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APPLICATION OF CALCAREOUS NANNOFOSSILS FROM THE WANDAN MUD VOLCANO IN HYDROCARBON EXPLORATION

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Abstract

Onshore mud volcanoes in southern Taiwan are primarily formed by faulting and fold-related tectonic processes, mainly occurring along the Gutingkeng Anticline and the Chishan Fault in the southwestern plains. Beneath the Pingtung Plain, anticline structures are likely created through the upward intrusion and uplift of mud diapirs, thereby meeting the critical requirement for hydrocarbon systems—an effective trapping configuration. Such structures may evolve into efficient hydrocarbon traps, making them important targets for future exploration.

This study aims to investigate the stratigraphic origins of mudflows from the Liyushan Mud Volcano in Wandan Township, Pingtung County, Taiwan, and their potential implications for petroleum exploration. Through biostratigraphic analyses of calcareous nannofossils within the mudflows, we identified an assemblage indicative of the Pleistocene NN19 *Pseudoemiliania lacunosa* zone. Composed of fine-grained late Pleistocene sediments, this assemblage exhibits an eruption age later than NN19 and is primarily sourced from the upper Gutingkeng Formation.

Our findings reveal that the Liyushan Mud Volcano, located along a fault zone in Wandan, is capable of transporting deeper stratigraphic materials to the surface, serving as a key geological conduit. The fossil assemblage reflects a complex depositional history shaped by active tectonics and mud diapirism, driven by the ongoing collision between the Luzon Arc and the Eurasian continental margin. Ultimately, our research provides unprecedented insights into otherwise inaccessible deep strata, carrying profound impli-

cations for regional geodynamics and hydrocarbon exploration applications.

Keywords: Nannofossil identification technology, Mud Volcanoes, Hydrocarbon, mud diapir

Introduction

Mud volcanoes represent a critical geological phenomenon that facilitates the vertical migration of fluids and the expulsion of mud in sedimentary basins worldwide. Recent studies have further elucidated that their formation is primarily driven by overpressure conditions generated within clay-rich, organic matter–bearing sediments. These conditions result in the widespread development of mud volcano complexes in both marine and terrestrial settings, underscoring their significance in understanding basin dynamics and hydrocarbon systems (Lin, 1965).

Understanding the processes underlying mud volcano formation not only provides valuable insights into subsurface fluid dynamics but also plays a significant role in hydrocarbon exploration. In southwestern Taiwan, the geological environment is exceptionally complex due to marked lithological variations and the absence of distinct marker horizons. These factors challenge traditional ithostratigraphic methods for stratigraphic subdivision and correlation, making it difficult to accurately characterize the region's stratigraphy. Additional studies (Ruppel, & Butler, 2004; Kim et al., 2021) emphasize that the intricate interplay between lithological heterogeneity and tectonic deformation in southwestern Taiwan further hinders conventional lithostratigraphic approaches. Such challenges necessitate the integration of biostratigraphic and geophysical methods to resolve the stratigraphy more accurately and to enhance hydrocarbon prospectivity assessments.

Previous studies indicate that the sediments erupted by mud volcanoes in southwestern Taiwan primarily originate from the Gutingkeng Formation and its overlying strata (Lin, 1965). Furthermore, research on the petroleum systems of the Chianan Foreland Basin has revealed that mud volcano complexes along the Gutingkeng Fault and in the Wandan area of Pingtung contain thermally mature oil and gas (Oung, 2003). This evidence is corroborated by basin-scale fluid flow models and geochemical analyses confirming the thermal maturity of hydrocarbons in these mud volcano complexes, reinforcing their significance in regional petroleum systems.

These findings underscore the substantial potential of mud volcanoes as key components in hydrocarbon systems. They suggest that mud volcanoes may act as conduits for deeper fluids and hydrocarbons, facilitating migration and potentially concentrating resources in structurally complex areas. In this context, the presence of abundant calcareous nannofossils in the erupted sediments offers a promising alternative These rapid evolutionary rates and extensive biogeographic distributions of calcareous nannofossils have been corroborated by high-resolution SEM analyses and geochemical data, further reinforcing their utility in refining stratigraphic models remarkably. (Bown, 2002; Pringle, 2005; Sims & Baldwing, 2007).

This study aims to integrate field data and micropaleontological analyses to elucidate the role of mud volcanoes in influencing hydrocarbon accumulation and migration. By addressing these challenges through a comprehensive, multidisciplinary approach, we seek to enhance our understanding of the geological processes that govern mud volcano formation and to improve hydrocarbon exploration strategies in southwestern Taiwan. The integration of high-resolution biostratigraphy with structural and geochemical data is expected to yield new insights into the petroleum system dynamics of this region.

Literature Review

Conduct a literature review on mud volcanoes, calcareous nannofossils, hydrocarbons, mud diapir and in relation to the research topic and objectives.

Mud Volcanoes

The formation of mud volcanoes is primarily driven by the interaction of water within subterranean rock formations and sediments under high pressure and elevated temperatures, resulting in the generation of pressurized mud. When this mud ascends through structural weaknesses or fractures in the strata, accompanied by the release of gases, a mud volcano vent is formed. These vents typically exhibit conical or crater-like morphologies, with their size and shape varying depending on geological conditions (Wan et al., 2021).

