Marine Research
of the National Academy of Marine Research
ISSN: 2709-6629 (Vol.4 Iss.2)
GPN: 2011200033

DOI: http://dx.doi.org/10.29677/MR.202412_4(2).0005
2024, 4(2), 75-94

Marine Geothermal Research in Taiwan: An Overview

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ABSTRACT

Taiwan's unique marine geologic setting, marked by complex tectonic features and active hydrothermal systems, offers critical insights into Earth's geological processes and renewable energy resources. This paper reviews the progress in marine geothermal research in Taiwan, including the development of instruments, field measurements, data analysis, thermal modeling, and interpretations, laying the groundwork for future exploration and development.

The use of Lister-Type Heat Probes (LTHP) and Miniature Temperature Loggers (MTLs) in heat probe measurements has been pivotal in acquiring highly accurate seafloor temperature data. These measurements provide valuable insights into regional thermal structures and fluid migration pathways around Taiwan. In addition to direct temperature measurements, indirect methods based on bottom-simulating reflections (BSRs) have been developed and applied to infer sub-seafloor temperatures, contributing to a comprehensive understanding of marine geothermal gradients. The results underscore the diverse geothermal gradients across different tectonic regions offshore SW Taiwan, influenced by tectonic activities and sedimentation rates. The presence of extremely high heat flows in the Southern Okinawa Trough suggests active hydrothermal systems around offshore northeastern Taiwan, while the detection of heat pulses at Turtle Island may indicate landslides and groundwater migration events. The influence of topographic effects on thermal structures has also been observed, necessitating corrections for accurate geological interpretations.

The potential of marine geothermal research for practical applications, such as the exploration of gas hydrates, hydrothermal minerals, and renewable energy resources, is immense. However, to fully harness these benefits, continued efforts are paramount. These efforts should focus on bridging data gaps, enhancing spatial coverage, and integrating diverse marine surveying data. The advancements in measurement and monitoring techniques, coupled with the support of government policies, will pave the way for sustainable development and efficient utilization of geothermal energy resources. Furthermore, the ongoing geological surveys and long-term monitoring of seafloor stability are indispensable for understanding and mitigating geohazards.

Keywords: geothermal, marine heat flow, heat probe, Taiwan.

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Received June 13, 2024, accepted July 30, 2024.

1 INTRODUCTION

Geothermal data provide critical constraints for tectonic accretion, core-mantle segregation, and crustal evolution. Therefore, geothermal research has been conducted to understand the Earth's interior heat source, lithospheric structures, and geological processes. Geothermal systems contain three essential components: a heat source, a heat sink, and a heat exchanger. The heat exchangers are elements containing fluids that are capable of transferring heat. Since most of Earth's surface heat is lost by conduction, the heat is higher in areas with either high radioactivity or where the Earth's crust is thinner. Therefore, geothermal energy aims to develop the heat contained within the Earth that gives rise to numerous geological phenomena.

In most cases, the breadth of heat flow anomalies is roughly equivalent to the depth of the thermal source or the depth scale over which some process produces the anomaly. Hence, anomalous heat flows may perturb heat transport processes and affect crustal thermal structures, which are desired targets for studying regional tectonics, hydrocarbon reservoirs, and geothermal energy. The potential of geothermal energy, especially in Taiwan's unique marine geologic setting, characterized by its diverse and complex tectonic features, is immense and inspiring for the future of renewable energy development.

Taiwan's unique marine geologic setting provides excellent conditions for studying marine geothermal systems and developing relevant technologies. As the Luzon subduction complex encroaches on the passive China Continent, offshore SW Taiwan lies where the southern Luzon subduction system transforms into a northern collision system (Hirtzel et al., 2009; Reed et al., 1992). A series of west-verging imbricated folds and emergent thrusts of the accretionary wedge (Liu et al., 1997) act as active fluid migration pathways and contribute to potential hydrocarbon reservoirs. On the other hand, offshore NE Taiwan is situated at the south tip of the Okinawa Trough back-arc spreading center where the Philippine Sea Plate subducts beneath the Eurasian Plate (Lee et al., 1980; Letouzey & Kimura, 1986; Sibuet et al., 1998). The recently extruded volcanoes act as potential heat sources, whereas the widespread normal faults may serve as fluid conduits, forming a natural hydrothermal field (Wu et al., 2019). To better understand the heat flow distribution offshore Taiwan, marine geophysicists have developed several direct and indirect methods to derive sub-seafloor temperatures and classify regional fluid migration patterns over the last two decades (Chang & Shyu, 2011; Chen et al., 2012, 2014, 2020; Chi & Reed, 2008; Chiang et al., 2010; Liao et al., 2014; Shyu et al., 1998; Shyu & Chang, 2005; Shyu & Liu, 2001; Wu et al., 2019).

The findings of this research are crucial in the context of Taiwan's energy transition and its commitment to sustainable development. We also express our gratitude to those excellent technicians and professors who have dedicated themselves to this rare research and continue to support this marine research in unique ways.

2 DEVELOPMENT OF INSTRUMENTS AND METHODOLOGIES TO OBTAIN SEAFLOOR TEMPERATURES

Fourier's Law of heat conduction describes that heat flows can be calculated by multiplying the thermal conductivity with the temperature gradient, which indicates the vertical transfer of heat from the Earth's interior to the surface (Stein, 1995). Geothermal gradient is commonly measured using a vertically oriented probe with temperature sensors mounted on a weight and lowered from a ship, penetrating seafloor sediments and measuring the temperatures corresponding with the subsurface depths. Thermal conductivity is either measured with in-situ sensors during seafloor penetration by transient heating experiments or from laboratory sediment

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DOI: 10.29677/MR.202412_4(2).0005

core analysis (Stein & Von Herzen, 2001). Drilling operations can provide in-situ ground truth information, but the cost is exceptionally high. The alternative method is penetrating the probes into the seafloor to measure the thermal parameters site-by-site, and the present standard "Pogo" measurements, multiple penetrations combined with nearly real-time acoustic telemetry of raw data have been proven helpful in investigating small-scale (<10–20 km) marine heat flow variability (Plaza-Faverola, 2022). However, the measured marine heat flows are still not evenly spaced. In the beginning, the instrument used only two thermal sensors at either end of a 3–4 m long probe with in-situ analog recording techniques on paper or film, and subsequently, the number of sensors has increased as the concepts of the measured nonlinear temperature gradients and thermal conductivity may vary with depth (Stein & Von Herzen, 2001).

