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Key Points:

- Mass wasting and rapid sedimentation can generate double BSRs and enhance hydrate saturation
- Rapid seabed processes might trigger hydrate dissociation and active venting of methane and other fluids in shallow sedimentary section
- Focused fluid flow updip along the slope basin strata can locally enhance the hydrate saturation

Supporting Information:

- Supporting Information S1

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A Shallow Seabed Dynamic Gas Hydrate System off SW Taiwan: Results From 3-D Seismic, Thermal, and Fluid Migration Analyses

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Abstract Large amounts of methane, a potent greenhouse gas, are stored in hydrates beneath the seafloor. Sea level changes can trigger massive methane release into the ocean. It is not clear, however, whether surficial seafloor processes can cause comparable discharge. Previously, fluid migration was difficult to study due to a lack of spatially dense seismic and thermal observations. Here we examine a gas hydrate site at Four-Way-Closure Ridge off SW Taiwan using a high-resolution 3-D seismic cube, together with bottom-simulating reflections (BSRs) mapped in the cube, a thermal probe data set, and 3-D thermal modeling results. We document, on a scale of tens of meters, the interaction between surficial sedimentary processes, fluid flow, and a dynamic gas hydrate system. Fluid migrates upward through dipping permeable strata in the limb, the slope basin, and along thrust faults and ridge-top normal faults. The seismic data also reveal several double BSRs that underlie seabed sedimentary sliding and depositional features. Abrupt changes in subsurface pressure and temperature due to the rapid seabed sedimentary processes can cause a rapid shift of the base of the gas hydrate stability zone. This shift may be either downward or upward and would result in the accumulation or dissociation of hydrate in sediments sandwiched by the double BSRs, respectively. We propose that dynamic surficial processes on the seafloor together with shallow focused fluid flow affect hydrate distribution and saturation at depth and may even result in methane expulsion into the ocean if such localized features are common along convergent plate boundaries.

Plain Language Summary Gas hydrates are ice-like compounds in marine sediments. Shallow surface dynamic processes may affect the hydrate saturation beneath the seabed. We combine 3-D seismic and thermal probe data, with numerical geothermal modeling to investigate the geological processes controlling the distribution and formation of gas hydrates beneath thrust ridge anticlines. We also study fluid flow patterns under the seabed and found that localized fluid flow and rapid surficial erosional processes have significantly altered the temperature and pressure conditions of hydrate bearing sediment strata at depth, ultimately influencing gas hydrate formation and dissociation. We propose to conduct hydrate exploration close to thrust anticlines, where such active processes might enrich the saturation of gas hydrates or even influence fluid emission into the ocean if similar processes are widespread along continental margins.

1. Introduction

Gas hydrates are crystalline, ice-like compounds composed of gas and water that occur in the sediments along continental margins. Hydrates are stable under low-temperature and high-pressure conditions where there are adequate supplies of gas and water (Kvenvolden, 1993). As gas hydrates contain vast and potentially unstable reserves of methane and other natural gases, they might affect future energy supply, seafloor biology, and ocean biochemistry and may cause geohazards (Beauchamp, 2004). Therefore, it is important to understand how and where gas hydrates form in marine sediments.

Gas hydrates can be inferred from a bottom-simulating reflection (BSR) in seismic data (Shipley et al., 1979). BSR usually appears subparallel to the seafloor, crosscuts dipping strata, and shows opposite polarity

compared to the seafloor reflection. A BSR is generally thought to approximate the base of the gas hydrate stability zone (BGHSZ). It forms in response to the strong acoustic impedance contrast between overlying hydrate-bearing and underlying gas-bearing sediments. Several factors affect hydrate stability in marine sediments and consequently can change the depth of the BGHSZ. The primary factors are pressure and temperature, but other factors include gas composition, pore water salinity, capillary forces, pore size, and thermal properties of the sediment (Clennell et al., 1999).

In a static state system, the BGHSZ and BSR usually refer to the same horizon in a seismic data set. However, because we are investigating a dynamic and transient hydrate system, two or more BSRs may be present, representing both the shifted modern and relic base of the hydrate stability zone. As the hydrate phase boundaries for different gas compositions are well constrained (Sloan, 1998), one can estimate in situ temperature at the BSR by calculating the pressure at the BSR depth, assuming a hydrostatic gradient. One can then use observed seafloor temperatures to further derive geothermal gradients, heat flow, and its regional as well as local variations (e.g., Chi & Reed, 2008; Yamano et al., 1982).