Mud volcanoes are a geological phenomenon characterized by the expulsion or seepage of subsurface mud, gases, and solid materials through fractures or openings in the Earth's crust. They are commonly found in tectonically active regions and have been identified across various locations worldwide. Although their activity resembles that of conventional volcanoes, the eruptive materials of mud volcanoes primarily consist of mud and gases rather than magma or lava (Shnyukov et al., 2020) (Figure 1). Recent studies have extensively explored the role of mud volcanoes in sedimentary basin evolution, focusing on their geomechanical and fluid dynamic provide robust scientific insights into the genesis and evolution of the Wandan Mud Volcano. According to Guliyev et al. (2023), mud volcano systems in the South Caspian Basin exhibit a strong correlation with hydrocarbon systems, breccia is extruded (Figure 1). The typical cross-sectional structure of a mud volcano. mud volcano from one major funnel called central or feeder channel. (Dimitrov, L. I. 2002). where geodynamic processes and structural evolution not only influence hydrocarbon migration but also serve as crucial indicators for deciphering sedimentary environments. As a representative geological feature, the Wandan Mud Volcano hosts abundant calcareous nannofossils, which record paleoenvironmental fluctuations and reflect the distribution and deposition of organic rich layers.Variations in the morphology, diversity, and spatial distribution of these calcareous nannofossils enable the reconstruction of past environments, allowing for the delineation of potential source rock locations and providing key indicators for hydrocarbon accumulation.

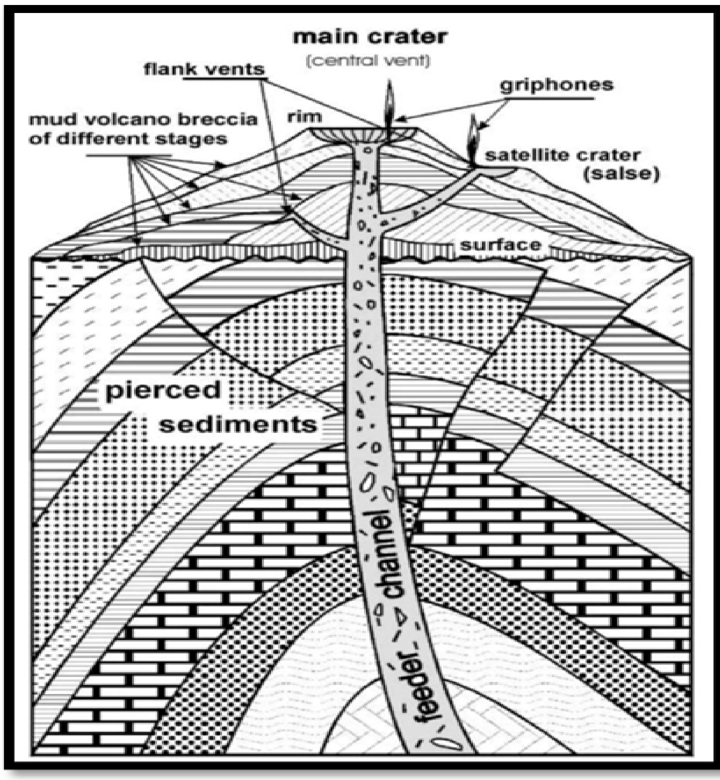


Figure 1.

Furthermore, existing literature highlights that mud volcano conduits frequently serve as primary pathways for deep-seated fluid migration to the surface, making them critical to understanding hydrocarbon migration and accumulation mechanisms (Guliyev et al., 2023). calcareous nannofossils identification techniques, researchers can precisely analyze the provenance and genesis of sediments within mud volcanoes, thereby revealing the dynamic

evolution of regional sedimentary environments. This method is widely employed in hydrocarbon exploration, as it enhances exploration efficiency while mitigating risks associated with resource development.

According to previous research, the integration of seismic data, well logging, and geochemical analyses has significantly enhanced the efficacy of calcareous nannofossils as paleoenvironmental indicators, assisting in the determination of source rock distribution and hydrocarbon migration pathways. Collectively, the calcareous nannofossils within the Wandan

Mud Volcano offer unique advantages in reconstructing paleoenvironmental conditions, defining depositional parameters, and predicting hydrocarbon migration mechanisms. These findings not only advance our understanding of mud volcano formation and development but also provide critical scientific and technological guidance for future hydrocarbon exploration. The results strongly affirm the importance and practical utility of calcareous nannofossils identification in petroleum geology and resource exploration.

Calcareous Nannofossil Identification

Calcareous nannofossil identification techniques play a pivotal role in hydrocarbon exploration, particularly within sedimentary basins and mud volcano systems. In the fields of geology and Earth sciences, micropaleontological methods are employed to analyze and identify minute fossils often remnants of microorganisms such as microalgae, foraminifera, and algal spores. Measuring only micrometers to millimeters in size, these fossils require high-magnification microscopy for observation. Successful identification thus demands extensive expertise in recognizing various morphological and structural traits among diverse microorganisms. Despite their minuscule scale, these fossils have been instrumental throughout Earth's evolutionary history. Research by (Asuaiko et al. 2022) demonstrates that different types of calcareous Nannofossils can serve as indicators of depositional environment variations, thereby influencing hydrocarbon reservoir conditions. In addition to providing critical insights into stratigraphic age, these microfossils also reflect the sedimentary environment and associated biogeochemical processes (Al-Helal et al., 2022).

