Mud volcanoes - a review

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- a review

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Contents

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Abstract

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Abstract: Mud volcanoes are pathways through and within which buried argillaceous loose sediments and lithified rocks are altered and transported back to the Earth's surface. The types of mechanisms of formation, maintenance and triggering of this natural, sedimentary recycling-process vary largely whereby external as well as internal properties of mud volcanoes differ greatly. Sizes range from millimetres to kilometres, shapes from caldera-like collapse structures to protruding cones, grade of activity from hardly noticeable to hazardous marked by kilometre-high flares of fire and emissions from flowing, low-viscosity and water-dominated to high-viscosity, toothpaste-like muds. Typically, mud volcanism also involve voluminous emissions of methane and carbon dioxide.

Of the roughly 2000 onshore and offshore mud volcanoes known today, most are located and act either along active, convergent plate boundaries although several examples are known from passive continental margins and continental interiors marked by high sediment accumulation rates. Evidently, mud volcanism is a pressure-dependant process.

As relatively unexplored windows into the Earth's interior, worldwide occurring hazardous geological features and significant contributors to global atmospheric and hydrospheric gas budgets, mud volcanoes are of high scientific, economical, environmental and societal interest.

Keywords: mud volcanism, mud volcanoes, methane, climate dynamics, LUSI

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Sammanfattning

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Åkesson, M., 2008: Mud volcanoes - a review. *Examensarbeten i geologi vid Lunds universitet*, Nr. 219, 16 sid. 15 ECTS poäng.

Sammanfattning: Slamvulkaner är geologiska fenomen inom vilka överlagrade leriga sediment och bergarter omvandlas och återförs till markytan. Av de drygt 2000 (terrestra och marina) slamvulkaner som är kända idag finns och verkar så gott som alla antingen längs aktiva, konvergerande plattgränser eller inom andra områden präglade av kompression och/eller höga sedimentationshastigheter.

Vidden av mekanismer och processer genom vilka denna tryck- och temperaturberoende, naturligt förekommande, sedimentära återvinningsprocess kan initieras och utvecklas är omfattande varför slamvulkaners yttre såväl som inre egenskaper – storlek, morfologi, aktivitetsgrad, innehåll - varierar kraftigt. Vissa är anonyma bildningar som endast framträder genom små utsläpp av högviskösa leror från millimeterbreda sprickor i markytan. Vissa omfattar kilometervida landskapssystem som mer eller mindre regelbundet släpper ifrån sig tiotusentals kubikmeter lågviskösa, vattenmättade leror och betydande mängder (ofta självantändande) växthusgaser.

Slamvulkaner är fortfarande relativt outforskade. Då de släpper ut betydande mängder metan och därmed spelar en viktig roll i det globala klimatsystemet samt regelbundet åstadkommer stor materiell, biologisk och ekologisk skada är de och processerna som bildar dem av stort vetenskapligt, ekonomiskt och samhällsmässigt intresse.

Nyckelord: mud volcanism, mud volcanoes, methane, climate dynamics, LUSI

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1 Introduction

Although described and studied for millennia, mud volcanoes and mud volcanism remain some of nature's most anonymous, mysterious and undiscussed geological features. This is rather remarkable considering a number of facts. First of all, thousands of mud volcanoes exist worldwide, defining and affecting the habitat and the daily lives of the millions of people living amongst them. Secondly, mud volcanism and mud volcano distribution is intimately related to the formation and the distribution of the world's petroleum assets, thus serving as an indicator for valuable natural resources (Kopf 2002). Thirdly, mud volcanoes offer an insight into otherwise hidden deep structural and diagenetic processes such as the formation of gas hydrates, mineral dissolution and transformation, degradation of organic material and high pressure/temperature-reactions (Hensen et al. 2007). Lastly, mud volcanism generally involves voluminous generation and emission of both methane and carbon dioxide whereby most mud volcanoes serve as an efficient, natural source of greenhouse-gases and consequently play an important role in global climate dynamics (Etiope & Klusman 2002, Judd et al. 2002, Kopf 2002, Dimitrov 2003, Milkov et al. 2003, Etiope & Milkov 2004, Judd 2005).

This thesis is a review of some of the existing literature on mud volcanoes. The main aim is to raise the awareness of these features and to discuss their relevance to us humans and the world we live in.

2 Mud volcanoes and mud volcanism - an overview

2.1 Definition

Essentially, mud volcanoes are geological features through which argillaceous material is altered and transported from the Earth's interior and expelled onto its surface. Hence, mud volcanism is the processes by which such features are initiated and sustained. However, mud volcanism is not one specific process and mud volcanoes are not uniform features – settings, driving forces, activity, materials and morphologies may vary almost immensely (Graue 2000, Milkov 2000, Dimitrov 2002, Kopf 2002, Huguen et al. 2004, Huseynov & Guliyev 2004).

2.2 Distribution

Although most common along active, convergent plate boundaries, mud volcanoes also occur along passive continental margins, within continental interiors and throughout deep-sea settings (*fig. 1*). About 2000 mud volcanoes have been confirmed, however, as exploration of the deep seas continues, this number is expected to increase substantially. Estimations suggest everything from 7000 to 1 000 000 in total (Milkov 2000, Judd 2005).

Of all known mud volcanoes, more than half (about 650 onshore- and *at least* 470 offshore) can be related to the Alpine-Himalaya Active Belt (Dimitrov 2003).

