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# Mud volcanoes in deep water of Andaman Forearc Basin

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***Summary***

*Mud volcanoes (MVs) are a natural phenomenon that has attracted geoscientists for a long time. They have lot of similarities in appearance to that of magmatic volcanism but widely differ in the origin. The term "mud volcano system" is coined to describe the set of structures associated with a constructional edifice (mud volcano) and feeder complex that connects the volcano to its source stratigraphic unit. Mud volcanoes are key features that reflect regional geological processes that are active in their place of occurrences. The majority of reported mud volcanoes occur at active plate margins which lead many authors to suggest that tectonic stress, mainly compressional, is the main driving mechanism for mud volcanoes. The Andaman Forearc basin is one such basin where occurrence of mud volcano is quite common. The Forearc basin of Andaman is situated along the obliquely converging boundary of the Indian plate and Burmese plate characterized by active tectonics. Important structural elements observed in the basin include transpressional faults and anticlinal structures (result of basin inversion). The interpretation of a 3D seismic survey from the study area helps in studying the structural elements, evolution and mapping of these mud volcanoes. These features are associated with high amplitude above a chimney of extremely chaotic seismic signature and data wipe out while their morphology is evident in RMS attribute map. Seismic data show that despite differences in form, mud volcanoes tend to have a 'Christmas-tree' structures interfingering with back ground sediments. Mud volcanoes always occur at the top of extrusive edifices that extend at least few kms down below, into the subsurface, occupying subsidence depressions developed above older strata.*

*In this study an attempt has been made to find out the role of mud volcanoes in petroleum systems of Andaman Forearc basin given the fact that they are often associated with petroleum seeps and has an intimate relationship with the petroleum reservoirs in the sedimentary basin. Apart from that, a model has also been proposed to explain their evolution within the basin.*

## Introduction

The deep water of Andaman Forearc basin always remains in news for being one of the future exploration locales for hydrocarbon exploration in India. The detail study of the 3D seismic data of the area within basin has revealed the presence of features interpreted to be of mud volcanoes. The Andaman- Nicobar island chain and associated basin is a part of large geotectonic unit that extends from Sumatra (Indonesian) Islands in the south to Myanmar (Burma) in the north. Numerous seabed anomalies were observed during early regional 2D seismic evaluations. They were generally characterized by positive topographic relief and very high seabed seismic amplitude above a vertical chimney characterized by partial to almost complete data wipe out. On seismic data, these anomalies always occur above deeper structural culminations. The seismic imaging associated with these features gives rise to ambiguity in their interpretation and consequently numbers of models were suggested for their formation. The basic objective of this paper is to present evidence supporting the interpretation that these features are mud volcanoes. Little has been published on mud volcanoes in deep water of Andaman Forearc. Earlier works on mud volcanoes are concentrated on onshore areas only. However, with the advent of the hydrocarbon exploration in vast deepwater area with improved 3D seismic data, it is now evident that mud volcanism do occur in the deep water of this basin. The basin has more than 5000m of thick sediments ranging in age from Cretaceous to Recent. Therefore, an attempt has been made to investigate the role of mud volcanoes in petroleum systems of Andaman in the light of an envisaged model proposed for their formation within the basin.

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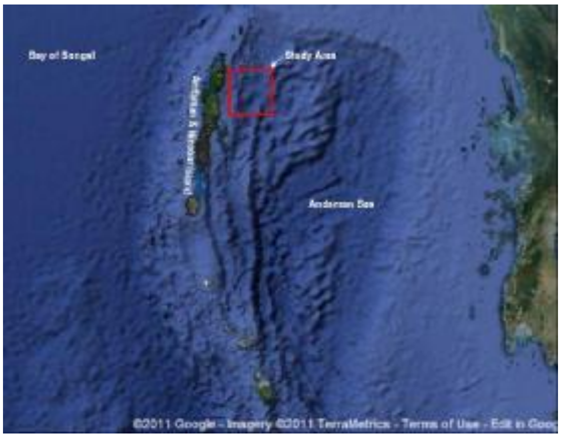

Fig1: Location map and area of study in Andaman-Nicobar Island (from Google Maps).

## Regional Tectonic Setup and Basin Evolution

The Andaman basin evolved through a polyphase, multigenetic tectonic history from Early Cenozoic/Late Mesozoic to Recent. The Paleo- bathymetry data shows progressive shallowing of sea during Paleogene and major uplift at the end of Late Oligocene resulting in emergence of Andaman- Nicobar chain of Islands. Further, rise of volcanic arc in east created a forearc ponded low, which accommodated thick Neogene sediments.

