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A submarine canyon as the cause of a mud volcano — Liuchieuyu Island in Taiwan

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Abstract

In this paper, based on 3.5 kHz, UNIBOOM and conventional seismic data, we propose a model for the creation of Liuchieuyu Island, a near-shore mud volcano off the southwestern coast of Taiwan. In support of this model, we also discuss the relationship between a nearby submarine canyon (Kaoping Submarine Canyon) and the mud diapirs and mud volcanoes in the region. Seismic data suggest that Liuchieuyu was originally a mud diapir with a thick, continuous accumulation of sediments on its upper surface. This sediment load or overburden prevented unconfined growth of the underlying mud diapir, while simultaneously acting as a seal that trapped gas and formed a high-pressure zone. However, Kaoping paleo-canyon eroded these overlying sediments, and the overburdening pressure was reduced. In consequence, the mud diapir rose up to the sea floor to become a mud volcano, the uppermost part of which is present-day Liuchieuyu Island. The formation of this island in the path of the paleo-canyon also diverted the channel of the canyon to its present location. © 2001 Elsevier Science B.V. All rights reserved.

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1. Introduction

In the early Pliocene, the paleoenvironment of the offshore area of southwestern Taiwan was deep marine (Covey, 1984). Large amounts of mud and silt derived from the Penglai orogeny were deposited in this region during that time, and in the Pliocene, a thick fine-grain sediment sequence was formed. However, as the arc-continent collision developed, the depositional environment in this area became shallow marine and deltaic, and the compressive tectonic forces of this still-active collision together with the unbalanced sediment load combined to trigger the mud diapirism in this region. Disturbance of the very young sedimentary strata on top of several mud diapirs suggests that they are still active (Chow et al., 1996).

Liuchieuyu Island, which is about 12 km off the southwestern coast of Taiwan (Fig. 1), is the only mud volcano in this offshore area to have emerged above sea level, even though there are many mud diapirs nearby. The island is located opposite the mouth of the Kaopinghsi River, and next to the Kaoping Submarine Canyon. Its northeast–southwest axis is about 5 km long, and its maximum width in the

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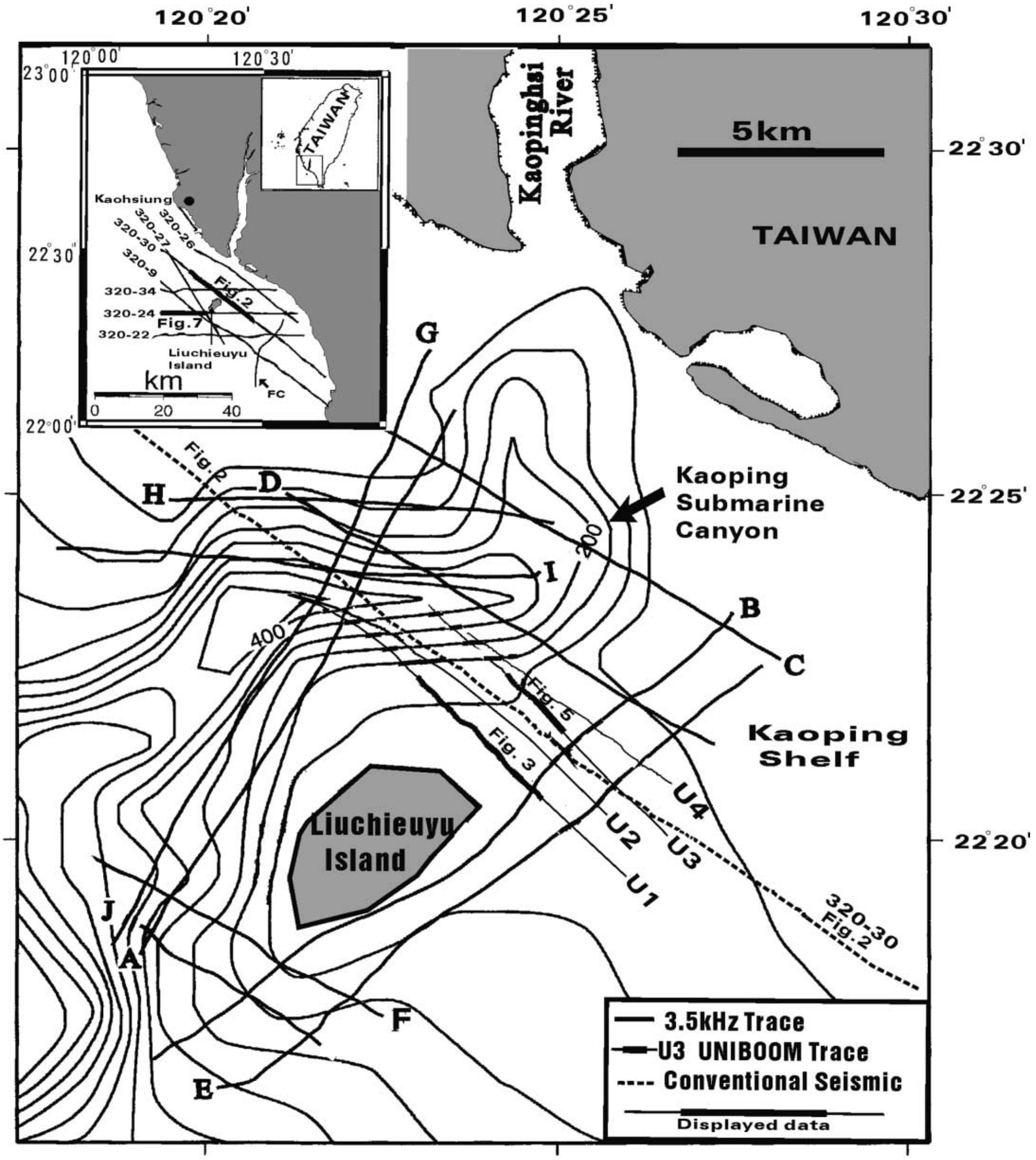