In the Wandan Mud Volcano of Pingtung County, Taiwan, the distribution and composition of calcareous nannofossils serve as crucial indicators for evaluating hydrocarbon generation and migration (Huang et al., 2021). Gases and fluids emitted from mud volcanoes may carry biomarkers originating from deeper sedimentary layers, thereby providing vital information on hydrocarbon sources and maturity (Zhu et al., 2020). Integrating these techniques furnishes robust calcareous nannofossil based micropaleontological evidence for hydrocarbon exploration, further enhancing the accuracy of stratigraphic correlation and reservoir prediction (Molina-Cruz et al., 2019).

Hydrocarbons

To date, natural gas hydrate reservoirs have continuously garnered worldwide attention because of their potential as a clean energy resource with vast reserves. Nevertheless, gas production from these hydrate reservoirs involves intricate geological challenges that warrant detailed investigation. The formation of gas hydrates and the accompanying methane seep mechanism in southwestern Taiwan provide essential geological references for hydrocarbon exploration (Huang et al., 2021). This work demonstrates that the accumulation of methane beneath structural unconformities or within authigenic carbonate layers can foster the formation of shallow gas hydrates. In the Wandan mud volcano area, micropaleontological evidence such as calcareous nannofossils and foraminifera serves as an indicator of stratigraphic permeability and geochemical conditions, thereby enabling the tracing of methane leakage and its association with natural gas reservoirs. Moreover, biomarker compounds derived from these microfossils aid in verifying the origin of natural gas and in distinguishing between biogenic and thermogenic gases. By integrating sediment geochemistry, geophysical exploration, and micropaleontological analyses, researchers can gain deeper insights into the hydrocarbon migration processes in the Wandan mud volcano system. This integrated approach not only improves the accuracy of hydrocarbon exploration but also enhances its overall economic viability.

Mud Diapir

The distribution of mud diapirs and mud volcanoes in southwestern Taiwan has been widely investigated, with research indicating that regional tectonic activities, sedimentary overpressure, and fluid dynamics collectively contribute to the formation of these unique geological features. According to Chen (2011), mud diapirs in this area predominantly occur in proximity to active fault zones and folded structures. Their spatial distribution shows clear tectonic control, suggesting that structural movements not only influence the pathways through which mud ascends but also regulate sediment deposition and deformation processes within the region. This tectonic influence is critical in facilitating both the formation and subsequent evolution of mud volcanoes. In addition to the structural controls, Lin et al. (2003) emphasize the role of subsurface fluid pressure in the generation of mud volcanoes. Their research suggests that the eruptive processes of these volcanoes are often synchronized with variations in the regional tectonic stress field. By employing detailed geological surveys and geochemical analyses, Lin and colleagues revealed that the ejecta from mud volcanoes contain a complex mix of organic and inorganic components.

Geological Settings

Taiwan is situated at the convergent boundary between the Philippine Sea Plate and the Eurasian Plate, forming a well-documented arc-continent collision zone in the western Pacific (Suppe, 1981). This ongoing tectonic Interaction has resulted in the accretion of rock masses in both the southwestern and southeastern regions of Taiwan (Huang et al., 11997). The Philippine Sea Plate is currently colliding with the Eurasian continental margin along a NW46° trend at an average rate of approximately 8. 2 cm per year (Yu et al., 1997).

Over the past 4 million years, this collision has compressed Cenozoic sediments by nearly 200 km, leading to mountain uplift at a rate of approximately 5 mm per year. (Figure 2).

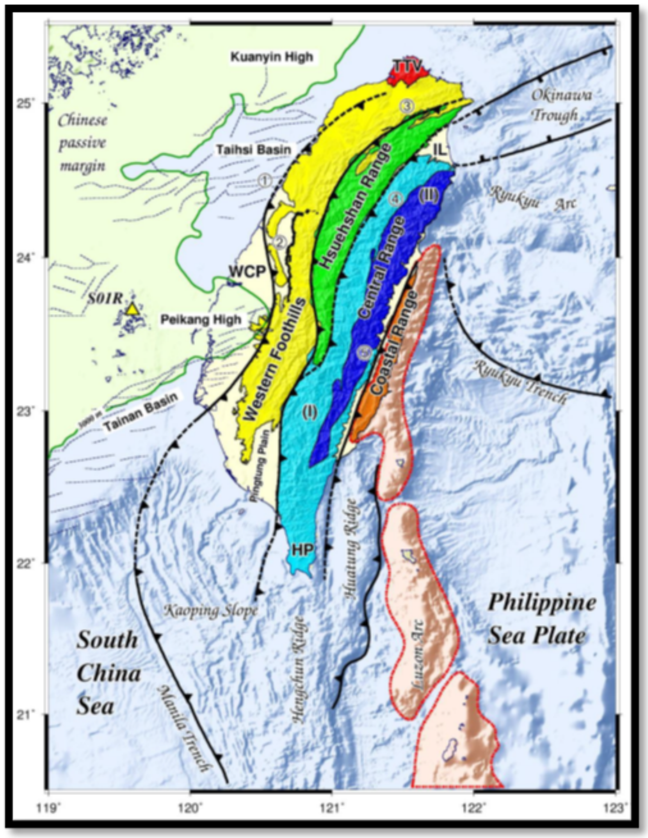


Figure 2:Tectonic Setting of the Taiwan Arc continent Collision Orogeny. (Lin et al., 2003)

