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# Gravity anomalies of the active mud diapirs off southwest Taiwan

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## SUMMARY

Overpressure and buoyant effect of underlying sediments are generally used to account for the upward motion or formation of submarine mud volcanoes and mud diapirs. In this study, we process and interpret the gravity anomalies associated with the active mud diapirs off SW Taiwan. Geologically, the mud diapirs are just formed and are still very active, thus we can better understand the initial process of the mud diapirs formation through the gravity analysis. Our results show that the density contrasts of the submarine mud diapirs with respect to the surroundings are generally positive. Because the study area is in a tectonically compressive regime and the gas plume venting from the submarine mud volcanoes is very active, we thus infer that mechanically the mud diapirs off SW Taiwan have been formed mainly due to the tectonic compression on the underlying sediments of high pore-fluid pressure, instead of the buoyancy of the buried sediments. The overpressured sediments and fluid are compressed and pushed upwards to pierce the overlying sediments and form the more compacted mud diapirs. The relatively denser material of the mud diapirs probably constrains the flowing courses of the submarine canyons off SW Taiwan, especially for the upper reaches of the Kaoping and Fangliao submarine canyons.

**Key words:** Gravity anomalies and Earth structure; Diapir and diapirism.

## 1 INTRODUCTION

Piercing and deforming overlying sediments, mud diapirs (MDs) are considered as bodies of muddy sediments driven upwards by buoyancy forces arising from the bulk density contrast between an overpressured muddy mass and the overburden of greater density (Brown 1990). On tops of submarine MDs, mud volcanoes may develop, when MDs extrude sediments and reach the seabed. Similarly, Dimitrov (2002) considered buoyancy contrasts, pore-fluid pressure and tectonic force as the driving mechanisms for the formation of mud volcanoes and MDs. An assumption for a diapiric formation is the existence of a source layer of lower bulk density due to high water and gas content than the surroundings or overlying sediments, so that a sufficiently low viscosity enables sediments to flow upwards. The source of an MD was usually traced to a deep stratum of highly plastic and probably undercompacted mud or shale. The existence of hydrocarbon generation is also an important factor for the occurrence of MDs and mud volcanoes (Dimitrov 2002). Accordingly, relative to the surrounding context, the gravity anomaly associated with an MD should be negative in response to its density contrast. However, the gravity signature of the onshore Chungchou and Panpingshan “anticlinal” structures (associated with inactive MDs) in southern Taiwan displays positive anomalies (Pan 1968; Hsieh 1970, 1972; Fig. 1). Hsieh (1972) proposed that a great compaction on the plastic material of the Gutingkeng mudstone caused the diapiric folding. Although the onshore result seems to conflict with the buoyant force assumption that triggered the upward flow of an MD, one may explain that the emerged onshore MDs are no more active and were already seriously dehydrated and compacted.

MDs and mud volcanoes are generally distributed around plate convergent zones where compressional tectonic force dominated (Yassir 1987; Milkov 2000; Kopf & Deyhle 2002). The area off southern Taiwan is situated in the transition zone between the eastward subduction of the South China Sea slab along the Manila Trench and the initial collision of the Taiwan orogenic belt (e.g. Teng 1990; Sibuet & Hsu 2004; Ku & Hsu 2009). Several studies (e.g. Sun & Liu 1993; Chiu *et al.* 2006; Lin *et al.* 2009) assess map distribution of MDs off SW Taiwan. Lee *et al.* (1992) proposed that the onshore diapiric structures in southern Taiwan are the