Fig. 1. Map showing the locations of Liuchieuyu Island, the UNIBOOM seismic profiles (U1–U4), the 3.5 kHz profiles (A–J) and the conventional seismic sections (inset). Bathymetric contour is at 50 m interval. FC in the inset is Fangliao Canyon. The thick lines on the UNIBOOM traces and on the conventional seismics in the inset indicate the seismic sections shown in the corresponding figures.

northwest–southeast direction is 3 km. The total area above sea level is about 10 square km. The island is composed of greenish-gray mudstone from the late Pliocene, covered with a 4–10 m thickness of reef limestone that was deposited in the Pleistocene (Shih et al., 1991).

2. Study method

2.1. Conventional reflection seismic sections

Two-channel reflection seismic profiles were acquired aboard the R/V *Ocean Researcher I* during cruise 320 (Fig. 1, inset). The total length of these profiles was about 521 km. The seismic source used was an array of three Bolt airguns with a maximum output volume of 920 in^3. (500 in^3 plus 300 in^3. plus 120 in^3.) at a pressure of 2000 PSI. Positioning was maintained using a Trimble Nav Graphic XL Global Positioning System and all the seismic data were digitally recorded. The seismic reflection data were processed using the SIOSEIS seismic data processing system.

2.2. High-resolution shallow seismic data

Since the high seismic source frequency of UNIBOOM profiles makes them very suitable for high-resolution study of shallow shelf areas, four NW–SE UNIBOOM profiles, of total length 34.8 km, were acquired northeast of Liuchieuyu Island (Fig. 1). These profiles run from the margin of the Kaoping Submarine Canyon in the NW, to the coastal shelf in the SE. The seismograph used was the UNIBOOM 230-1 (EG&G) provided by Energy and Resources Laboratories, ITRI. This UNIBOOM system provides a sonic-impulse seismic source with an energy of up to 300 J. The generation rate is 3.3 impulses per second with a main frequency range of 400 Hz ~ 14 kHz. In 300 m of water, the stratigraphic resolution is 15 ~ 30 cm, and penetration depth is 30–60 m. During acquisition, the vessel speed was kept at about four knots and a Trimble Nav Graphic XL Global Positioning System was used to maintain position and record the profile location. Data was recorded up to a two-way time of 250 ms. Since the quality of the profiles was good, no processing was done on the data set except for the bandpass filtering (low cut 800 Hz, high cut 4 kHz) used during the acquisition.

2.3. 3.5 kHz Echo profiles

During cruise 434 of the R/V *Ocean Researcher I*, about 130 km of 3.5 kHz echo profiles were acquired. These profiles were located around Liuchieuyu Island, with some of them crossing Kaoping Submarine Canyon (Fig. 1). During the acquisition of the 3.5 kHz profiles, the vessel speed was kept about at 5.5 ~ 6.5 knots, and the on-board GPS was used to record the profile location. The quality of the data was good enough not to require any subsequent special processing of the digital record.