In Andaman, the Forearc basin was initiated as residual basin (Dickinson, 1979) and evolved into a broad composite basin with younger sediments onlapping the arc massif (Invisible bank part) on one flank and the subduction complex on the other (Fig2). Among the major tectonic elements of the Andaman Basin, the Forearc Basin (Ponded fill) is an important tectonic element lying between the Outer High in the west and Volcanic Arc in the east. The western margin of the Forearc basin is down faulted with a large vertical throw against a major fault traceable all along the eastern margin of the high and mapped as Eastern Margin Fault (EMF) indicating this margin as steeper and may have been the source of most sediments (EMF; Roy 1983). However, the dividing line between the outer arc ridge and the Forearc Basin is the Diligent fault (DF) in the central and the northern parts of the basin (Curray 2005). Invisible bank is another important geo-tectonic feature that lies at the eastern part of the basin. In the Forearc Basin, sediments in the Paleogene and Neogene section show extreme variations. The Forearc Basin is composed of various compartments and, sediments in these compartments have been deposited under different environments due to relative base level changes and underwent different tectonic deformational regimes viz., accretionary prism phase (Upper Cretaceous to Oligocene) and the forearc phase (Miocene and Post- Miocene).

In the forearc phase, most of the sediments were trapped in the arc-trench gap. This phase has been divided into two stages, i.e., ponded fill stage (Miocene) and sag fill stage (Post-Miocene) based on the existence of a major unconformity at top of Miocene. Ponded fill stage is characterized by basin inversion tectonic events during Early Miocene and dominantly consists of sediments derived from MTDs and mudflows forming multiple MTCs that took place due to frequent base level changes in the area. This was followed by a quiescent period when sedimentation in shallow water had taken place. The Compressional event continued till the close of Miocene leading to the formation of inverted structure at the middle of the study area. The post lower middle Miocene sediments are mainly clastics. After post Miocene the area had undergone passive filling in Sag fill stage (2 to 3 episodes), depositing mainly Pelagites.

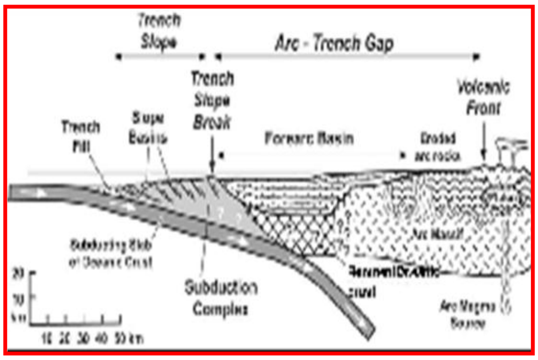

Fig2: Generalized Forearc model.

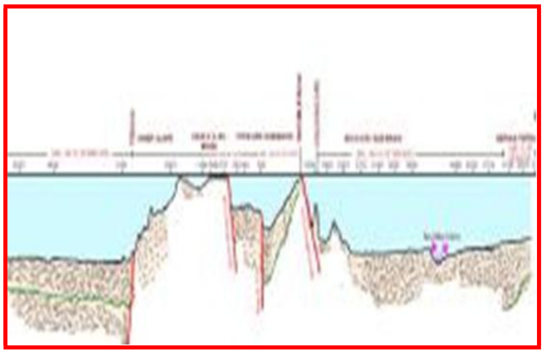
Fig3: A Geological Section across the Andaman-Nicobar Basin (E-W direction)(Source: DGH website)

What is a Mud Volcano?: Mud volcanoes were defined by Guliev (1992) as "periodic expulsion from a deep part of the sedimentary cover of mixtures of water, various gases and solid material" but currently the term "Mud Volcano" refers to a constructional edifice, either buried or outcropping (Milkov, 2000). On the other hand, the term "Mud volcano system" is used to describe the full 3D structure from source to extrusives. Mud volcanoes throughout the world documents a characteristic conic shape with upper surface slope angles typically ranging from 2° to 20°. Seismic imaging of the base and lateral margins of volcanic edifices reveals a variety of morphologies and internal structures. The simplest edifices can be described as radially symmetrical biocones (two cones placed base to base). A stack of overlapping biocones creates an edifice with a "Christmas tree" appearance in cross section. This term was first used in Gulf of Mexico in 1997 to describe the salt structures.