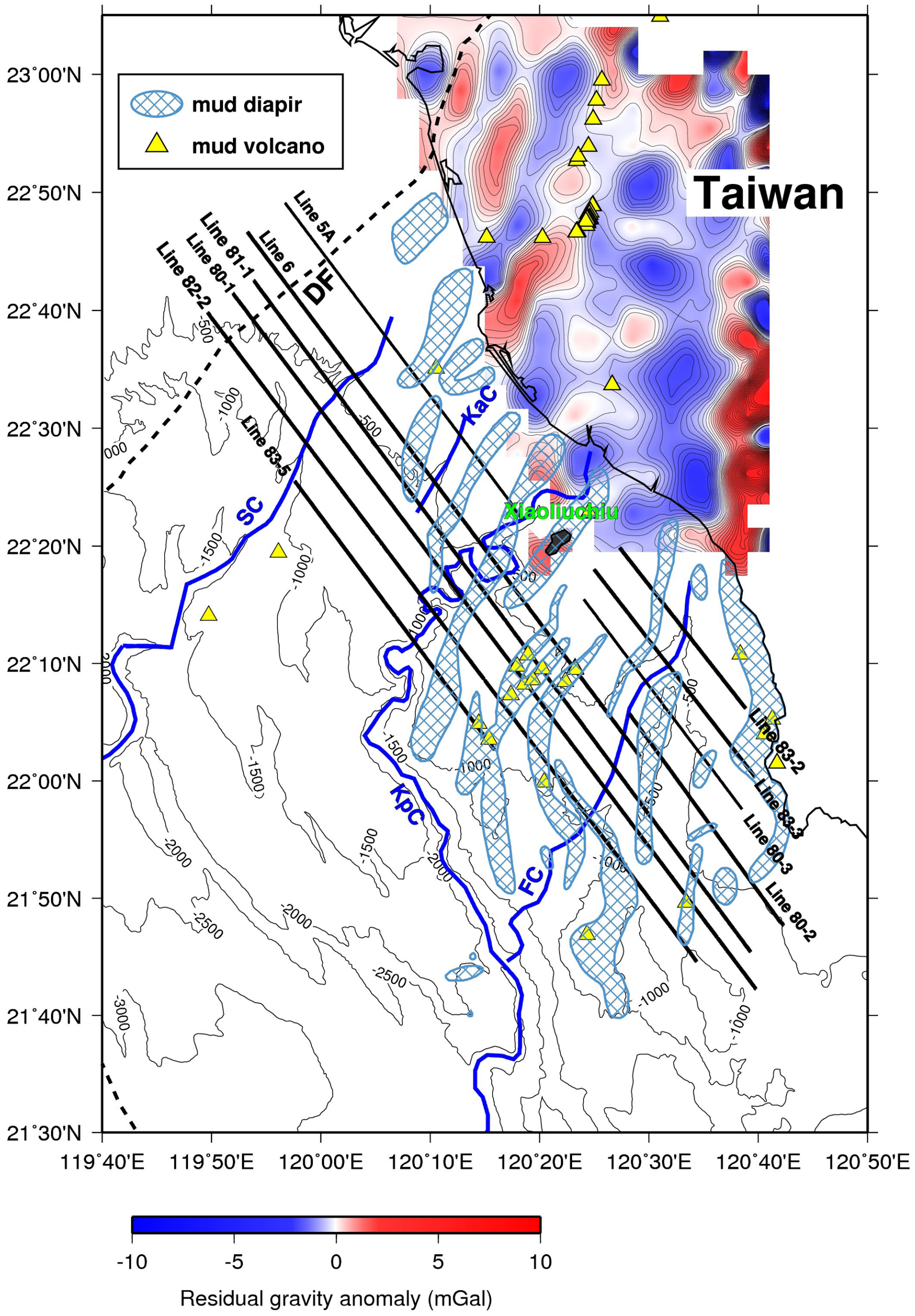

**Figure 1.** Residual gravity anomalies map onland Taiwan (Hsieh 1970, 1972). Thick blue lines indicate canyon's locations and black dashed line indicates deformation front. Thick black lines indicate newly collected gravity profiles.

continuation of the offshore MDs. Since new seismic reflection profiles have been collected off SW Taiwan recently, a more comprehensive distribution of the mud diapiric structures has been achieved (Chen *et al.* 2014). The submarine MDs off SW Taiwan represent young and active MDs; however, their gravity characteristics are unknown. In order to better understand the formation mechanism of these submarine MDs, we analyse the shipboard gravity data collected in 2012 and 2013, almost perpendicular to the mud diapiric structures (Fig. 1).

## 2 TECTONIC AND GAS HYDRATE CONTEXTS

The Taiwan mountain belt is formed due to the collision of the Luzon Arc against the Asian continental margin (e.g. Ho 1986; Teng 1990; Sibuet & Hsu 2004). The offshore area of the southern Taiwan is in an initial stage of arc-continent collision (Liu *et al.* 1997; Sibuet & Hsu 2004; Lo & Hsu 2005). Because of the convergence between the Philippine Sea Plate and the Eurasian Plate, to the east