3. Interpretation of seismics

The following interpretations of the seismic profiles are based on analytical techniques that have been described elsewhere (e.g. Sangree and Widmier, 1979; Bouma et al., 1983, 1989). Fig. 1 shows the locations of all the seismics discussed below.

3.1. Liuchieuyu mud volcanoes

To the northeast of Liuchieuyu Island, the conventional seismic section (Fig. 2) and the high-resolution UNIBOOM shallow seismic profiles (see Fig. 3) show a structureless mud volcano, about one km wide. This submarine mud volcano pierces the sedimentary cover, and the surrounding sedimentary strata dip away from it (Fig. 2 and 3). Fig. 3 also shows a crater that was formed by the natural rapid release of large volumes of over-pressured gas. Structurally, this crater conforms to the three-dimensional model used by Prior et al. (1989) to interpret a similar mud volcano crater in the Gulf of Mexico. These data further confirm that Liuchieuyu Island itself is the above-sea-level part of a large submarine mud volcano. The extent of the submarine part of this volcano is indicated in Fig. 4.

3.2. Gas seepage

The presence of gas is suggested by a small, acoustically reflective plume in the water column immediately above the crater of the submarine mud volcano (Fig. 3, Gas). We interpret this plume as representing a continuous supply of new gas bubbles from the sea bed. This feature could also represent a shoal of fish. However, its conical plume shape, its position immediately above the submarine mud volcano and the occurrence of the assumed gas-charged and over-pressured sediments below, all suggest that it represents a gas seepage.

3.3. Sea floor erosion

Sea floor erosion is common in this area. Some sea floor erosion sites are very steep and deep, resulting in gullies and canyons. However, the erosion over the

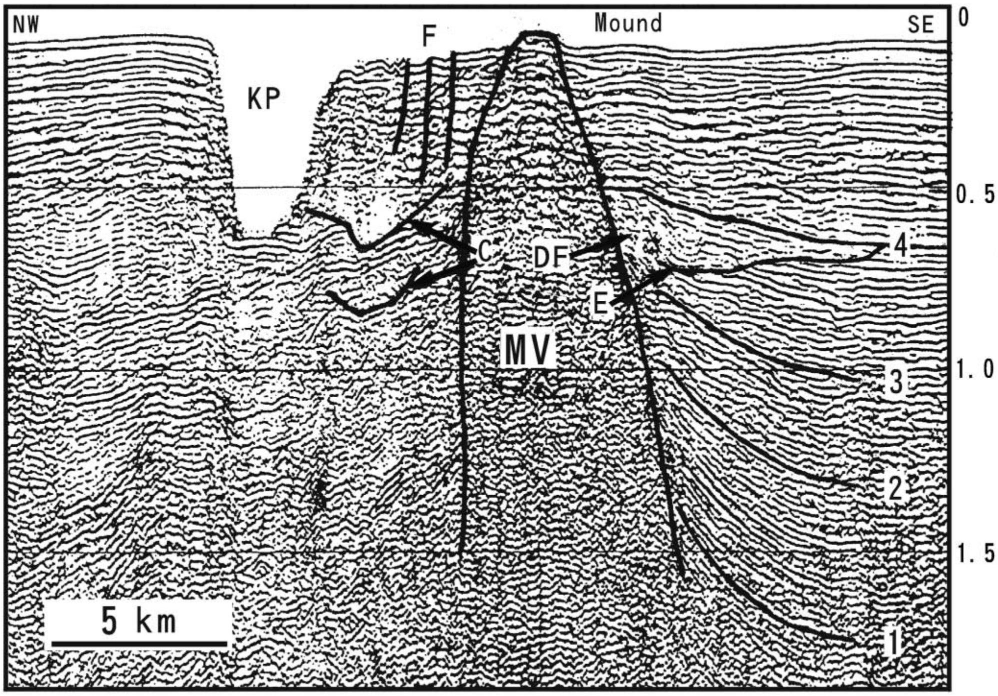

Fig. 2. Conventional seismic reflection profile 320-30 showing the Liuchieuyu mud volcano (MV) and Kaoping Canyon (KP). Structural and sedimentary features such as debris flow (DF), channel cuts (C), erosional truncation (E) and shallow faults (F) near the mud volcano can be observed. The numbers 1–4 represent sedimentary sequence boundaries of Pleistocene.