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

- thick sedimentary cover;
- the presence of plastic stratum in the subsurface;
- enough gas supply and high hydrocarbon potential;
- the rapid sedimentation rate and as a consequence of that abnormally high formation pressure within Tertiary and younger sequence;
- the occurrence of faults;
- compressional settings or active tectonism and
- seismicity.

According to the State Oil Company of Azerbaijan Republic, mud volcanoes can be grouped into four basic groups (Yusifov, 2003) which are:

1. Explosive - powerful flow of mud and gas that spontaneously ignites.
2. Effusive - ejection of large amount of mud breccia with non-ignited gas emission.
3. Effusive - flow of low viscous of mud without intense gas emissions.
4. Extrusive - slow extrusion of viscous mud with very insufficient amount of gas (Fowler, 2000).

Among these types of mud volcano eruptions, the first two can be very hazardous. Others have less destructive power and might be considerably predictable.

Mud volcanoes on the seismic lines have different shapes and forms. Some form a distinguished feature on the sea floor, whereas others merge into the surrounding relief and form pools of unconsolidated gas charged mud. Based on their shape and appearance on the sea floor four types of mud volcanoes are identified, which are: Concave, Convex, Flat and Buried. The "Buried" type of mud volcano is characterized by the lack of any surface manifestation. The body of the mud volcano is covered by sediments and has no connection with the surface. Such mud volcanoes usually have sets of stacked wedge like features interpreted as paleo flows that reveal their activity in the past.

## Present Study

Features resembling signatures of mud volcano extrusives are seen in the study area at several positions (Fig.4). Fig.5 and Fig.6 clearly show these features on seismic section and their morphology on the RMS attribute map respectively. Each of these features have associated vent through which fluidized sediments have possibly erupted (Fig.5) This also corroborates with the known aspect that mud volcanism is a prominent feature, particularly along convergent plate boundaries, as is the case in Andaman Forearc Basin.

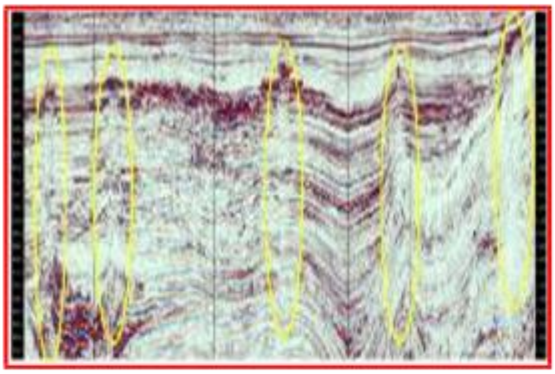

Fig.4. Arbitrary line showing mud volcano like features throughout the study area.

A prominent high amplitude anomaly is seen in the seismic volume, with an elongated geomorphic expression in NW-SE orientation as shown in the RMS amplitude map (Fig.6). This feature sits in the central part of the study area just above the underlying structural high. Expressions of a channel system in the NW-SE orientation circumventing this anomalous feature is seen in the Time slice map (Fig.7), suggesting the possibility of presence of hard compact material within the anomaly, which could not be eroded by the channel system.

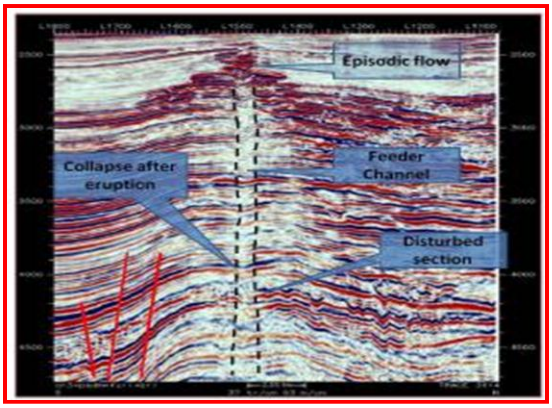


Fig.5. Seismic section showing mud volcano with signature of pulsed flow, sediment wedge subsiding into feeder channel/ caldera and the disturbed section.