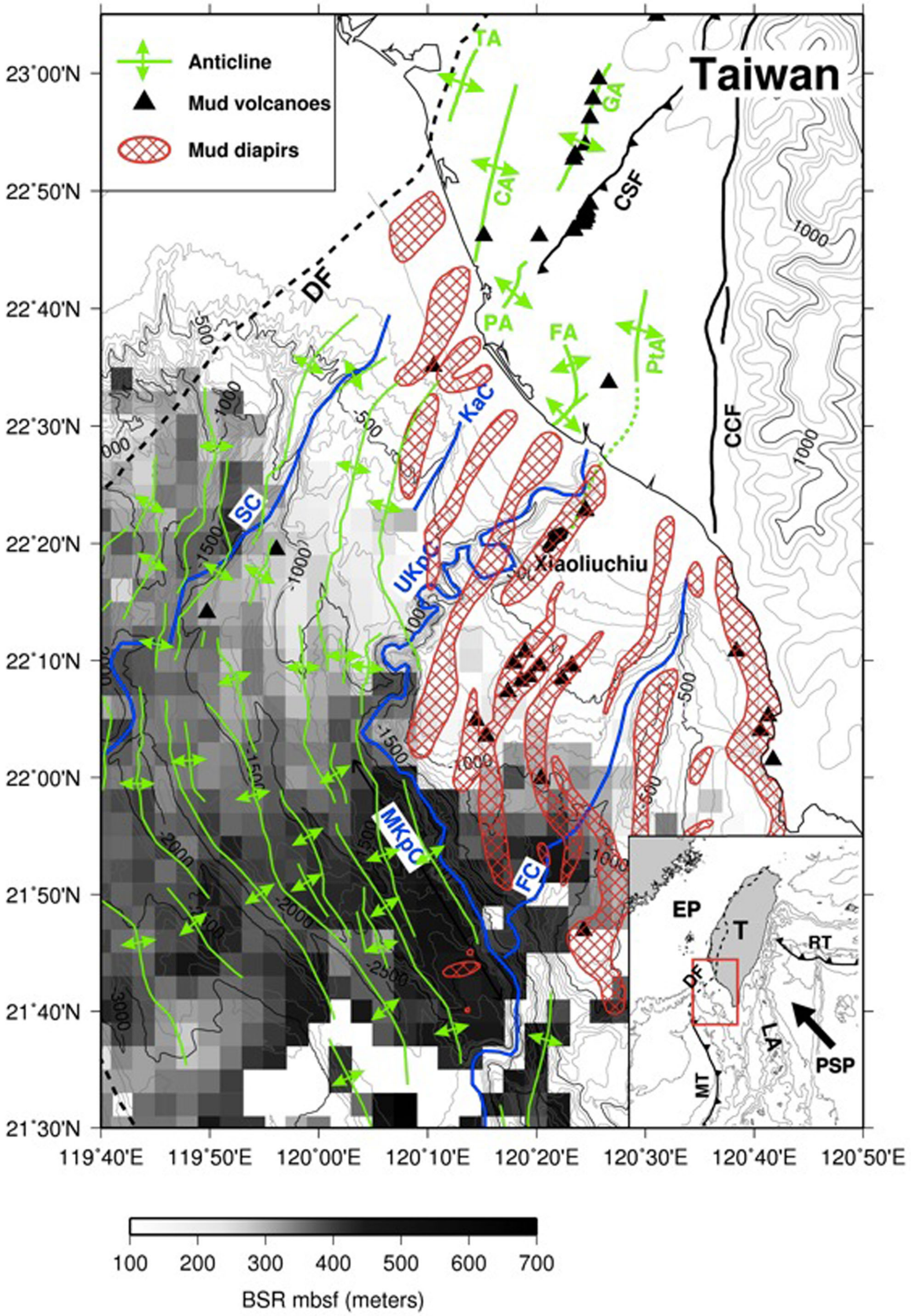

**Figure 2.** Structural map and bottom simulating reflector (BSR) depth distribution of southwest Taiwan. Structures are modified from Liu *et al.* (1997), Lin *et al.* (2009) and Chen *et al.* (2014). Blue lines indicate canyon's locations. Bottom-left shows the tectonic setting of Taiwan and two adjacent subduction systems. Vector of relative motion between the Philippine Sea plate and the Eurasia plate as black arrow. CA: Chungchou anticline; CCF: Chaochou fault; CSF: Chishan fault; DF: deformation front; EP: Eurasian Plate; FA: Fangshan anticline; FC: Fengliao Canyon; GA: Gutingkeng anticline; KaC: Kaohsiung Canyon; mbsf: meter below seafloor; LA: Luzon arc; MKpC: middle reach of the Kaoping Canyon; MT: Manila trench; PA: Panpingshan anticline; PSP: Philippine Sea Plate; PtA: Pintung anticline; RT: Ryukyu trench; SC: Shoushan Canyon; T: Taiwan; TA: Tainan anticline; UKpC: upper reach of the Kaoping Canyon.

of the deformation front, the crust has been compressed and formed thrusts and folds (Liu *et al.* 1997). A large quantity of sediments has been deposited in the foreland basin since 5 Ma in response to the uplift and erosion of the Taiwan mountain belt (Lee *et al.* 1993; Liu *et al.* 1997). The Pliocene-Quaternary foreland basin off southwest Taiwan is filled with sediments up to 5 km thick (Teng 1990; Chiang *et al.* 2004). The compressional stress has created the high pore-fluid pressure in the study area (Sung *et al.* 2010). The structures off SW Taiwan show NW–SE orientations that gradually change, from ∼22°N northwards, to NE–SW orientations (Reed *et al.* 1992),

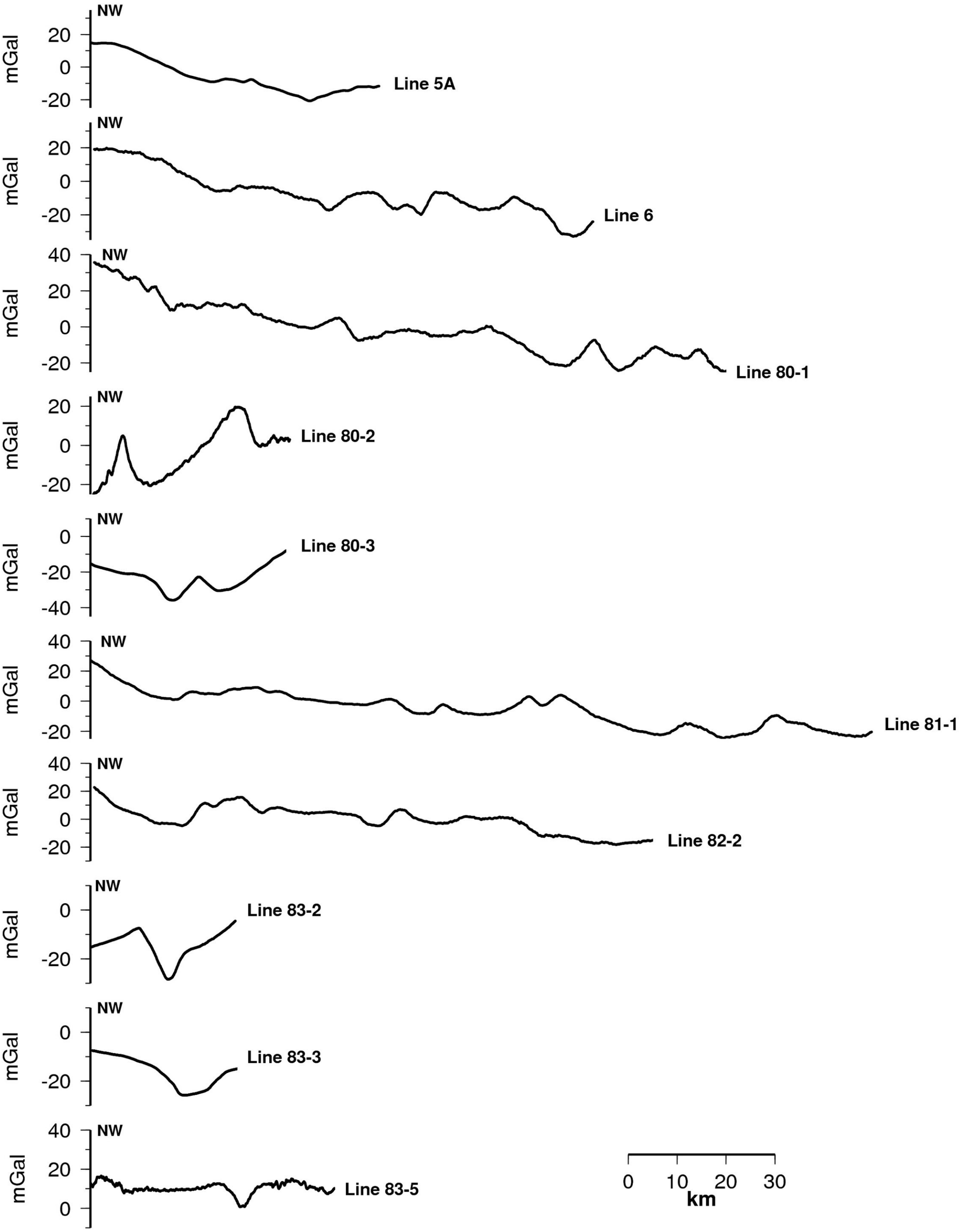

**Figure 3.** Free-air gravity anomalies along each profile.

generally following the trend of the Manila Trench and the deformation front (Fig. 2). It is noticed that the trend of the MDs is roughly parallel to the structural trend to the SW of the middle reach of the Kaoping submarine canyon and perpendicular to the plate convergence direction (Fig. 2). It indicates that the most MDs area is considerably dominated by the plate convergence and also implies that the middle reach of the Kaoping submarine canyon might be a major structural boundary.