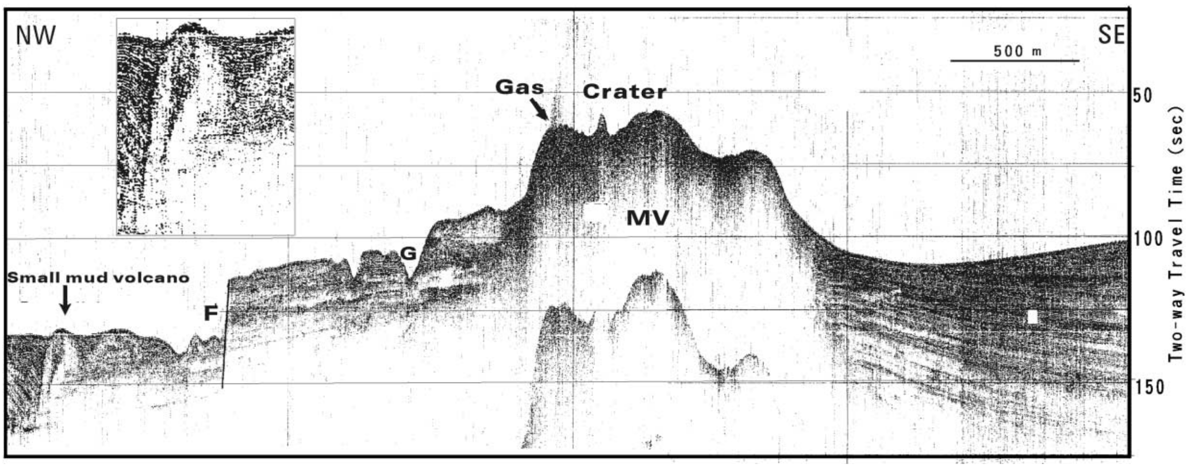

Fig. 3. UNIBOOM 1 seismic profile. MV is Liuchieuyu submarine mud volcano. Gas seepage can be observed from the top left corner of the crater. F is a fault scarp and G a gully incision. The inset shows an enlargement of the small mud volcano on the left.