2.1 Direct Marine Heat Probe Measurements

Heat flow is the amount of thermal energy that passes through a unit area over time and is calculated as the vertical geothermal gradient and thermal conductivity of the material over the depth interval where the geothermal gradient is obtained (Goto et al., 2023). Besides directly deriving the ground truth at high costs (Chen et al., 2014; Kinoshita et al., 2011; Liao et al., 2014) by borehole measurements, geothermal gradients in marine areas are generally calculated from sediment temperatures obtained using a heat probe (typically 3–5 m in length) with several high-resolution sensors (spaced vertically about 50 to 100 cm) to measure temperatures at different depths. The thermal conductivity of sediment is measured in the laboratory on sediment core samples (Goto et al., 2017; Von Herzen & Maxwell, 1959) or in situ (Hartmann & Villinger, 2002; Hyndman et al., 1979; Villinger & Davis, 1987). In particular, Lister (1979) proposed a pulse heating method as an alternative to the continuous short-calibrated heat pulse to apply to a cylindrical probe to analyze the temperature gradient and thermal conductivity simultaneously (Hyndman et al., 1979; Lister, 1979).

Acquiring the thermal structures of the oceanic crust through conventional heat probes could be challenging for environments with shallow water depths and hard surface sediments. A successful case from the area near Turtle Island offshore NE Taiwan, where the water depth is less than 30 meters, was conducted by deploying a 30kg-steel bar with two attached miniature temperature loggers (Figure 1) (Chiang, 2008). However, a critical aspect of obtaining reliable heat flow data in marine areas is that the sediment temperature measurements must be made under stable bottom-water temperature conditions, such as deep-sea areas. Therefore, during the last three decades, two major types of ship-operated underwater instruments have been developed by the Geothermal Lab of the Institute of Oceanography, National Taiwan University (IONTU), to measure marine heat flows of the seafloor surrounding Taiwan, including Lister-Type Heat Probes (LTHP) and Miniature Temperature Loggers (MTLs). The improved LTHP by IONTU includes updating the design of circuit boards, improving performance, and adding new functional features, which makes the new design more reliable and efficient (Chang, 2013). The MTLs are attached to a piston or gravity core to penetrate the seafloor better and measure the temperature gradient (Chang, 2013).

The LTHP contains multiple high-resolution marine heat probes (HR) that are capable of simultaneously measuring in-situ thermal gradients and conductivities of sediments (Hyndman et al., 1979; Lister, 1979; Shyu et al., 1998, 2006; Shyu & Chang, 2005) (Figure 2). Recently, the upgraded generation HR (HR3) has equipped 12 temperature sensors in a 1 cm diameter tube with a resolution up to 0.1 mK that is capable of identifying most temperature differences of the sediments within 1-centimeter depth (Chiang et al., 2015). The LTHP is designed to be 6 m long and weigh 800 kg to ensure penetration capability. Scientists have recorded three typical temperature stages according to the heat probe penetrating status (Chen et al., 2020; Shyu & Chang, 2005) (Figure 3).The first stage is when the LTHP measures temperatures that vary with water depth before penetrating the seafloor sediments. This stage can be used for sensor calibration. In the second stage, thermal decay resulting from the frictional heating during penetration is observed. The third and most important stage

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is characterized by a noticeable thermal decay associated with an instantaneous temperature rise caused by an artificial heat pulse generated from the instrument. The temperature curve from the third stage is used to derive the thermal conductivities by applying a least-squares best fit to the cylindrical decay function (Bullard, 1954; Shyu & Chang, 2005). With the calibrated artificial heat pulse, the efficient "trust region" numerical scheme (Moré & Sorensen, 1983) can be derived to perform nonlinear inversion from the temperature evolution (Wu et al., 2019).

On the other hand, the MTL measures temperatures at different depths with an attached solid-steel lance or a core barrel (Pfender & Villinger, 2002). However, the seafloor sediments' thermal conductivities must be measured with additional needle probes (Lister, 1979; Von Herzen & Maxwell, 1959). Attached to the gravity coring device, the MTL can be used to derive seafloor temperatures with controllable offsets (Figure 4) with a resolution of up to 0.1 mK (Chang & Shyu, 2011; Shyu & Chang, 2005). When the MTL reaches the seafloor, the frictional heat abruptly raises temperatures and then gradually decays. Then, the equilibrium temperatures can be derived from the in-situ seafloor temperatures (Figure 5). Afterward, the thermal conductivity of the retrieved sediments can be determined from the slope of the temperature decay curve recorded by a thermal conductivity analyzer (Figure 6). With the known geothermal gradients and thermal conductivity, heat flow values can be derived.

Figure 1. The portable miniature temperature loggers attached to a steel bar allowed us to use workforce to detect the seafloor temperature around Turtle Island. (after Chiang et al., 2008)

