anyar (near Surabaya), Socah (Bangkalan, Madura), Wringin Anom (border of Gresik-Mojokerto), Semolowaru, Pulungan, and Sedati (Sidoarjo). Based on historical chronicles, folklore, and geologic data, recent paper by Satyana (2007) elaborated the presence of mud volcanoes complex erupted in historical time during the periods of Jenggala and Majapahit Kingdom in Indonesia (12^{th}-15^{th} 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 kms.

The Kendeng Zone is one of the youngest tectonic features in the eastern Java area. It was formed virtually at the early to late Pliocene (Lunt *et al*., 1996). It was part of a continuously subsiding basin from Miocene to the end of the middle Pleistocene. Late Miocene and older sediments in the Kendeng Zone are typically thick, interbedded mudstones and volcaniclastic sands. The marls and limestones of the Lower and Upper Kalibeng Formation were deposited in almost entirely marine environment during the Pliocene. At the time, volcanic activity probably began in the volcanic arc to the south (Wilis and Lawu volcanoes). This activity influenced the western part of East Kendeng Zone at the beginning of the Pleistocene. Here early Pleistocene Pucangan volcaniclastic sediments conformably above the Upper Kalibeng. Above this in conformable contact occur volcanic sandstones of the middle Pleistocene Kabuh and then the Notopuro Formation. During the early Pleistocene, marine blue clays of Pucangan were deposited in the east where finally volcanic deposits prograded (Duyfjes, 1936). The volcanic material was initially deposited in a marine environment in the west, but filled the basin very fast, so that sediment input near the volcanic centers soon exceeded the accommodation. In the east, where volcanic sediments arrived later, the volcaniclastic input was not sufficient to fill the basin until the late Pliocene.

The gravity data of the Kendeng Zone shows strongly negative anomalies indicating considerable depth to the basement in the Kendeng Zone. The Kendeng Zone is the deepest part of the Java's depression from Bogor-North Serayu-Kendeng-the Madura Strait. The Kendeng Zone is strongly folded and sometimes heavily faulted in the western part. Structuring is very recent and is probably still active. The sudden change of the Brantas River in the time of King Airlangga (11^{th} century) was due to the Recent deformation of fold underlying the river (Satyana, 2007). Fold axes in this area are oriented in E-W direction; an indicator that the adjacent and parallel volcanic chain is, at least in part, is responsible for compression. In the east, south of Surabaya where numerous mud volcanoes occur, the folds are nearly lost under recent alluvium and even Pleistocene rarely crops out.

The Kendeng Depression/Zone is the best elisional basin in Indonesia therefore, numerous mud diapirs and mud volcanoes occur here. Young tectonic feature, subsided basin, compressed, very thick young sediments deposited rapidly in relatively short period, and thermally significant due to nearby volcanic arc make the Kendeng Depression to be elisional. High sedimentation rate initiated during Upper Miocene – Early Pliocene time causing deposition of a very thick highly overpressured sedimentary succession. Clayey and silty sediments interbedded with sand beds contain great amount of fluids. The presences of overpressured sediments, less dense plastic shale succession underlying more dense beds and saturated with the fluids, and high tectonic activity favors the mud diapirs and mud volcanoes development in the region. Mud diapirism and mud volcanism apparently plays important role in the regional geology of the area. They also critical in the formation of folds at shallow depth. Seismic sections show that many folds in the Kendeng Zone are cored by diapirs.

Presently erupting-LUSI mud volcano provides good opportunity to know the origin of mud volcanoes in the Kendeng Depression. All other active, extinct, or dormant mud volcanoes in the Kendeng Depression might occurred several hundreds, thousands, or several million years ago. Historical chronicles (Kitab Pararaton – Book of

Kings) during the Majapahit Kingdom from 13th to 15th century show the occurrences of natural disasters may be interpreted as mud volcanoes eruption (Satyana, 2007). The main Kendeng Depression has existed since 5 Ma, it has been compressed since then. It can be expected that mud volcanoes in the Kendeng Depression were triggered by tectonics and seismicity as most mud volcanoes in the world originated. LUSI mud volcano, began erupting on 29 May 2006 however, can not provide straightforward explanation on its origin due to possibility that LUSI may relate to drilling of exploration well located 200 meters away from LUSI.

The origin of LUSI mud volcano has been a matter of debate. Three trigger mechanisms have been proposed : (1) tectonic re-activation by the May 27th 2006's Yogyakarta earthquake, (2) well drilling operations (Banjar Panji-1 well by Lapindo Brantas) in progress near the initial eruption site at the time of the eruption, and (3) a combination of earthquake and drilling operations. Earthquake trigger was argued among others by Mazzini *et al*. (2007) and Svensen *et al*. (2007). Drilling operations trigger was argued among others by Davies *et al.* (2007). Earthquake trigger was challenged by Brumm *et al*. (2007). Mori *et al.* (2007) indicated that the trigger of LUSI may a combination of both the 27th May 2006's Yogyakarta earthquake and drilling of Banjar Panji-1. The controversy on the origin of LUSI has complicated the legal aspect of LUSI in the court.

Based on geochemical and field results, Mazzini *et al*. (2007) proposed a mechanism that LUSI mud volcano eruptions started following the May 27th 2006's Yogyakarta earthquake due to fracturing and accompanied depressurization of > 100º C pore fluids from > 1700 meters depth. This resulted in the formation of a quasi-hydrothermal system with a geyser-like surface expression and with an activity influenced by the regional seismicity. Brumm *et al.* (2007) challenged this idea since the earthquake is too distant and too small to trigger the LUSI eruption, and plotting of LUSI to cross plot of Manga and Brodsky (2006) which is a statistic cross plot between occurred earthquakes and related liquefaction and mud volcanoes show that LUSI plotting is out of general trend. Brumm *et al.* (2007) also argued that in the past 35 years, tens to hundreds of other earthquakes caused stronger ground shaking at the site of the eruption but why did not trigger an eruption. Davies *et al.* (2007) suggested that LUSI eruption appears to have been triggered by drilling of overpressured porous and permeable limestones at depths of ~2830 m below the surface. They proposed that the borehole provided a pressure connection between the aquifers in the limestones and overpressured mud in overlying units. As this was not protected by steel casing, the pressure induced hydraulic fracturing, and fractures propagated to the surface, where pore fluid and some entrained sediment started to erupt.