Marine gas hydrate deposits have been suggested around the world, mostly inferred by the existence of bottom simulating reflectors (BSRs) from seismic reflection profiles. Likewise, multichannel seismic reflection profiles in the offshore area of SW Taiwan show that the BSRs are widely distributed (Liu *et al.* 2006; Fig. 2). The gas-related MDs and mud volcanoes are distributed from the onshore to the offshore area of SW Taiwan (Yang *et al.* 2004; You *et al.* 2004; Chiu *et al.* 2006; Chen *et al.* 2014). However, the

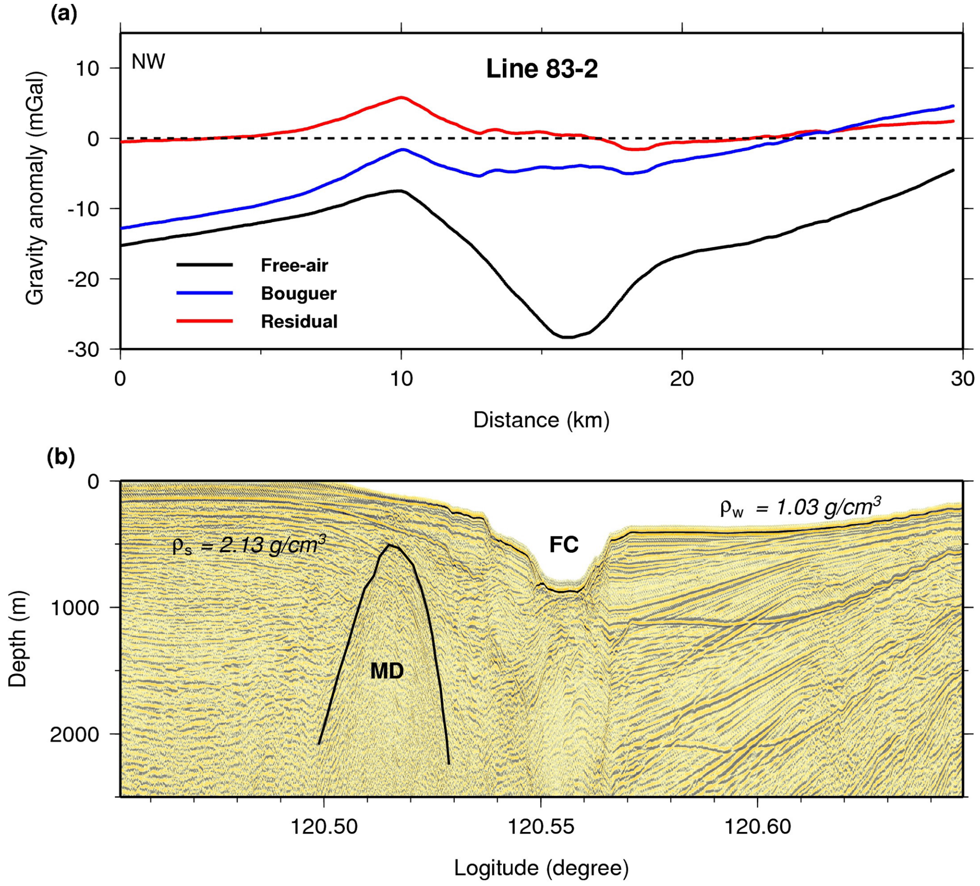

**Figure 4.** Gravity anomaly and seismic interpretation along Line 83-2 (see location in Fig. 2). (a) Black line indicates free-air gravity anomaly; blue line indicates Bouguer gravity anomaly; red line indicates residual gravity anomaly. (b) Seismic interpretation, black line indicates mud diapir's location. MD: mud diapir; FC: Fengliao Canyon.

distributed MDs and the distributed BSR areas are seldom overlapped (Fig. 2). The few overlapping area occurs in the areas of very active mud volcanoes and of the shallowest BSRs in the continental slope (Fig. 2; Hsu *et al.* 2013). In fact, the gas hydrate becomes unstable at a water depth less than 650 m and may disassociate into free gases (Hsu *et al.* 2013). Therefore, most of the MDs off SW Taiwan are formed in the context that contains high-pressured fluid in the underlying sediments.

## 3 SHIPBOARD GRAVITY DATA AND PROCESSING

Using R/V Ocean Researcher I, we have conducted the shipboard gravity survey along roughly perpendicular to the trends of the MDs tracks (Fig. 1). The data accuracy of the shipboard LaCoste & Romberg Air-Sea gravimeter is 1 mGal. After the elevation, tidal, Eötvös and latitude corrections, we have obtained the along-track free-air gravity anomalies as shown in Fig. 3. The latitude correction is based on the 1980 International Gravity Formula.

In order to enhance the gravity signal from the subsurface structures, we have to remove the gravity effect from the seawater-sediment interface and do the Bouguer correction. For that, we need to know the density contrast between the seawater and the underlying sediments. We then used Nettleton's profile method (Nettleton 1942) to determine an optimum density contrast between the seawater and the sediment for each profile. For example, the profile Line 83-2 passes through an MD structure as well as an obviously bathymetric depression (the Fangliao Canyon in Figs 1 and 4). We used different density contrasts to reduce the topographic effect; and, the optimum density contrast gives the least correlation between the gravity anomaly and the bathymetry. In Fig. 4, we obtain the density contrast equal to $1.10\ \mathrm{g\ cm^{-3}}$. This optimum density contrast is then used to obtain the Bouguer gravity anomaly (the blue curve in Fig. 4a). The optimum density contrast of each profile may be different.

