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Miocene shallow-marine cold seep carbonate in fold-and-thrust Western Foothills, SW Taiwan

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ABSTRACT

A mound-shaped authigenic carbonate buildup (50 m wide and 5 m high) occurred in the middle part of the Late Miocene shallow marine succession (the Hunghuatzu Formation) exposed along the Nantzuhsien River, SW Taiwan. The carbonate concretions are classified into four types based on morphology, which appeared to develop in upward sequence with vague boundaries: (1) flat-pipe shaped nodules: highly dolomitic small pipes or nodules subparallel to the host strata, (2) bulb-shaped nodules: discrete or combined small mesoclots with subspherical to irregular shapes, (3) mushroom-shaped concretions: large mushroom-like or irregular shaped blocks with chimney or vent structures, and (4) carbonated layers with sedimentary structures. These concretions are mainly composed of dolomite micrites, quartz, feldspar, muscovite, and clay minerals, ubiquitously interweaved with blackish brown colored low magnesium calcite (LMC) veins. Low $\delta^{13}C_{VPDB}$ values (−51.8‰ to −29.8‰) of all types of the carbonates reveal that the carbonates were mainly derived from anaerobic oxidation of hydrocarbons. Many samples are also ^{18}O-depleted ($\delta^{18}O_{VPDB}$: −11.5‰ to 1.00‰) due to the mixture with isotopically light LMC veins, likely precipitated from meteoric waters. There are numerous chemosymbiotic bivalve fossils (genus *Monitilora*? diameter 3–4 cm) in growth position just above the carbonate buildup. According to the geological and isotopic signatures, the Hunghuatzu carbonates are related to a cold seep pseudobioherm, which formed in a very shallow marine environment like tidal-flat in a passive margin setting. Exposures of the Hunghuatzu pseudobioherm may provide clues for tracking and comparing the evolution history of gas reservoir systems and hints of active tectonics of the SW Taiwan region.

1. Introduction

Cold seeps are relatively ephemeral, laterally limited but indicate a particular geological phenomenon involving discharge of geofluids, such as groundwater, natural gas, petroleum, or brine (Paull and Neumann, 1987; Parnell, 2002; Judd and Hovland, 2007). Submarine cold seeps typically occur in the continental slope to deep sea (bathyal to abyssal depths; Campbell, 2006; Chen et al., 2005; Huang et al., 2006), but also in shallow marine environments even intertidal (Dando et al., 1994; Huang et al., 2009), and have been documented from active to passive margins (Aharon, 1994, 2000; Campbell, 2006). In hydrocarbon discharging environments, characteristic phenomena due to various intensities and styles of geofluid extrusions (Greinert et al., 2001; Roberts, 2001) could develop, including mud volcanoes (Milkov, 2000), pockmarks (Chand et al., 2009; Rise et al., 1999), bacterial mats of sulfide oxidizing bacteria (SOB), endemic chemosynthetic macrofauna (e.g. Vesicomyid, Solemyid, and Lucinid bivalves; vestimentiferan tube worms; Levin, 2005; Sahling et al., 2002; Sibuet and Olu, 1998) on the seafloor, and authigenic iron sulfide framboids (Chen et al., 2007; Popa et al., 2004). Within the sulfate–methane transition zone (SMTZ) in the sediment column, pore water alkalinity would increase along with anaerobic oxidation of methane (AOM) by sulfate reducing bacteria (SRB):

$$CH_4 + SO_4^{2-} \rightarrow HCO_3^- + HS^- + H_2O \qquad (1)$$

thus methane-derived ^{12}C-enriched seep carbonate also commonly develop in these environments (Aharon, 1994, 2000; Aloisi et al., 2000; Stakes et al., 1999; Teichert et al., 2005). Seep carbonates take on several forms, such as small nodule (bleb or bulb), pipe, chimney, mushroom, block, lens, crust, and mound (Aiello et al., 2001; Campbell et al., 2008; Conti and Fontana, 2002; Nyman et al., 2010; Stakes et al., 1999). Production of cold seeps could preserve as inland seep carbonate buildup remnants with associated fossils.