It is not the aim of this paper to examine in detailed the mechanism responsible triggering the LUSI mud volcano. However, there are facts indicating that the Yogyakarta earthquake was significant triggering the LUSI mud volcano eruption. The facts are hereafter : (1) drilling operations sequence show that partial loss of drilling mud in Banjar Panji-1 well occurred ten minutes after the earthquake, (2) total loss in the well occurred after several the earthquake's aftershocks, (3) mud erupted two days after the earthquake, (4) early eruptions of hot mud and salt water occurred in several localities forming the SW-NE trend parallel with the main structural trend of faults or fractures in this area, (5) mud eruption never expel from the well, it is 200 meters to the southwest of the well and engineering test showed that there is no communication between the site of mud eruption and the wellsite, (6) LUSI lies within major faults (Watukosek Fault) trending SW-NE from Penanggungan volcano to the Strait of Madura, the fault becomes the sites of extinct or dormant mud volcanoes of Kalang Anyar, Pulungan in Sidoarjo area, Gunung Anyar in Surabaya area, and Socah in Bangkalan, western Madura area, (7) the occurrence of a fracture in the wellsite hundreds meters long and tens of centimeters wide trending NE-SW a few days after the eruption (8) there was a decrease in gas flow rate at nearby Carat well at about the time of the Yogyakarta earthquake took place, (9) the Yogyakarta earthquake re-activated the Semeru volcano three days after the earthquake by increasing its surface temperature and erupting volcanic ash (NASA's Terra satellite data), (10) the Yogyakarta earthquake was recorded 34 seconds after the main shock in Ujung Pangkah waters to the northwest of Surabaya and its energy affected the seismic recording which was being surveyed at the area at the time of earthquake occurred in Yogyakarta, (11) the energy propagation of the earthquake was mainly eastward and northeastward as shown by the trend of its aftershocks and the areas affected, (12) regional satellite data show the presences of major faults and fractures from Yogyakarta to Sidoarjo area in a right-stepping pattern, (13) there is a positive correlation between mud eruption rates of LUSI and swarms of earthquakes measured 300 kms around the site, high rates followed occurrences of earthquakes, (14) recent deuterium isotope data of erupted water showing a mixing with static magmatic fluids from depth deeper than 20,000 feet, indicating the presence of deep basement faults or fractures within the site as the conduits, (15) the sudden bending of railway to south of the eruption site occurring after the May 27th earthquake is exactly at the crossing between the Watukosek Fault and the railway and in line with the bending of the Porong River, confirming that the fault was re-activated by seismic activity.

On the other hand, argument of Davies *et al*. (2007) based on the assumption that Banjar Panji-1 total depth in porous Kujung aquifer limestone is not supported by the well data. Well logging data show no direct evidence that the Kujung Formation has been intersected in the borehole. The deepest cuttings did not reveal the presence of any carbonate, and calcimetry data indicate only 4 % calcite with no significant increase or changes. The presence of Oligo-Miocene Kujung Formation in this area is also mis-conception. Based on the available data and facts explained above, the idea that LUSI eruption is triggered entirely by drilling is inconclusive. Earthquake-related tectonic re-activation of fault where the well is located and the elisional condition which has been critical for mud volcanism in the area may play significant role for the birth of LUSI mud volcano.

In terms of morphology, LUSI mud volcano is of the type of combination between swamp-like area and crater muddy lake. It is obviously stage-3 development (on eruptive phase). Similar type of morphology is shown by Kalang Anyar mud volcano. Whereas, Pulungan, Gunung Anyar, and Socah mud volcanoes show morphology of classic conic volcanic edifice. The stages of those mud volcanoes are as follows : Kalang Anyar (dormant, -stage 3 to 4), Pulungan (extinct –stage 4), Gunung Anyar (extinct –stage 4), Gresik (dormant-stage 3), Socah (dormant –stage 3 to 4), Porong (extinct –stage 4). Collapse of mud volcano crater of Porong is obviously shown by successive concave horizons (*Figure 7*).

Submarine Mud Volcanoes in the Madura Strait Depression

The Madura Strait is an offshore extension of the Kendeng Depression. On the basis of structural style and the tectonic events, Widjonarko (1990) divided the Madura Strait block into five structural domains : wrench domain, slide domain, western basinal domain, eastern basinal domain, and southeastern fault block domain. Wrench and slide domains bound the Madura Strait to the Madura-Kangean High in the north. Southeastern fault block becomes the southern border of offshore Madura Strait. The main parts of the Madura Strait where mud diapirs and volcanoes exist are composed by western and eastern basinal domains.

The Madura Strait Depression or Sub-Basin is one of the two deepest and thickest basins in Indonesia, the other is the Kutei Basin. In western basinal domain, very rapid sedimentation since the Late Miocene time resulted in the development of more than 3000 meters of Plio-Peistocene section. Eastern basinal domain is similar to western domain, the only difference is that the eastern basinal domain began to subside in the late Oligocene – early Miocene, much earlier than the western domain.

Stratigraphy of the Madura Strait started in Middle Eocene time by deposition of transgressive clastics unconformably on top of pre-Tertiary basement. The deposition was terminated by a local uplift at the end of Eocene time. Subsidence during the Oligocene resulted in deposition of deep marine sediments. An uplift at the end of the Oligocene resulted in a regional unconformity throughout the basin. During the Early Miocene time the rapid subsidence resulted in deposition of deep marine sediments in the area. In the mid-Late Miocene time, the basin was filled and another uplift took place. After a short subsidence to the end of Late Miocene, sedimentation interrupted again by an uplift in Early Pliocene time. Rapid subsidence in the late Pliocene time characterized by the deposition of overpressured thick clays. The area subsided again into a shallow marine environment after the Plio-Pleistocene regional uplift (Widjonarko, 1990).

In the Madura Strait area, east-west trending left-lateral wrench faulting triggered mobilization of Miocene basinal shales during the Plio-Pleistocene, resulting in a series of shale diapirs. Further south, the impact of on-going subduction along the Java Trench becomes increasingly significant and structures are dominated by north-directed thrusting, which may be independent of basement faulting.

Very thick young sediments deposited rapidly and compressed initiated elisional system in the Madura Strait depression. Mud diapirs and mud volcanoes occur numerously in the basin (*Figures 4, 7*).

Recently acquired seismic data in this area obviously show the presences of mud diapirs and submarine mud volcanoes in Pliocene to Pleistocene sections. Classic conic volcanic edifice typed-submarine 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 be observed in some seismic sections.

PETROLEUM IMPLICATIONS

Intensive study of mud volcanoes underwent acceleration in the middle of 20^{th} century when a relationship of mud volcanism to petroleum system development has been postulated based on the fact that mud volcanoes are often met in oil and gas regions (Akhmanov and Mazzini, 2007). Mud volcanoes may have a spatial and genetic relationship with oil and gas fields and thus may provide evidence of petroleum potential (Guliyev and Feizullayev, 1997). Sediments and fluids expelled from these features provide useful information on the geology and petroleum potential of deep sedimentary basins. Mud volcanoes are often associated with large petroleum basins (e.g., Azerbaijan, the Gulf of Mexico) where they expel thermogenic hydrocarbons enriched in C_{2+} gases. Mud volcanoes documented outside of large petroleum basins (e.g., Norwegian Sea, Copper River basin) expel mainly bacterial methane or CO_2 (Milkov, 2003).