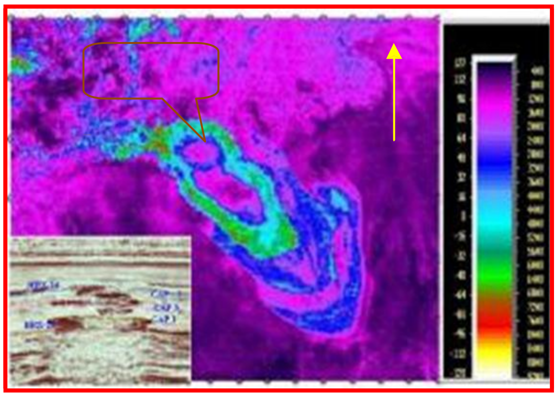

Fig.6. RMS amplitude map showing the mud volcano with episodic flow and its flow direction. In inset the high amplitude anomaly observed in seismic section. The anomaly gives an impression of Christmas tree with interdigitating margin.

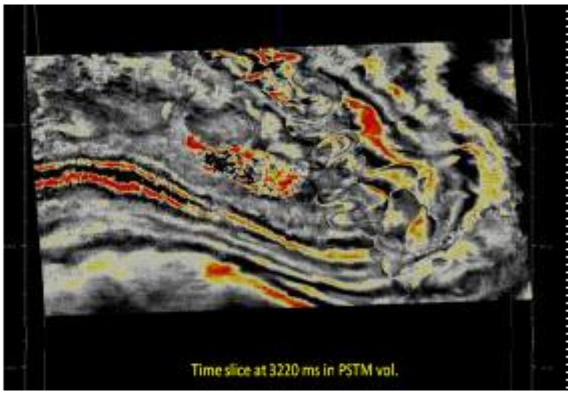


Fig.7. Expression of a channel system in the NW-SE orientation, circumventing the anomalous feature at the centre.

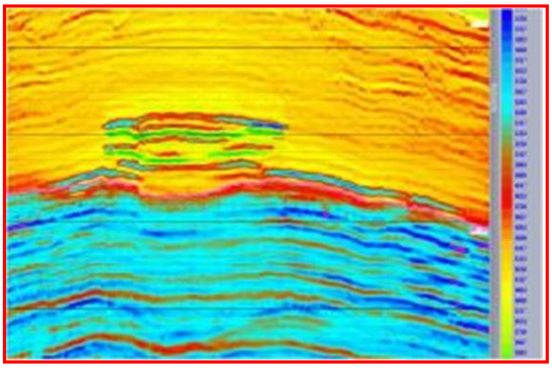

Fig.8. P-impedance section showing alternate occurrence of high and low impedance layers within the mud volcano indicative of pulsed eruption punctuated by a quiescent period and high rates of background sedimentation of finer clastics that gives rise to interdigitating margin and Christmas tree appearance.

Lowering of velocity is also seen in this anomalous feature in both the PSTM and PSDM volume, interpreted during the study. It is opined that this feature is expressive of a mud-volcano ejected from the shallower/deeper MTC through fissures, indications of which are seen in (Fig.5). Similar expressions are also observed at two other positions within the same time zone at SE and SW part of the study area, with relatively smaller areal extent.

Fig.8. Shows a P-impedance section, where alternate occurrence of high impedance layers occurring within the mud volcano, suggestive of pulsed eruption punctuated by period of quiescent period and high rates of background sedimentation of finer clastics. This give rise to interdigitating margin and “Christmas tree” appearance.

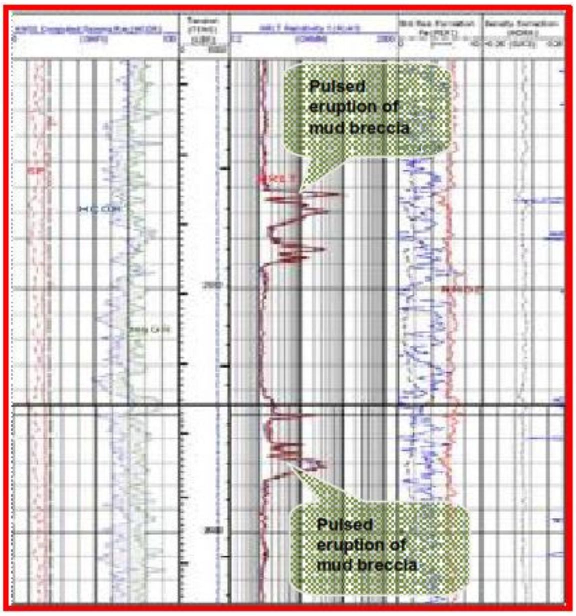


Fig.9. The conventional log recorded in the well that has penetrated this high amplitude anomaly (mud volcano) show pulsed eruption of mud breccias punctuated by deposition of finer clastics sedimentation.

