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Editorial

Mud volcanism: Processes and implications

Mud volcanoes: generalities and proposed mechanisms

Mud volcanoes can be large and long lived geological structures that morphologically resemble magmatic volcanoes. Because of their capricious behaviour and their spectacular morphology and landscapes, mud volcanoes have attracted attention since antiquity. More recently, mud volcanoes have become the focus of extensive studies for natural science research, including geologists and biologists.

Mud volcanoes can be essentially divided in two groups: those associated with magmatic complexes and those related to petroleum provinces. Their occurrence is broadly distributed throughout the globe in both passive and predominantly active margins, often situated along faults, fault-related folds, and anticline axes. These structures act as preferential pathways for deep fluids to gather and ultimately reach the surface. Mud volcanoes episodically experience violent eruptions of large amounts of gas mixed with water, oil, mud and rock fragments forming the so called "mud breccia". The periodical eruptions can produce volcano-shaped mountains that can reach kilometres in size.

Detailed studies of mud volcanoes have been conducted for decades (e.g. Jakubov et al., 1971; Higgins and Saunders, 1974; Barber et al., 1986; Brown, 1990; Camerlenghi et al., 1992; Kholodov, 2002; Kopf, 2002). Below I summarize the main findings so far, combined with my own suggested mechanisms (Fig. 1). The main driving engine of the eruptions is overpressured methane rising from source rocks and hydrocarbon reservoirs at greater depths. Other known overpressure buildup mechanisms that contribute to the brecciation of the deep sedimentary units include for example the dewatering of thick clay-rich sedimentary units, and geochemical reactions in sedimentary units with high temperature gradients. These fluids overpressured fluids gather along morphological discontinuities and favorable geological structures (e.g. fault planes, anticline axes, preexisting deformations). During this overpressure buildup a dome or diapir-shaped feature of brecciated sedimentary units forms in the subsurface. The rise of the fluids and the growth if this diapir is partly self-sustained by buoyancy and by the constantly increasing volume of fluids at shallower depth. A suggested scenario summarizing the birth of a mud volcano and the eruption mechanisms envisages that when the subsurface overpressure reaches a threshold depth where the overburden weight is exceeded, fracturing and breaching of the uppermost units occur, sometimes facilitated by external factors (e.g. earthquakes). Brecciated sediments throughout the feeder channel have a reduced cohesion. As breaching of the overburden occurs, the accumulated pressure drops and the lower cohesion media is easily fluidized and ultimately vacuumed to the surface. This suggested mechanism does no imply significant movement of the brecciated sediments prior to the eruption neither during the growth of the emerging diapir. An eruption where large rocks rise directly from the roots of the feeder channel all the way up to the surface, is unrealistic to happen. This is especially unlikely when considering basins like the Caspian where some mud volcanoes have root as deep as 15 km. I suggest that the huge blocks observed at some mud volcano locations and proven to originate from several kilometres of depth, reach the surface after several eruptive cycles, each one contributing to the rise of the oldest sediments. In this sense, I envisage that the youngest eruptions have a larger amount of old rocks.

The intimate association of petroleum reservoirs and mud volcanoes in sedimentary basins makes such structures interesting for hydrocarbon exploration. However mud volcanoes may also pose a geohazard for drilling and platform constructions due to the potentially violent release of large amounts of hydrocarbons and mud breccia. Additionally, the eruption of greenhouse gases via mud volcanoes may influence global climate regimes and several attempts to estimate their contribution have been made. Offshore mud volcanoes are frequently associated with the presence of gas hydrates. As these buried methane reserves are likely to be exploited in the future, mud volcanoes will undoubtedly remain a key part of the geological arena.

The special issue

The idea of a special issue on mud volcanism was suggested by Elsevier after the successful AGU session on "Mud volcanoes and their eruption dynamics" held in San Francisco in December 2007. Marine and Petroleum Geology Journal was the best choice to gather contributions on mud volcanism investigated both onshore and offshore with constantly updated approaches.