To extract the gravity anomalies linked to the mud diapiric structures, the long wavelength signal in the Bouguer anomalies must be removed. For that, we determine the regional gravity anomaly for each segment by fitting a second-order polynomial in the sense of the least-squares error. We then subtract the second-order polynomial gravity anomaly (or trend) from the Bouguer anomaly and obtain the residual gravity anomaly (the red curve in Fig. 4a). Comparing the residual gravity anomaly with the corresponding seismic reflection profile, we can observe that the MD is associated with the positive gravity anomaly in Fig. 4(b). Using the same procedure, we can obtain the residual gravity anomalies associated with the MDs in this study. MDs are generally related to the positive residual gravity anomalies (Fig. 5).

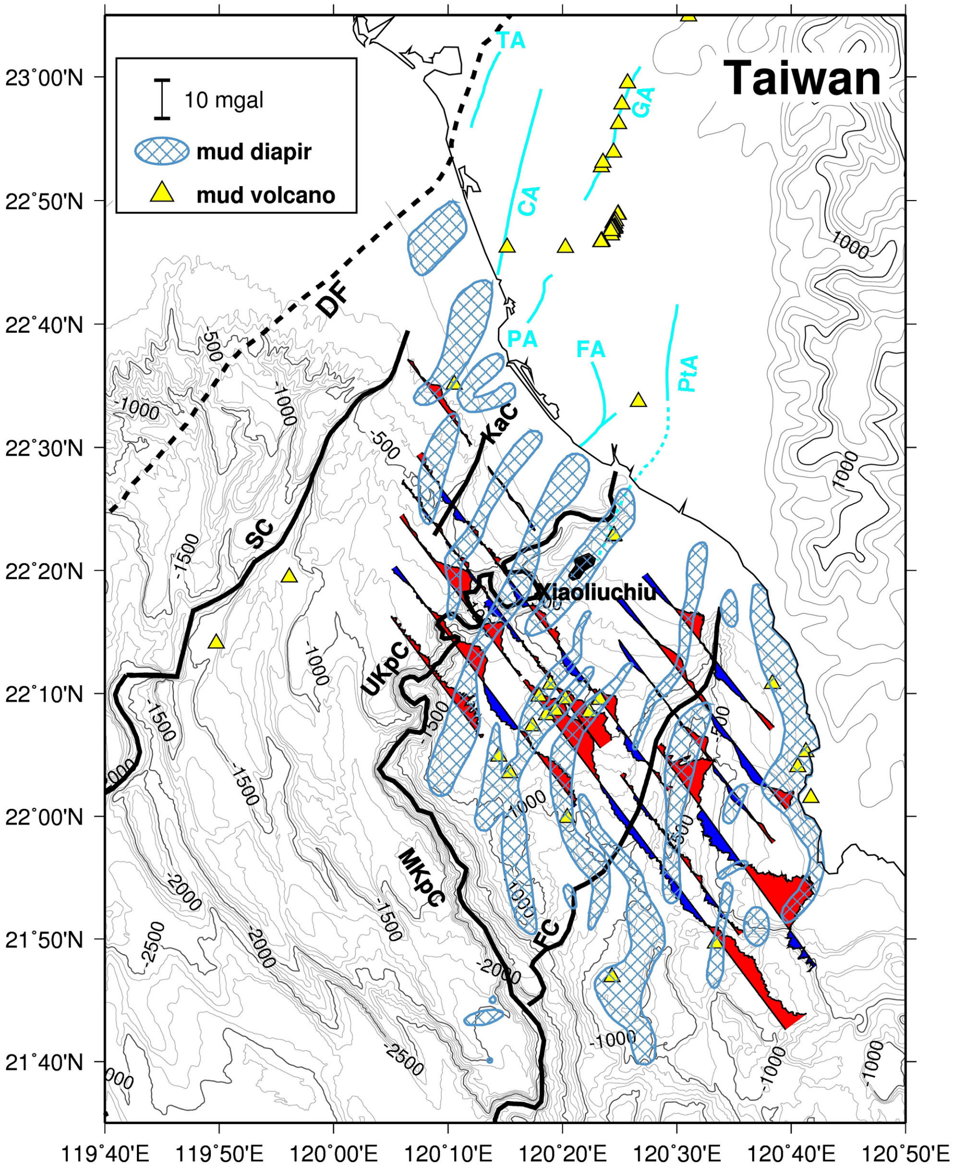

**Figure 5.** Residual gravity anomalies along the surveyed profiles. Red colour indicates positive gravity anomaly while blue colour indicates negative gravity anomaly. Heavy black lines indicate canyon's channels and black dashed line indicates deformation front (DF). FC: Fengliao Canyon; KaC: Kaohsiung Canyon; MKpC: middle reach of the Kaoping Canyon; SC: Shoushan Canyon; UKpC: upper reach of the Kaoping Canyon.

## 4 DENSITY CONTRASTS BETWEEN SUBMARINE MUD DIAPIRS AND SURROUNDING SEDIMENTS

To obtain the density contrast of each MD with respect to its surrounding rocks, we need to fit the simulated gravity anomaly with the observed data. Won & Bevis (1987) proposed an algorithm and Fortran subroutines to calculate the gravitational anomalies which result from an *n*-sided polygon in a 2-D space. Using this method to estimate the gravity anomalies, we need to provide the geometry (polygon) and density contrast of the source body. In this study, for simplicity, we assume a 2-D model to represent the mud diapiric structure, whose width and depth to top is established by the seismic profile interpretation of Chen *et al.* (2014). However, base depths of the MDs in the seismic profiles are unclear. In fact, the residual gravity signal mainly comes from the contribution of the upper portion of the MD. The bottom of the diapir generally has much less contribution in the gravity anomaly. Based on our simulations along seismic line 83-2 (Figs 4 and 6), we find that the thickness of the source will influence the amplitude width of the gravity anomaly and the gravity signal variation becomes insignificant when the thickness of source is greater than 2.5 km. In Fig. 6(a), the gravity anomaly curves calculating from the body thickness of 2.5 and 3.0 km respectively are almost the same. We thus use the body thickness of 2.5 km for each diapir. Then, adjust the density contrast of the MD, calculating the synthetic gravity anomaly to fit the residual gravity anomaly. As shown in Fig. 6(b), the optimum density contrast of $0.18\ \mathrm{g\ cm^{-3}}$ is obtained. In this study, we only