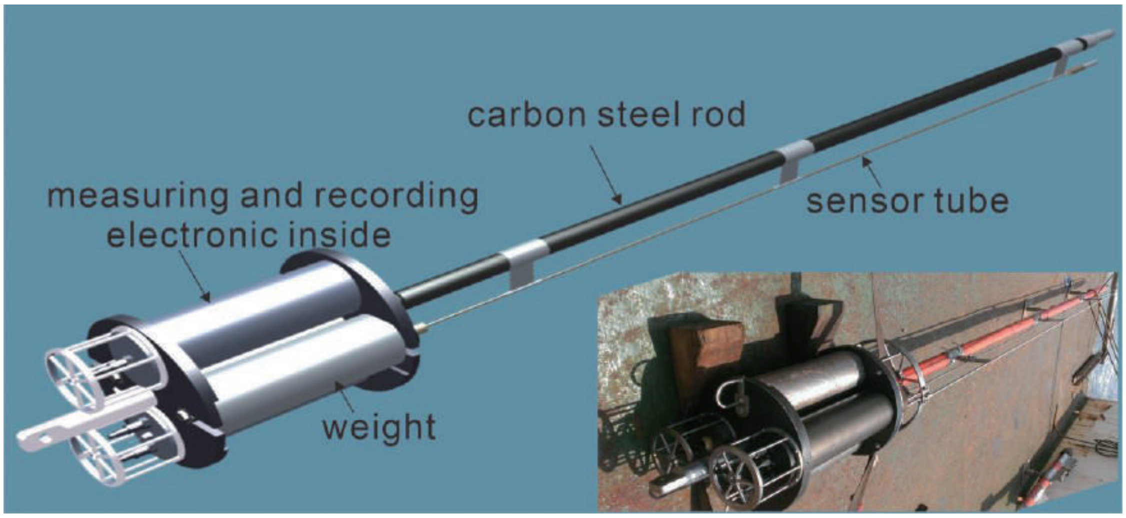

Figure 2. The instrument sketch and operating pictures of Lister-type Marine Heat Probes. (after Chen et al., 2019)

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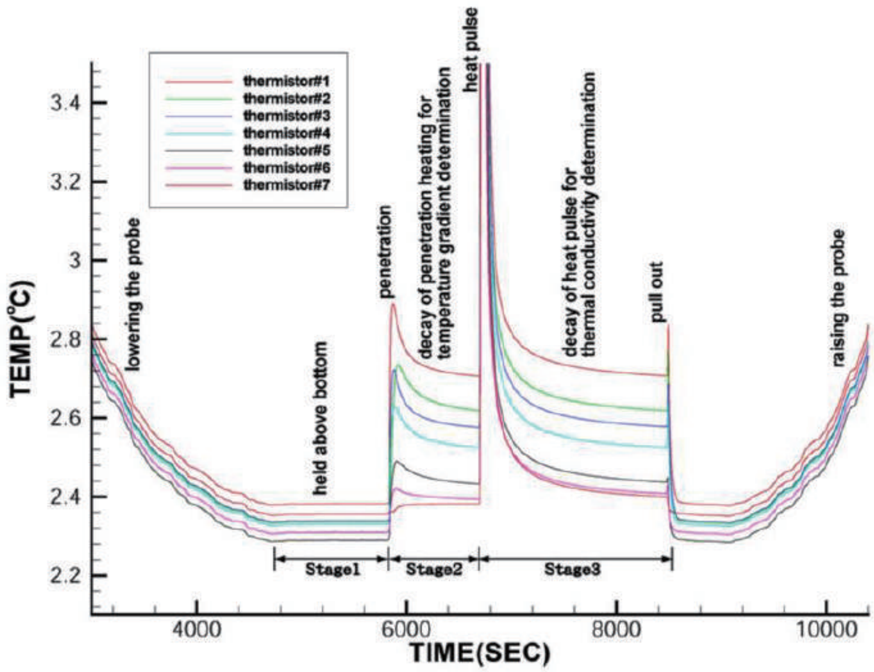

Figure 3. The temperature recorded by the Lister-type Marine Heat probe penetration (after Shyu and Chang, 2005). There are three stages for geothermal data analysis on a Lister probe: Stage 1 refers to when the probes are staying above the seafloor and waiting for the instrument to become stable; Stage 2 indicates that the probes are penetrating the seafloor and waiting for the temperature equilibrium, and the temperatures in different subbottom depths could be used to calculate the geothermal gradient; Stage 3 shows the self-heating pulse to derive the thermal conductivities.

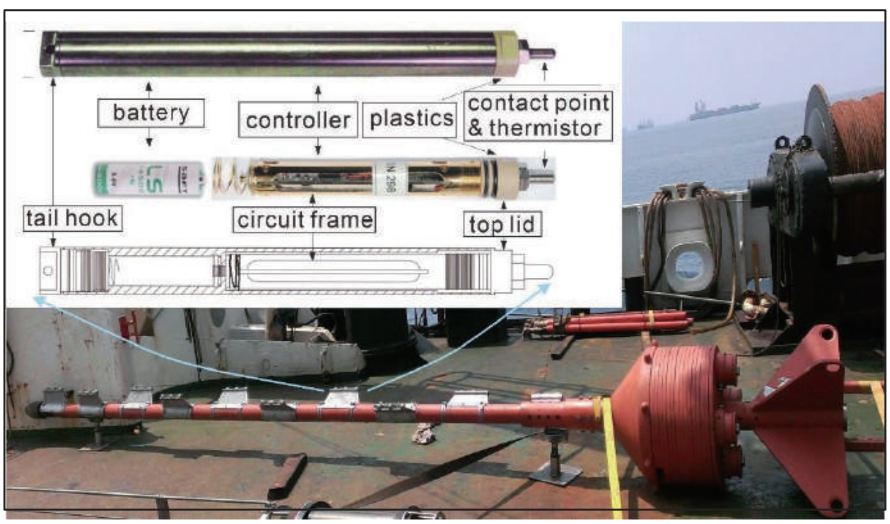

Figure 4. Photos of Miniature Temperature Loggers (MTLs) attached to the coring equipment, making the MTLs capable of penetrating the seafloor and measuring in-situ temperatures in marine sediments. (after Shyu, 2013)

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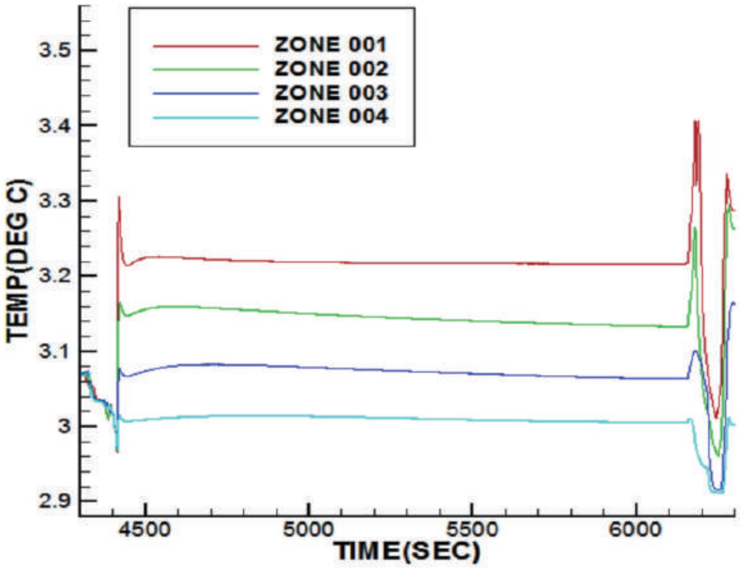

Figure 5. Typical temperature records by MTL (after Lee, 2008). When MTL probes penetrate the seafloor, the frictional heat raises temperatures abruptly and then gradually decays until it reaches thermal equilibrium.