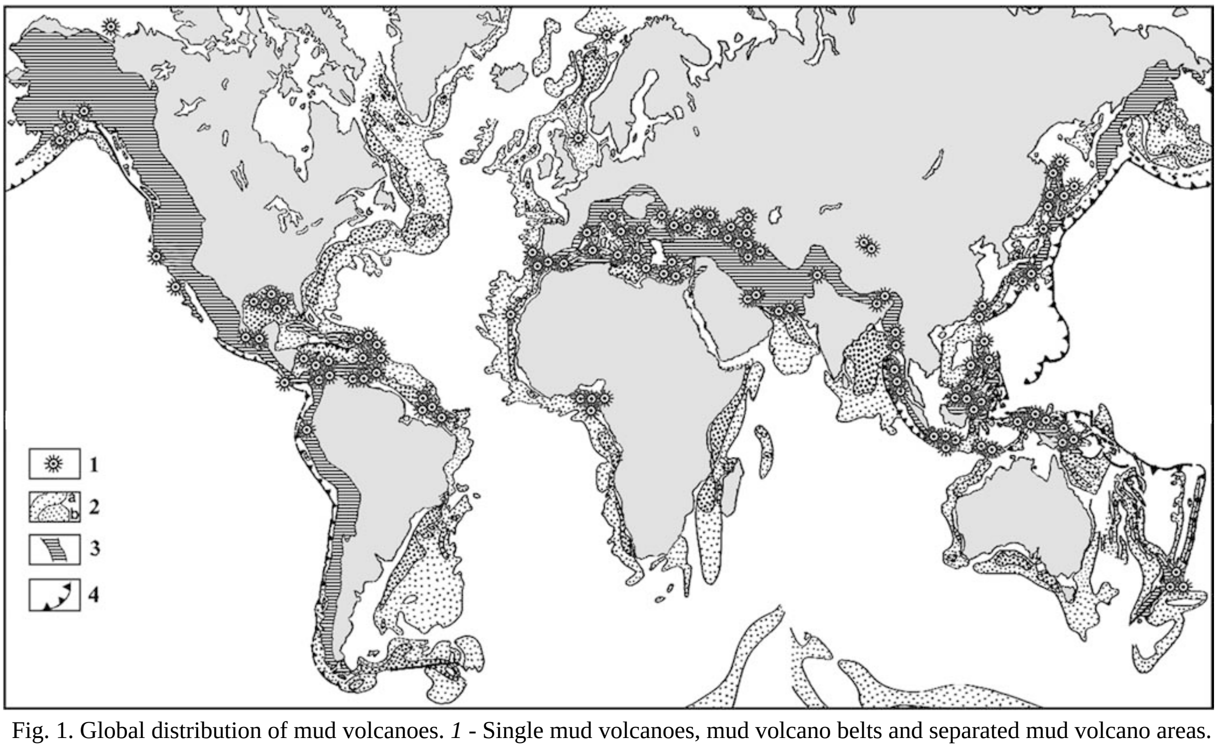

Fig. 1. Global distribution of mud volcanoes. *1* - Single mud volcanoes, mud volcano belts and separated mud volcano areas. *2* - Sediment thickness in the areas out of the continental shelves: *a)* 1-4km, *b)* >4km. *3* - Active compressional areas. *4* - Subduction zones. From Dimitrov (2003).

Starting with the Mediterranean Ridge, this mud volcanic belt continues all the way down to the Indonesia-Australia accretion and collision complexes via Romania and the Black Sea, the Caucasus/Caspian Sea region, Iran, Pakistan, India and China (Dimitrov 2003).

The western flank of the Pacific ocean – from the Sakhalin Island/Sea of Ochotsk-area in the north via Japan, Taiwan, the Marianas, Melanesia, Samoa and Australia to New Zealand in the south – holds some 150 onshore individuals (Kopf 2002, Dimitrov 2003). The total number of offshore mud volcanoes along this belt is not yet fully determined but can be expected to be even higher.

The eastern flank of the Pacific Ocean is markedly less dense in mud volcanoes. Yet, examples are known from and around the Aleutian Trench, Alaska, British Columbia, California, Costa Rica, Ecuador and inland Peru (Kopf 2002, Dimitrov 2003).

The Atlantic Ocean comprises several hundreds of both onshore and offshore mud volcanoes. Whereas the vast majority is concentrated along the Caribbean thrust belts and within the Barbados accretionary complex (Dimitrov 2003), smaller clusters/individual features have been confirmed in connection to the Amazon and the Niger deltas (Graue 2000, Rimington 2000 in Dimitrov 2003), along the Gulf of Cadiz (Mazurenko et al. 2000), within the southern Canary basin (Müller et al. 2001) and offshore Portugal and Morocco in the Alboran Basin (Perez-Belzuz et al. 1997).

Smaller numbers of mud volcanoes have also been described from the Mississippi and the Nile delta (Hovland et al. 1997), Lake Michigan (Kopf 2002), Greenland (Kopf 2002), the North Sea (Vogt et al. 1997) and the Netherlands (Paine 1968 in Kopf 2002).

2.3 Mud volcanic material

Mud volcanoes are composed of three main components – *mud breccia*, *water* and *gas*. Depending on local geology and processes at work, the relative quantities and the exact qualitative properties of these components vary.

Fig. 2. Clast-rich mud breccia. From Planke et al. (2003).

Mud breccia is basically clasts in a clay mineral-rich matrix (*fig. 2*) and is what makes up most mud volcanic features. Whereas the mud typically stems from one specific carrier bed and thus has a distinct geochemical signature reflecting subsurface mud volcanic conditions and processes (clay mineral dehydration/ transformation processes), clast fragments are derived from units through which the mud pass on its way to the surface and are consequently of variable lithologies, sizes (up to 5 m) and shapes. Young and forceful mud volcanoes generally extrude mud breccias with a very high clast-matrix ratio (virtually clast-supported deposits) whereas the mud breccia of older mud volcanoes may be virtually clast-free with a mud content of up to 99% (Graue 2000, Dimitrov 2002, Kopf 2002).

The water in mud volcanic extrusions typically stems from both shallow and deep sources and is normally derived through a variety of processes. Consequently, exact geochemical properties may vary virtually indefinitely (Planke et al. 2003, Hensen et al. 2007). However, clay mineral-dehydration water often makes up a significant proportion (Kopf 2002). Mud breccia and mud volcanic water commonly mix whereby *mud volcanic flows* of different viscosities may form. During fierceful mud volcanic eruptions, up to 5 million cubic metres of such flow-material can be expelled (Graue 2000).

Gases produced by and emitted through mud volcanism are almost always dominated by methane (70-99%). Since most mud volcanoes are very deeply rooted, thermogenic, ^{14}C-depleted (fossil) methane is more common than biogenic (Kopf 2002, Etiope 2005, Judd 2005). Remainders typically include (in falling order) carbon dioxide, nitrogen, hydrogen sulfide, argon and helium (Dimitrov 2002, Huseynov & Guliyev 2004, Judd 2005). The extent and rate of mud volcanic gas emissions is discussed in more detail in chapter 3.