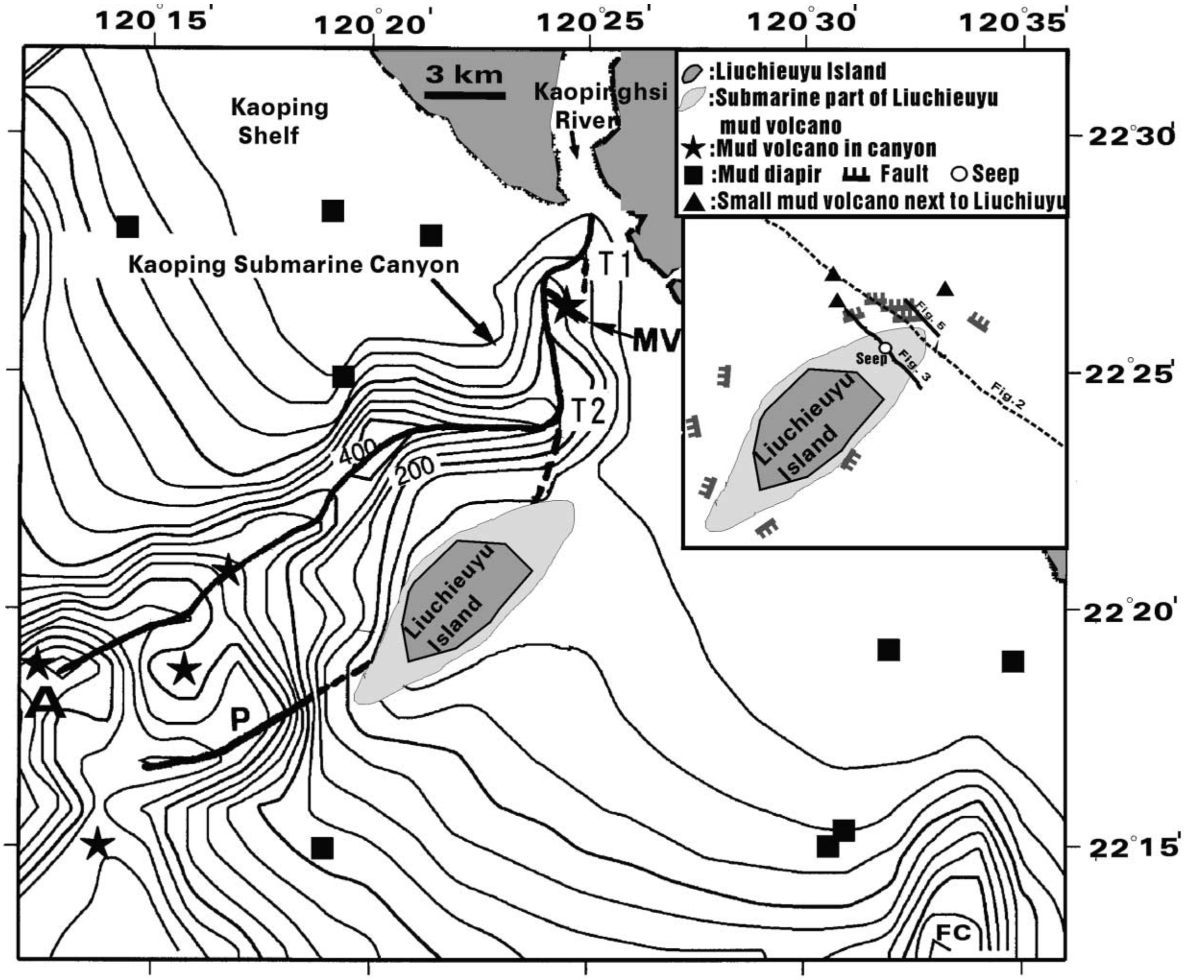

Fig. 4. Liuchieuyu Island and Kaoping Canyon. T1 and T2 mark the two bends in present-day Kaoping Canyon (thick line). MV is the mud volcano associated with bend T1. The thick dashed line indicates the route of the paleo-canyon. P indicates the area where traces of the paleo-canyon still exist. The solid squares are mud diapirs and the stars represent mud volcanoes in Kaoping Canyon. Seismic image of the mud volcano A is shown in Fig. 7. FC is part of Fangliao Submarine Canyon. The inset shows the locations of shallow faults, small mud volcanoes and displayed seismic sections around Liuchieuyu mud volcano.

top of mud diapirs in UNIBOOM seismic section 3 (Fig. 5) appears to be associated with the uplifting of the mud diapir. The overlying sediments have been removed at some time with no apparent subsequent sedimentary drape over the angular erosional surface (Fig. 5).

3.4. Faults

Many small shallow faults were found around the Liuchieuyu mud volcano. Some of these faults appear on the high-resolution UNIBOOM seismic profiles as an abrupt discontinuity in sedimentary bed reflectors that are otherwise well correlated on both sides of the fault (e.g. Fig. 5F), but fresh fault scarps can also be seen on the present sea floor (e.g. Fig. 3F). None of these faults were extended, and they were mostly located around the Liuchieuyu mud volcano (Fig. 4, inset). Following Berryhill (1987), we hypothesize that these small faults were caused by the differential loading forces that accompany mud diapirism. When a mud diapir and/or mud volcano rises, the