Mud volcanoes represent a relatively young field of study especially when compared with the more popular magmatic volcanoes. A special issue devoted entirely to mud volcano contexts, processes, and resultant landforms is both relevant and timely not only because the subject is gaining increased attraction within the scientific community but also because a cohesive presentation of the state of research is required to direct avenues of research.

There are several issues that still remain unresolved. For example what are the geochemical reactions that occur during

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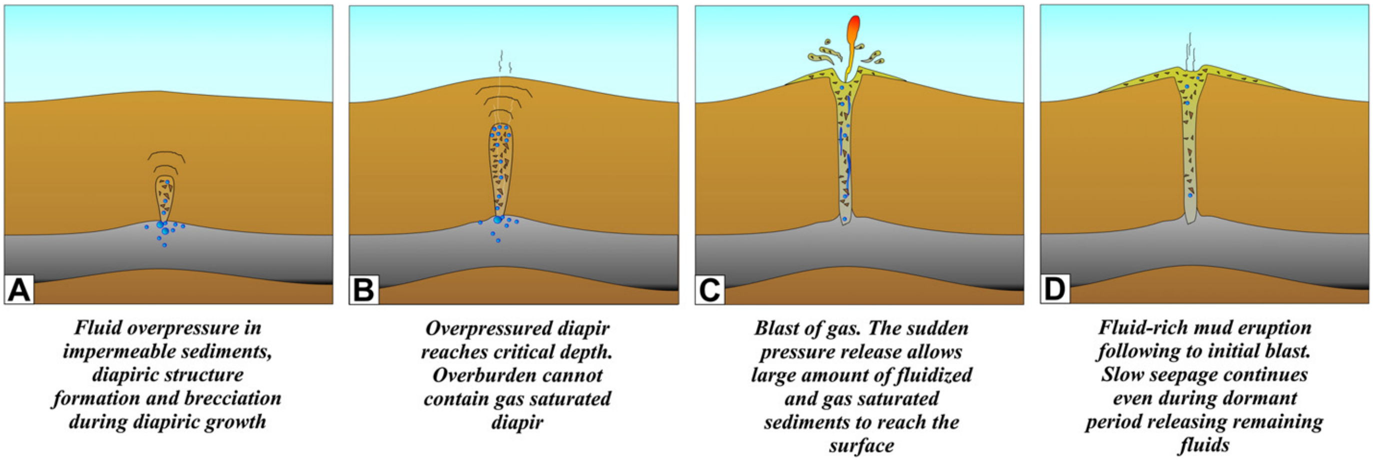

Fig. 1. Cartoon sketching the growth stages of a mud volcano from its initial subsurface formation to final manifestation on the surface with eruption of mud breccia.

the rise of fluids at dormant stage? Is it possible to predict mud volcano eruptions? What are the possible triggers for the eruptions? Is there any rise of the brecciated sediments along the conduit prior to an eruption? From what depth are the solids being erupted during a single event? What do the seeping fluids tell us?

This special issue aims to provide an overview of the different settings and disciplines to investigate mud volcanoes and their processes, and to present the state-of-the-art in the most recent ongoing research.

The themes described in this issue (Fig. 2) are divided in five main sections: 1) Onshore mud volcanism, 2) Lusi mud volcano, 3) Offshore mud volcanism, 4) Extraterrestrial mud volcanism, 5) Modelling mud volcano eruptions.

Essentially all offshore and onshore mud volcanoes are studied during their dormant period (intervals between eruptions that are characterized by no seepage, or microseepage or focussed seepage of fluids and sediments). Onshore mud volcano provinces are located throughout the globe mainly in collisional settings. Sampling onshore is facilitated and petrography and geochemical analyses of the seeping sediments and fluids represent the most traditional approach to explore the geometry of the subsurface plumbing system and the origin of the fluids during the quiescent periods. Using this type of approach, Etiope et al. (2009) and Mazzini et al. (2009) tried to estimate the main geochemical processes ongoing in the feeder channel and in the near subsurface during the dormant activity. New analytical and monitoring approaches (e.g., cyclicity of the eruptions, temperature logging, and penetrometry tests) are also described aiming to understand the mechanisms ongoing during the slow seepage of fluids and to predict the charging of the mud volcano system prior to new eruptions (Deville and Guerlais, 2009; Kopf et al., 2009).

