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Mud volcanoes along the Chishan fault in Southwestern Taiwan: A release bend model

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ABSTRACT

Both land and offshore mud volcanoes have been investigated thoroughly in southwestern Taiwan in terms of morphological expression, spatial distribution, composition, and evasion flux of extruded material. The interactive relationship between mud volcanoes and their associated structures, however, has rarely been examined. This study proposes a release bend model that explains the spatial distribution and relative activity of mud volcanoes along the Chishan Fault, southwestern Taiwan. The surface movement of the Chishan Fault and mud volcano activity were monitored by GPS stations and gas flux measurements, respectively. The resistivity sub-structure of strata across the fault was investigated by the magnetotelluric (MT) method and resistivity image profiling (RIP). Analytical results support the contention that extensional activity at the release bend provides openings to fissures associated with the Chishan Fault, thereby increasing the potential for a mud volcano. The proposed model may facilitate future exploration of mud volcanoes.

1. Introduction

Recently mud volcanoes (MVs) have garnered considerable attention due to their contribution to atmospheric methane degassing from deeply buried sediments (Dimitrov, 2002; Etiope and Klusman, 2002; Kopf and Deyhle, 2002; Milkov et al., 2003). Notably, mud volcanoes are generally distributed around subduction zones and orogenic belts where compressional tectonic settings dominate (Yassir, 1987; Milkov, 2000; Kopf and Deyhle, 2002). The occurrence of MVs is strongly associated with sedimentary or tectonic loading due to rapid sedimentation, accretion, or overthrusting. The existence of thick, clayey sediment deep in a sedimentary succession also promotes the development of MVs. Taiwan is located at the collision zone between the Eurasian Plate and the Luzon Arc (Teng, 1990) and forms a typical accretionary prism in southwestern and southeastern Taiwan (Huang et al., 1997), where many terrestrial and offshore MVs exist along the tectonic structure and suture zones (Shih, 1967; Liu et al., 1997; Wang et al., 1988; Chow et al., 2001; Yang et al., 2004; Liu et al., 2006). Morphological expression and spatial distribution of terrestrial MVs in Taiwan have been investigated by Shih (1967) and Wang et al. (1988). Five zones of terrestrial MVs are grouped based on their tectonic characteristics (Shih, 1967; Wang et al., 1988). Composition and gas evasion flux from offshore and terrestrial MVs have also been investigated thoroughly in southwestern Taiwan (e.g., Gieskes et al., 1992; Yang et al., 2004; You et al., 2004). Although multiple gas sources exist for MVs, the most active MVs in Taiwan release methane-based gases that originate primarily from the deep crust. The MV fluids are characterized by high chlorine content, indicating a marine origin from actively dewatering sedimentary pore waters along major structures (You et al., 2004). Faults provide pathways for the release of gases and fluids. However, the interactive relationship between MVs and their associated structures has rarely been studied. For instance, Shih (1967) and Wang et al. (1988) merely mentioned MVs in southwestern Taiwan distributed along the Gutingkeng anticline and the Chishan Fault without discussion of their spatial occurrence and temporal activities with respect to the associated structures. The origin of extruded materials was studied by geochemical approaches, assuming that MVs are structurally controlled (Yang et al., 2004; You et al., 2004). Specifically how the structures control the activity of MVs remains uninvestigated. MVs do not occur along each of the many faults in the mudstone area in southwestern Taiwan. Instead, they appear to occur at some specific positions along a certain fault.

The MVs distributed along the Chishan Fault are probably the most spectacular and active MVs in Taiwan. They are clustered at the southern sector of the Chishan Fault, which has been recently deemed an active fault (Chang et al., 2005), playing an important role in the tectonic escape in southwest Taiwan (Ching et al., 2007). To examine

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the interactive relationship between the MVs and the Chishan Fault, this research established four continuous GPS recording stations along the Chishan Fault to monitor its activities. An automated gas gauge was also installed to continuously record gas flux of MV no. 19, one of MVs along the Chishan Fault. Both activities of MVs and the Chishan Fault were concurrently monitored by video recording, gas gauges, and GPS, and the MV-related geological structures were investigated by a geoelectrical profiling campaign. The occurrence and activities of MVs are discussed with respect to the Chishan Fault. A tectonic model is proposed to explain the formation of MVs along the Chishan Fault. The model is then discussed in the context of escape tectonics in southwestern Taiwan.