Fig.9 shows the part of conventional log recorded in the well that has penetrated this high amplitude anomaly (mud volcano) in the area of study. The log clearly shows the pulsed eruption of mud breccias/ muddy material punctuated by finer sediments. Also, the interesting aspect of these logs are that, they have the similarity with that of the logs recorded in Milano and Napoli mud volcanoes from Mediterranean ridge under ODP Leg-160 (Robertson,1998) (Fig.10). Logs like HCGR/CGR, Resistivity, and Density shows great amount of similarity in all the three mud volcanoes. The only difference between them is their history of occurrence, while Andaman mud volcano is buried; the other two are erupted on the sea floor.

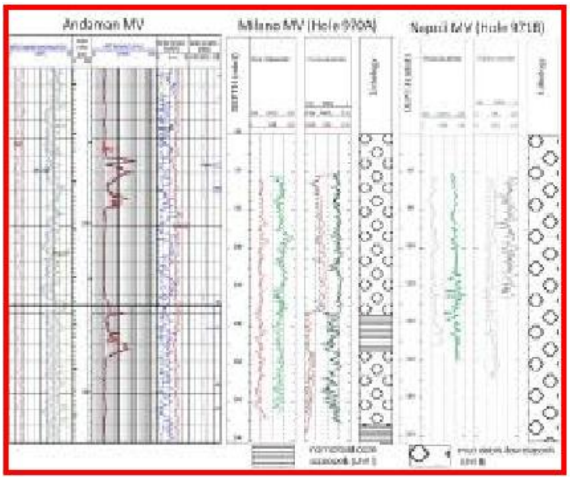


Fig.10. Different logs recorded in the Andaman mud volcano show great similarities with logs from that of two well known mud volcanoes of the Mediterranean region.

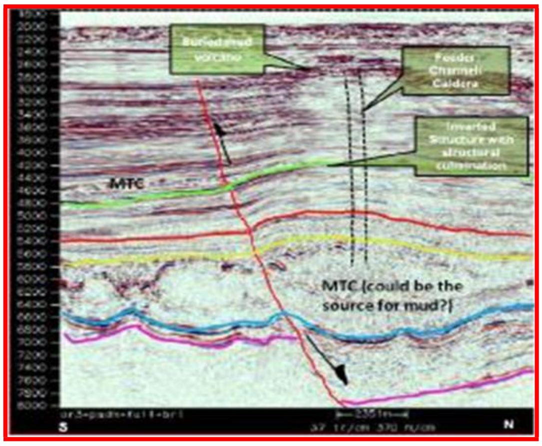


Fig.11. N-S Seismic section showing the mud volcano occurring on the top of the inverted structure. The main fault in the area was reactivated and turned into a reverse fault from the normal fault. The inversion in the basin might have taken place during Early Miocene time. The deeper MTC as well as the shallower MTC might have contributed for the supply of mud during the eruption of mud volcano.

Most of the mud volcanoes in the world occur on the top of a structure which corroborates the theory of mud volcano formation because of pressure breakthrough (association with faults, occurrence above the structural crest, and time of activity). The mechanism for formation of mud volcanoes on the structures is due to pressure release through deep faults. Mud volcanoes occur in different shapes and there is not much regularity in it.

In Andaman Forearc also there is not much deviation from the theory mentioned above. Here, the MV is occurring on the top of an anticlinal structure formed due to basin inversion and reactivation of a deep seated normal, non-planar fault into a reverse fault. This inversion might have taken place during early Miocene age ("Ponded Fill" stage) and the eruption of mud volcano took place around Pliocene time during "Sag fill" stage of the Basin. Here the source of the erupted mud is from the MTC occurring both at the deeper level as well as at the shallower level within the Miocene time (Fig.11). The occurrence of MTC clearly suggest the presence of plastic stratum within the sequence and that there was rapid sedimentation in the basin, which was responsible for abnormally high formation pressure within Miocene and younger sequence.