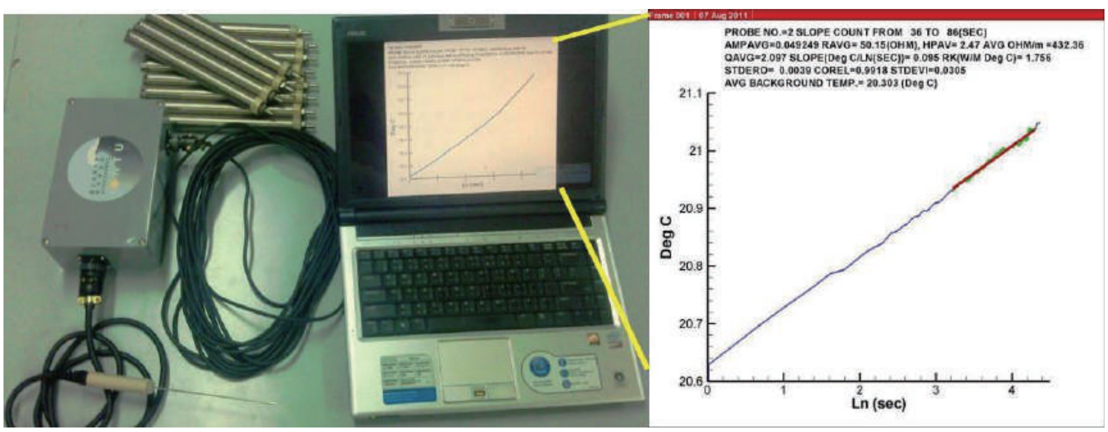

Figure 6. The thermal conductivity coefficient of the sediment can be determined from the slope of the temperature decay curve recorded by a thermal conductivity analyzer. (Chiang et al., 2008)

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2.2 Indirect Methods (BSR-based temperature fields)

Besides the direct measurements using heat probes, seafloor temperatures can also be indirectly derived from the subbottom depth of bottom-simulating reflections (BSRs) and the pressure-temperature (P-T) diagram of gas hydrates (Figure 7). Gas hydrates are ice-like solid molecules composed of water and gas, they commonly occur in deep marine sediments with high pressures and low temperatures (Kvenvolden & McMenamin, 1980). BSRs are seismic reflections sub-parallel to the seafloor (Figure 7a) with reversed polarity regarding seafloor reflection (Figure 7b), which indicates a negative acoustic impedance contrast (high-velocity hydrate above and low-velocity free gas below). The BSRs are considered indicators of the base of the gas hydrate stability zone (BGHSZ) (Stoll & Bryan, 1979), where hydrate-bearing sediments lie above the sediments containing free gases (Tucholke et al., 1977). The P-T condition of BSR is generally consistent with the maximum temperature and pressure at which gas hydrates are stable (Figure 7c).

The BGHSZ is defined as a "phase boundary" separating the stable gas hydrate above from the unstable field below (Hyndman & Davis, 1992); therefore, it is possible to estimate the temperature at the bottom simulating reflections (BSRs) by combining the information of hydrate phase boundary, pressure, and salinity (Figure 7c) (Brown et al., 1996). Since the geothermal gradient of marine sediments significantly dominates the BSR depths, the BSR depths can be used to derive seafloor temperatures, and the heat flow can be estimated using the given regional thermal conductivity (Chi & Reed, 2008; Liao et al., 2014). The widespread BSRs (Figure 8) observed in both the active and passive margins offshore SW Taiwan (Chen et al., 2012; Chi et al., 2006; Chi et al., 1998; Han et al., 2019, 2021; Lin et al., 2009, 2014; Lin et al., 2022; Liu et al., 2006; Lundberg et al., 1992; Schnurle et al., 1999; Shyu et al., 1998) provide the basis for deriving seafloor thermal structures indirectly. Figure 9 shows an example of marine geothermal gradients and heat flow values derived from the interpreted BSRs from seismic profiles offshore SW Taiwan (Chi & Reed, 2008).

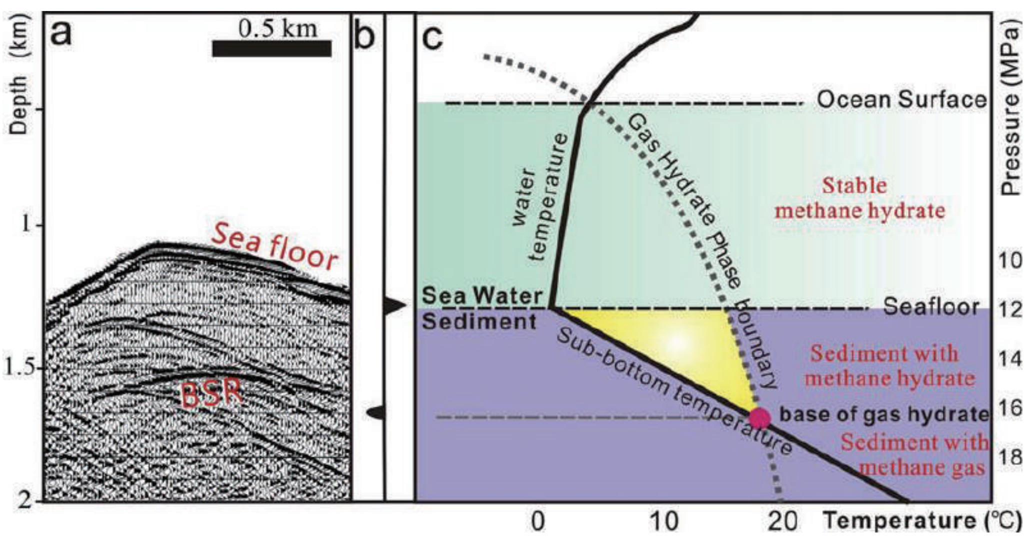

Figure 7. An example showing the BSR with reversed polarity regarding the seafloor on seismic profile and the diagram revealing the P-T conditions of the gas hydrate stability zone. (after Hyndman and Davis, 1992)