Taiwan's tectonic framework is illustrated here. The pale green region along the continental margin marks the position of the preTertiary basement high. The numbers 1–5 indicate the deformation front, Chelungpu Fault, Chuchih Fault, Lishan Fault, and Longitudinal Valley Fault, respectively. The roman numerals I–II denote the slate belt on the western flank of the Central Range and the metamorphic complex on the eastern flank of the Central Range. The dashed lines represent normal faults formed prior to the collisional orogeny.

The abbreviations are as follows:
WCP = Western Coastal Plain,.
TTV = Datun Volcano.
HP = Hengchun Peninsula.
IL = Yilan Plain.

These components are interpreted to reflect thecharacteristics of deep-sourced materials, thereby providing evidence that the material feeding these features originates from considerable depths within the crust. This interplay between fluiddynamics and tectonic stress highlights a coupled mechanism in which the ascent of mud is driven by both mechanical forces and fluid overpressure. Field investigations have further documented that southwestern Taiwan is crisscrossed by several major fault systems, such as the Chukuo Fault, Gutingkeng Anticline, and Chishan Fault. These structural elements are key to the regional crustal dynamics and create zones where subsurface fluids can accumulate. The concentration of fluids along faults or fracture zones leads to localized overpressure conditions, which in turn promote the upward movement of mud along the path of least resistance, forming mud diapirs. When these mud bodies approach near-surface conditions, they may erupt to create mud volcanoes. This process demonstrates a clear link between tectonic activity, fluid migration, and sedimentary processes.

The integrated analysis of these tectonic features and the distribution patterns of mud bodies is essential for understanding the dynamic evolution of the regional sedimentary environment. Not only do mud diapirs and mud volcanoes represent the direct results of ongoing tectonic evolution, but they also serve as markers for long-term changes in sedimentary regimes. Their study is particularly significant in the context of hydrocarbon exploration, as the mechanisms that control mud migration and eruption are often associated with hydrocarbon-rich sedimentary basins. By correlating structural data with fluid and sedimentary analyses, geoscientists can better predict the locations of potential hydrocarbon accumulations and assess the risks associated with resource development.

The combined influence of tectonic processes, sedimentary overpressure, and fluid dynamics plays a crucial role in shaping the distribution of mud diapirs and mud volcanoes in southwestern Taiwan. The studies by Chen (2011) provide valuable insights into the genesis of these features and underscore their importance in understanding both regional geological evolution and the prospects for hydrocarbon exploration.

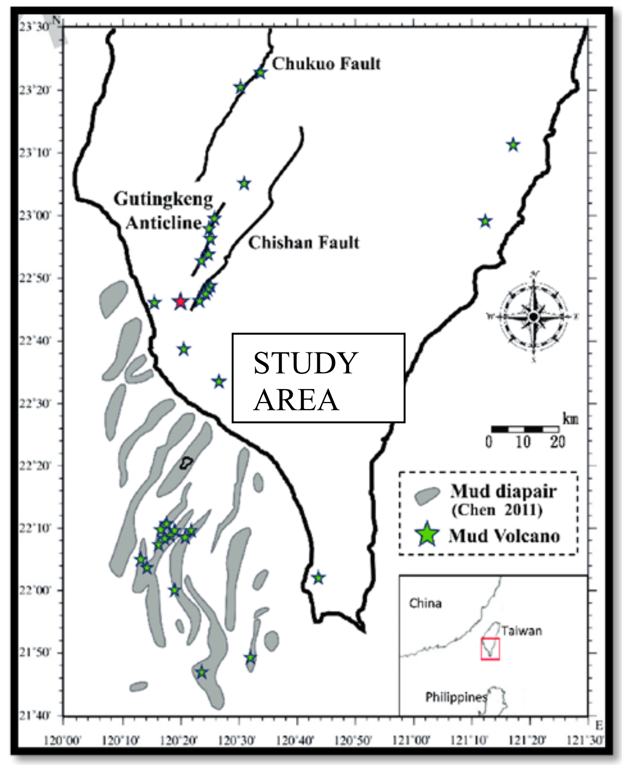


Figure 3: Distribution of Mud Volcanoes in the Mudstone Regions of Taiwan (Chen, 2011).

