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Origin of gases and water in mud volcanoes of Andaman accretionary prism: implications for fluid migration in forearcs

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ABSTRACT

Extensive mud volcanism on the Andaman accretionary prism occurs above a complex network of faults and is caused by the convergence of the Indian plate and the Burmese microplate. Mud volcanoes of the Andaman forearc have received little attention in spite of the fact that they are one of the important features of this tectonic setting, located within an ocean basin that has one of the highest sedimentation rates in the world, and that the materials emitted by them present a unique opportunity to study the chemistry of the detachable parts of the subducting slab. In this study we present mineralogical, chemical and isotopic data for argillaceous matter (mud matrix), gases and water emitted by these mud volcanoes and attempt to understand the variations in terms of their sources and processes within the forearc. The mud matrix is composed of smectite–illite–kaolinite–chlorite–plagioclase–quartz–calcite assemblage derived both from sediments and altered oceanic crust and originates from a deep-burial diagenetic environment. The modes of $\delta^{13}C$ distributions for methane (>−42‰), ethane (>−27‰) and CO_2 (<−3‰) indicate thermogenic origin for these gases, with TOC and N of associated mud suggesting marine organic matter as the source. The water ejected at these mud volcanoes is much fresher (Cl^- = 45 to 135 mM) than seawater and its $\delta^{18}O$ (−0.2 to 2.6‰) and δD (−24 to −14‰) isotopic compositions fall well below the global meteoric water line. From their trace element contents and stable isotopic compositions we infer that the mud water is a mixture of sediment pore water (ancient seawater) and water released from dehydration of clay minerals. The $^{87}Sr/^{86}Sr$ of mud water (~0.7071) confirms the above inference and points out that altered oceanic crust plays a significant role in controlling the chemistry of water. The formation temperatures of mud ejecta, derived from mineralogical (smectite/illite), chemical (K^+/Na^+) and isotopic ($\delta D/\delta^{18}O$) geothermometers, lie in the range of 50 °C–120 °C — which corresponds to a depth zone of 2 to 6 km within the Andaman forearc. Based on all the evidences we conclude that the sampled mud volcano ejecta originate at the plate-boundary décollement zone, from the sediments and altered oceanic crust of the subducting Indian plate.

1. Introduction

Mud volcanoes (MVs) are subaerial and submarine sedimentary structures whose surface morphology resembles that of a real volcano, but on a much smaller scale. They form as a result of emission of depressurized pore water, gases and argillaceous material from deep seated sources and occur either on top of surface-piercing shale diapirs or along faults/fractures (Dimitrov, 2002; Kopf, 2002). The latter is more common in convergent margins, where lateral tectonic compression leads to rise of fluidized mud, derived from subducting materials, along the basal décollement (Hensen et al., 2004; Saffer and Tobin, 2011). The gases emitted by the mud volcanoes are generally hydrocarbon rich, with methane being the main component (Dia et al., 1999; Dimitrov, 2002; Milkov et al., 2003; Etiope et al., 2004). Molecular and stable isotopic compositions of gases suggest that majority of these MVs (>76% globally) emit thermogenic hydrocarbons, whereas the rest emit either pure microbial methane or gases of mixed origin (e.g., Etiope et al., 2008, 2009). Predominantly carbon dioxide emitting MVs are also not uncommon (Shakirov et al., 2004; Yang et al., 2004). Thermogenic hydrocarbon emitting MVs are believed to suggest the presence of petroleum source rocks beneath these structures (e.g., Milkov, 2005). A large number of MVs are indeed observed in actively producing petroleum basins, e.g., Azerbaijan, Mexico and Columbia. Recent estimates suggest that MVs are one of the significant contributors of methane to the atmospheric budget of green house gases, and hence require appropriate consideration in climate models (Dimitrov, 2003; Etiope and Ciccioli, 2009). These estimates also require regular modifications, keeping track of new discoveries of MVs and the amount of methane emitted by them (Etiope et al., 2008).

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Hydrocarbon emissions from MVs at convergent margins owe their origin to decomposition of sedimentary organic matter in response to increase in temperature and pressure due to tectonic compression (Kopf, 2002). This process also leads to compaction and dehydration of sediments resulting in release of low saline water with a mixed composition of seawater and water from dehydration of clay minerals (e.g., Bebout, 2011; Saffer and Tobin, 2011). Such waters, released at a greater depth, are believed to play an important role in the transfer of elements from the slab to the overlying mantle wedge leading to metasomatism and subsequent melting to generate arc magmas (Peacock, 1990; Girardeau and Lagabrielle, 1992). The solid phase that accompanies the fluids in MVs is known as mud breccia, which is made of clay rich mud matrix (~90% by volume) and rock clasts derived from formations through which the MVs erupt (Dimitrov, 2002; Kopf and Deyhle, 2002). Mud matrix is generally composed of variable amounts of smectite, kaolinite, chlorite, illite, calcite and quartz (Kopf and Deyhle, 2002). Molecular composition (CH_4 / (C_2H_6 + C_3H_8)) and carbon isotopic composition ($\delta^{13}C$) of gases have been widely used to decipher the mode of their origin (Etiope et al., 2007, 2009). Chemistry of water provides valuable insight into the unique dewatering process in accretionary prisms (Moore and Vrolijk, 1992; Dia et al., 1999; Hensen et al., 2004, 2007; You et al., 2004). Understanding of processes that control the composition of expelled gas, water and mud breccia in MVs at convergent margins is likely to provide much needed insight into the chemical transformation of slab material within the forearc and shed some light on the recycling of elements into the mantle at subduction zones.