2.4 Mud volcanism and mud volcano morphology

A mud volcano comprises two main morphological elements – an internal feeder system and an external edifice (*fig. 3*). The characteristics of these elements are highly dependant on prevailing mud volcanic processes and in some cases, vice versa.

The internal feeder systems of mud volcanoes are not well known. Studies imply rather large variabilities, however, typically, they consist of one main, cen-

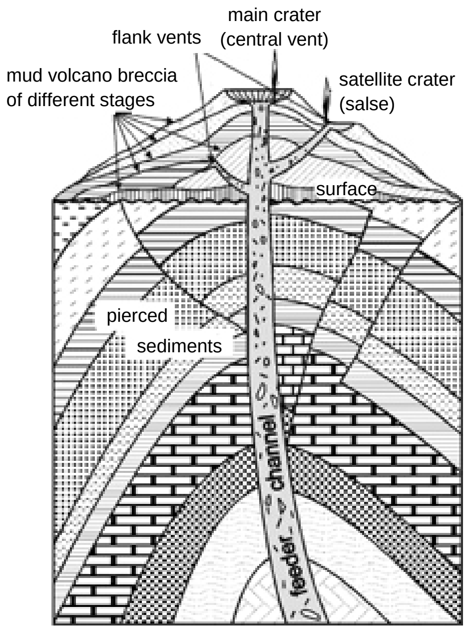

Fig. 3. Basic structure and main elements of a conical mud volcano. Adopted from Dimitrov (2002).

tral and deeply (km-scale) rooted *feeder channel* through which most mud volcanic material is transported. Feeder channels can be everything from cylindrical to irregular shaped to mere slits (Kopf 2002). Near the surface, feeder channels tend to thin off and split into smaller *flanking*/*lateral pipes* (Stewart & Davies 2006). The diameters of volcanic conduits may have a profound impact on mud volcanic activity. Generally, the wider the conduit, the more voluminous the expulsions (Kopf 2002).

The external morphology and expression of a mud volcano may vary almost indefinitely. The outcrops (*vents*/*craters*) of feeder channels may take on a variety of shapes; from plano-convex or flat and bulging to concave collapse structures of caldera-type (Dimitrov 2002). Some mud volcanoes are in fact rather anonymous and quiescent features appearing merely as solitary, mm-scale openings in the ground surface, gently seeping small amounts of high-viscosity mud breccias and/or gas (Hovland et al. 1997, Graue 2000). However, some mud volcanoes are really hazardous and expel voluminous amounts of low-viscosity mud-flows through frequent, short but fierce, phreatic and explosive eruptions. This type of mud volcanoes typically evolve into kilometre-scale, chaotic and complex landscapes that comprise anything from clusters of cone-shaped morphologies rising hundreds of meters above ground to mounds, ravines, pools of bubbling mud and/or water (*salses*), mud cracks and clastic lobes (Hovland et al. 1997, Huseynov & Guliyev 2004, Evans et al. 2006). During and following this type of active, hazardous mud volcanism, combustion of emitted gases may produce columns of flames rising up to several hundreds of meters, potentially burning for months or even years (Laufeld 2000, Huseynov & Guliyev 2004).

Examples of some mud volcanic manifestations are shown in figure 4 (a-e). Obviously, the scope of mud volcano morphology, just as the scope of mud volcanism, is great.

Fig. 4. External manifestations of mud volcanism. *A* - Chandragup mud volcano, Pakistan (2005). *B* - Methane seeping out of a small, anonymous mud volcano in Taiwan. From Kopf (2002). *C* - Cm-scale, high-viscosity mud volcano, Taiwan (2005). *D* - Crater field of the Dashgil mud volcano, Azerbaijan. From Planke et al. (2003). *E* - Dm-scale vent, Palo Seco, Trinidad (2007). *F* - Mud volcano crater, Morne Diablo, Trinidad (2007).

2.5 Mechanisms of formation

Mud volcanism and mud volcanoes have repeatedly been suggested to be a natural way of degassing the Earth's interior (Hedberg 1974, Ali-Zade 1984, Guliev 1992 in Graue 2000, Dimitrov 2002). Although mud volcanism typically do involve thermogenic formation and expulsion of gas (a natural process which to a certain extent independently would be able to force deeply buried material to the surface), such processes can hardly serve to explain the truly vast extent and scope of worldwide mud volcanism. As stated by Graue (2000): "based on the large differences observed in shape, size and eruption styles of mud volcanoes, it is clear that there is no unique model that can explain them all".

Ultimately, mud volcanoes form either as clay diapirs that reach and pierce the ground-surface or as fluidized argillaceous sediments, together with water and various amounts of hydrocarbon gases, that are extruded along structural weaknesses (conduits) within subsurface sediments/rocks (*fig. 5)* (Milkov 2000). Either way, a fundamental requisite for mud volcanism is the existence of a potential source domain; solitary or interconnected argillaceous carrier beds for migrating fluids and gases. Yet, for the actual volcanic processes to commence and continue – for gases to form and/or for the source material to move, rise and eventually extrude from the subsurface – additional forces are needed.

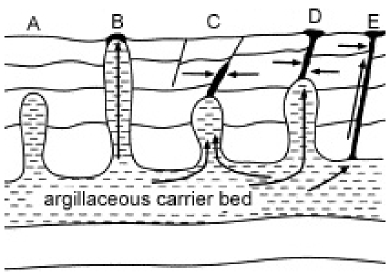

Fig. 5. Basic mud volcano formation. *A* - clay diapir. *B* - seafloor-piercing clay diapir - a mud volcano. *C* - seafloor seepage. *D, E* - mud volcanoes formed due to rise of fludized sediments along faults. Adopted from Milkov (2000).