The figure3 shows the distribution of mud diapirs and mud volcanoes in southwestern Taiwan, where:The gray shaded area (dashed box) represents the mapped distribution of mud diapirs. The green stars indicate the locations of known mud volcanoes. The figure 3 also marks the major tectonic structures, including the Chukuo Fault, Gutingkeng Anticline, and Chishan Fault. The inset in the lower right corner displays the relative location of the study area within Taiwan and its surrounding regions. The genesis of mud diapirs and mud volcanoes is generally related to regional crustal structures, sedimentary overpressure, and fluid dynamics; this figure assists geologists and researchers in quickly grasping the spatial distribution of mud diapirs and further exploring their association with regional tectonic activity.

Table1:Correlation of Tertiary and Pleistocene Rock in the Western Foothills of Taiwan (Modified by Wen Rong Chi).

<table>
<tr><td colspan="2" rowspan="2">Region
Age</td><td colspan="2">Northern Taiwan</td><td>South-Central Taiwan</td><td colspan="3">Southern Taiwan</td></tr>
<tr><td colspan="2">Chilung, Taipei, Taoyuan</td><td>Chiayi, Tainan</td><td>Tainan, Kaohsiung</td><td colspan="2">Kaohsiung, Pingtung</td></tr>
<tr><td colspan="2">Pleistocene</td><td colspan="2">Toukoshan Formation
(Kuanyinshan Formation)</td><td>Liushuang Formation
Erchungchi Formation
Kanhsialiao Formation</td><td>Yuching Shale</td><td colspan="2">Liushuang Formation
Liukuei Conglomerate</td></tr>
<tr><td colspan="2" rowspan="4">Pliocene</td><td colspan="2">Cholan Formation</td><td rowspan="2">Liuchungchi Formation
Yunshuichi Formation</td><td rowspan="2">Peiliao Shale
Chutouchi Formation</td><td rowspan="4">Gutingkeng Formation</td><td>Gutingkeng Formation
(limited)</td></tr>
<tr><td colspan="2">Chinshui Shale</td><td>Nanshihlun Sandstone</td></tr>
<tr><td rowspan="4">Sanhsia Group</td><td>Erchiu Formation</td><td rowspan="2">Niaotsui Formation
Chunglun Formation</td><td rowspan="2">Maopu Shale
Ailiaochiao Formation
Yenshuikeng Shale</td><td rowspan="2">Katzuliao Shale</td></tr>
<tr><td rowspan="2">Tapu Formation</td></tr>
<tr><td rowspan="2">Miocene</td><td rowspan="2">Late Miocene</td><td>Tangenshan Formation</td><td>Tangenshan Formation</td><td colspan="2">Wushan Formation</td></tr>
<tr><td>Nanchuang (Wutu)
Formation</td><td>Nanchuang Formation</td><td>Changchihkeng Formation
Hunghuatze Formation
Sanmin Shale</td><td colspan="2"></td></tr>
</table>

Table 1 is a stratigraphic correlation chart of Tertiary and Pleistocene rock units in the Western Foothills of Taiwan. The chart is arranged in descending order of age—from the youngest at the top to the oldest at the bottom—and juxtaposes the stratigraphic units deposited during equivalent geologic periods across northern, south-central, and southern Taiwan. This facilitates the interpretation of stratigraphic equivalencies among different regions. In terms of overall significance, the horizontal axis represents geographic regions. The chart is divided into three major sectors (from left to right) based on variations in geological settings and sedimentary basins: Northern Taiwan: encompassing the Keelung, Taipei, and Taoyuan areas; South-Central Taiwan: including the Chiayi and Tainan regions; Southern Taiwan: covering Tainan, Kaohsiung, as well as the Kaohsiung–Pingtung areas. The vertical axis primarily displays the stratigraphic units in the Western Foothills of Taiwan from the Late Miocene (part of the later Tertiary) to the Pleistocene, illustrating the interrelationships among regionally designated formations. This correlation chart integrates the local stratigraphic nomenclatures into a comprehensive stratigraphic framework, which is crucial for correlating the source strata of ultrafine fossils from the Wandan mud volcano mudflows and for reconstructing the sedimentary environments and tectonic evolution of the region.

Methods

Nannofossil Identification Technology

The study initially focused on collecting samples from the mudflow emitted by the Wandan mud volcan(figure 3), with an emphasis on extracting microfossils from the mudflow. Through detailed identification and analysis of these extremely minute fossils, it is possible to determine the types and distribution of biogenic remains within the regional sedimentary deposits.

Establishment of Bioevent Datum Surfaces

By utilizing the characteristics of the first appearance (FAD/FOD) and the last disappearance (LAD/LOD) of index microfossils, researchers can establish bioevent datum surfaces. These datum surfaces facilitate the delineation of specific microfossil zones corresponding to distinct time intervals, thereby serving as a basis for the chronological dating of the mudflow deposits.

Sample Collection and Nannofossil Analysis.

Methodology for the Preparation of Nannofossil Specimen Slides Equipment: A hot plate, cover slips, glass slides, label paper, beakers, AYAC powder, a scraper, a spoon, forceps, a glass rod, and ultrapure water.

Procedure:

1. Sample Collection and Pulverization:

A small rock specimen is collected from the field and manually crushed into a fine powder using a stainless steel tool.