Since mud diapirs and mud volcanoes moved buoyantly due to gas-content, the importance to petroleum exploration of a causal relationship between methane generation and under-compacted shales, shale diapirs, and mud volcanoes, is principally that these features are indicative of areas or intervals where gas or hydrocarbons have been, or are, actively originating. Because of their association with hydrocarbon gas, and frequently with oil seeps, mud-volcano areas particularly attracted early petroleum exploration drilling. Some of this drilling resulted in abundant oil and gas production; e.g., Baku and adjacent parts of the South Caspian Basin (Hedberg, 1974). Sands underlying or overlying an under-compacted shale body reasonably may be supposed to have received hydrocarbons generated in a border zone below or above the under-compacted shale; and sands laterally interfingering with the under-compacted shale should be in a particularly favorable position for such accumulations.

Petroleum has been discovered and produced for more than 100 years in areas where diapirs and mud volcanoes occur in Bogor-North Serayu-Kendeng-Madura Strait Zone (*Figures 8, 9*). Prolific oil seeps occur in the eastern part of the Bogor Zone and the western part of the North Serayu Zone between area of Mount Ciremai and the Pemali River – Cicabe, Cisenti, Cikaro, Sahang, Cibabakan seeps (Hetzel, 1935; ter Haar, 1935). Ciuyah mud volcano and some mud diapirs occur in this area. These oil seeps associate with the Pliocene Pemali Formation or its equivalent (Lunt *et al.*, 2004). The first well drilled for oil in Indonesia by plantation manager Jan Reerink in 1872 (van Bemmelen, 1949) was from prolific seeps in Pemali Beds near Maja which are still active today (Lunt *et al*., 2004).

In the North Serayu Zone, van Bemmelen (1949) reported a number of oil seeps and one oil field. The seeps occur in the areas of Karangkobar, Bawang and Subah, Klantung and Sodjomerto, Kaliwaru, West of Mount Ungaran (many seeps), and east of Mount Ungaran. Exploratory drillings had been carried out by Dutch oil companies since early 1900s near the seeps but with no success. However, in Klantung and Sodjomerto, drillings were success and discovered the Cipluk Field. Pertamina recently re-worked the Klantung structure. During 35 years of production, an average yearly production of Cipluk Field was a few hundreds of tons (van Bemmelen, 1949). Cipluk Field is formed by a faulted anticline of expected Late Miocene Banyak volcaniclastic sandstones. The oils are considered to be sourced from shales of the underlying Merawu Beds or Eocene aged shales of Worowari (equivalent to Ngimbang shales in the East Java Basin) which charged the trap through faults as conduits. Interbedded marls of the Cipluk Beds provide the vertical/lateral sealing. (Satyana and Armandita, 2004). The seeps share some place with mud diapirs formed in subsided North Serayu therefore, the diapirs are considered to affect the formation of trap and maturation of source rocks.

Kendeng Zone and two physiographic zones to the north of it, the Randublatung and Rembang Zones (van Bemmelen,1949) and continues into the Madura Strait compose prolific petroleum provinces of the East Java Basin (*Figures 3, 8*). This area is also rich in mud diapirs and mud volcanoes. The implication of mud diapirism to the petroleum geology of this area was firstly discussed by Soetarso and Patmosukismo (1976) and Baciou (1981 – *unpublished*). They proposed that structures in the East Java Basin consist of two types : normal structures and diapiric structures. The diapiric structures are generally small, narrow and elongated east-west. The diapiric structures have the following characteristics :

- structural deformations increase in the younger formations,
- thickening of strata over the anticlinal crests and thinning in the synclines,
- a few or no reflections in the core of the anticlines because of mass material (shales), and
- a higher geothermal gradient than in the normal structures.

Almost all of oil fields in the basin were considered as diapiric structures. However, a study by Soeparyono and Lennox (1989) argued that anticlines either related to wrench faulting or not are dominant structural traps forming the fields, the oil fields in the western East Java Basin (Nglobo-Semanggi trend) are mainly basement-involved, and oil fields in the eastern East Java Basin (Kawengan-Tambakromo trend) are detached. Pertamina and Beicip (1985) documented several types of traps in the East Java Basin including : diapiric structures, en echelon folding, domal structures, draping over basement highs, wrench-related drag folding, growth fault anticlines, reefal build-ups, and erosional channels.

Shale or mud movements and differential compaction occurred during the climax of the compressional Plio-Pleistocene period. The structural deformations are long, narrow, disharmonic anticlines with bulging of the incompetent middle Miocene and Pliocene “OK” and “GL” Formations (Tawun, Ngrayong,Wonocolo, Ledok, Mundu) (*Figure 9*) over the less ductile Kujung or Prupuh limestones. In addition to the purely compressional stress resolution effects, the diapirism may often be related to basement wrench movements, reverse faulting, and even flower structures (Pertamina and Beicip, 1985). The diapiric structures are observed commonly in the Kendeng, Randublatung, and South Rembang zones in onshore East Java and the Madura Strait. The oil and gas found in younger reservoirs (Pliocene Mundu and younger) is believed to be associated with shale diapirism which induced higher temperature and cooked the underlying Tawun-Wonocolo source rocks whilst simultaneously forming the traps.

Since the gradient geothermal in diapirism is uplifted, in the diapiric structures, the top of oil window is also uplifted, oils was generated recently coeval with the occurrence of diapirism in Plio-Pleistocene, and in shallow layers. Because the generation of oil is recently, the migration of oil is firstly in the upper structures. Diapirism is directly responsible for the accumulation of hydrocarbons and maturation of source rocks (Soetarso and Patmosukismo, 1976; Baciou, 1981 – unpublished).

CONCLUSIONS

1. Mud diapir is an intrusion of relatively mobile mud/shale mass that intrudes into pre-existing strata caused by buoyancy and differential pressure. When mud diapir breaches the surface due to accommodation by reactivated faults, fast migration of depressurized materials occur resulting in mud volcano. It is a more or less violent eruption or surface extrusion of watery mud which almost invariably is accompanied by methane gas.

2. Mud diapir and mud volcano occur in “elisional” basin where the following factors exist : stable tectonic submergence, rapid deposition of thick young sediments, presence of plastic strata in the subsurface, fluid overpressure and under-compacted sediments, enough gas supply and high hydrocarbon potential, production of diagenetic waters from buried clayey series, compressional setting-numerous faults-high seismicity, and possibly high geothermal gradient.

3. The Bogor-North Serayu-Kendeng-Madura Strait Zone was an axial depression of Java to Madura into which Miocene to Pleistocene sediments were rapidly deposited and undercompacted. Due to located at the plate convergent boundary, the depression has been compressed and uplifted since Plio-Pleistocene time and closed to the high geothermal gradient of the nearby volcanic arc. The Bogor-North Serayu-Kendeng-Madura Strait Zone represents good elisional basin where numerous mud diapirs and mud volcanoes are found along this zone.