Since a vast majority of the mud volcanoes that are known today exist along active plate boundaries and, more specifically, along the anticlinal crests of accretionary prisms (the major depositional centres), compression through convergent tectonics and associated high sediment accumulation rates are generally considered the major mechanisms of mud volcanic initiation and sustenance. Argillaceous sediments and rocks are typically very weak and therefore, under the influence of compressive forces, prone to various clay mineral alteration and dehydration processes (Hensen et al. 2007) and to brittle deformation through e.g. faulting. Moreover, under these very conditions, thermal and/or biogenic formation of hydrocarbon gases typically increases. Together, this implies formation of potential volcanic conduits, liquefaction, fluidization, gasification, density inversion, pore pressure increase and focused migration of mud volcanic material – i.e. mud volcanism – either through diapirism or along newly created faults/conduits (Hovland et al. 1997, Graue 2000, Laufeld 2000, Dimitrov 2002, Kopf 2002).

Ultimately, the same forces and processes may explain mud volcano formation along passive continental margins. Although tectonic forces are lacking in such settings, compression, fluidization, gasification, overpressuring and mud volcanism may take place due to loading through rapid deposition of large amounts of (argillaceous) sediments (Graue 2000, Milkov 2000). A common characteristic for regions of mud volcanism located outside convergent plate boundaries are that they measure greatly in the vertical section (at least 2km) and that they are a compound of undercompacted sedimentary sequences (Dimitrov 2003).

Consequently, although local settings may vary, the main mechanism of formation for mud volcanoes and mud volcanism is *compression* – either through tectonic forces or through high sediment accumulation rates – eventually leading to *overpressuring* through in situ gas generation, fluidization and liquefaction.

2.6 Eruption triggering

Although some mud volcanoes experience fairly continuous activity, generally, mud volcanism varies in both volume and intensity – most mud volcanoes have some kind of activity eruption frequency.

The fact that most mud volcanoes present regular, distinct seasonal changes in activity on a range from weeks to tens of years suggests an influence of more than one external agent, initiating and sustaining some kind of continuous, cyclic, natural pressure-recharging process within the mud volcanoes themselves. Astronomical cycles – e.g. orbital forcing – undoubtedly serve as one explanation. Through altering atmospherical and hydrospherical PT-conditions over a great variety of time-scales, such cycles may also affect and alter PT-conditions in the sediments and thereby mud volcanic processes via e.g. fluid access and bacterial activity (gas formation) (Judd et al. 2002). As an example, after studying mud volcanism in the south Caspian Basin, Gorin & Buniatzadeh (1971 in Huseynov & Guliyev 2004) concluded that as much as 60% of all eruptions took place during either new or full moon. Moreover, Mekhtiev & Khalilov (1988 in Huseynov & Guliyev 2004) suggested a relationship between an 11-year cycle of the sun's activity and the initiation of mud volcano eruptions.

Even though astronomical cycles may explain most of the steady variations in mud volcanic eruption frequencies, they do not explain the rather frequent, more irregular eruptions. These are rather a result of ample, sudden seismic activity. If earthquake hypocenters are located within/in connection to potential carrier beds, shaking of the sediments may induce liquefaction and faulting as well as a significant increase in gas formation and dissociation. Consequently, rather sudden, eruptive mud volcanism may be generated in a normally quiescent or even dormant mud volcanic area (Huseynov & Guliyev 1994, Dimitrov 2002, Kopf 2002, Manga & Brodsky 2006). The very same processes may also be induced anthropogenically through large-scale drilling projects. This was most likely the case with the eruption of the mud volcano LUSI in Java in 2006 (see chapter 4).

3 Mud volcanic gas emissions and global climate dynamics

Although hydrocarbon gas dissociation alone hardly serves to explain all of the world's mud volcanism, it is typically a crucial aspect of it and definitely one of the most interesting features of it. Estimations suggest that total releases exceed 27 billion cubic metres each year of which, on average, 85.5% is methane, 9.5% carbon dioxide, 4.5% nitrogen and 0.5% higher hydrocarbons (Judd 2005). Clearly, as stated by Hovland et al. in 1997; "the natural contribution of atmospheric greenhouse gases from the world's terrestrial and submarine mud volcanoes is highly significant". However, this was not realised until recently whereby relations with climate dynamics is poorly understood and proper recognition effectively missing. For example, the International Panel of Climate Change, when discussing natural sources of atmospheric methane in its 2001-report, did not even mention mud volcanoes.

3.1 Estimating emissions - scientific rationale

Estimating global mud volcanic gas fluxes is truly a delicate matter. First of all, the actual extent of worldwide mud volcanism is by no means agreed upon. As noted earlier, approximations of the total number of direct volcanic outcrops – distinct mud volcanic features – span from 2000 to 1 000 000. Moreover, soil gas flux may be significantly high even at distances as large as 1 km from main vents. If included in estimations, such *diffuse microseepage* could make up a profound component (50-90%) of total gas output (Etiope 2005). The possible quantitative extent of actual worldwide mud volcanism obviously spans over a huge range. As been discussed, qualitative properties may also vary greatly depending on local geology. Furthermore, the actual fate of mud volcanic gas emissions depends on several factors.

Gases originating from onshore mud volcanoes are emitted straight into the atmosphere and thus affect atmospheric gas budgets directly. Quantitatively, emissions are mainly dependant upon mud volcano size and mud volcano eruption frequency (Kopf 2003, Huseynov & Guliyev 2004). Whereas gas emissions associated with *quiescent* mud volcanism range from just over nothing at all up to 10^6 m^3 per day (Milkov et al. 2003), *active* mud volcanism (eruptive phases) typically involves corresponding volumes of up to 25-250*10^6 m^3 (Milkov et al. 2003, Judd 2005). During fierceful eruptions, combustion might occur whereby methane is oxidised (depleted) and instead enters the atmosphere as carbon dioxide (Dimitrov 2003, Judd 2005).