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Seep carbonates are distributed worldwide and are found in rocks from possibly the Cambrian to the Quaternary (Aharon, 1994; Aiello et al., 2001; Campbell, 2006 and references therein; Campbell et al., 2002, 2008; Clari and Martire, 2000; Conti and Fontana, 2002; Dong et al., 2008; Gómez-Pérez, 2003; Johnston et al., 2009; Nyman et al., 2010). Off SW Taiwan, modern methane seeping authigenic carbonates (water depth from −800 m to −1200 m; Huang et al., 2006) and mud volcanoes (Chiu et al., 2006) were reported in the Kaoping Slope following the active folds and thrust fault lines developed by an active arc-continent collision (Lin et al., 2007).

In addition to modern cold seeps and mud diapirs found offshore SW Taiwan (Huang et al., 2006; Chiu et al., 2006; Yang et al., 2006), several fossil cold seep carbonates are also preserved onshore in southwestern Taiwan (Wang, 2006). Their origins were previously overlooked and unexplained. One of these localities described here is in the Late Miocene Hunghuatzu Formation exposed along the Nantzuhsien River near the Nangisalu (formerly Minzu) Village, SW Taiwan (Fig. 1). Based on sedimentary structures in host rocks, the existences of chimney structures and lowly diverse chemosymbiontic bivalve fauna, and analysis of stable carbon isotopic signatures, we recognized this authigenic carbonate buildup as a tidal flat methane seep remnant.

2. Geological setting

The Taiwan orogeny was resulted from an oblique arc-continent collision between the Philippine Sea Plate and the Eurasian Plate since the Late Miocene (Suppe, 1984; Huang et al., 2000, 2001). In western part of this island, the stratigraphy in the Western Foothills includes Eocene syn-rifting strata unconformably underlying Oligocene–Miocene post-rifting sequences and Pliocene–Pleistocene foreland basin deposits in a passive margin setting (Lin and Watts, 2002; Huang et al., submitted for publication), though they have been tectonically deformed in a fold-and-thrust belt during the collision. The Kaoping Slope offshore southwestern Taiwan (Fig. 1) is geologically equivalent to the Western Foothills (Huang et al., 2001), and both of them have mud-volcanoes that release natural gases within the fold-and-thrust belts (Chiu et al., 2006; Huang et al., 2006; Lin S. et al., 2007; Lin C.C. et al., 2009; Shih, 1967; Sun et al., 2008, 2010; Yang et al., 2004, 2006). There are also many active cold seep sites on the passive margin of the northern rim of the South China Sea (Chen et al., 2006; Huang et al., 2009). For example, the Yinggehai Basin in the western part of the northern SCS yields many fault-related gas seepages/pockmarks with water depths less than 50 m; the Jiulong methane reef (Chen D.F. et al., 2005; Chen Z. et al., 2006; Han et al., 2008) in the eastern middle slope of the northern SCS lays many methane-derived authigenic carbonate buildups.

Our research area is located in southern part of the Western Foothills near Nangisalu Village, SW Taiwan (Fig. 1). The lithostratigraphic rock units exposed along the Nantzuhsien River consist of finely layered siltstones to thick bedded sandstones that represent several sedimentary cycles. According to ichnofacies and lithofacies analyses, Ting et al. (1991) suggest that these strata were primarily deposited in wave and episodic storm dominated environments with the oscillatory alternations from middle shelf (*Cruziana–Zoophycos–Nereites* facie) in the lower part, inner shelf (*Cruziana–Zoophycos* facie) in the middle part, and lower shoreface (*Skolithos–Cruziana* facie) in the upper part. The sedimentary environments became shallower upsection. The main deformational features are the Chiahsien Fault, the Hsiaolin Syncline, the Ne-In Fault and the Hunghuatzu Anticline (Fig. 1; Chung, 1962; Sung et al., 2000).

