Marine Geology 403 (2018) 109–122

Contents lists available at ScienceDirect

Marine Geology

journal homepage: www.elsevier.com/locate/margo

Neotectonic implications and regional stress field constraints on mud volcanoes in offshore southwestern Taiwan

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ARTICLE INFO

Editor: Shu Guo

Keywords:
SW Taiwan
Mud volcanoes
Neotectonics
Coulomb stress change

ABSTRACT

Recently discovered numerous mud volcanoes (MVs) and mud diapirs (MDs) in SW Taiwan, both onshore and offshore, show eruption lineaments suspected to be related to neotectonic processes. Spatial and temporal distribution of the MVs eruption events shows an obvious switch of the lineament orientation from NNE-, NE-, N-S-, NW- and E-W-trending in N-S direction. The mud volcanoes have experienced multi-stage eruptions, and should have occurred < 50 km from the earthquake rupture zones. Along with the weakness zones, the intrusion appears to have occurred on the possible vertical feeder dikes along N25°E and N30°W directions. In this paper, the Coulomb stress changes have been employed to calculate these earthquakes to model the relationship between the fractures and volcanoes, and the source fault geometry of a total of 15 earthquakes constructed from the Globe CMT center and USGS Earthquake and Hazard Program. According to the regional fault geometry, we built the receiver feeder dikes parameters as 330/25/0 and 25/25/0 in strike/dip/rake directions, respectively. Coulomb normal stress changes were computed for the short-time eruption analysis and strain stress changes for the long-scale eruption assessment. Our results indicate that the stress changes are sensitive to the distribution of the eruption events and the Coulomb stress change should be able to facilitate prediction of the future eruptions triggered by the seismicity activities. Finally, the schematic model we proposed well demonstrated the neotectonic effects and regional stress field constraints on the MVs eruption mechanism.

1. Introduction

A mud volcano or mud diapir is a landform created by the eruption of mud or slurries, water and gases. Worldwide, numerous mud volcanoes exploding and transporting fluids and gases like methane greatly impact the Earth's ecosystem and sometimes this would be a geohazard, damaging the petroleum exploitation and human life. Thus, many researchers have conducted both geophysical and geological work in the world. SW offshore Taiwan is an ideal place to observe and explore the mechanism of the MVs eruption. In some recent publications, Sun et al. (2010), Sung et al. (2010) and Chen et al. (2014) reported the presence of an intrusive MVs/diapir zone within the offshore region of southwestern Taiwan (Fig. 1). large amount of geophysical data including multibeam bathymetry and multichannel seismic reflections have been employed to locate the accurate distribution of the MVs, as well as their sediments and fluid components. The analysis of geochemical characteristics has proved the gas emitted and composed by both the deep inorganic CO_2 and deep-seated or shallow biogenic thermal gas. Spatially, these MVs generally occur on a linear trend, with NE-, N-S-, and E-W-strikes (Fig. 1), being clearly exposed on land and offshore and its regional iso-baths ranges from 0 to 3000 m. The larger MVs/diapir belt has been proved to be closely linked to the gas-hydrate accumulations, and some cold seepage and gas fluids even have been observed, and give us a better understanding of the mechanism of the gas-hydrate reservoirs (Aloisi et al., 2000; Sauter et al., 2006; Hui et al., 2016a, 2016b). However, previous works did not provide many clearly defined tectonic or stress constraints on the alignment of these belts or zones.

In a recent research paper, Chen et al. (2014) examined the morphology and formation mechanisms of about 13 active or inactive MVs (Fig. 1). Most of these MVs are distributed on the axis of the anticlinal structures or where the faults are deep-seated. They concluded that the vigorous upward flux of free gas is necessary for mud formation and overpressuring in sedimentary layers, and is possibly caused by tectonic activity and convergent stress between the Philippine Sea Plate (PSP)

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https://doi.org/10.1016/j.margeo.2018.05.002
Received 19 January 2018; Received in revised form 20 April 2018; Accepted 8 May 2018
Available online 12 May 2018
0025-3227/