Studies of erupting mud volcanoes are exceptional. The 29th of May 2006 eruption of the Lusi mud volcano (Indonesia) provided a unique opportunity to experiment with multidisciplinary studies an erupting mud volcano from its birth. This seemingly unstoppable eruption (to date, June 2009) is an ideal event to constrain the mechanisms driving mud volcano eruptions and their association and similarities with magmatic volcanoes. Moreover, the artificial dams built around the crater provide an exceptional setting that allows sampling of fluids from the crater during the eruption. Lusi represent a real natural laboratory to explore the origin of fluids during eruption events (as opposite to common studies) and to distinguish between the possible triggers and, most importantly, the causes that lead to an eruption. Novel multidisciplinary studies that are described herein include a review of triggering mechanisms complemented with GPS monitoring, SAR interferometry, mathematical and analogue simulations. These are used to monitor and to understand the Lusi event as well as provide possible alternatives to explain the trigger of Lusi and other mud volcanoes (Fukushima et al., 2009; Istadi et al., 2009; Manga et al., 2009; Mazzini et al., 2009; Sawolo et al., 2009).

Numerous studies of offshore mud volcanoes have been completed during the last decades. This issue describes acoustic, video and sampling techniques from recently discovered mud volcano provinces in the Mediterranean Sea, Gulf of Mexico and Black Sea. Deep seismic and sidescan sonar approaches are used to define the morphology, the history of the activity of volcanoes as well as the internal structure of the feeder channel (Praeg et al., 2009; Savini et al., 2009). Detailed studies on the near subsurface, including fluid flow rates, thermal anomalies and video-sampling observations, describe the possible link between gas hydrates stability and the eruption dynamics, and give important estimate about the transport of methane to the atmosphere (Feseker et al., 2009; MacDonald and Peccini, 2009; Sahling et al., 2009).

The phenomenon of mud volcanism has been recently suggested for other planets in the solar system and in particular for Mars. Here, we describe recent studies that review the possible regions where Martian sedimentary basins might fulfil the requirements for mud volcanism and where satellite surveys reveal images similar to those observed in mud volcano provinces on Earth (Skinner and Mazzini, 2009).

Despite the numerous studies, the mechanisms controlling mud volcano eruptions are still debated. Among the most advanced and innovative approaches are the numerical modelling simulations. In this special issue are included some examples of revolutionary techniques that help to test hypotheses from the bosom of the Earth exploring the cyclicity and the parameters controlling the blasts (Gisler, 2009; Zoporowski and Miller, 2009).

