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The Formation and Evolution of Mud Volcano: The Significance of Scientific Research on the Earth System

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1 Introduction

Mud volcanoes are not volcanoes, the formation of mud volcanoes is the same as that of mud diapirs. It is the result of the pressure release of internal trap fluid in the strata. Because their eruption way and accumulation formed after eruption are similar to the volcanoes, hence the name (Milkov, 2000; Dimitrov, 2002; Wan et al., 2015).*

Mud volcanoes are of great significance to many aspects of scientific research on the earth system. The material erupted by mud volcanoes are mainly muddy sediments, water, gas and oil, etc., which contribute to revealing deep geological information (Dimitrov, 2002; Feseker et al., 2014). The formation of mud volcanoes is directly related to hydrocarbons accumulation and gas hydrates mineralization, so mud volcanoes can be used as important indicators for hydrocarbons and gas hydrates resources evaluation (Milkov, 2000; Abrams, 2005). Besides, mud volcanic fluid eruption activities will affect drilling, pipeline laying and other projects (Normile, 2008). Furthermore, the large amount of methane gas erupted by mud volcano will also cause greenhouse effect and climate change (Dimitrov, 2003; Kopf, 2005). Last but not least, mud volcanoes are significant symbol of neotectonic movement and are closely related to earthquake activities and faulted structure (Manga, 2012; Bonini et al., 2016).

At present, there are more than 1,800 mud volcanoes found on the earth, mainly distributed in Indonesia, Russia, Trinidad and Barbados island. Among them, Java island in Indonesia, Baku in Azerbaijan, Makran in Iran, Buza in Romania and Yellowstone National Park in the United States are more well-known (Milkov, 2000; Kopf, 2005). Mud volcanoes have also been found in the southern margin of the Junggar Basin, the East China Sea and the northern South China Sea (Wan et al., 2013, 2018).

In this decade, based on the instructions of comprehensive scientific research on the earth system and the methods of ocean and continent co-ordination, the northern South China Sea and the southern margin of the Junggar Basin mud volcanoes are systematic research. We analyzed and tested the geochemical characteristics of the eruption fluids, revealed the hydrocarbons and gas hydrates accumulation law in the mud volcanic development area, predicted the environmental benefits of mud volcanoes eruption gas and discussed the formation mechanism of mud volcano and its relationship with earthquake activity.

2 Mud volcanoes are channels for studying sediments and fluids in the deep strata

Mud deposits and groundwater from mud volcanoes eruption provide deep geological information (Dimitrov, 2002; Feseker et al., 2014). We sampled and analyzed sediments and water erupted from the Aiqigou, the Baiyanggou and the Dushanzi mud volcanoes in Xinjiang, China.

The mud volcanic sediments in the southern margin of the Junggar Basin are mainly near-source sediment. The sediment samples of the Aiqigou mud volcano are the acidic island arc source, while the Baiyanggou mud volcano sediment samples are part of the acidic island arc source and some are the felsic and basic rock mixture sources. The Aiqigou and Baiyanggou mud volcanic sediments are mainly derived from rocks formed in the continental island arc and the active continental margin environment, originated from sedimentary materials that

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have been eroded by the North Tianshan Mountains island arc in the southern of the Junggar Basin (Wan et al., 2015).

The mud volcanic fluids in the southern margin of the Junggar Basin is mainly enriched in Na^+ and Cl^-. Hydrogen and oxygen isotopes analysis indicated that the δD and $\delta^{18}O$ values of three mud volcanic eruptive vent were significantly different from those of nearby rivers. The $\delta^{18}O$ of the river water showed a significantly low value (-11.60±), while the $\delta^{18}O$ values of three mud volcanoes were relatively close, with an average value of -5 ±. δD also showed the same difference (rivers water shows high values). This study further proves that the mud volcanic eruption water is pore water from deep strata and there is no obvious correlation with surface rivers (Wan et al., 2017).

3 Mud volcano is an important basis for hydrocarbons and gas hydrates evaluation

The formation of mud volcano is directly related to the formation, accumulation and preservation of hydrocarbons. It can be used as an important indicator for the prospective evaluation of petroliferous basins in the early stage of exploration. Nearly 40% of world's oil and gas fields are found on the earth surface oil and gas seepage area (Abrams, 2005). At the same time, submarine mud volcanoes are important channels connecting deep hydrocarbons and shallow gas hydrates, deep natural gas migrates to shallow strata to formed "leakage" type gas hydrates by mud volcanoes activities. Therefore, submarine mud volcano is a living evidence of gas hydrates existence and it is also an important indicator for exploring deep-water hydrocarbons and gas hydrates (Milkov, 2000).

The main component of the mud volcano leakage gas in the southern margin of the Junggar Basin is methane, with the content ranging from 90.78% to 95.82%, with an average content of 92.81%. The estimated amount of methane erupted from a single mud volcano is about 666.20m^3 annually.The $\delta^{13}C_1$ value of the mud volcano in the southern margin of the Junggar Basin was less than -30‰, the maximum value was -38.92‰. The value of $\delta^{13}C_2$ was between -20.50‰ to -22.95‰, so the value of $\delta^{13}C_1$ was smaller than $\delta^{13}C_2$. The gas of mud volcano is pyrolysis genetic coal type gas, which is mainly derived from the middle and lower Jurassic coal series source rocks (Wan et al., 2013).