The Andaman accretionary prism, located at the active convergent margin of the Indian and Burmese plates, is home to numerous subaerial and submarine MVs spreading over the entire width of the >300 km long forearc (Fig. 1). These MVs provide a unique opportunity to study and understand the defluidization processes in a forearc located within an ocean basin (north eastern Indian Ocean) that has one of the highest sedimentation rates in the world. High magnitude earthquakes along the Indonesia–Andaman subduction zone are known to trigger large scale eruptions of these MVs (e.g., Chaudhuri et al., 2011) and therefore, chemistry of the erupted material is likely to provide the much needed background information which can aid future investigations on the chemical changes (if any) linked to the depth of origin and removal pathways. Since MVs at subduction zones are generated by ascent of slab material through offscraping, they offer the only means to sample the down going plate directly and therefore, study of the expelled fluids and mud breccia in the Andaman forearc can offer insight into the chemical transformation of Indian slab materials before these are underthrusted into the mantle and participate in the production of volcanic arc magmas. It would be the first step towards characterization of the contributions of the slab to the chemical evolution of the mantle wedges in general. In this work, we attempt to achieve these objectives with the help of elemental and isotope geochemistry of gases and water, and mineralogy of mud breccia emitted by these sparsely studied MVs. We also make the first ever attempt to estimate the amount of methane emitted by Andaman MVs using gas bubble diameters and rate of bubble bursts.

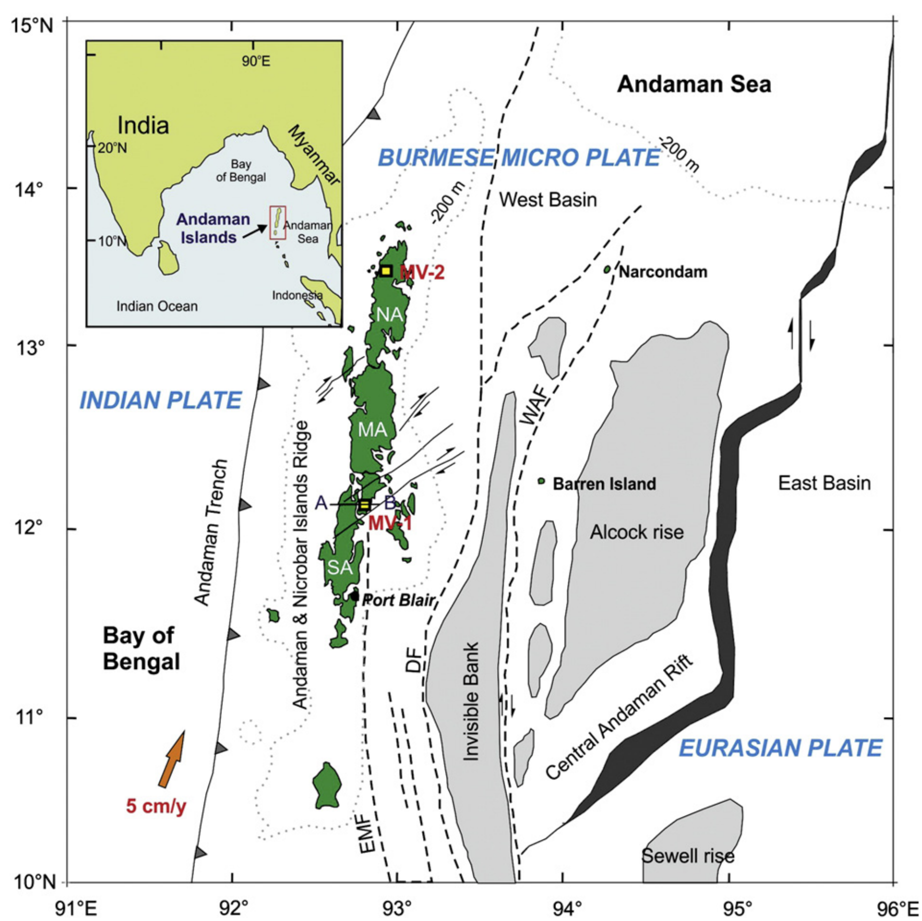

Fig. 1. Map of the north eastern Indian Ocean after Curray (2005) showing parts of the Andaman and Nicobar Islands archipelago, locations of major geological and tectonic features including different ocean basins, submarine seamount chains (grey shaded), major fault systems (dashed lines) and volcanic islands of Barren and Narcondam. The inset shows the location of the Andaman Islands in South-East Asia. The major known mud volcano fields (MV) are marked with rectangles. MA = Middle Andamans; NA = North Andamans; SA = South Andamans; EMF = Eastern Margin Fault; DF = Diligent Fault; WAF = West Andaman Fault. 5 cm/y vector on the map is the direction (and rate) of motion of the Indian plate. The line AB marks the geological profile in Fig. 2.