The fate of offshore mud volcano gas emissions is somewhat more complex. It is generally accepted that the deeper a submarine mud volcano is situated, the less likely it is to contribute to atmospheric gas budgets. It has been estimated that gas emissions from submarine mud volcanoes located on depths shallower than 20 metres are to be compared with those located onshore (Etiope 2005). However, of the gas emissions from mud volcanoes located on depths exceeding 50 meters, hardly anything reaches the atmosphere in an original state and quantity (Etiope & Klusman 2002, Dimitrov 2003, Kopf 2003, Etiope & Milkov 2004). This is due to dissolution and anaerobic oxidation transforming methane into carbon dioxide, processes whose effect on emitted gases in turn depend on both external factors such as depth, water temperature and fluid motion, and on the actual nature of the mud volcanic activity (Judd et al. 2002, Etiope 2005). Continuous submarine mud volcanic gas emissions are generally not included in estimations of direct contributions to atmospheric gas budgets at all since they typically are very weak and therefore a) easily dissoluted and b) concentrated along the seabed-water interface where oxidation processes are most effective. Yet, such emissions may, if substantial enough over longer periods of time, alter hydrospheric conditions (gas budgets, biomass and productivity) to such an extent that atmospheric gas budgets eventually are affected (Huseynov & Guliyev 1994, Judd et al. 2002, Milkov 2003, Etiope 2005). Moreover, this type of mud volcanism is generally considered as responsible for the formation of offshore gas hydrates. These ice-like mixtures of methane and water probably constitute the largest methane-reservoir on Earth and would, upon release, undoubtedly have a profound impact on atmospheric gas budgets and global climate. Active, frequently erupting submarine mud volcanoes may, on the other hand, affect atmospheric gas budgets directly through strong eruptions during which expelled gases may rise in "shielded" plumes towards the sea-surface without being oxidized or dissoluted. Such distinct eruptions may virtually burst through the water-surface and into the atmosphere and are occasionally associated with combustion (Etiope 2005, Judd et al. 2002, Dimitrov 2003). However, although not defined, there is generally considered to be a depth-limit to these processes as well.

When estimating mud volcanic contributions to global atmospheric gas budgets, all of the above must be taken into account. Clearly, such estimates require and rely on several dubious approximations and extrapolations whereby results may be disputable. Still, attempts have been made.

3.2 Estimated emissions and global budgets

During the last few years, several exploratory reports on mud volcanic gas emissions have been presented (e.g. Dimitrov 2002). Some are based on extensive literature studies, some on actual surveying and some on combinations of both. All have aimed at coming to conclusions on the influence of mud volcanism on global climate dynamics. Hence, the main focus of all of these studies has been the associated methane emissions (though it should be noted that not all mud volcanoes are hydrate bearing). The quantitative results of these studies are presented in table 1.

Reference	Methane flux to the atmosphere (Tg/year)
Dimitrov (2002)	10.3-12.6
Etiope & Klusman (2002)	2-10
Kopf (2002)	0.07-1.4
Milkov et al. (2003)	6
Kopf (2003)*	0.00005-0.328
Dimitrov (2003)	5
Etiope & Milkov (2004)	6-9
Judd (2005)	3.6

Table 1. Estimated mud volcanic methane emissions. *significant arithmetic uncertanties" (Kopf 2003), and therefore not accounted for in further discussions.

Considering the span of uncertainties/range of possible alternatives surrounding the fundamental assumptions these estimations are based on (the amount of mud volcanoes accounted for, the extent of and way in which offshore mud volcanism and diffuse microseepage is included, what mud volcanic areas that have been set as type-examples and the way in which average quiescent/eruptive gas emission rates have been calculated in), most final results fall into a remarkably small range. In most recent discussions, the span is set at 3.6-12.6 Tg y^{-1} (Judd 2005).

Clearly, the available literature is dominated by a rather limited number of authors. It would be naive to say that this doesn't serve to explain some of the striking similarity amongst the final results of conducted studies – many of the referred reports are in fact extensions of each other. Yet throughout, these extensions include evaluations on previous assumptions and are often the results of criticism, discussions and debates among the authors in questions whereby the subject is in effect under constant development and improvement.

The total identified atmospheric methane budget is estimated at around 500-600 Tg y^{-1} (IPCC 2001, Judd et al. 2002). Of this volume, about 65% stems from anthropogenic activities such as biomass burning and waste treatment whereas the remaining 35% is considered as natural contributions. The total geologic contributions are estimated at 7% (Judd et al. 2002, Etiope & Milkov 2004). Drawing from the results and conclusions of the studies referred to above, mud volcanism is accountable for about 1-2% of *total* contributions to atmospheric gas budgets, 2-7% of *natural* contributions and 10-30% of *geological* contributions (calculated on mud volcanic methane emission rates of 3.6-12.6 Tg y^{-1}, and an average global atmospheric budget of 550 Tg y^{-1}). Such figures are comparable to several acknowledged both natural and anthropogenic contributions such as those from termites, manure, domestic sewage and landfills (Etiope & Milkov 2004, Judd 2005). In addition, estimates on possible contributions to *hydrospheric* gas budgets by offshore mud volcanism range from 11 (Judd 2005) to 27 (Milkov et al. 2003) Tg y^{-1}. This implies a profound impact on ocean biomass and productivity, quite possibly extensive formation of gas hydrates, and thus eventually on the nature of ocean – atmosphere fluxes (Etiope & Klusman 2002, Kopf 2003, Judd 2005). However, such processes are yet poorly understood.

3.3 Mud volcanism and climate dynamics

As a natural source of both hydrospheric and atmospheric methane, mud volcanism evidently affects global climate. However, global climate in turn affects the rate and extent of mud volcanism. The two are highly interdependent and has, due to the introduction of anthropogenic activities, most likely been so to an even larger extent than today for the previous hundreds of millions to billions of years. In order to exemplify and visualise the role of mud volcanism in climate dynamics of today, two possible scenarios may be considered – global cooling and global warming.

During periods of global cooling (*fig. 6a*), the advance of permafrost and ice-sheets can be expected to physically constrain gas leakage from mud volcanoes and associated gas hydrates located within high-latitudes, thereby providing positive feedback to the climatic processes at work. Also, due to falling sea-levels, an increase in the erosion of coastal sediments would most likely diminish the rate of microbial (and thereby mud volcanic) methane generation. However, in low-latitude settings and on continental shelves where mud volcanism is most abundant, gas leakage to the atmosphere would be favoured and global cooling probably constrained due to the fall in eustatic sea-level meaning a) increase in direct atmospheric contributions through the uncovering of shallow, coastal mud volcanoes, b) increase in offshore emission rates through decreasing hydrostatic pressures and thereby increasing internal sedimentary pressures and c) increase in survival potential of offshore emitted gases because of the reduced depth and thus reduced dissolution potential of the water. Furthermore, the stability zones of gas hydrates (typically associated with deep sea/continental slope-mud volcanism) can be expected to migrate down-slope together with sea-level whereby hydrates at higher levels may dissociate and voluminous amounts of methane be released (Judd et al. 2002, Etiope 2005).