Transfer to Beaker:The resulting rock powder is carefully transferred into a 50 mL beaker.

2. Suspension Preparation:

Forty milliliters of distilled water is added to the beaker, and the mixture is stirred thoroughly before being allowed to stand for 25 minutes to facilitate particle dispersion.

3. Sedimentation and Ultrasonic Treatment:

After removing the coarse particles from the mixture, the remaining suspension is transferred into a beaker preheated to 50 °C and subjected to ultrasonic oscillation for 2 to 5 minutes to further disaggregate the sample.

4. Supernatant Collection:

Following ultrasonic treatment, the suspension is allowed to settle for 2 minutes, after which the supernatant, containing the finer particles, is carefully decanted into a clean test tube.

5. Centrifugation:

The test tube is centrifuged at 1, 200–1, 500 RPM (typically for about 5 minutes) to concentrate the microfossils.

6. Resuspension of the Sediment:

The supernatant is gently decanted, leaving only a few drops of water. The sediment at the bottom is then homogenized using a clean glass rod to ensure an even distribution.

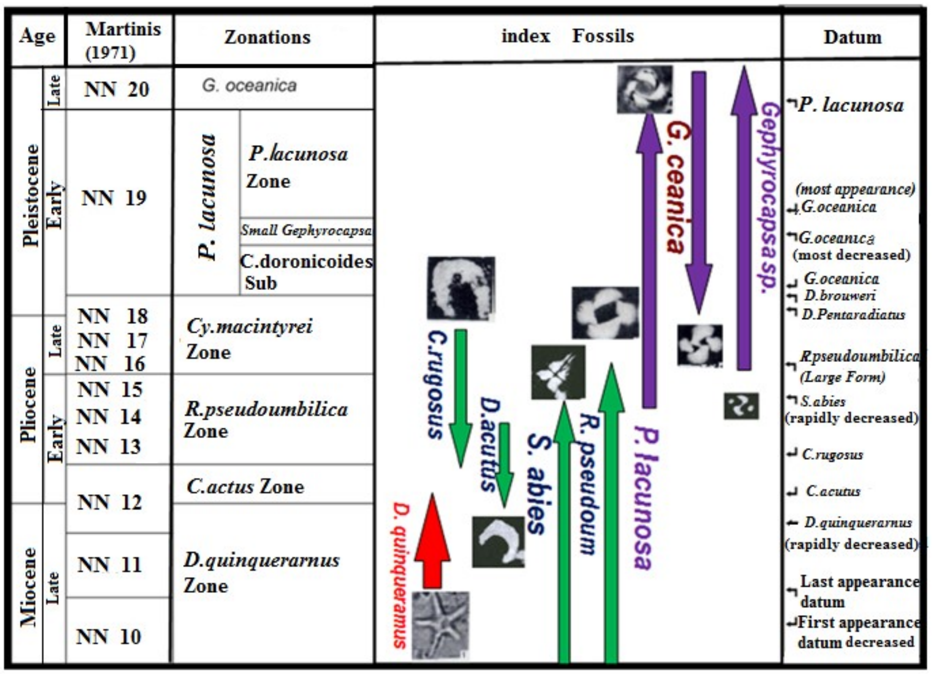
7. Deposition onto Cover Slip:

A small aliquot of the sediment is transferred onto a clean cover slip using a glass rod. The sediment is spread so that it becomes concentrated in the central region of the cover slip.

8. Slide Preparation:

The cover slip is placed on a hot plate preheated to 100–130 °C, and a glass rod is gently used to press the cover slip, facilitating the removal of air bubbles from the sediment layer.

Table 2 :Calcareous Nannofossil Datums, Zonations, and Index Fossils of the Upper. Miocene to Pleistocene Sequences of the Tainan , Kaohsiung, and Pingtung to Area



9. Post-treatment:

After heating, the slide is removed from the hot plate and allowed to cool to room temperature, then appropriately labeled for subsequent analysis.

Results

The Nannofossil assemblage of the Liyushan Mud Volcano in Wandan Township, Pingtung County, mainly includes the following components:

- *Coccolithus pelagicus* (Wallich)
- *Cycloccolithina leptopora* (Murry and Blackman)
- *Cy. macintyrei* (Bukry and Bramlette)
- *Coccolithus* sp.
- *Discoithina* sp.
- *Discoaster variabilis*
- *Gephyrocapsa* spp.
- *Gephyrocapsa oceanica*
- *Helicosphaera karmpteri*
- *Pseudoemiliania lacunosa*
- *Reiculofenestra pseudoumbilical*

Based on the research and analysis of Calcareous Nannofossil biostratigraphy, zonation, and stratigraphic correlation(Table 2), it was found that the characteristics of this fossil assemblage indicate that it belongs to the early Pleistocene, and the stratigraphic level is primarily inferred to be derived from the upper Gutingkeng Formation.

Conclusion

This study found The Calcareous Nannofossil fossil assemblage from the Liyushan Mud Volcano mudflow in Wandan Township, Pingtung County is inferred to belong to early Pleistocene strata, providing precise biostratigraphic markers. The depositional environment and tectonic background reflected in this assemblage also offer significant referential and practical application value for paleoenvironment reconstruction, tectonic evolution research, and hydrocarbon exploration.