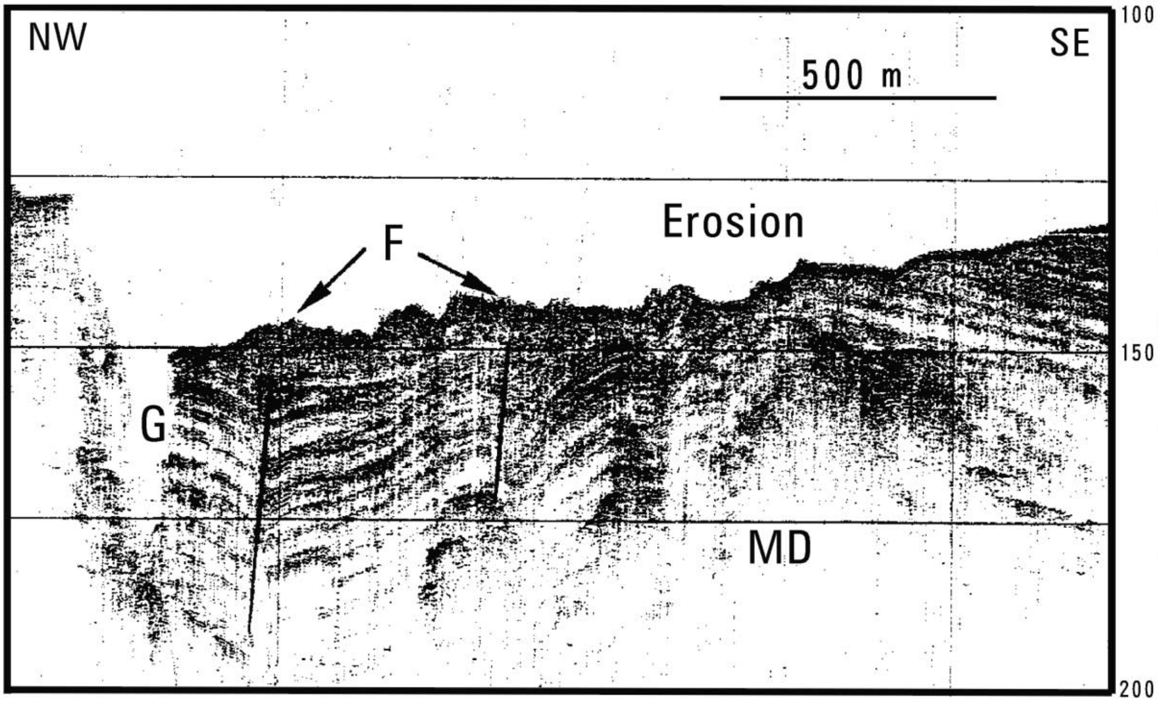

Fig. 5. UNIBOOM 3 seismic profile. Erosion and channel incision are common near the mud volcano. F are faults and G is a gully incision.

surrounding strata are also influenced by a rising force. The nearer the strata are to the diapir or mud volcano, the stronger the rising force. However, as the mud diapirs are drawn from the source beds, the beds above the newly emptied space will subside, and where the rising and subsidence forces occur adjacently, faults will occur.

3.5. Small mud volcanoes

The UNIBOOM sections also show several small mud volcanoes in the area to the northeast of Liuchieuyu mud volcano (e.g. Fig. 3). These conical structures are less than 200 m wide and about 4 m high above the seafloor, and they do not appear to be aligned with any of the faults (Fig. 4, inset). The surrounding strata are tilted and distorted. The acoustic voids beneath these small mud volcanoes appear to almost pierce the sedimentary strata, but it is also possible that these voids are artificial phenomena since the conical geometry alone might have caused a loss of seismic energy. Nevertheless, these seafloor features clearly are small mud volcanoes, and as such they are also presumably connected to the large underground part of Liuchieuyu mud volcano.

4. Bends in Kaoping Canyon

There are two distinct bends near the head of the Kaoping Submarine Canyon (Fig. 4, T1 and T2), and they are both associated with submarine mud volcanoes (i.e. MV in Fig. 4 and Liuchieuyu mud volcano). We hypothesize that the eruption of these respective mud volcanoes in the original channel of Kaoping Canyon led to the formation of both the dogleg bend near the estuary of the Kaopinghsi River (Fig. 4, T1), and the other, sharper bend towards Liuchieuyu Island (Fig. 4, T2). Similar diversions in submarine canyons have been reported elsewhere. For instance, in Fangliao Submarine Canyon, which is about 25 km to the southeast of the study site (see Fig. 1 inset, FC), an uplifted mud volcano has caused a bend in the canyon (Yu and Lu, 1995). The Var Canyon in the Liguro–Provencal Basin also has a sharp bend when the canyon runs into evaporitic