During periods of global warming (*fig. 6b*), the opposite reactions and processes can be expected – mud volcanism and associated gas hydrates at high latitudes would be released and reactivated upon the retreat of ice sheets and permafrost whereas low-latitude, offshore mud volcanic gas emissions would be increasingly constrained as the eustatic sea-level rises.

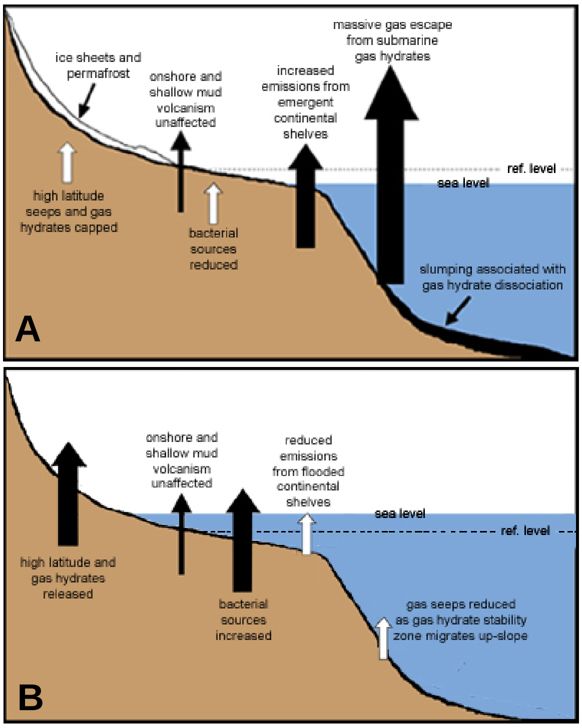

Fig. 6. Interrelationships mud volcanism and *a)* global cooling, *b)* global warming. Adopted from Judd et al. (2002).

As stated by Judd et al. (2002): "the processes by which mud volcanism is generated and released provide conflicting feedbacks to both global cooling and global warming". Evidently, the actual role of mud volcanism in climate dynamics is complex. However, most agree that, mainly because of the enormous potential of gas hydrates, the negative feedback-systems overrule the positive and that mud volcanism therefore might have played, and still plays, an important role in constraining the glacial-interglacial cycles of the past two million years (Judd et al. 2002, Etiope 2005).

Historically, several authors argue that mud volcanic influence on global climate might have been even greater. This is very likely considering Precambrian and early Palaeozoic time, when neither wetlands nor termites existed and mud volcanism therefore probably was one of the overall major sources of atmospheric greenhouse gases. It has repeatedly been suggested that large-scale dissociation of gas hydrates and an increase in overall mud volcanic activity, mainly induced and intensified through extensive magmatic activity, collectively may have been major acts in bringing about the major global climatic shift marking the Palaeocene-Eocene boundary (Dickens et al. 1995, Svensen et al. 2004). However, this is still very speculative.

4. Case study: the eruption of LUSI, Java, 2006

In the early morning of May 29th 2006, numerous scattered seepages of steam, water and mud suddenly appeared in an area outside the coastal city of Sidoarjo, north-eastern Java, Indonesia (*fig. 7*). Within hours, the initially gentle leakages had turned into voluminous, viscous, interfingering expulsions of mud marked by 50m high flares of steam. A fierceful mud volcano – LUSI (an abbreviation of the Indonesian word for mud (**lu**mpur) and **Si**doarjo) – had formed.

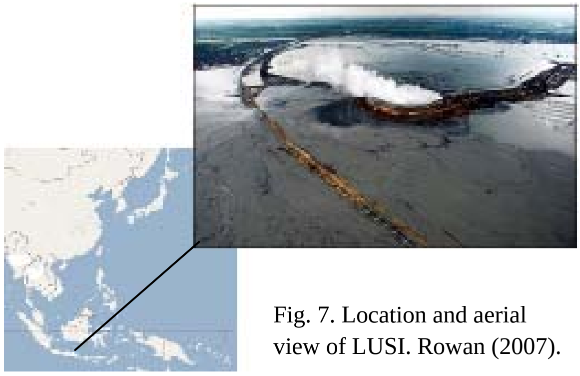

Fig. 7. Location and aerial view of LUSI. Rowan (2007).

Over the next few days, expelled materials were counted in tens of thousands of cubic metres. Peak flows of 180,000 m^3 *a day* were reached within months (Mazzini et al. 2007). One and a half year later, hundreds of hectares of land stands covered by a thick black sea of watery mud pockmarked with bubbles of gas. More than 20,000 people have been forced to move as houses and croplands have been flooded (*fig. 8, 9*). Although expulsions have somewhat subsided and attempts to stem flows have had some success, roughly one hundred thousand cubic metres of mud is still expelled each day from a central cauldron rising several metres above ground surface. Experts expect the eruption to continue for years (Davies et al. 2007).

Fig. 8. A roof buried in mud from the LUSI-eruption. Estey (2006).

Fig. 9. The effects of LUSI. To the left, a satellite picture taken prior to the eruption (20061006), to the right, the same view one year later (20071122). Courtesy to the University of Singapore's Centre for Remote Imaging, Sensing and Processing.

4.2 Geological setting

The island of Java is a result of ongoing oceanic-plate subduction within the Indonesia-Australia accretion and collision complexes (Mazzini et al. 2007, Williams et al. 1984). The north-eastern part of the island, where LUSI is located, is part of an inverted extensional backarc basin resting on a metamorphic basement complex of Cretaceous age (Matthews and Bransden 1995). Here, a prolonged pulse of normal faulting associated with the main subsidising event of the Early Eocene resulted in an extensive series of east-west striking half-grabens that throughout the remaining Palaeogene were filled with highly compacted marine to alluvial carbonates and muds recording an overall transgressive regime (Matthews and Bransden 1995, Davies et al. 2007, Mazzini et al. 2007). Regional contraction and inversion resulting in folding and faulting have been continuous since the Early Miocene (Matthews and Bransden 1995). Neogene and Quaternary sediments are dominated by carbonates and sandstones recording "rapid relative sea-level changes..., erosional truncation, channelling and slumping" (Matthews and Bransden 1995). Volcanic activity, magmatic as well as sedimentary (mud volcanism), is abundant throughout the area.