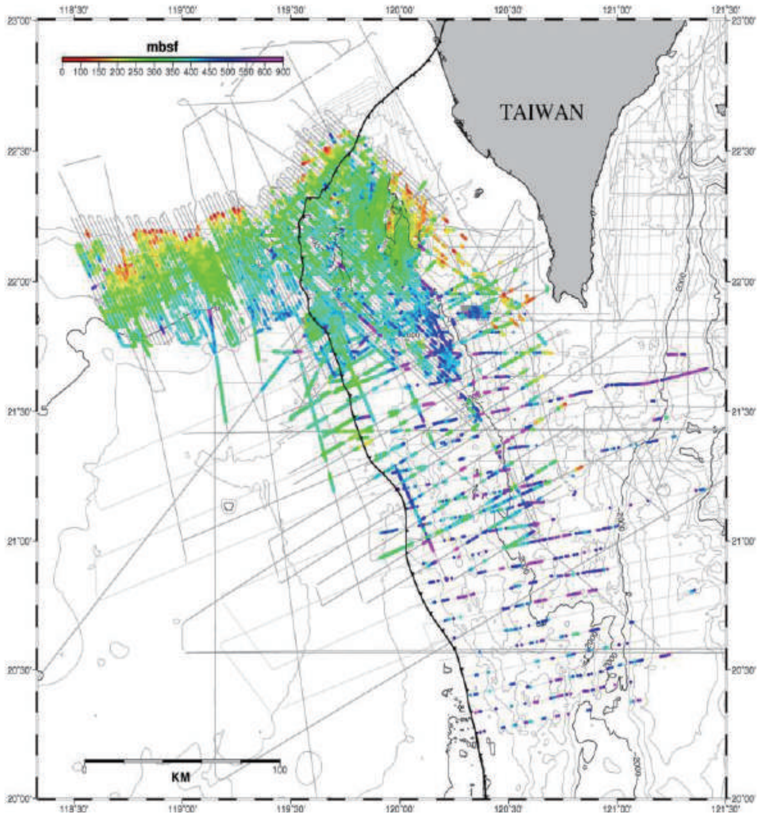

Figure 8. BSR distribution map offshore SW Taiwan. (integrated from Chi et al., 1998; 2006; Liu et al., 2006; Liu, 2015)

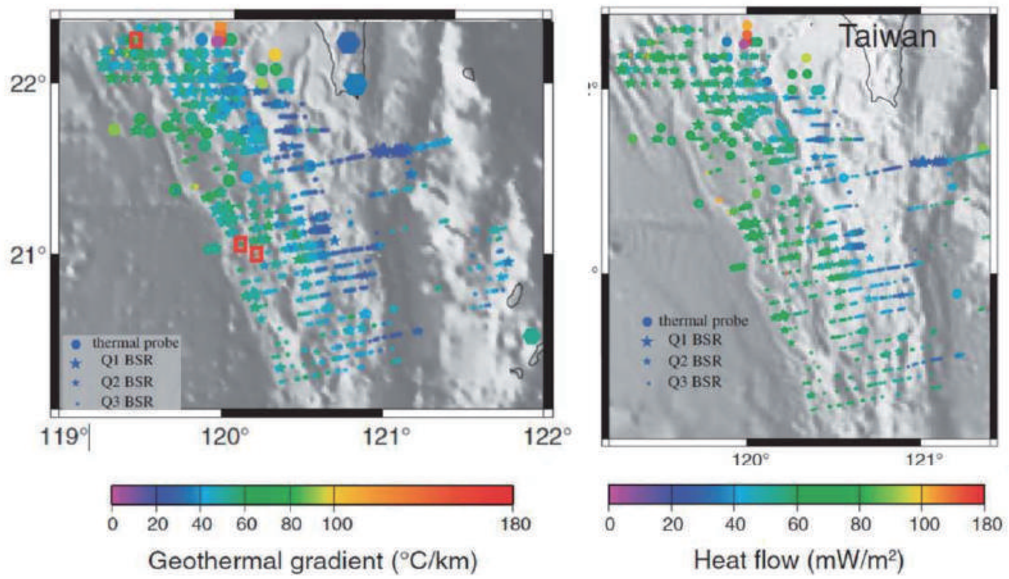

Figure 9. Geothermal gradient (left) and heat flow (right) derived from thermal probes and BSRs offshore SW Taiwan (after Chi & Reed, 2008). The Q1, Q2, and Q3 BSRs refer to different confidence levels from high to low in BSR interpretations from seismic profiles.

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3 OVERVIEWS AND APPLICATIONS

3.1 Seafloor Thermal Patterns Offshore Taiwan

Controlled by the P-T conditions of bottom waters and geothermal gradients, gas hydrates generally form sediments with water depths greater than 500 meters offshore SW Taiwan (Liu et al., 2006). The average geothermal gradient offshore SW Taiwan is about 0.05 °C/m, and the geothermal gradient increased from the continental slopes toward the Manila Trench (Chung et al., 2016) (Figure 10), consistent with the global averages in sedimentary basins (Kolawole & Evenick, 2023). The relatively high and low geothermal gradients near the deformation front (~ 0.4 °C/m) and the accretionary wedge (~ 0.04 °C/m) might indicate that seafloor thermal patterns are likely controlled by regional structures and sedimentations.