4. The origins and natures of mud diapirs and mud volcanoes of Java to Madura area are basically similar. The origins were related to factors in elisional system, the surface morphology of mud volcanoes are commonly

swamp-like area, crater muddy lake, classic cone edifice, and collapsed synclinal depression. The development stages include stage-2 (pre-eruption), stage-3 (syn-eruption), and stage-4 (post-eruption). The mud diapirs and mud volcanoes examined include : Ciuyah mud volcano (Kuningan, eastern West Java), North Serayu diapirs (northern Central Java), mud volcanoes of Bledug Kuwu, Bledung Kesongo, Bledug Kropak (southern Purwodadi, Central Java), mud diapir and mud volcano of Sangiran Dome (Central Java), LUSI (erupting mud volcano, Sidoarjo, East Java), Porong, Kalang Anyar, Pulungan (Sidoarjo), Gunung Anyar (Surabaya), Gresik, Socah (Bangkalan, Madura), and submarine mud diapirs and mud volcanoes in the Madura Strait.

5. Mud diapirs and mud volcanoes may have spatial and genetic relationship with oil and gas fields and thus may provide evidence of petroleum potential. Oil and gas seeps and producing oil and gas fields of Java to Madura partly occur in same areas with mud diapirs and mud volcanoes of Bogor-North Serayu-Kendeng-Madura Strait Zone. Here mud diapirism and mud volcanism have implied the petroleum system especially in maturing the source rocks and generating diapiric structural traps.

ACKNOWLEDGMENTS

We acknowledge the Management of BPMIGAS for support, permission and sponsorship to publish and present this paper. We thank Soffian Hadi and Handoko (BPLS) for updated data on LUSI. We thank Indra Prasetya (Pertamina) for providing seismic sections showing the presence of diapirs in the North Serayu Zone. We thank Waluyo (Pertamina) for sharing ideas on development stages of mud diapirs and mud volcanoes. We thank Bambang Istadi and Agung Darmoyo (both from EMP) for sharing some data and discussions on mud volcanoes in East Java. We thank John Bates (formerly at Santos) for sharing data on mud diapirs and mud volcanoes in the Madura Strait. We acknowledge the IPA technical committee and reviewer/s for accepting this paper to be published and improving the paper manuscript.

REFERENCES

Akhmanov, G.G. and Mazzini, A., 2007, Mud volcanism in elisional basin, International Symposium on LUSI, BPPT-IAGI-LIPI, Jakarta, February 2007.

Aliyev, A., Gasanov, A., Bairamov, A., 2003, Mud volcanism and earthquakes, Advanced Research Workshop "Mud Volcanism, Geodynamics, and Seismicity, May 20-22, 2003, Baku, Azerbaijan.

Baciou, T., 1981, A briefly synthesis and evaluaton of the oil prospects in the Northeast Java Basin, Exploration Pertamina Unit EP III, Jakarta, unpublished.

Bagirov, E., Baganz, O.W., Krenov, M.B., 2003, Dynamics of mud diapirs in the South Caspian Basin and its influence on the petroleum system, AAPG Annual Meeting, May 11-14, 2003, Salt Lake City.

Brumm, M., Manga, M., Davies, R.J., 2007, Did an earthquake trigger the eruption of the Sidoarjo (LUSI) mud volcano ?, American Geophysical Union, Fall Meeting, December 2007.

Burgon, G., Lunt, P., and Allan, T., 2002, IPA Field trip to Eastern Java, Indonesian Petroleum Association, Jakarta.

Davies, R., Swarbrick, R., Evans, R., Huuse, M., 2007, Birth of a mud volcano : East Java, 29 May 2006, GSA Today, 17, p. 4-9.

Duyfjes, J., 1936, The geology and stratigraphy of the Kendeng area between Trinil and Surabaya (Java) (in German), De Mijningenieur, vol. 3, no. 8, August 1936, p. 136-149.

Giovanni, M., 2003, Geology, geophysics and geochemistry of mud volcanoes : introduction, Advanced Research Workshop "Mud Volcanism, Geodynamics, and Seismicity, May 20-22, 2003, Baku, Azerbaijan.

Guliyev, I.S., Feizullayev, A.A., 1997, All About Mud Volcanoes, Nafta Press, Baku, Azerbaijan.

Hedberg, H.D., 1974, Relation of methane generation to undercompacted shales, shale diapirs, and mud volcanoes, AAPG Bulletin, 58, p. 661–673.

Hetzel, W.H., 1935, Explanation of sheet 54 (Majenang), geologic map of Java, scale 1 : 100,000 – in Dutch, Geological Survey of Indonesia, Bandung.

Kadar, D., Mey, P.H., Siemers, C.T., Dolan, P.J., 1989, IPA geological field trip Central Java, Indonesian Petroleum Association.

Kartanegara, L., Uneputty, H., and Asikin, S., 1987, Tatanan stratigrafi dan posisi tektonik Cekungan Jawa Tengah Utara selama zaman Tersier, Proceedings Indonesian Association of Geologists (IAGI), 16th Annual Convention, Bandung.

Kholodov, V.N., 1983, Postsedimentary Transformations in Elisional Basins (example from Eastern Pre-Caucasus) (in Russian), 150 ps.

Kopf, A.J., 2002, Significance of mud volcanism, Rev. Geophysics, 40, p. 1-52.

Lunt, P., Netherwood, R., Huffman, O.F., 1998, IPA field trip to Central Java, Indonesian Petroleum Association.

Lunt, P., Schiller, D., Kalan, T., 1996, East Java Geological Field Trip, Indonesian Petroleum Association, Post-Convention Field Trip, 1996.

Lunt, P., Burgon, G., Baky, A., 2004, The Pemali beds, Central Java, Bulletin of the Geological Research and Development Centre (GRDC), Geological Survey of Indonesia, Bandung.

Manga, M. and Brodsky, E., 2006, Seismic triggering of eruptions in the far field : volcanoes and geysers, Annu. Rev. Earth Planet. Sci, 34, p. 263-291.

Mazzini, A., Svensen, H., Akhmanov, G.G., Aloisi, G., Planke, S., Sørenssen, M., Istadi, B., 2007, Triggering and dynamic evolution of the LUSI mud volcano, Indonesia, Earth and Planetary Science Letters, 261 (2007), p. 375-388.

Milkov, A.V., 2000, Worldwide distribution of submarine mud volcanoes and associated gas hydrates, Marine Geology, 167, p. 29–42.

Milkov, A.V., 2003, Global distribution of mud volcanoes and their significance as an indicator of active petroleum systems, a source of methane in the atmosphere and ocean, and a geohazard, Advanced Research Workshop "Mud Volcanism, Geodynamics, and Seismicity, May 20-22, 2003, Baku, Azerbaijan.

Mori, J., Fukushima, Y., Kano, Y., Hashimoto, M., 2007, Some geophysical observations and interpretations of LUSI, International Symposium on LUSI, BPPT-IAGI-LIPI, Jakarta, February 2007.