Seismic profiling and remote sensing indicate that LUSI lies upon an east-west trending anticlinal fold within a regional northeast-southwest striking fault-section (Davies et al. 2007, Mazzini et al. 2007). Local stratigraphy is well known from various borehole data provided by Lapindo Brantas (*fig. 10*). From bottom-up, it consists of 1) The Kujung formation – Miocene overpressurised, coralline limestone (?-2850 m), 2) Pleistocene volcaniclastic sand with some interbedded clay-layers (2850-1850 m), 3) Pleistocene undercompacted and overpressurised clays with some interbedded sand-layers (1850-900 m), 4) Pleistocene alternating sands and shales (900-300 m), 5) recent alluvial alternating sands and shales (300-0 m) (Davies et al. 2007, Mazzini et al. 2007).

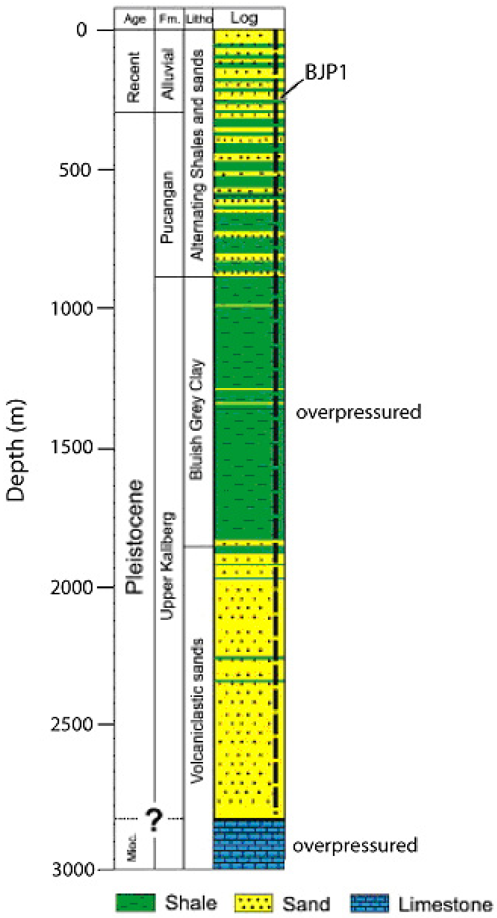

Fig. 10. Stratigraphic column at LUSI-site. Adopted from Mazzini et al. (2007).

4.3 LUSI - properties, interpretations and process modelling

When compared to some of the world's most prominent and active mud volcanoes, LUSI emerges as a rather exceptional feature both in volume, duration and spatial extent (*table 2*). Moreover, what comes out of LUSI – CO_2, CH_4 and a 70-100°C mud containing about 70% water – is truly an outlier in "the dilute, watery end" (Cyranoski 2007) of the mud volcanic viscosity spectrum. The processes feeding LUSI evidently requires vast sources of both water and mud – materials that, as noted, are common beneath and around the Sidoarjo-area. Geochemical and biostratigraphical analyses of extruded materials suggest a) a main source for the mud within the Pleistocene undercompacted and overpressurised interbedded clays and sands at a depth somewhere between 1220 and 1850m, b) both shallow and deep sources of water and c) mixed biogenic and thermogenic origin of gases (Cyranoski 2007, Mazzini et al. 2007).

Two models for the initial triggering event and the continued mud volcanic activity have been presented. The first to be considered, and the most acknowledged of the two, suggests that one of Lapindo Brantas exploratory wells (BJP1 in *fig. 10*), upon reaching and punctuating the overpressurised Kujung limestone formation in search of gas, allowed high-pressure water and gas to fracture, escape into and liquefy shallower sediments (clays and sands), thereby inducing mud volcanic processes and the actual eruption (Davies et al. 2007). Increases in flow rates are explained by growing and propagating fractures. The fact that the eruption started as several smaller seeps, all some hundred metres away from the actual drilling well, is seen as evidence for insufficient casing, facilitating the propagation of hydraulic fracturing (Cyranoski 2007, Davies et al. 2007). Moreover, Lapindo Brantas has acknowledged the fact that the day before the eruption, the drilling experienced a 'kick' (instead of drilling fluids leaking out of the borehole, they rush into cracks within the sediments along the borehole) at 1239 metres depth. Such an event undoubtedly weakens badly cased boreholes and penetrated sediments and would serve to facilitate an eruption.

Mazzini et al. (2007) argue that "the hypothesis of an eruption entirely attributed to drilling....is inconclusive" and instead propose that the LUSI-eruption was triggered by a 6.3 M (Richter scale) earthquake taking place about 280 km southwest of Sidoarjo on the 27^{th} of May 2006, causing fracturing and reactivation of already existing faults and piercement structures within overpressurised argillaceous units directly underneath LUSI. Such a course of events would, according to the authors, serve to cause fluidisation and sudden pressure drops sufficient to exsolve gases, thereby initiating a mud volcanic eruption. However, this theory is challenged by the results of earlier studies (Manga & Brodsky 2006) suggesting that the magnitude of and the distance to the concerned earthquake collectively would be insufficient to trigger a mud volcanic eruption like LUSI (*fig. 11*). Also, if the LUSI-eruption actually was triggered by the earthquake event of May 27^{th}, a sooner response would be expected since seismogenic liquefaction of sediments usually occurs immediately (Davies et al. 2007).

Whatever the exact, actual triggering-event, most seem to agree that LUSI, once initiated, will remain a hazardous feature for many months or even years to come, the critical factor for maintenance of flow being the pressure relationship between the source bed and the vertical column of the erupting material (Davies et al. 2007).