2. Regional settings

The Taiwanese mountain belt resulted from the oblique collision of the Luzon Island Arc and the Chinese continental margin in the last 5 Ma. The active Longitudinal Valley Fault separates two main geological provinces in Taiwan (Ho, 1986; Tsai, 1986). To the east, the Coastal Range comprises primarily volcanic and siliciclastic sequences of the accreted Luzon Arc–Trench system, and the area to the west comprises metamorphic and sedimentary sequences of the deformed Chinese continental margin (Fig. 1). The Central Range in Taiwan is characterized by pre-Tertiary basement and Tertiary metamorphic rocks, in contrast to the adjacent non-metamorphic fold-and-thrust belt in the Western Foothills (Ho, 1986). In the foothills, the Neogene and Early Pleistocene shallow-marine to shelf clastic sediments are affected by west-northwest-vergent folds and low-angle thrust faults. The Coastal Plain of western Taiwan and offshore areas further west are underlain by flat-lying Cenozoic sedimentary sequences. The Coastal Plain is composed of Quaternary alluvial deposits derived from the Central Range and the Western Foothills. The sigmoidal Mountain Belt runs northeast–southwest in the northern section, turns counterclockwise to northwest–southeast, then north–south in the central section, and resumes its northeast–southwest direction again in southern Taiwan. Two buried basement highs in western Taiwan, the Peikang High to the south and Kuanyin High to the north, have been identified by subsurface studies. The presence of such crustal highs probably plays an important role in the development of lateral tectonic escape in

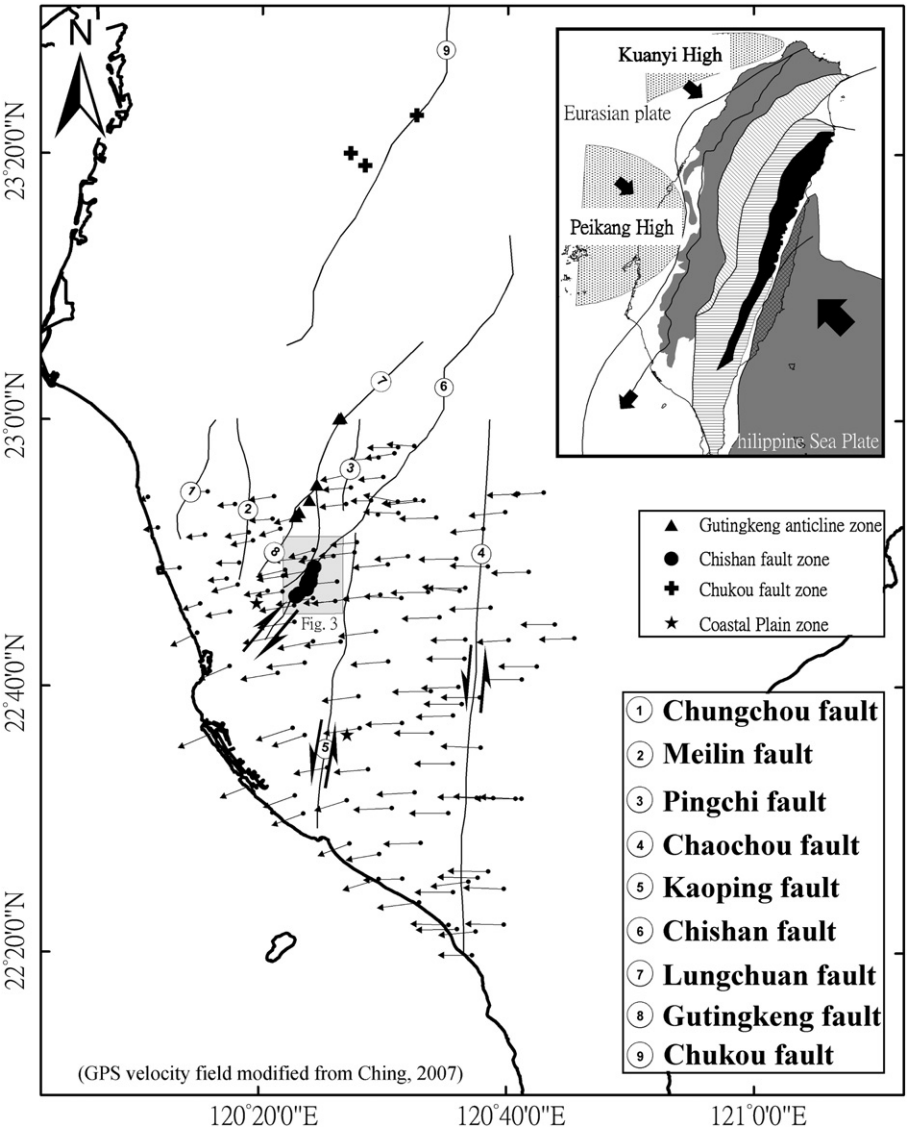

Fig. 1. The GPS velocity field in southwest Taiwan with respect to station S01R in the stable continental margin of Penghu Island in the Taiwan Strait (Ching et al., 2007). The boxed figure shows a southwestward tectonic escape in southwest Taiwan due to oblique convergence between the Luzon Volcanic Arc of the Philippine Sea Plate and the passive continental margin of the Eurasian Plate (Suppe, 1984). The velocity field indicates a counterclockwise rotation with station velocities of 44.7–55.3 mm/yr and azimuthal changes of 247–277°. The rectangle denotes the study area. Mud volcano zones in southwestern Taiwan are also shown in symbols.