Many processes can potentially disrupt the BSR in an otherwise static hydrate system. Prominent processes include (1) the ascent of warm and/or high-saline fluids toward the seafloor (Boswell et al., 2012; Minshull & White, 1989; Taladay et al., 2017; Tréhu et al., 2004); (2) sudden increases in water-bottom temperature, rapid sedimentation, and tectonic uplift (Bangs et al., 2005, 2010; Foucher et al., 2002; Zander et al., 2017); and (3) variations in gas compositions (Andreassen et al., 2000; Geletti & Buseti, 2011; Tinivella & Giustiniani, 2013) and the subsurface pressure field (Pecher et al., 2017; Tinivella & Giustiniani, 2013). These disturbances of the hydrate system can change the appearance of the BSR. For example, ascent of high-saline or warm waters into the GHSZ are often accompanied by shoaling of the BSR or the disruption of an otherwise continuous BSR (Chen et al., 2012, 2014; Crutchley et al., 2014; Hyndman & Davis, 1992; Pecher et al., 2010). Also, other processes may produce multiple BSRs that occur in the same place but at different subbottom depths (Popescu et al., 2006; Zander et al., 2017).

In some areas where pressure-temperature (PT) conditions and sediment properties are favorable, highly concentrated gas hydrates may form. However, the response time of the hydrate system, including the formation of free gas zones and hydrates, to different perturbations will differ depending on the rate of change and magnitude of perturbations and the physical properties of the sediments. Typically, the hydrate system should respond more rapidly to pressure field changes in the subsurface, while temperature changes might require more time to reach the BGHSZ (Foucher et al., 2002; Pecher et al., 2017; Zander et al., 2017).

A geophysical experiment was carried out in 2013 over the Four-Way-Closure Ridge (4WCR) near the toe of the accretionary prism off SW Taiwan to determine the influence of tectonic processes on the gas hydrate system (Berndt et al., 2019). This experiment generated a data set using a high-resolution P-Cable 3-D seismic imaging system, which allows us to study fluid migration and gas hydrate dynamics in more detail on a scale from meters to tens of meters (Planke et al., 2009; Plaza-Faverola et al., 2014; Riedel et al., 2018). Localized temperature field variations, derived from spatially dense measurements, are usually impossible to observe using a thermal probe due to technical and logistical difficulties at sea. In contrast, the P-Cable 3-D seismic cube allows us to document small-scale variations in the BSR depth that may indicate temperature field perturbations related to localized thermal processes separate from large-scale diffuse heat conduction (e.g., focused advective heat transfer).

The overall objective of this work is to construct a detailed fluid migration model for the accretionary wedge anticline from 3-D seismic and heat flow data using simulations of the thermal field. The first objective is to identify fluid pathways into the GHSZ within the anticline. The second objective is to quantify temperature perturbation due to fluid flow along the different fluid pathways. The final objective is to investigate whether the gas hydrate stability zone has experienced abrupt changes due to external forces such as surficial erosion or tectonic movements, and their implications for methane release mechanisms under the seabed.

2. Geologic Setting

Offshore SW Taiwan, the Eurasian plate subducts eastward underneath the Philippine Sea plate at a rate of 7 to 9 cm/year. As the Manila Trench encroaches on the passive China continental margin, the subduction

Figure 1. (a) Location map. Red box inset displays the study area. Four-Way-Closure Ridge (4WCR) represents typical settings for the active margin. Tectonic structures from Lin et al. (2009) and sand transport pathways from Lin et al. (2014). YAL = Yung-An lineament. (b) Twenty-meter resolution bathymetry map of the study area. On top of the bathymetry, black lines show locations of seismic sections from the 3-D seismic volume shown in this study. Red circles locate the SO-266 heat probe measurements. Red polygons highlight the area where we mapped the bottom-simulating reflection (BSR). Blue polygons mark the area where we observe double BSRs.

system (south of $20^{\circ}30'N$) changes into an incipient arc-continent collision system ($20^{\circ}30'N$ to $21^{\circ}30'N$) from south to north (Teng, 1990).

The morphotectonic features offshore of SW Taiwan (Figure 1) demonstrate the ongoing transition from subduction to collision and from a passive to an active tectonic environment (Liu et al., 1998). Preexisting normal faults exist within the Chinese continental margin, while fold-and-thrust structures are found in the convergent zone east of the deformation front (Lin et al., 2008, 2014; Liu et al., 1997, 2004). The west vergent deformation front extends from the offshore Manila Trench to the frontal thrust onshore Taiwan (Han et al., 2017; Liu et al., 2004). Several prominent bathymetric lineaments occur in the offshore

accretionary prism and continue onshore; geodetic data across some of these lineaments show strike-slip movement (Liu et al., 2004). In particular, the Yung-An lineament (YAL) runs across the northern portion of Ridge A. Deep towed side scan sonar images of the 4WCR reveal several cold seeps parallel to the orientation of the YAL (Klaucke et al., 2016).