The heat probe temperature measurements offshore NE Taiwan illustrate that some focused heat flow signals (Shyu & Liu, 2001) (Figure 11a) might correspond with the magmatic and geothermal activities (Lin et al., 2007). Near Taiwan Island, the anomalous seafloor temperatures (Figure 11b) from limited measurements around Turtle Island (Chiang et al., 2008) indicated the presence of hydrothermal vents. The Southern Okinawa Trough (SOT) is an active hydrothermal system as demonstrated by the active gas ventings in the water column (Tsai et al., 2021) and several enormous heat flows (Figure 11c) (Shyu & Liu, 2001). Previous studies suggest that the downgoing cold seawater along the normal faults is first heated by volcanism, then dissolves metals and igneous materials to the surface through hydrothermal discharge (Figure 12) (Chen et al., 2020). Across the hydrothermal vents of Yonaguni Knoll IV (YK4) and Geolin Mound (GLM), the heat flow fluctuation varies from 10 to 3,200 and 180 to 31,477 mW/m^2 over a distance of 2 km and 1 km, respectively (Chen et al., 2020; Suzuki et al., 2008; Wu et al., 2019).

When interpreting local-scale thermal anomalies, it is critical to eliminate the topographic effects. Topography may dominate the heat transfer from the Earth's interior to the surface since it tends to take the shortest path. For example, valleys show higher geothermal gradients than topographic highs (Figure 13a). Ganguly et al. (2000) quantitatively studied the topographic effects on a 1–2 km scale based on the BSRs interpreted from seismic data, revealing ~50% variation in heat flow due to the topographic effect in the Cascadia margin. More than 20 °C/km of perturbation caused by topographic effect alone is observed by modeling a geothermal profile in the subduction zone 20.5°N offshore SW Taiwan (Chi & Reed, 2008). Another example in the Yung-An Ridge shows that the topographic effects can cause the geothermal gradients to vary 3.5 times (Q values vary from 0.028 to 0.098 °C /m) within a small region (Chen et al., 2014). Based on the finite element thermal modeling, apparent topographic effects on the thermal structures of the shallow crust are revealed by combining the BSR-based temperature fields (Figure 13c) (Chen et al., 2014). The curvature of BSR-based temperature is typically less than that of the seafloor topography (Figure 13). Such significant topographic effects suggest that the heat flow data acquired at shallow depths in a high topographic relief area require topographic corrections before they can be used for geological interpretation.

Joint seismic data with in-situ temperature measurements may reveal the regional thermal effects perturbated by geological processes, such as diapirism, fluid migration, or sedimentation (Chen et al., 2012, 2014; Chi et al., 2014). However, when analyzing the origin of seafloor thermal anomalies, some may argue the uncertainties from the velocity used for time-depth conversion. Due to the absence of boreholes and physical logging data offshore Taiwan, the best P-wave velocity models could be those derived from large-offset seismic data, especially those performed with pre-stack depth migration (PSDM). The Yuan-An Ridge offshore SW Taiwan presents an example of seismic-derived and empirical (Hamilton, 1980) velocity models with less than 10% differences (Tsai, 2010), while the PSDM velocity model in the Formosa Ridge shows less than 5% differences (Tu, 2010). These results suggest that the errors in geothermal gradient estimation are less than 2%; therefore,

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the empirical velocity model (Hamilton, 1980) is considered applicable for deriving geothermal gradients (Chen et al., 2014).

3.2 Applications and Outlook

Taiwanese scientists have developed technologies/methods to study marine heat flows for decades (e.g., Shyu et al., 1998; Shyu & Liu, 2001; Chiang et al., 2010; Chang & Shyu, 2011; Peng, 2012; Chen, 2014; Liao, 2014). The dynamic of thermal structures provides crucial information for evaluating the potential of seafloor resources and submarine geohazards after integration with other geophysical approaches. In the following three paragraphs, some potential applications/outlooks of marine geothermal research in gas hydrates, geological processes, and geothermal energy, respectively, are described for reference.

Since the conditions of the gas hydrate stability zone strongly depend on a function of temperature rather than pressure (Hyndman & Davis, 1992; Liu et al., 2006; Chen et al., 2014) (Figure 7), the gas hydrate occurrence is mainly controlled by the water bottom temperatures and the geothermal gradients. However, the geologically controlled thermal structures may be recognized from integrated geophysical surveys (Berndt, 2013; Bohrmann et al., 2023). As the upward fluid migration along fluid conduits can raise local temperatures, it would benefit understanding the petroleum system of the reservoir potential. For instance, the BSR-based heat flows derived from 3D seismic data were used to estimate the gas hydrate composition near the Palm Ridge, where the deformation front lies offshore SW Taiwan (Sahoo et al., 2018). The result is consistent with previous geochemical results (Chuang et al., 2006; Feng & Chen, 2015; Wu et al., 2011), which indicate that 99% methane and 1% ethane (Sahoo et al., 2018) are contained in the sediments. This illustrates an example of using seismic data to derive the molecular composition of hydrate-bound gases at a few hundred meters below the surface, where typical sediment coring systems cannot sample (Sahoo et al., 2018).

The seafloor thermal structures reveal interesting geological processes, including hydrothermal, diapirism, fluid flow systems, and sedimentary processes offshore Taiwan. However, some data gaps exist between nearshore NE Taiwan and the SOT, which could be critical to improving the regional hydrothermal discharge model. Well-distributed geospatial data must be acquired to understand the regional fluid migration pattern, which might affect the potential mineralization in the SOT. Systematic marine geothermal measurements, monitoring, and seismic and geochemical investigations are essential to advance scientific research toward sustainable development by understanding deep-sea hydrothermal activities. Marine HVs may provide diverse seafloor evolutionary conditions of the early Earth and future climate predictions for marine life (Dahms et al., 2018). Thus, hydrothermal venting (HV) detected by various marine technologies is the most apparent evidence of a potential geothermal reservoir on the seafloor (Atkins & Audunsson, 2013). For example, recent heat flow measurements show an extremely high flow (31,477 mW/m^2) contributed by an active hydrothermal system (Figure 12) around the Geolin Mound, which also exhibits the fault system extension of Taiwan and the southern rifting end of the Okinawa Trough under a tectonic junction (Chen et al., 2020).