Mostly "buried" mud volcanoes that do not have any surface representation appear only in seismic. They are covered by sediments and are usually recognized on the seismic data as features with chaotic reflections and distinct paleo-activity patterns. In the study area also, the mud volcano was formed as a buried mud volcano and is recognized only in seismic section (Fig. 4, 5 and 11). This mud volcano most probably was active in the past but its activity subsequently stopped and it became dormant.

Based on above observations and study, following conceptual model is envisaged.

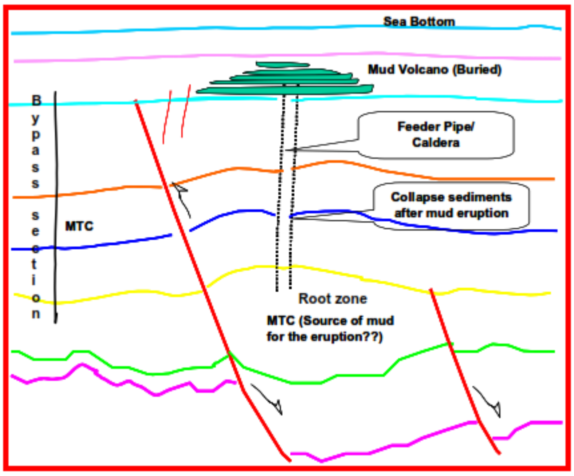


Fig.12. The conceptual model for the formation of mud volcano in the deep water of Andaman Fore arc basin. MTCs could be the source of mud for the pulsed eruption.

## The conceptual model for the origin of the mud volcanoes in Andaman area:

The critical elements believed to be responsible for the eruption of mud volcano illustrated in Fig.11 and 12 are severely overpressured gas- charged carrier beds overlain by low integrity seals. Overpressure was generated by rapid deposition of shaly sediments/highly plastic material (MTC). These prevented decompacted water from escaping from the section during burial. Over pressure was further enhanced with depth by clay diagenesis releasing excess pore water, by trapped hydrocarbon (possible thermogenic and/or biogenic origin), by focusing of decompaction water, by migrated hydrocarbons and by tectonic loading.

Focused migration of decompacted water and hydrocarbons mainly methane from the subsiding basin may eventually build up pressures that exceed the fracture pressure at the structural closure and caused a seal failure. Because of the compressibility of gas (particularly methane) the seal failure will be accompanied by a gas expansion that provides the explosive power of the system and enables vertical penetration through overburden (Graue, 2000 and Hovland etal. 1997). The sudden pressure release associated with eruption will cause an implosion at the root, shaking the under compacted shale such that the poorly consolidated clay fabric disintegrates into liquefied mud with complete loss of mechanical strength. The liquefied mud subsequently flows up the vent together with gas, liquids, rock fragments and sand from the carrier bed. This provides a plausible explanation for the extremely distorted seismic image at the root zone and root complex. This type of eruption had taken places in pulses with quiescent period in between along with high background sedimentation leading to the formation of buried mud volcano with interdigitating margin and "Christmas tree" appearance. The rapid kinetics of such eruptions are also likely to cause a rapid depletion of pressure to a level below that of the fracture pressure of the seal, which is the point when the roof and the side wall of the feeder channel collapse into the vent and plugs the conduit. The over burden labeled "bypass section" in Fig.12, is relatively less disturbed apart from the vent itself, and nearby sediment collapse within the feeder channel. This indicates that activity of the mud volcano had a limited impact on the stratigraphic section other than the immediate surroundings of the vent.

## Conclusions

Summarizing above discussion the following are the major conclusions drawn from the analysis and interpretation of the data as well as the extensive literature research:

- Mud volcanism in Andaman offshore is associated with the fluid pressure gradient in the subsurface.
- The morphology of the mud volcano in Andaman is related to the driving force (pressure), material supply and width of conduit.
- Mud Volcano formation in the deepwater of Andaman is mainly controlled by tectonic forces (areas of local tension, within regional compressional fields) and overpressured sediments.
- Mud volcano activity is related either to the shale succession or to the MTCs occurring both at the deeper and shallower level. Mud volcano occurs at shallow depth by pressure breakthrough from the deeper stratigraphic zone.
- The episode of mud volcano activity in the Andaman Forearc Basin coincides with the time of high sedimentation rate, a regional contraction episode and major stage for hydrocarbon generation (mainly methane).
- There is no relationship between the mud volcano parameters such as size, shape areal extent etc. and their distribution.

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