Taiwan has some of the highest denudation rates in the world, and much of the orogenic sediments from the Taiwan mountain belts are transported through the major submarine canyons, for example, Penghu, Kaping, and Fangliao canyon, into the sedimentary basins in the South China Sea (SCS).

The sedimentary facies off SW Taiwan show lateral variations, from coarse fluvial conglomerates proximal to the topographic front onshore to fine-grained deep marine mud close to the deformation front (Chiang et al., 2004). Due to the lack of borehole information, the lithostratigraphy in the study area is poorly constrained. However, Penghu canyon was once located close to our study area (Lin et al., 2014). It is therefore likely that less frequent, high-volume canyon-flushing turbidity currents have deposited turbidities there (Klaucke et al., 2016). Background sedimentation, however, is expected to be hemipelagic mud deposited out of suspension (Lundberg et al., 1992).

There is ample evidence of the occurrence of gas hydrate offshore SW Taiwan. At a large scale, BSRs cover an area of more than 15,000 km² both in the accretionary wedge and in the SCS (Chi et al., 1998; Liu et al., 2006). In addition, Lin et al. (2009) investigated geological controls on gas hydrate occurrences in the area SW of Taiwan, while hydroacoustic data and geochemical data sets derived from sediment cores and bottom-water samples (Berndt, 2013; Chen et al., 2017; Chiu et al., 2006; Chuang et al., 2010; Liu et al., 2006; Oung et al., 2006) identified hydrate related fluid venting in the region. Also, seafloor photographs by deep-tow camera systems and sediment samplers show carbonates, carbonate mounds, chimney structures, and chemosynthetic communities associated with bacterial mats (Berndt, 2013). Finally, actual gas hydrate samples were recently recovered at a site north of 4WCR (MOST, 2018).

3. Data and Methods

3.1. Three-Dimensional Seismic Data

The seismic cube was acquired with GEOMAR's P-Cable system (Berndt et al., 2019; Planke et al., 2009). The source was a GI gun firing every 4 s at 210 bars, equivalent to ~7 m shot spacing at an approximate ship speed of three to four knots. Noise bursts in the data volume of the streamer cables of each shot were replaced by average spectral amplitudes from the two nonzero neighboring traces in overlapping 3-D time-space windows. Three-dimensional F-K domain dip filters and spatial prediction filters were further used to suppress random, coherent, and swell noise. The remaining anomalous amplitudes were detected and rejected in a time sliding window. Normal move-out corrections with an average velocity of the water column and constant gain were applied before stacking. The cube was stacked in 3.125 × 3.125 m bins. Trace interpolation was performed in the in-line and cross-line directions to fill data gaps, and a poststack 3-D F-K coherency filter was integrated into the processing workflow to obtain spatial continuity. First, a Stolt migration with a constant velocity of 1,500 m/s was applied. This was then followed by a residual finite difference time migration and a time to depth conversion using a smoothed velocity field derived from the ocean-bottom seismometer (OBS) data to get the final processing result. Berndt et al. (2019) contains further details on the processing flow and derived seismic velocities.

3.2. Seismic Attribute Analysis

To investigate relationships between structural features and fluid migration indicators in the shallow marine sediment, a series of seismic attribute volumes were extracted from the seismic data using dGB's OpendTect and IHS Kingdom software, such as coherency, root-mean-squared (RMS) amplitude, sweetness (ratio between instantaneous amplitude and squared root of the instantaneous frequency), and fault enhancement filters. The workflow includes tracking of prominent horizons and structures in 3-D. The coherency attribute represents the degree of spatial continuity along a reflection and can be used to highlight discontinuities. Amplitude- and frequency-based attributes help to detect lithological patterns and provide evidence for fluid migration (Chopra & Marfurt, 2007; Ligtenberg, 2005; Meldahl et al., 2001).

Figure 2. (a) Results of the 3-D steady-state conductive-only numerical model of the temperature field of the study area. We assigned a constant temperature on the seafloor using an average value derived from the heat probe data. We impose no-flow boundary conditions on all sides. GG is the best fit geothermal gradient used for the BSR-derived temperatures and the theoretical temperature field. (b) P-T conditions for gas hydrate stability beneath the seafloor. The inset shows a schematic geothermal gradient calculated from the position of the BSR. dT/dz = geothermal gradient; T_s = seafloor temperature; and T_{BSR} = temperature at BSR. Based on the 3-D numerical model, we can estimate the effect of topography on temperatures derived at the subbottom depths of the BSR at different parts of the volume.