Considering the geological background, Northern Taiwan possesses rich geothermal resources due to volcanic activities and the rapid uplifting of plate collision, which may play an experimental site for monitoring climate change or evaluating the potential of developing geothermal energy. However, detailed geological and geophysical surveying is essential to assess the geothermal potential and environmental impact. The observations of the Tatun Volcano Group (TVG) showed that the main volcanic center in Northern Taiwan is considered a potentially active volcano (Konstantinou et al., 2009; Pu et al., 2020). However, offshore exploration relies on towed equipment operated from a vessel, a different HV hunting technique. Offshore engineering, including vessels, equipment, and technologies, may flourish along with Taiwan's pathway to net-zero emissions by 2050, emphasizing expanding cutting-edge energies, including geothermal and ocean energies (National Development Council, 2022). Since the traditional penetration measurement is still being

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used site-by-site to fulfill the small spatial coverage offshore Taiwan, it may be time to value and upgrade marine geothermal measurement and monitoring techniques to meet the net-zero emissions policy. To achieve that, well-distributed and long-term geothermal observations corresponding to the seafloor stability and geohazards are essential. With the improved surveying technologies and data distribution, including heat probe, seismic, bathymetry, magnetic, and sediment coring methods, the geological model can be thus updated, assessing the potential of geothermal energy offshore Northern Taiwan where active volcanism may exist.

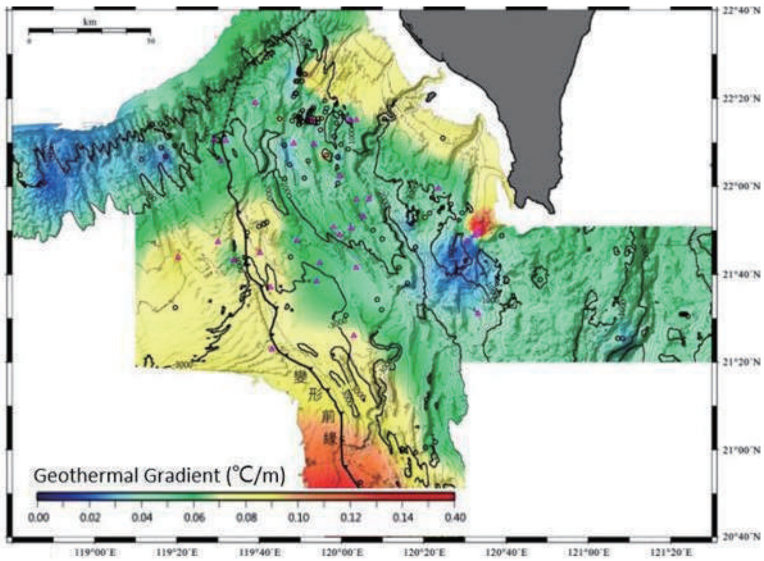

Figure 10. Contour map of geothermal gradients offshore SW Taiwan. (after Chung et al., 2016)

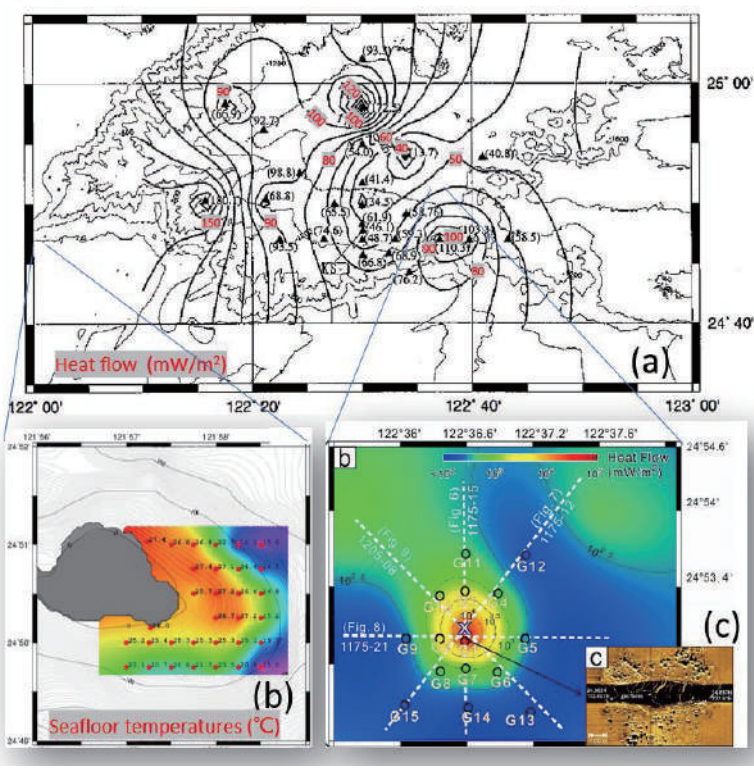

Figure 11. The results of seafloor temperature measurements offshore NE Taiwan. (a) The contour of the heat flow map (Shyu & Liu, 2001), (b) The seafloor temperatures around Turtle Island (Chiang et al., 2008), (c) The focus extreme high heat flow around Geolin Mound(Chen et al., 2020).