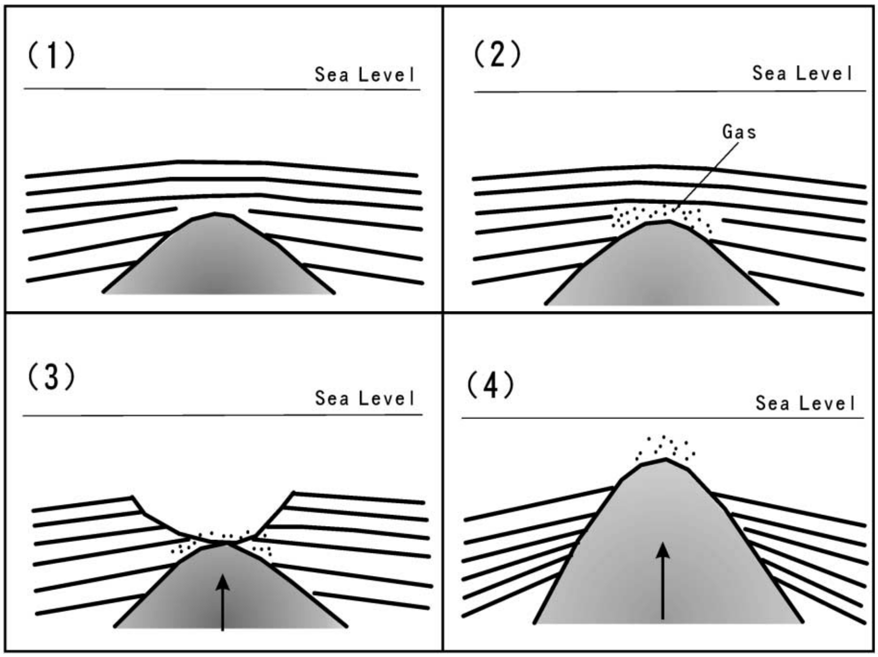

Fig. 6. Graphic representation of the origin of the Liuchieuyu mud volcano. (1) The overlying sediment load prevented unrestrained growth of the original mud diapir. (2) Gas was trapped by the overlying sediment load to form a high-pressure zone. (3) Kaoping paleo-canyon eroded the overlying sediment away, the confining load became insufficient, and the mud diapir, augmented by the high-pressure zone, grew rapidly upward. (4) The mud diapir finally made its way to the sea floor and became a submarine mud volcano.

massifs (Pautot et al., 1984). In the case of Kaoping Canyon, we further hypothesize that before it was diverted at T2, the paleo-canyon originally used to cut through the present Liuchieuyu area (see Fig. 4 for the projected channel of the original paleo-canyon). In support of this, we interpret the seismic features labelled 'C' in Fig. 2 as paleo-channel cuts incised by the original canyon. In addition, although the bathymetry of the area to the southwest of Liuchieuyu Island (Fig. 4, P) could be interpreted either as a rotational slump scar or as the ancient route of Kaoping Canyon, more evidence for the latter interpretation is provided by Wen (1991), who found traces of a paleo-canyon in 3.5 kHz seismic profiles acquired in this area.

5. Relationship between Kaoping Submarine Canyon and the origin of Liuchieuyu mud volcano

Even though there are many large mud diapirs and several small mud volcanoes in this offshore area, only the Liuchieuyu mud volcano has emerged above sea level as a large mud volcano. While various models have been proposed to account for the formation of mud diapirs and mud volcanoes in different parts of the world (see e.g. Ogawa and Kobayashi, 1993; Hedberg, 1974; Henry et al., 1996; Yu and Lu, 1995; Vernette et al., 1992; Bishop, 1978; Berner et al., 1972), it is hard to explain completely the origin of Liuchieuyu mud volcano in terms of any of the seven causes listed in Barber et al. (1986), i.e. (1) sedimentary loading resulting from rapid sedimentation; (2) tectonic loading due to overthrusting; (3) abnormally high pore pressures developed in under-compacted shale formations; (4) gas generated from organic matter within shale; (5) dehydration of expandable clays through mineralogic transformation; (6) density inversion; and (7) faulting and seismic activity.

We therefore propose here that Liuchieuyu submarine mud volcano was formed as a result of erosion of the sedimentary layers above a mud diapir and that this erosion was effected by the Kaoping paleo-canyon,