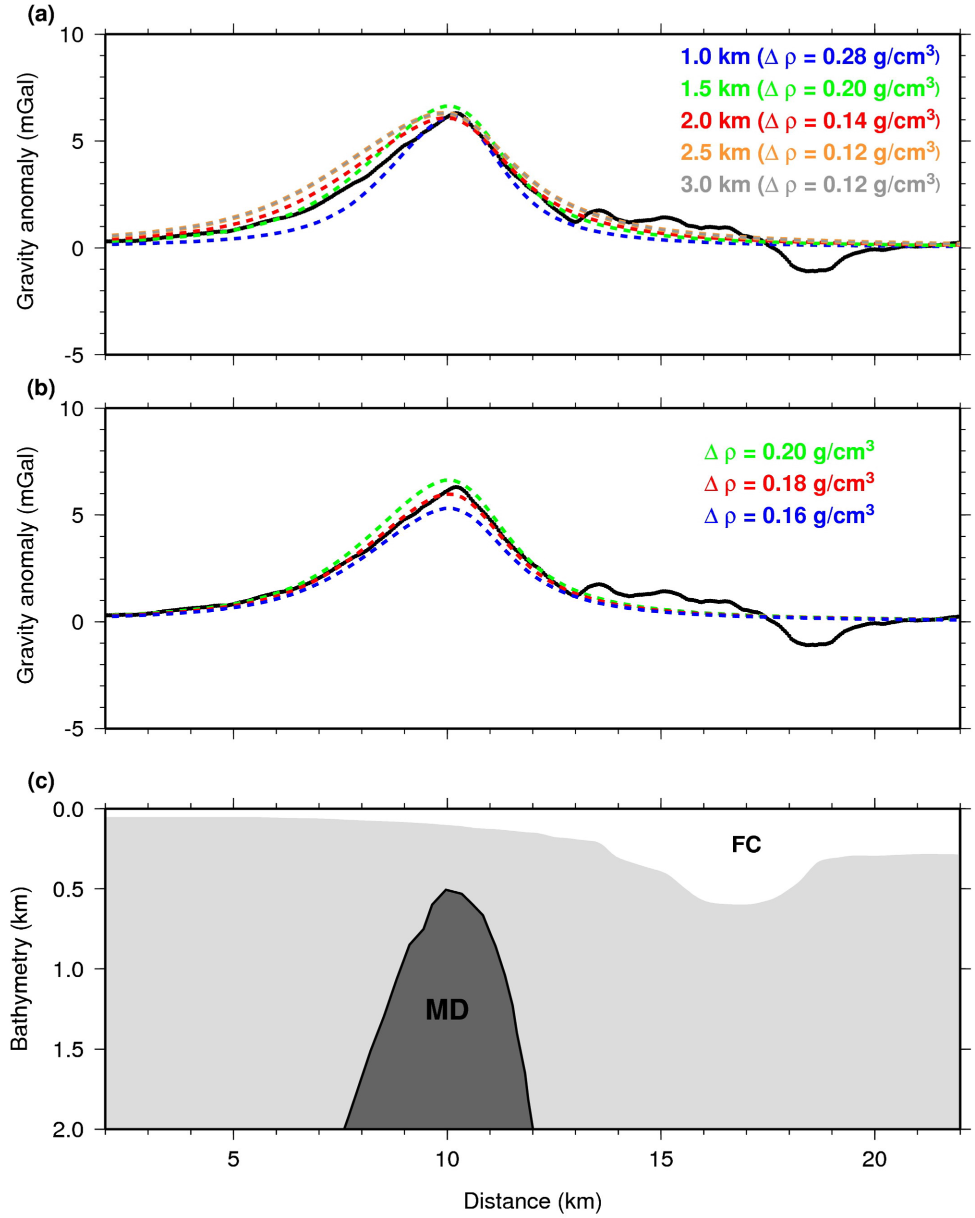

**Figure 6.** Forward gravity modelling using a 2-D model. (a) Test of different bottom depths of the mud diapir and their associated synthetic gravity anomalies. The black line indicates the observed gravity anomaly. (b) Different densities of the mud diapir and their associated synthetic gravity anomalies. (c) A 2-D model represents the mud diapir (dark grey body). MD: mud diapir; FC: Fengliao Canyon.

simulate the MDs that are clearly related to residual gravity anomalies. 24 gravity models (MDs) have been processed and 10 MDs do not reveal clearly related residual gravity anomalies. Our results of the density contrasts and the spatial distributions are shown in Fig. 7. The results show that MDs may display a variety of density contrasts; however, the mean density contrast is about 0.06 g cm$^{-3}$ as shown in the statistics (Fig. 8).

## 5 DISCUSSION

Despite the variability in appearance, the formation context of mud volcanoes and diapirs has a numbers of features in common: (1) rapidly deposited, overpressured, thick sedimentary sequences; (2) compressional tectonic environment; (3) the presence or influx of gaseous and liquid fluids to facilitate diapiric intrusion and extrusion (Kopf 2002). And these features present the area offshore SW Taiwan. Unlike salt diapirs that are triggered by buoyancy force (Jackson & Vendeville 1994), our positive gravity anomalies of the young submarine MDs off SW Taiwan do not support the buoyancy as the major force to trigger the mud diapirism. Taken into account the area off SW Taiwan is under tectonic compression and the high pore-fluid pressure of buried sediments could be an important factor for the mud diapirism (Dimitrov 2002), the formation of the submarine MDs may be described as the model shown in Fig. 9. First, some gas-bearing sediments must exist and be covered by some less porous sediments. Buoyancy force may play a significant role in the diapiric stage, but is not powerful enough and an