Natawidjaja, D.H., 2007, Active tectonics of Java : relationships to mud volcanoes ? International Symposium on LUSI, BPPT-IAGI-LIPI, Jakarta, February 2007.

Pertamina and Beicip, 1985, Hydrocarbon Potential of Western Indonesia, Jakarta.

Satyana, A.H. and Armandita, C., 2004, Deep-Water play of Java, Indonesia : regional evaluation on opportunities and risks, Proccedings International Geoscience Conference of Deepwater and Frontier Exploration in Asia and Australasia, Indonesian Petroleum Association (IPA) and American Association of Petroleum Geologists (AAPG), Jakarta, p. 293-320.

Satyana, A.H., 2007, Geologic disaster in demise of Jenggala and Majapahit Kingdom : hypothesis on historical mud volcanoes eruption based on historical chronicles, folklore, LUSI mud volcano analogy, and geologic analysis of Kendeng-Delta Brantas depression (in Indonesian), Proceedings Joint Convention Bali 2007- HAGI, IAGI, and IATMI, 14-16 November 2007.

Soeparyono, N. and Lennox, P.G., 1989, Structural development of hydrocarbon traps in the Cepu oil field, Northeast Java, Indonesia, Proceedings Indonesian Petroleum Association (IPA), 18th Annu. Conv., p. 139-156.

Soetarso, B. and Patmosukismo, S., 1976, The diapiric structures and its relation to the occurrence of hydrocarbons in Northeast Java Basin, Proceedings Indonesian Association of Geologists (IAGI), Annual Convention.

Svensen, H., Mazzini, A., Akhmanov, G.G., Aloisi,G., Planke, S., Sørenssen, A., Istadi, B., 2007, Triggering and dynamic evolution of the LUSI mud volcano, Indonesia, American Geophysical Union, Fall Meeting, December 2007.

ter Haar, C., 1935, Explanation of sheet 58 (Bumiayu), geologic map of Java, scale 1 : 100,000 – in Dutch, Geological Survey of Indonesia, Bandung.

van Bemmelen, R.W., 1949, The Geology of Indonesia, Vol. 1A, Gov. Printing Office, The Hague, 732 ps.

Watanabe, N., and Kadar, D. eds., 1985, Quaternary geology of the Hominid fossil bearing formations in Java; Report of the Indonesia-Japan Joint Research Project, CTA-41, 1976-1979, Geological Research and Development Centre, Bandung.

Widjonarko, R., 1990, BD field – a case history, Proceedings Indonesian Petroleum Association (IPA), 19th Annu. Conv., p. 161-182.

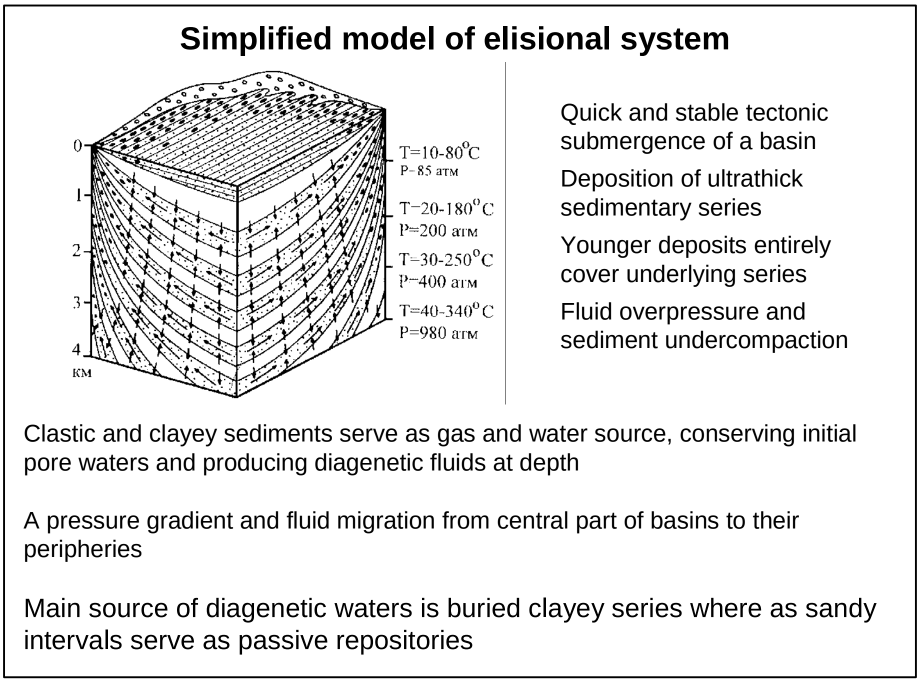

Figure 1 – Environmental conditions for the occurrences of mud diapirs and mud volcanoes are called elisional basins. They are characterized by relatively quick and stable tectonic submergence resulted in deposition of ultrathick (up to 15 km) sedimentary series. Positive tectonic movements, if happened, are very recent. With a depth of burial it causes fluid overpressure and sediment undercompaction and, often, a pressure gradient and fluid migration from central part of basins to their peripheries. (after Akhmanov and Mazzini, 2007)

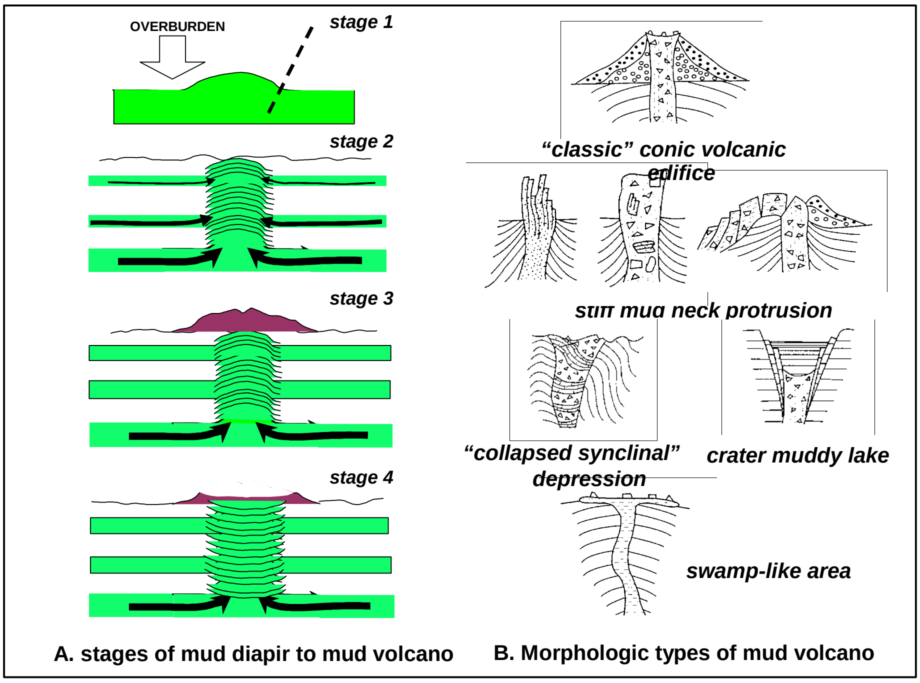

Figure 2 – A. Development of mud diapir to mud volcano. Stage 1 is embryonic phase, stage 2 : diapiric phase, stage 3 : erupting mud volcanism phase, stage 4 : post-eruptive/ collapse phase. (after Waluyo, 2007-*unpublished*). B. Morphological types of mud volcanoes based on field studies in Caucasus, Crimea, Turkmenistan. It is applicable worldwide. (Akhmanov and Mazzini, 2007).