Biostratigraphic Framework Establishment

The fossil assemblage is predominantly composed of fine-grained sediments from the early Pleistocene and includes several representative calcareous nannofossils such as *Coccolithus pelagicus*, *Cycloccolithina leptopora*, and *Gephyrocapsa oceanica*. These microfossils are widely utilized as biostratigraphic markers, enabling the precise subdivision of stratigraphic units and accurate determination of depositional ages. Their abundant occurrence suggests that the area likely represented an open marine environment during that time, characterized by vigorous planktonic activity and high productivity, which in turn led to the development of unique sedimentary characteristics.

Potential Implications for Hydrocarbon Accumulation

Rapid and fine-grained sedimentary environments are conducive to the preservation of organic matter and the formation of hydrocarbon reservoirs. The stratigraphic unit represented by this fossil assemblage not only aids in the precise determination of the stratigraphic age but may also reveal potential hydrocarbon accumulation zones, thereby providing significant guidance for regional hydrocarbon exploration. Moreover, mud volcano activity is often characterized by the migration of fluids and organic matter within the sedimentary sequence; under such circumstances, rapid sedimentation combined with tectonic movements may collectively promote the preservation of organic matter as well as the generation and migration of hydrocarbons. The composition of the fossil assemblage from the Liyushan Mud Volcano in Wandan Township, along with its associated stratigraphic unit, provides evidence for hydrocarbon generation and accumulation during the Neogene in this area. Further sedimentological and structural analyses suggest that the region may possess favorable conditions for hydrocarbon accumulation, such as high sedimentation rates, abundant organic matter supply, and tectonically controlled fluid migration pathways.

Sedimentation and Tectonic Activity

Based on the characteristics of the fossil assemblage, this stratigraphic unit is attributed to the early Pleistocene and is primarily derived from the upper Gutingkeng Formation. The upper Gutingkeng Formation may reflect an environment characterized by rapid sedimentation, a condition often associated with intense tectonic activity. Mud volcano phenomena are unique geological features that arise under tectonic processes and are closely linked to vigorous tectonic movements, rapid sediment deposition, and fluid expulsion. The fact that this fossil assemblage originates from the upper Gutingkeng Formation indicates that, under the driving force of tectonic activity, a thick accumulation of fine-grained sediments may have formed. This rapid sedimentation not only facilitates the preservation of abundant nannofossils but may also lead to an increase in local sediment load, which can further trigger the development of mudflow piercing structures. These findings provide important evidence for regional tectonic evolution and sedimentary dynamics.

Paleoenvironment Reconstruction

Calcareous nannofossils typically flourish in open marine settings, and their species diversity and abundance can reflect the seawater temperature, nutrient conditions, and structure of the marine ecosystem at the time. The presence of this fossil assemblage indicates that the area was characterized by a mature and stable marine depositional environment during the early Pleistocene, thereby facilitating the reconstruction of the paleoceanographic conditions and depositional settings of that period.

Geological Significance and Applications

The fossil assemblage from the Liyushan Mud Volcano mudflow in Wandan Township, Pingtung County, holds significant biostratigraphic value, offering researchers an understanding of the early Pleistocene marine environment and depositional conditions. Simultaneously, it sheds light on the dynamic processes of tectonic activity and rapid sedimentation in the region. This information is crucial for elucidating the stratigraphic evolution and sedimentary environments of southwestern Taiwan, as well as providing important guidance for hydrocarbon resource exploration.

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References

Al-Helal, M. A. S., Al-Kuwari, N. H., & Hossain, M. S. (2022). Calcareous nannofossils as indicators of paleoenvironmental conditions in the northern Arabian Gulf. *Marine Micropaleontology, 188*, 101121. doi:org/10. 1016/j. marmicro. 2022. 101121

Bown, P. R. (2002). Calcareous nannofossil biostratigraphy. In R. L. Stanley (Ed.), Micropaleontology: Evolutionary Trends and Applications (pp. 147–175). Springer. doi:10. 1007/978-3-642-18969-9_7

Bown, P. R. (2002). Calcareous nannofossil biostratigraphy. In R. L. Stanley (Ed.), *Micropaleontology: Evolutionary Trends and Applica-*

tions (pp. 147–175). Springer. doi:10. 1007/978-3-642-18969-9_7

Bollmann, J. (2005). Automated particle analysis: Calcareous microfossils. In *Image analysis, sediments and paleoenvironments* (pp. 229–252). Springer. doi:10. 1007/1-4020-2122-4_12

Biete, C., Lee, Y. H., & Lu, C. Y. (2018). Geochemical and geochronological constraints on the origin and evolution of the Central Range volcanic rocks, Taiwan. Geochemistry, Geophysics, Geosystems, 19(7), 2027–2042. doi:org/10. 1029/2018GC007902

Chen, C. -H. (2011). Tectonic and sedimentary controls on mud volcano distribution in southwestern Taiwan. *Marine and* Petroleum Geology, 28(3), 357–366. doi:10. 1016/j. marpetgeo. 2011. 03. 002