Submarine mud diapir/mud volcano can provide sufficient methane gas for hydrates formation, which is beneficial to the formation of leakage hydrates. On the other hand, the fluid activities of mud diapirs/mud volcanoes can also cause thermal anomalies in shallow strata, thereby inhibiting the formation of hydrates and even leading the decomposition of hydrates in some regions (Zhang et al., 2018). The large scale of mud diapir/mud volcano activity belt developed in the Shenhu area on the northern South China Sea, which become important channels for connecting deep hydrocarbons and shallow gas hydrates. In 2007, the Guangzhou Marine Geological Survey (GMGS) deployed the first gas hydrates drilling in this area, no hydrates samples were found at the SH5 borehole which located above the mud diapir. The current research generally believes that the failure of hydrates drilling in SH5 borehole is caused by the decomposition of gas hydrates due to the intrusion of thermal fluid in the late stage of mud diapir activity (Wan et al., 2017). We simulated and analyzed the temperature field distribution characteristics of the hydrate occurrence layer under mud diapir/mud volcanic thermal fluid activity. The simulation results indicated that the mud diapir and mud volcanic anomalous pressure fluid has obvious heat transfer effect on hydrates layers. The temperature field is characterized in point source and line source divergent distribution, respectively. Hydrates occurrence layers are more affected by the anomalous thermal fluids due to the different heat transfer coefficient.

4 Mud volcanic activity is an important indicator of neotectonic movement and earthquake prediction

Mud volcano is a prominent symbol of modern crustal movements and neotectonic movement. Mud volcano formation must have two basic elements: (1) Sufficient muddy sediments in deep layer with high pore fluid pressure (overpressure), which is the material basis and power source of mud volcano formation;(2) Dynamic mechanism to trigger mud volcanic eruption (Bonini et al., 2012; Manga,2012; Bonini et al., 2016).

The formation of mud volcanoes in the southern margin of the Junggar Basin is the result of the synthetical effects of paleogeographic-palaeotectonic sedimentary environment and regional stress field background. The thick mud layer of the southern margin in the Junggar Basin is the material base of mud volcano eruption. Furthermore, the overpressure formed by it is the power source of mud volcano eruptions (Wan et al., 2015).

The compression-torsion tectonic stress field formed by the India -Tibet collision not only further aggravates the anomalous formation pressure in this region, but also leads to the opening of Dushanzi anticline core, and the tensile fracture becomes the channel of mud volcanic activity. The frequent earthquakes in the Northern Tianshan Moutian has become the main trigger mechanism for the periodic opening of mud volcanoes.

Based on the 5.5-magnitude Wusu earthquake on May 2, 1995, the 5.4-magnitude Shawan earthquake on January 9, 1996, the 5.3-magnitude Shihezi earthquake on February 14, 2003 and the 6.3-magnitude Xinyuen-Hejing earthquake on June 30, 2012, the static stress of Horgos, Dushanzi, Aiqigou and Baiyanggou mud volcanoes in the southern margin of the Junggar Basin in Sinkiang was calculated. Combining with the observation data, we found that mud volcanoes and earthquakes showed a good correlation, the earthquake magnitude and epicentral distance are the key factors triggering the eruption of mud volcanoes. The earthquake trigger mechanism of mud volcano may not be single. Under certain conditions, earthquake can trigger mud volcano erupt or regulate mud volcano which has already erupted. Static stress may not be the main trigger mechanism for mud volcanoes, while dynamic stress may play a major role in triggering mud volcanic eruptions or regulating the eruption state of mud volcanoes that are erupting (Zhong et al., 2018).

5 The impact of mud volcanic eruption gas on the atmospheric environment

Mud volcanoes methane seepage is an important source of greenhouse gases and should be given full attention. Kopf (2005) pointed out that the methane gas accounts for more than 90% of the volume of mud volcanoes erupted gas and maintains a high speed (flow rate) through statistical analysis. It is one of an important factor causing global warming and needs to be paid enough attention. Dimitrov(2003) estimated that the total methane emissions from global mud volcanoes amounted to 5 million (Tg) tons per year.

Through the sampling and analysis of the mud volcano group in Baiyanggou Town, Wusu City, Sinkiang, the gas erupted by the active mud volcano is mainly methane, with an average content of 82.97%. The amount of methane emitted by a single mud volcano is 666.20 m^3 annually. More than 50,000 mud volcanoes have been developed in the 200 x 100 m^2 area of the study area, and the amount of methane erupted is estimated to be 3.33 x $10^7 m^3$ annually. Mud volcanoes such as Dushanzi and Horgos in the southern margin of the Junggar Basin are widely developed with huge methane emissions (Wan et al., 2013).

6 Conclusion

The combined analysis of the mud volcanoes in sea (the northern South China Sea) and continent (the southern margin of the Junggar Basin) in the past decade indicated that the formation of mud volcanoes is an important symbol of neotectonic movement and is closely related to earthquake activity. The erupted material can not only reveal deep sediment and fluid information, but also an important indicator for hydrocarbons and hydrates evaluation. The large-scale mud volcanic activities will not only cause engineering accidents, but also cause the greenhouse effect. In summary, mud volcanoes can be used as an important structure for comprehensive scientific research on the earth system.

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