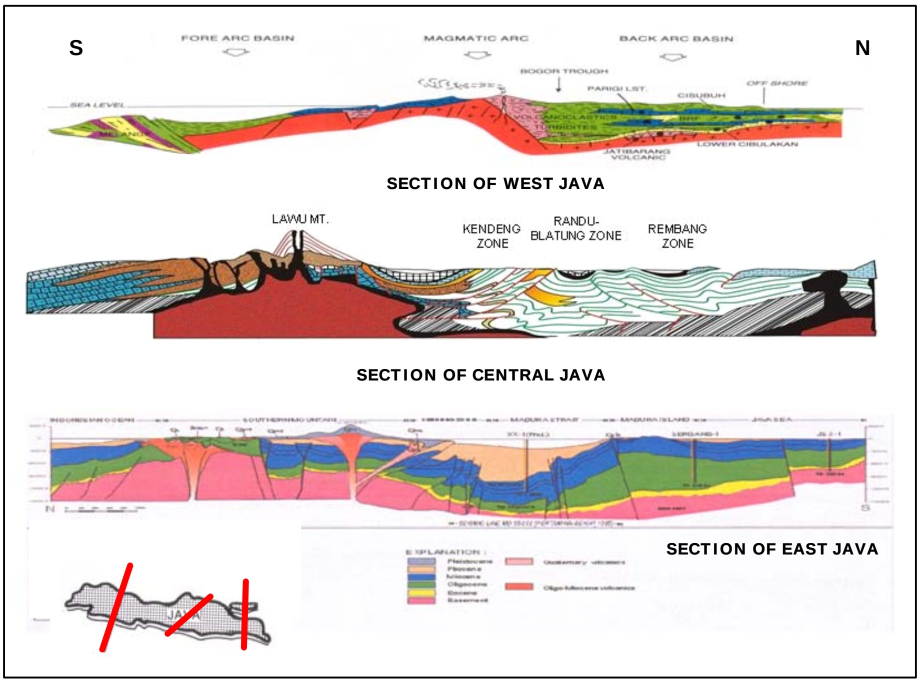

Figure 3 – Schematic section across Java from the Indian Ocean to the Java Sea showing the presence of axial depression including : Bogor Trough in West Java, North Serayu-Kendeng-Randublatung in Central-East Java, and the Madura Strait in East Java. The depression becomes the main sites of mud diapirs and mud volcanoes. (section for Central Java is modified from van Bemmelen, 1949)

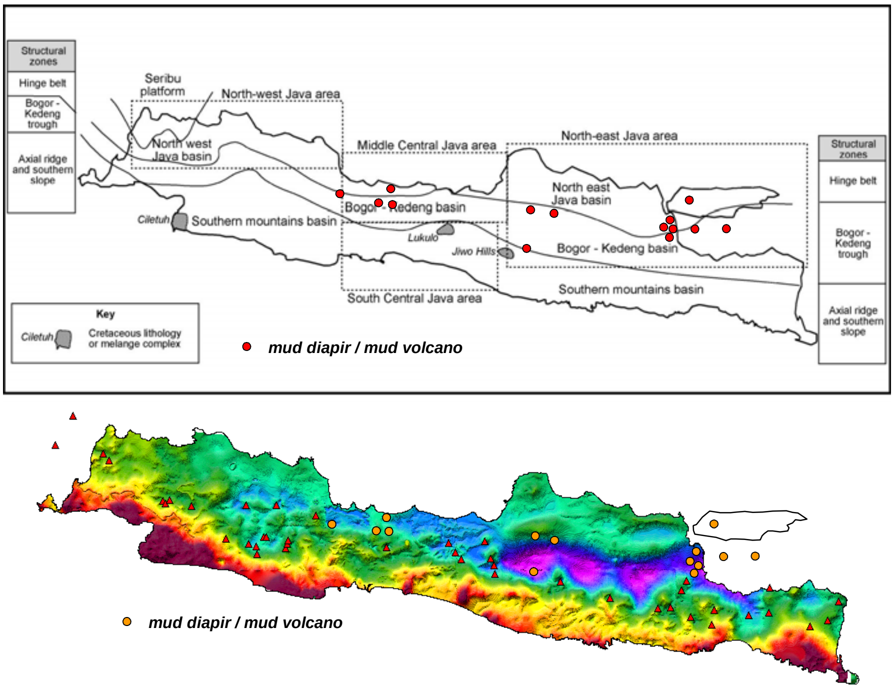

Figure 4 – Distribution of studied mud diapirs and mud volcanoes in Java to Madura. The name of mud diapir and mud volcano see figures 6 and 7. Most of the mud diapirs and mud volcanoes occur along the Bogor to Kendeng depression – the Java's elisional basin. Basemap of Java on below is gravity map.