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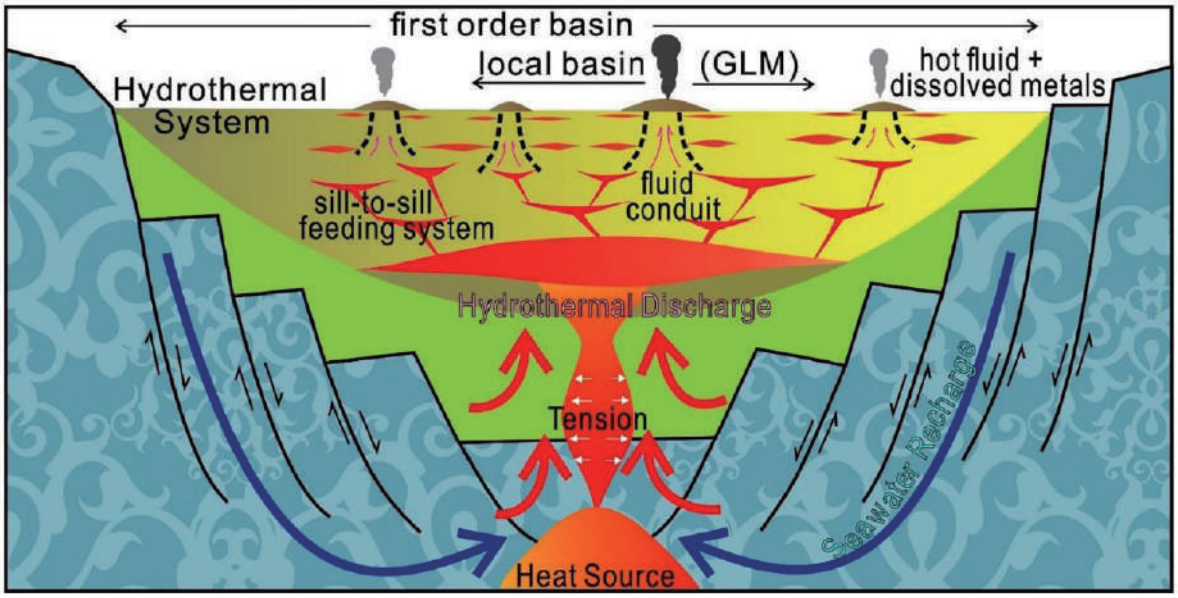

Figure 12. The geological thermal model of the Southern Okinawa Trough. (Chen et al., 2020)

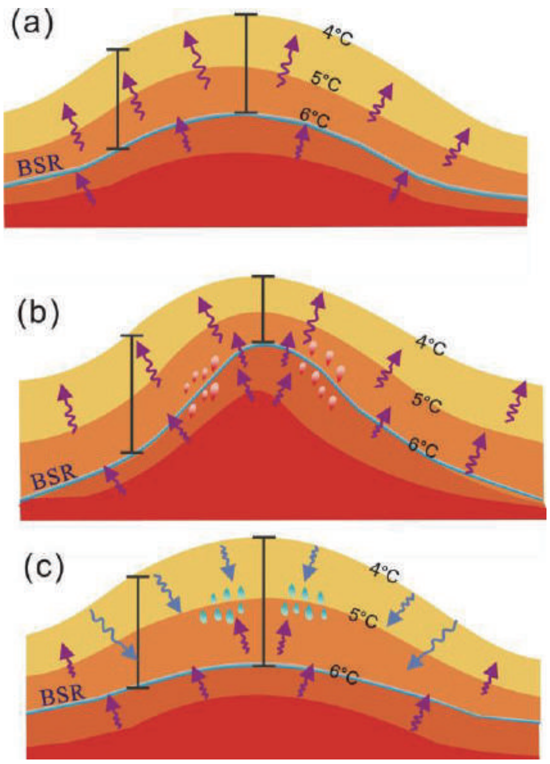

Figure 13. Conceptual models showing how topographic effects influence the temperature fields: (a) The temperature fields become focused beneath the topographic high (ridge) in a non-vertical heat transfer way to keep similar geothermal gradients near the surface. (b) The BSR-based temperature field and geothermal gradients will increase in shallow sediments if there is some heat flow beneath the ridge. (c) The BSR-based temperature field and geothermal gradients will decrease in shallow sediments if some cold flows (e.g., seawater) penetrated the ridge temperature field in shallow sediments and lower the regional geothermal gradients.

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4 CONCLUSIONS

Studying geothermal data and marine geothermal systems in Taiwan is crucial for gaining insights into Earth's geological processes, developing renewable energy resources, and assessing potential hazards. Researchers have used direct measurements like heat probes and indirect methods like BSR-based temperature fields to reveal important information about seafloor thermal patterns, regional fluid migration, and potential hydrothermal reservoirs. Advances in instruments such as Lister-Type Heat Probes (LTHP) and Miniature Temperature Loggers (MTLs) have allowed for more precise measurements and a better understanding of marine heat flows.

Marine geothermal research is valuable for both academic and practical purposes. By studying the thermal structures of the oceanic crust, researchers can assess the potential of seafloor resources like gas hydrates and hydrothermal minerals, which contribute to energy exploration and sustainable development efforts. Through direct measurements using heat probes and indirect methods such as BSR-based temperature fields, marine geothermal research in Taiwan has provided significant insights into seafloor thermal patterns, regional fluid migration, and potential hydrothermal reservoirs.

Continued efforts in marine geothermal research are crucial, especially in filling data gaps, expanding spatial coverage, and integrating various marine surveying data. Improvements in marine geothermal measure ment and monitoring techniques, supported by government policies, will pave the way for efficient and sustain able development of geothermal energy resources. Additionally, ongoing geological and geophysical surveys and long-term monitoring of seafloor stability and geohazards are essential for harnessing the full potential of marine geothermal systems and ensuring environmental safety.

This overview of marine geothermal research in Taiwan reminded us that continuing efforts in marine geothermal research are essential for better spatial distribution and time-series recording. In summary, improvements in marine geothermal measurement and monitoring techniques will pave the way for the power-efficient and sustainable development of seafloor resources. Long-term monitoring of seafloor stability through jointing divergent techniques to monitor marine seafloor resources is the key to advancing renewable energy technologies and fostering sustainable practices in energy exploration.

ACKNOWLEDGEMENTS

We extend our gratitude to the scientists and technicians dedicated to offshore geothermal exploration around Taiwan. We give special thanks to Dr. Hong-I Chang, our memorable level III Technician of the IONTU, for his remarkable contribution to making many things possible. We express our gratitude to the Geological Survey and Mining Management Agency (previously the Central Geological Survey), MOEA, for its long-term support and dedication to natural resources exploration and technology development. We also thank the National Science and Technology Council (previously the Ministry of Science and Technology) for the financial support of research projects and international cooperation. We sincerely appreciate the relentless efforts of the crews and technical staff on research vessels to fulfill their missions. Finally, we express our gratitude to all scientists and technicians in the marine geophysical exploration community who continue to uphold their professional legacy in this field.

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