The outcrop of the anomalous mound-shaped carbonate is situated in the type locality of the Hunghuatzu Formation along the middle stream of the Nangtzuhsien River (Fig. 1). The Hunghuatzu Formation contains strongly bioturbated, thick-bedded siltstone interbedded with thick-to-thin-layered fine sandstone (Ting et al.,

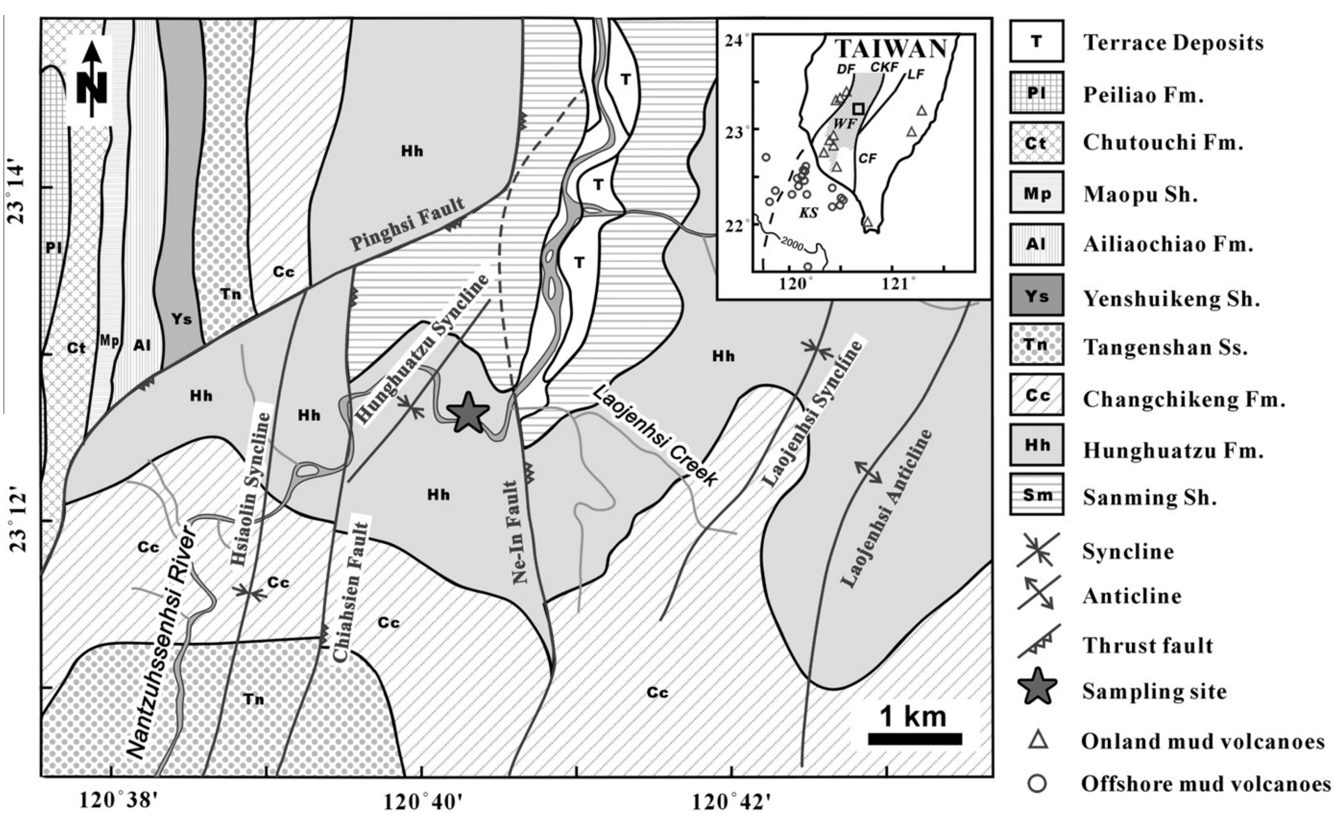

Fig. 1. Geological map of the Hunghuatzu area (after Chung, 1962; Ting et al., 1991; Sung et al., 2000) and mud volcano localities of onshore (Shih, 1967) and offshore (Chiu et al., 2006). Solid star indicates the location of the Hunghuatzu mound-shaped carbonate. WF: the Western Foothills; KS: the Kaoping Slope; LF: the Lishan Fault; CKF: the Chukou Fault; CF: the Chishan Fault; DF: the deformation front.