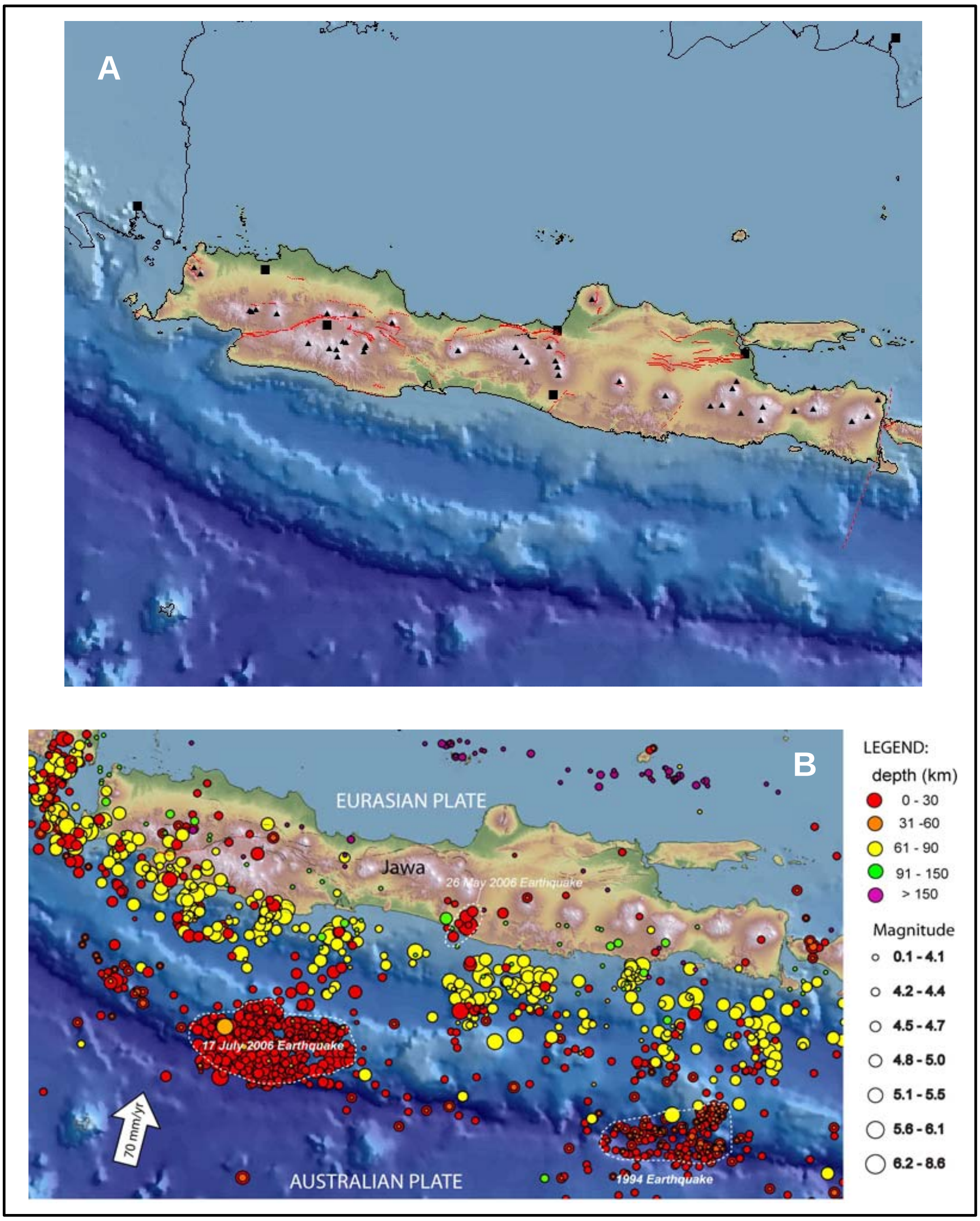

Figure 5 – A. Position of Java is frontal to the subduction of Indian oceanic crust to the south of Java. Red lines on Java onshore are active faults often to be re-activated.(after Natawidjaja, 2007) B. Seismicity of Java since 1973 (USGS data) showing that Java is earthquake-prone area. Recent active tectonics and seismicity favor mud diapirism and mud volcanism. Many mud volcanoes are located at re-activated faults.

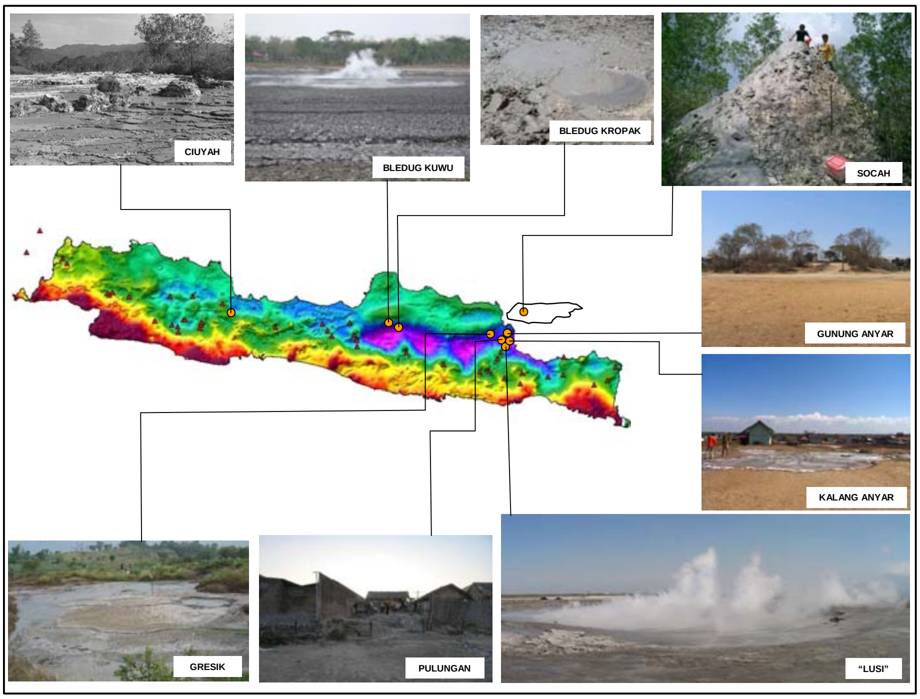

Figure 6 – Surface expression (morphology) of identified mud volcanoes in Java to Madura. The morphologic types include swamp like area (Ciuyah, Bledug Kuwu, Bledug Kropak, Gunung Anyar, Kalang Anyar, Pulungan, Gresik), crater muddy lake ("Lusi")and classic volcanic edifice (Socah).

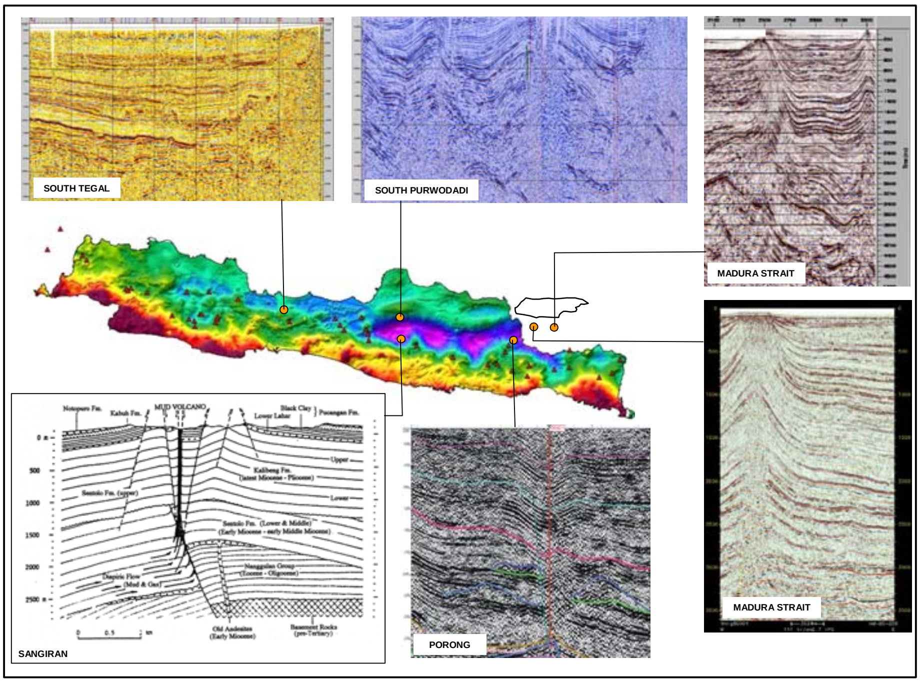

Figure 7 – Seismic characteristics of mud diapirs and mud volcanoes of Java to Madura. Shallow anticlines in Purwodadi area are cored by mud diapirs. Submarine mud volcanoes are observed in the Madura Strait. Porong mud volcano is stage-4 post eruptive phase forming caldera collapse structure. Mud diapir and mud volcano in Sangiran Dome transported basement rocks upward. (Sangiran Dome is after Watanabe and Kadar, 1985)