Dimitrov, L. I. (2002). Mud volcanoes The most important pathway for degassing deeply buried sediments. Earth-Science Reviews, 59(1–4), 49–76. doi:10. 1016/S0012-8252(02)00069-7

Guliyev, F., Khusainov, A., & Mahmoud, A. (2023). Dynamics of mud volcanoes: Fluid flow and tectonic controls in sedimentary basins. *Journal of Volcanology and Geothermal Research, 418*, 108795. doi:10. 1016/j. jvolgeores. 2023. 108795

Huang, K. -S., Chen, C. -C., Tsai, M. -T., & Liu, J. -C. (2021). Calcareous nannofossils as hydrocarbon indicators in the Wandan mud volcano, Pingtung County, Taiwan. Journal of Asian Earth Sciences, 215, 104600. doi: org/10. 1016/j. jseaes. 2021. 104600

Huang, Y. -J., Chang, C. -C., & Lee, M. -H. (2021). Occurrence and distribution of gas hydrates in the western Taiwan continental margin. Marine and Petroleum Geology, 123, 105330. doi:org/10. 1016/j. marpetgeo. 2021. 105330

Huang, C. Y., Yuan, P. B., & Tsao, S. (1997). Tectonic evolution of accretionary prism in the arc-continent collision terrane of Taiwan. Tectonics, 16(5), 801–813. doi:org/10. 1029/97TC01276

Huang, K. -S., Chen, C. -C., Tsai, M. -T., & Liu, J. -C. (2021). Calcareous nannofossils as hydrocarbon indicators in the Wandan mud volcano, Pingtung County, Taiwan. Journal of Asian Earth Sciences, 215, 104600. doi:10. 1016/j. jseaes. 2021. 104600

Kim, Y., Lee, S., & Park, J. (2021). Tectonic controls on mud volcano formation in complex sedimentary basins. *Journal of Geophysical Research: Solid Earth, 126*(4), e2020JB020025. doi:10. 1029/2020JB020025

Lin, H. (1965). Mud volcanoes and their formation mechanisms. Journal of Sedimentary Geology, 9(3), 201–210. doi:10. 1016/j. jsedgeo. 1965. 03. 001

Lin, A. T., Watts, A. B., & Hesselbo, S. P. (2003). Cenozoic stratigraphy and subsidence history of the South China Sea margin in Taiwan and the East China Sea. Basin Research, 15(4), 453–478.

Molina-Cruz, A., Schmitt, A. K., & Garcia, F. (2019). Enhancing reservoir prediction through calcareous nannofossil-based micropaleontological analysis: A case study from the Mediterranean. *Journal of Petroleum Geology, 42*(3), 211–225. doi:org/10. 1144/jpg. 2019. 211

Oung, J. -N. (2003). The petroleum systems and hydrocarbon potential of Taiwan's offshore sedimentary basins: A basin evolution perspective. Mining and Metallurgy: Journal of the China Mining and Metallurgical Engineering Society, 47(1), 103–111. doi:10. 30069/MM. 200303_47(1). 0009

Pringle, M. S. (2005). Calcareous nannoplankton evolution: Its impact on biostratigraphy and paleoceanography. *Journal of Paleontology, 79*(2), 225–240. doi:10. 1666/0022-3360(2005)079[0225:CNEII]2. 0. CO;2

Ruppel, C. D., & Butler, K. (2004). Submarine mud volcanoes: Global distribution, genesis and significance. Marine and Petroleum Geology, 21(6), 879–893. doi:10. 1016/j. marpetgeo. 2004. 03. 006

Sims, B. D., & Baldwing, K. (2007). Palaeobiogeography of calcareous nannofossils. Marine Micropaleontology, 65(3–4), 216–234. doi:10. 1016/j. marmicro. 2007. 03. 001

Shnyukov, A. N., Zlotnikov, M., & Karp, A. (2020). Mud volcanoes in active tectonic regions: Their formation and global distribution. Journal of Volcanology and Geothermal Research, 389, 106842. doi:10. 1016/j. jvolgeores. 2020. 106842

Suppe, J. (1981). Mechanics of mountain building and metamorphism in Taiwan. Memoir of the Geological Society of China, 4, 67–89.

Wan, H., Li, D., & Chen, Z. (2021). Formation mechanisms of mud volcanoes in sedimentary basins. Marine and Petroleum Geology, 130, 105116. doi:10. 1016/j. marpetgeo. 2021. 105116

Wan, H., Li, D., & Chen, Z. (2021). Formation mechanisms of mud volcanoes in sedimentary basins. Marine and Petroleum Geology, 130, 105116. doi:10. 1016/j. marpetgeo. 2021. 105116

Yu, S. B., Chen, H. Y., & Kuo, L. C. (1997). Velocity field of GPS stations in the Taiwan area. Tectonophysics, 274(1–3), 41–59 doi:org/10. 1016/S0040-1951(96)00297-1

Zhu, H., Zhang, Q., & Li, X. (2020). Biomarker analysis of gases and fluids from mud volcanoes in the South China Sea. Marine Geology, 432, 106861. doi:10. 1016/j. margeo. 2020. 106861