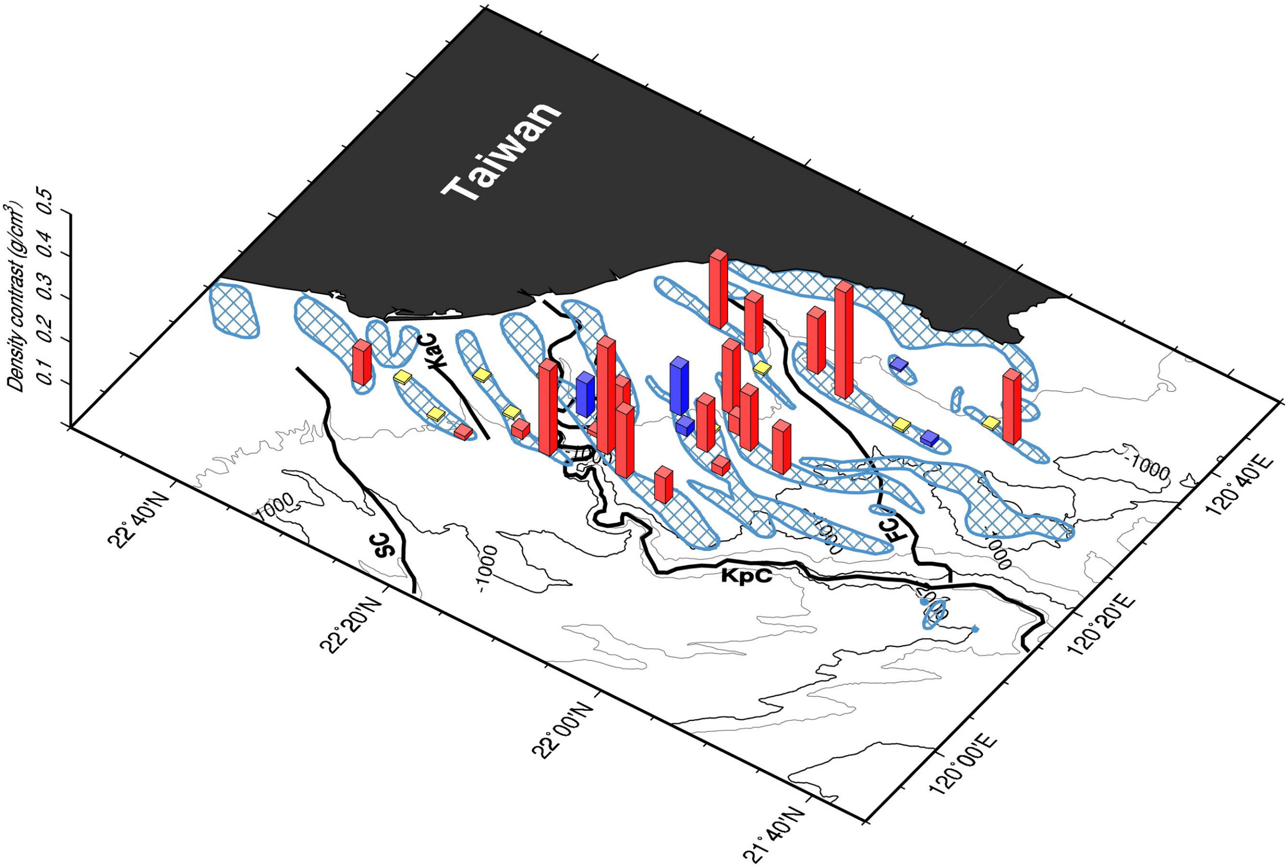

**Figure 7.** Density contrasts of the mud diapir distribution map. Red colour indicates positive density contrast; blue colour indicates negative density contrast; yellow colour indicates no clear density contrast of the mud diapirs. Thick black lines indicate canyon's locations. Thin grey and black lines indicate bathymetry contour.

additional force is needed (Dimitrov 2002). When the gas-bearing layers are compressed, the overpressured fluid and sediments may pierce the overlying sediments through a structural fault or a weak zone and form a more compact diapir (Fig. 9). According to seismic reflection profiles, Liu *et al.* (1997) proposed that many of the MDs have moved up along thrust faults. This may explain why the submarine MDs off SW Taiwan generally display NE–SW trends, roughly perpendicular to the Philippine Sea/Eurasia plate convergent direction (Fig. 2). Additionally, because the plate collisional intensity increases northwards from the area off SW Taiwan to the middle Taiwan (Lo & Hsu 2005), the submarine MDs mainly occur to the northeast of the middle reach of the Kaoping Canyon, where the tectonic compression could be large enough to trigger an MD where the pore-fluid pressure has been high in the underlying sediments.

Onshore Taiwan, the density contrasts between the rock of the inner anticline ($2.6\,\mathrm{g\,cm^{-3}}$) and surface rock ($2.1$–$2.3\,\mathrm{g\,cm^{-3}}$) are about $0.3$–$0.5\,\mathrm{g\,cm^{-3}}$ (Hsieh 1970, 1972). Lee *et al.* (1992) proposed that the onshore diapiric structures in southern Taiwan are the continuation of the offshore MDs. According to our gravity simulation results, the density contrasts of the MDs in the area off SW Taiwan are roughly smaller than $0.20\,\mathrm{g\,cm^{-3}}$. Compared to the MDs offshore SW Taiwan, the MDs onshore SW Taiwan are well compacted. Considering the tectonic background and the associated gravity anomaly features, we suggest that compaction, the degree of dehydration and the high pore-fluid pressure could be the reasons to cause density variation of the submarine MDs. However, the accurate reason needs further investigation.