	Lokbatan (Azerbaijan, 2001)	**Koturdag (Azerbaijan, 1950-present)**	**Piparo (Trinidad, 2001)**	**LUSI (Java, 2006-present)**
Volume (km^3)	0.0003	0.00045	0.025	0.028
Duration	30 minutes	counting	1 day	counting
Area (km^2)	0.098	0.3	2.5	6.7
Average rate (km^3/day)	0.0144	0.000000025	0.025	0.001

Table 2. Volume, duration, aerial coverage, and rates of four contemporary mud volcanoes. Adopted from Davies et al. (2007). LUSI update from Montlake (2007).

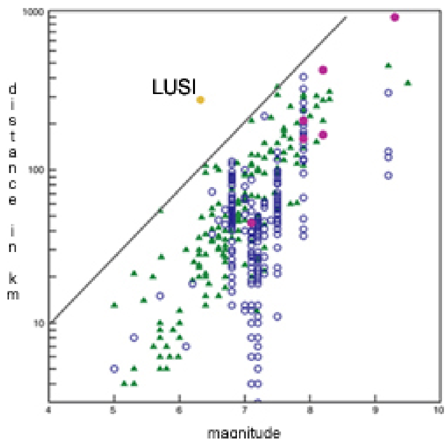

Fig. 11. Relationship between earthquake magnitude and distance over which liquefaction *(solid green triangles)*, significant changes in streamflow *(open blue circles)* and mud volcanoes *(solid purple circles)* have been reported. The grey line demonstrates an upper limit as indicated by these observations. LUSI *(solid yellow circle)* lies well above this limit. Adopted from Manga & Brodsky (2006).

4.3 Future development

There are indications that LUSI is switching down – intensity-pulsation intervals has gone up and the water-content of the erupted mud has gone down, increasing the viscosity and decreasing the flow-rates of erupted materials. Yet, the flow-rate is, as noted, still highly significant and moreover, as the water content has gone down, the clast content has gone up and consequently, there is now the threat of large amounts of solid material being erupted throughout the area. Also, there is the issue of subsurface collapse and ground-surface subsidence. Based on the above discussed process models and on the observations of the evolution of other, similar mud volcanoes, it has been predicted that the region around the main vent eventually will collapse to form a caldera-like structure (with depths potentially reaching several hundreds of metres) and that the overall area affected by the mud flows gradually will subside (Cyranoski 2007, Davies et al. 2007). To some extent, this course of events has already begun. As of June 2007, the average subsidence of the area was measured at 10.7m (Mazzini et al. 2007).

Several projects to diminish damage have been undertaken. Levees have been built in order to divert flow into nearby rivers and the ocean, relief wells have been constructed in order to intercept, replace and counteract main flows and 300 kg-concrete balls have been dropped in thousands down main conduits in order to tire flows (Cyranoski 2007, Davies et al. 2007, Mazzini et al. 2007). None of these efforts can be considered as truly successful. Furthermore, the chemical, biological and ecological effects of diverting millions of cubic metres of mud into flourishing rivers and oceans are rather dubious and controversial.

So far, urgent humanitarian needs have been superior to pure scientific interests. Yet, in order to understand LUSI and to be able to minimise future devastation, the latter now ought to be given more support and more thorough efforts. This would undoubtedly increase the understanding of mud volcanism and maybe, similar events or at least the effects of similar events could be minimized in the future.

5 Discussion and concluding remarks

The reason for and the main aim of this review was to come to terms with what mud volcanoes actually are and if and why we ought to have any (apart from pure scientific) interest in them. Since virtually all of the characteristics and properties normally used for differentiation and definition purposes (size, shape, setting, grade of activity, eruption frequency, content, formation-, sustenance- and triggering processes) differ greatly, studying, understanding and explaining mud volcanoes and their occurrence turned out to be a rather extensive and complicated (although very interesting) task. Upon reviewing and concluding overall findings, what defines and unites mud volcanoes are that they are all the results of a pressure-dependant recycling-process that with the help of water and gases transforms and transports buried argillaceous sediments and rocks back to the surface. Should we have any interest in such processes then? Should we bother to urge and expand the study of mud volcanoes and mud volcanism? Without doubt, yes. Considering the worldwide extent and the frequently spectacular (although hazardous) nature of mud volcanoes, they are and remain strikingly anonymous to the general public as well as within the scientific community. The truly vast scope of mud volcanism suggests a wide range of potential controlling factors and processes. Some of these – i.e. the most fundamental characteristics and properties of mud volcanism – have been identified; however, much remains to be discovered and even more so to be properly *understood*. It is hard (if not impossible) to say exactly what would come out of an expansion and an intensification of the studies of mud volcanoes. However, we would obviously increase our understanding of them and the gains would not only cover a wide range of scientific areas (geological, chemical, biological, ecological, physical and maybe even astronomical) but we would undoubtedly also be able to reduce future, unavoidable human, environmental and economical losses.

In order to facilitate and make the most out of future studies, the following might be considered:

- Much of the work done on mud volcanoes is published in Russian. Without doubt, all would benefit from these studies being translated into English and thereby reaching a wider public. However, the need for more thorough studies of mud volcanoes and mud volcanism outside the Caucasus/Caspian-Sea region is inevitable.

- Many authors refer to their respective datasets built upon years of theoretical and practical research. Perhaps naïve, it would be better to create one single, comprehensive database collecting, organising and concluding all studied mud volcanoes. Such a database should include everything from size, shape and precise geographical position to geological settings, content, estimated/documented emissions, eruption frequencies where possible, recorded “irregularities” and considered theories. Not only would such a database structure and assist future research and understanding but it could also, with the help and implementation of GIS, enable and facilitate mitigation and rescue projects. A prerequisite is, of course, a generally accepted and applied nomenclature/classification scheme.

- When it comes to climate & climate dynamics, it ought to stand clear that mud volcanoes (i.e. mud volcanism) do play a significant role. Instead of stressing this fact and instead of arguing and conducting further calculations (estimations) on exact but unavoidable greenhouse-gas emissions, research should be focused at the more uncertain but critical aspects of mud volcanism, mainly the actual scope, fate and effect of offshore emissions and in extent, how these might be affected by and interact with predicted climatic changes.

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