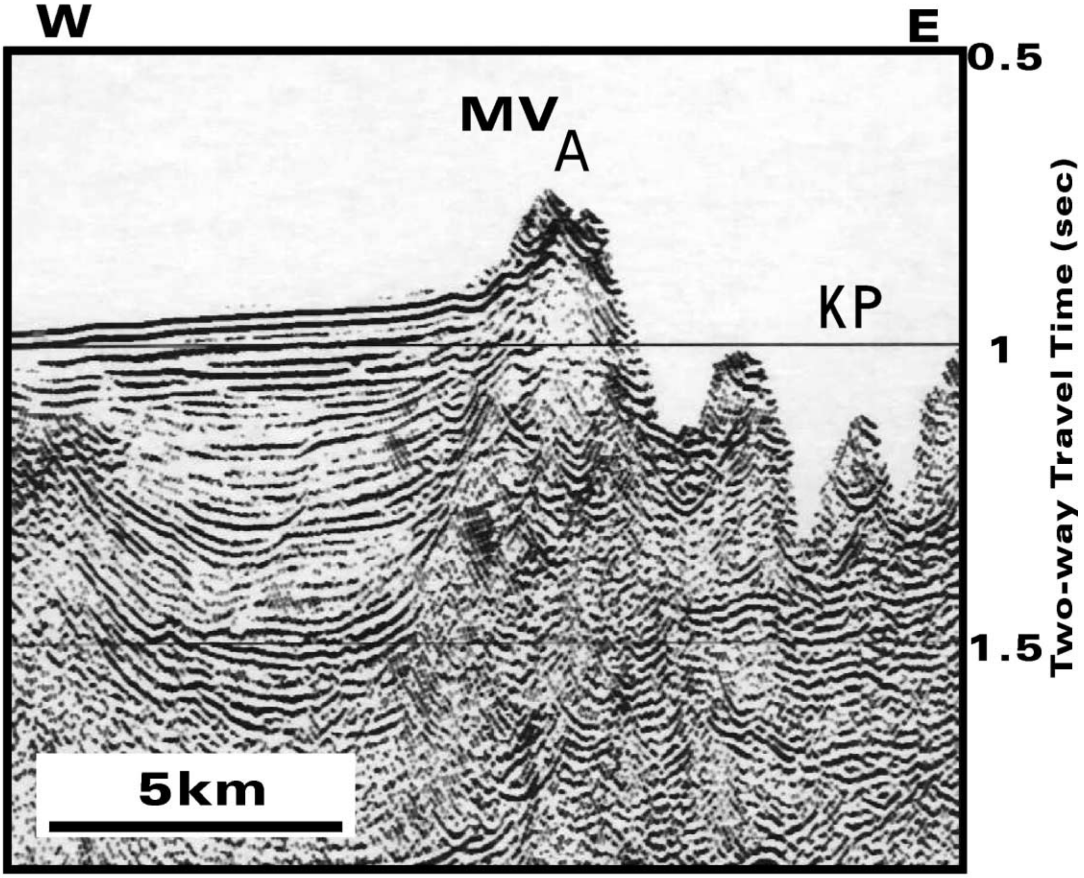

Fig. 7. Conventional seismic profile 320-24 showing a mud volcano in Kaoping Submarine Canyon. Location of the mud volcano is shown in Fig. 4.

which, as we have already argued, originally cut through the site of the present-day mud volcano. The stages of this process are illustrated in Fig. 6. Stage 1: At the initial intrusion stage, Liuchieuyu mud diapir, that is, the precursor of Liuchieuyu mud volcano, lay entirely beneath the sea floor. Layers of overlying sediment functioned as cap rock for the diapir and constrained its free growth. Stage 2: During this intrusion stage, gas migrated upward from deeper strata, but could not escape into the sea because of the cap rock. The migrating gas then accumulated on top of the diapir and a high pressure zone was formed. (Gas still escapes from present-day Liuchieuyu mud volcano as shown by the gas seepage in Fig. 3). Stage 3: The paleo-canyon (Kaoping Canyon) incised or eroded the sedimentary strata above the diapir. Stage 4: As the overlying strata eroded away, its constraining effect on the upward growth of the diapir would progressively be reduced, until finally a large amount of high-pressure gas would suddenly explode upward. Since this gas would be mixed with the mud in the mud diapir, the erupting mud diapir would thus become a mud volcano.

After the eruption of Liuchieuyu mud volcano from the bottom of the canyon, its huge mass would be sufficient to divert the paleo-canyon from its original course. Subsequently in the middle-Pleistocene, when the growing mud volcano rose near enough to sea level, a coral reef formed on its summit. This later became the present Liuchieuyu reef limestone.

In addition to the Liuchieuyu Submarine mud volcano, Mud volcanoes were also found in Kaoping Canyon (Fig. 7) and Fangliao Canyon (Yu and Lu, 1995). Although none of these other mud volcanoes were as large as Liuchieuyu, this repetitive association of mud volcanoes with submarine canyons supports our proposal that some shallow marine submarine mud volcanoes are formed when the overburdening pressure is released by canyon erosion. This model, which postulates a relationship between submarine canyons and the origin of mud volcanoes might also be applied to other mud volcanoes in various parts of the world.

6. Conclusion

From our analysis of seismic sections in the vicinity of Liuchieuyu Island, we draw two main conclusions. First, the two distinctive bends near the head of Kaoping Submarine Canyon were caused by mud volcanoes that erupted in the path of the canyon and blocked the channel. These detours in Kaoping Canyon are similar to those found in nearby Fangliao Submarine Canyon and also in the Var Canyon in the Liguro–Provencal Basin.

Second, we propose that Liuchieuyu mud volcano was formed from a mud diapir by the incision of Kaoping paleo-canyon. This model postulates that initially the overlying sediment load prevented unconfined growth of the Liuchieuyu mud diapir and simultaneously acted as a seal that trapped gas in a high-pressure zone. Subsequently, Kaoping Canyon eroded the overlying sediment away until there was no longer sufficient sediment to constrain the diapir. The mud diapir, augmented by the high-pressure zone, then grew upward through the sea floor and became Liuchieuyu mud volcano. This model is probably applicable to the formation of other submarine mud volcanoes adjacent to submarine canyons in other areas.

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