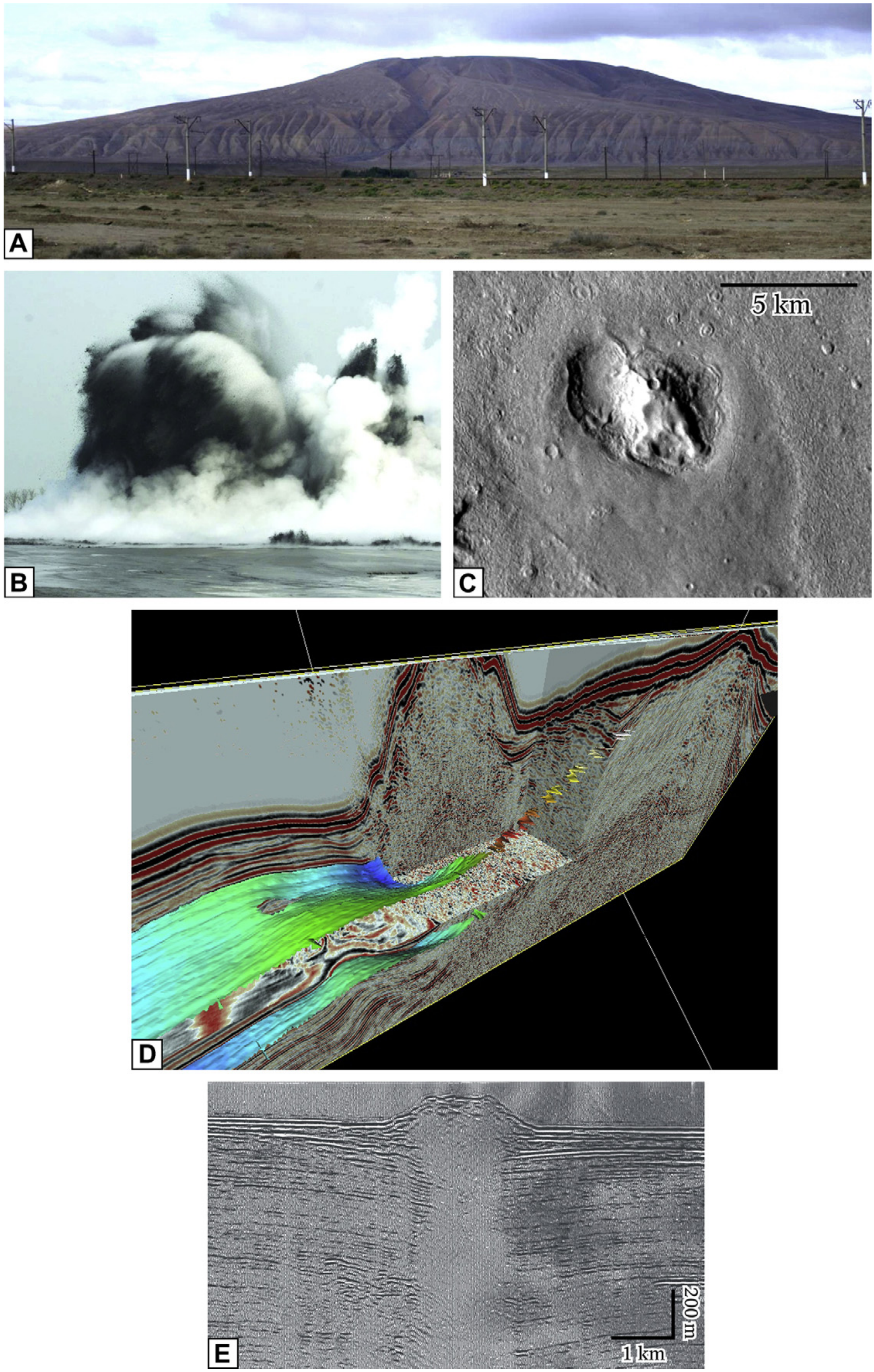

Fig. 2. Some spectacular examples of onshore, offshore and extraterrestrial mud volcanoes. (A) Tuorogai Mud volcano (Azerbaijan) is considered to be one of the biggest onshore mud volcanoes, with estimated 343 millions cubic meters of mud breccia reaching a size between 2900 and 3200 m and a height of 500 m (Jakubov et al., 1971). (B) Steam-dominated eruption of the Lusi mud volcano where mud was ejected in the air for several tens of meters. Note the trees in the background. Since May 2006 the Lusi mud volcano is erupting mud that is now covering a surface of nearly 7 km^2. The flooded area would certainly be much wider without the containment dams that are constantly build around to protect the surrounding villages. Image courtesy of the Lusi Media Center. (C) Inferred mud volcano features on the Martian surface, located in the Galaxias Fossae region. Note the moat surrounding the conical shape similar to collapse features observed on Earth and the flow towards the south east. Excerpt of THEMIS V19054019, centered at 141.0E, 38.9N, 19 m/px. (D) High-resolution 3D seismic data show the internal structure of the Mercator mud volcano and a buried diapir in the Gulf of Cadiz (after Berndt et al., 2007). Horizontal scale ca. 6 km. (E) Historic seismic profile of MSU mud volcano, Black Sea (Ivanov et al., 1992).

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