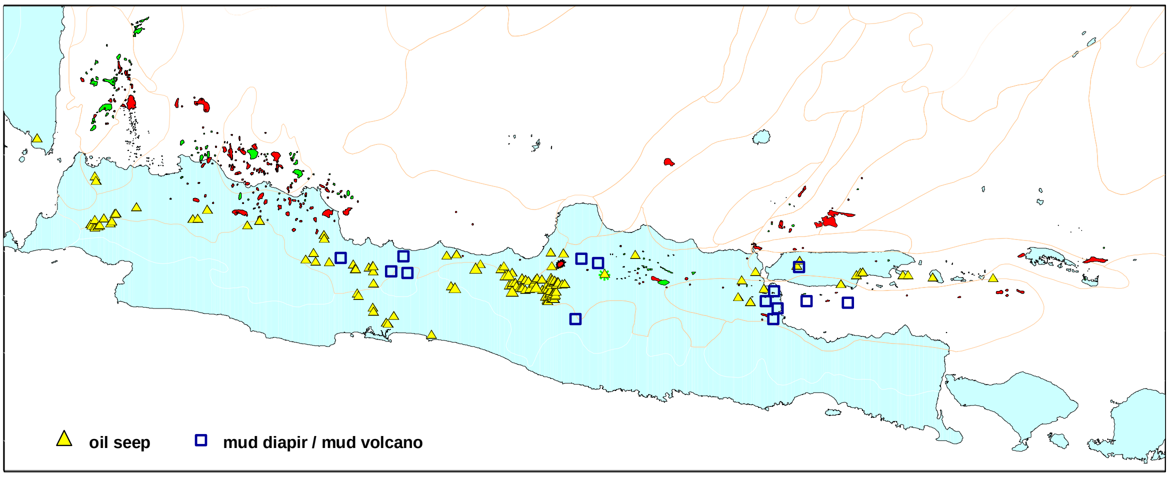

Figure 8 – Distribution of oil and gas fields and hydrocarbon seeps in Java to Madura area showing the same spatial occurrences with mud diapirs and mud volcanoes. The mud diapirs and mud volcanoes have affected some of petroleum system elements and processes in this area.

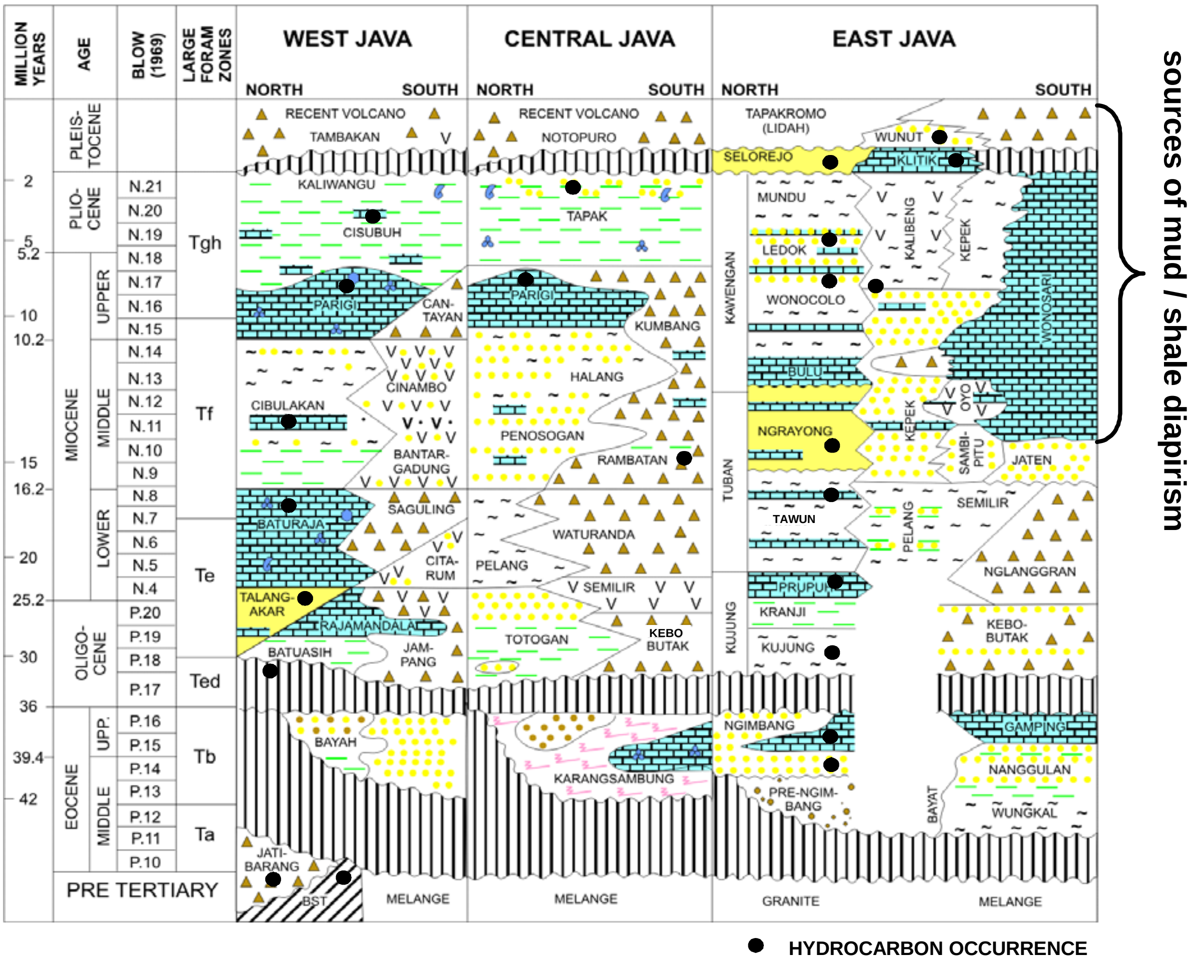

Figure 9 – Stratigraphy of West Java, Central Java, and East Java showing the occurrences of hydrocarbons in the reservoirs. The reservoirs occurred in mud/shale sequences at which mud diapirism and mud volcanism were sourced mainly from Middle Miocene to Pleistocene sediments.