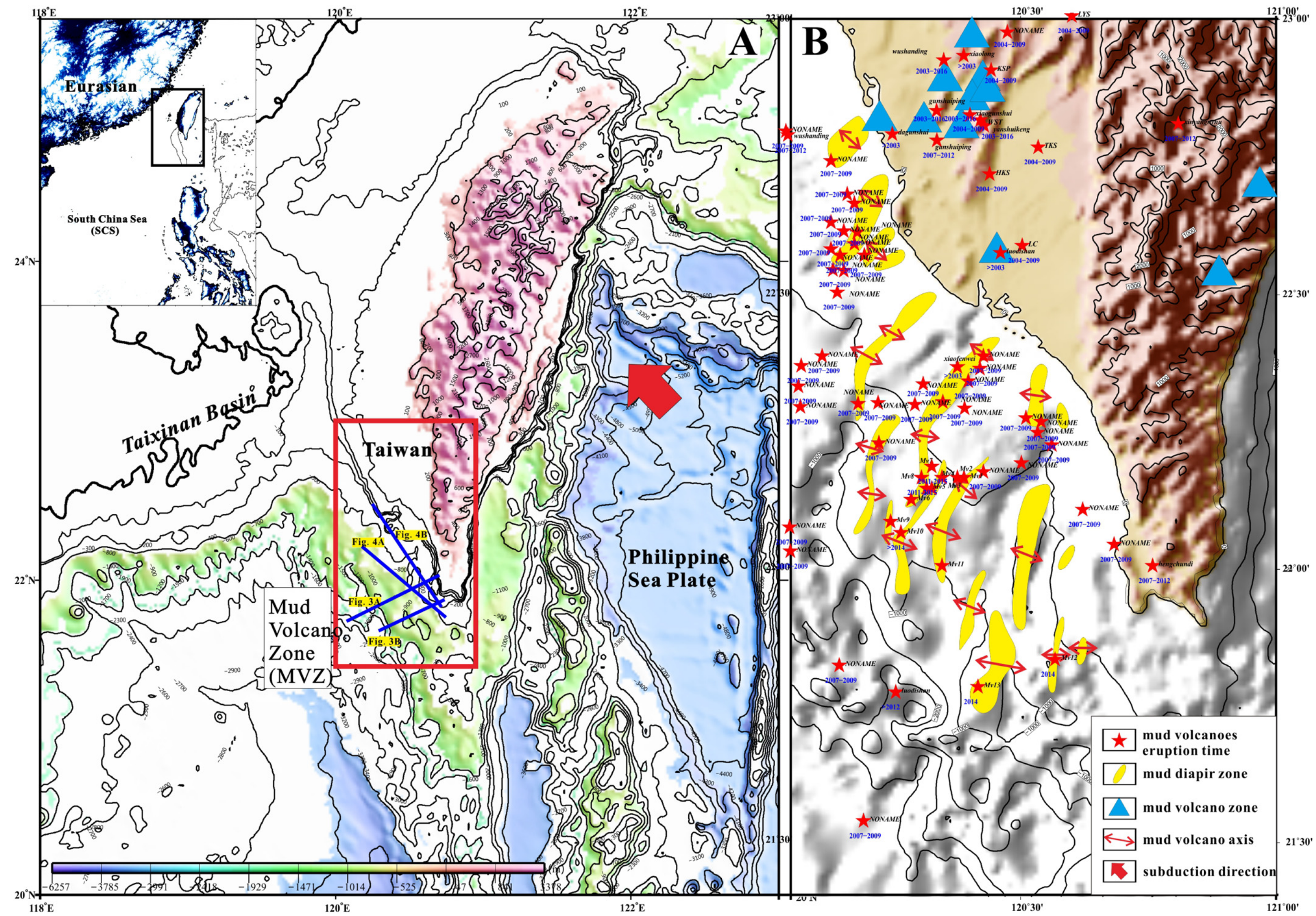

Fig. 1. A. Location map of the Taiwan study area in northern South China Sea (see inset map, top left) and (B) the recorded mud volcanoes and activity time in both inland (blue triangles) and offshore (red stars) parts of SW Taiwan. The yellow bands defined the lineament and stretching of these eruptions and the red double arrows represent the axis of these events (modified from Chen et al., 2014). Blue seismic lines have been interpreted in this paper (Figs. 3 and 4). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

and the Eurasian Plate (EP). Notably, a majority of the MVs occur on the anticlines which has a compressional regime giving a good explanation on the fluid argillaceous material extrusion (Fryer et al., 1999; Deville et al., 2003; Mazzini and Etiope, 2017). Yet, the mobilization process and linear distribution of the MVs and MDs zones still remains poorly understood.

Taiwan is located at the convergent zone where the EP subducts eastwards beneath the Luzon Arc and the PSP subducts northwards beneath the Ryukyu Arc, and numerous earthquakes have been generated along the convergence zone, both inland and offshore at the same time (Liu et al., 2000; Suppe et al., 2002; Shyu et al., 2005; Wu et al., 2008). These geological phenomena indicate that the elastic strain and stress distribution are changing under different tectonic settings of Taiwan. The purpose of this paper is to delineate the characteristics of the MVs offshore of southwestern Taiwan, by analyzing the major faults across the study area. The results suggested that the mud volcanoes have ascended through the structural pathways/feeder dikes associated with active faults and fractures (Praeg et al., 2009). In addition, mud diapir eruptions often being recorded within hours to days after one earthquake explosion, have further convinced us of this hypothesis (Sung et al., 2010; Wan and Shen, 2010). Many geophysicists have suggested that the static stress change can cause the stress shadow, that is to say, the argillaceous fluid or magma rocks will ascend when there is cap layer dilatation or deep chamber contraction. This theory has been used to assess the long-time scale eruption (Kilb et al., 2002; Nostro et al., 2005; Mellors et al., 2007). However, for the short-time scale analysis, dynamic normal stress changes are employed for evaluating the far-field eruptions feeder dikes (Manga et al., 2009; Dieterich et al., 2000; Wan et al., 2010; Bonini, 2009; Bonini et al., 2016). We obtained and interpreted a series of seismic profiles, in particular the neotectonic fault system (Fig. 1) and then calculated the Coulomb stress on about 10 earthquakes (5.5 < Mw < 7.5) from 1977 to 2017 in the Taiwan area and 9 earthquakes (Mw > 5.5) off SW Taiwan (https://earthquake.usgs.gov/earthquakes/; http://bats.earth.sinica.edu.tw/; Institute of Earth Sciences, Academia Sinica, Taiwan, 1996). A careful examination of these onshore features is that the faulting activity has caused the recent mud diapir/volcano explosion. Meanwhile, the correlation between Coulomb stress and this neotectonic faulting has documented the conjugate stress field for the Taiwan escape model. Finally, we perform the joint modeling of the faulting and the regional stress field, as well as the formation mechanism of the diapir/volcano zones and its neotectonic evolution.

2. Geological framework

The study area is a convergence area located in the northern South China Sea (SCS) continental margin, known as the Ocean-Continental Transition (OCT), which is well known for its complicated geological record. The Taiwan orogen belt is an ongoing arc-continent collision zone, that witnessed the oblique convergence history between the west PSP and the EP since the late Cenozoic (Suppe, 1981; Ho, 1986; Teng, 1990). The dynamic process in the deep crust evolution has dominated