The residual gravity anomalies of the young and active MDs off SW Taiwan are generally more positive than the surrounding areas (Fig. 5), which is consistent with the results of the inactive onshore MDs in southern Taiwan (Hsieh 1970, 1972). The rapidly deposited material in the Kaoping submarine canyon is fine-grained, trapped gas, and it developed overpressure sufficient to allow the material to extrude (Chow *et al.* 2001). Near the head of the Kaoping submarine canyon the Xiaoliuchiu islet is situated on top of an MD and is the only mud volcano off SW Taiwan that have emerged above sea level. The Xiaoliuchiu-related MD has a relatively higher density contrast that could explain the stiff body of the Xiaoliuchiu islet as indicated by Chow *et al.* (2001; Fig. 5). Chen *et al.* (2014) proposed that the courses of the Kaoping Canyon and Fangliao Canyon are controlled by mud diapiric intrusions. Off SW Taiwan, overall, when the canyon course hits the MDs (positive residual gravity anomaly) then the course direction changes (Fig. 5). In consequence, we interpret that not only the gravity force but also the distribution of the more rigid MDs may control the flowing courses of the submarine canyons off SW Taiwan. This phenomenon is especially obvious for the upper reaches of the Kaoping and Fangliao canyons (Fig. 5).

## 6 CONCLUSION

In southern Taiwan, the MDs are distributed from the offshore area to the onshore area. The MDs off SW Taiwan are young structures and are still active, while the onshore MDs in SW Taiwan are much old structures and almost inactive. These MDs are all situated in

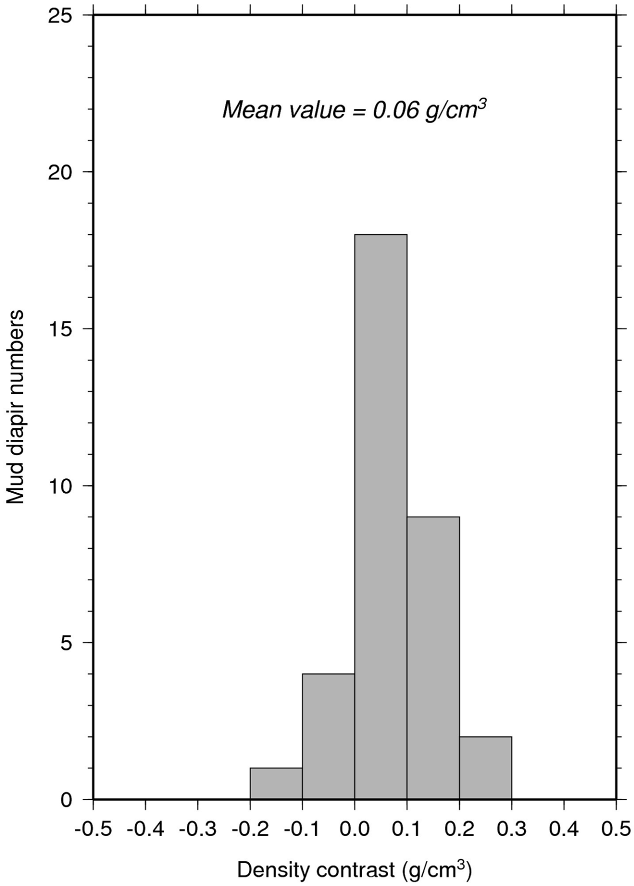

**Figure 8.** Statistical diagram of the mud diapir densities off SW Taiwan. In general, a mud diapir has a slightly higher density than its surroundings.

the tectonic compression regime where the collisional uplift of the Taiwan mountain belt is in an initial stage. On the other hand, the distributed gas hydrate off SW Taiwan is not stable at a water depth less than ~650 m, thus a large quantity of methane or $CO_2$ exist in the underlying sedimentary layers and gradually emit out of seafloor through crustal fissures or submarine mud volcanoes (Hsu *et al.* 2013). Because our gravity simulation results indicate that the MDs off SW Taiwan generally have slightly higher densities than their surroundings, we infer that the formation of the MDs off SW Taiwan is mainly due to the tectonic compression on the overpressured underlying sediments, instead of the buoyancy of the underlying sediments. The overpressured sediments and fluid are compressed and pushed upwards to pierce the overlying sediments and form MDs. The existence of the more solid MDs than their surroundings may constrain the flowing courses of the submarine canyons off SW Taiwan.

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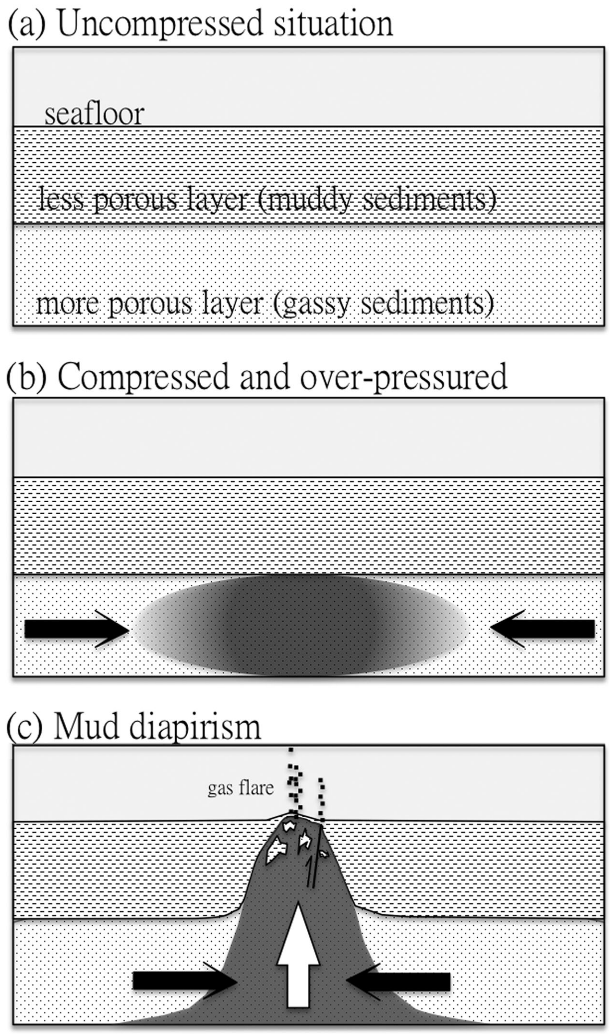

**Figure 9.** A model depicting the formation of a mud diapir. The buried gassy sediments have been compressed and the overpressured fluid forces the upward piercing, forming a mud diapir. The tectonic compaction may cause a slightly higher gravity anomaly than its surroundings.

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