3.3. Heat Probe and BSR Thermal Data

In situ sediment temperature and thermal conductivity measurements were carried out using a 6 m-long heat flow probe during voyage SO-266 (Bohrmann, 2018; refer to Figure 1b for the locations). The heat probe has a Lister-type violin bow design comprising 22 thermistors (e.g., Villinger et al., 2010). The in situ thermal conductivity was determined using the pulse probe method (Lister, 1979).

In situ thermal gradients were calculated at 14 sites from temperature-depth profiles from the heat probe data starting at the subseafloor depth where the profiles were sufficiently linear to eliminate possible time-varying bottom-water temperature effects (Figure S1 in the supporting information). Geothermal gradients were converted to heat flow using results from the in situ thermal conductivity measurements.

Geothermal gradients were also constrained from BSR depths. The temperature at the sediment-water interface was derived from in situ thermal probe measurements in this region (Bohrmann, 2018; Chi & Reed, 2008; Shyu et al., 2006), while the temperature at the BSR depth was inferred from hydrate phase equilibria and estimated in situ hydrostatic pressures. Similar approaches to study heat flow on a regional scale have been conducted along several convergent margin settings (e.g., Chi & Reed, 2008; Townend, 1997; Yamano et al., 1982; Zwart et al., 1996). A total of 100% methane hydrate was assumed based on the geochemical analysis of a number of seafloor cores from off SW Taiwan (Chuang et al., 2010). The Heriot-Watt Hydrate (HWHYD) program, developed at Heriot-Watt University, was used to fit the hydrate phase boundary to the pressure at the depth of the BSR (Figure 2b).

3.4. Modeling the 3-D Conductive Temperature Field

To generate a 3-D thermal model, a 3-D finite element thermal model was used that solves the 3-D conductive heat transport equation (e.g., Carslaw & Jaeger, 1959):

$$\rho c \left(\frac{\partial T}{\partial t} \right) = \frac{\partial}{\partial x} k \frac{\partial T}{\partial x} + \frac{\partial}{\partial y} k \frac{\partial T}{\partial y} + \frac{\partial}{\partial z} k \frac{\partial T}{\partial z},$$

where t is the time; T is the temperature; ρ is the average rock density; x , y , and z are the locations along the profile and the depth; k is the thermal conductivity; and c is the specific heat. We used a workflow similar to that in Chen et al. (2014), who modeled the 2-D fluid flow pattern and 3-D temperature at Yung-An Ridge, which is northeast of our survey area. Our model extends the method from 2-D to the 3-D bathymetry in order to constrain the geometric shape and temperature field across the region (Sahoo et al., 2018; Zander et al., 2017).

To calculate the geothermal gradient throughout the model, steady-state heat conduction was used, given as

$$\nabla \times (k \nabla T) = 0.$$

This steady-state equation was then solved for an average regional geothermal gradient. The shallow sedimentary section was assumed to have the same thermal conductivity and a constant seafloor temperature of 2.6°C, as derived from average in situ thermal probe measurements. The final temperature field is not dependent on the thermal conductivity used in this static-state, homogeneous modeling. To find the regional geothermal gradient, the BSR depth where the seafloor has gentler slopes and is less affected by topography was used.

Neumann's boundary conditions were imposed along the top (seafloor) and at the bottom of the model, while all other boundaries were closed. The model bottom is flat, and its depth must be sufficiently large (~6 km) to avoid artifacts arising from forcing the temperature contour to be flat near the bottom of the profile. Once a 3-D steady-state conductive temperature field was generated across the 3-D seismic volume, the regional geothermal gradients were interactively changed to minimize the misfit between the BSR-derived temperatures and the theoretical temperature field. To study the topographic effects, the theoretical 3-D conductive temperature field (Figure 2a) was used without the influence of fluid flow. A comparison of the expected BSR depth from these 3-D steady-state calculations with the observed BSR depth reveals the locations of anomalous BSR depths in the seismic volume.

4. Results

4.1. Seismic Evidence for Gas Hydrate and Free Gas

The 3-D seismic data provide good images down to at least 2,500 m below sea level. The east-west oriented survey has a length of 11.4 km and a width of 2.1 km covering anticlinal ridges: Ridge A and 4WCR, as well as the adjacent slope basins (Figure 3). Due to an interpreted west verging thrust below it, 4WCR is uplifted, causing a gentler backlimb under its eastern flank.

The seismic data show that BSRs exist both beneath 4WCR and the western flank of Ridge A (Figure 1b). The BSRs show clear reversed polarity compared to the seafloor (Figure 4). Where the seismic image is clean and without a continuous BSR, we identified the BGHSZ from the polarity reversal of individual reflectors due to the change in impedance contrast. The BSR is best recognized from where it crosscuts the dipping sedimentary strata, for example, within the crest and the limbs of the two ridges and through growth strata in slope basins. High-amplitude BSRs occur in the anticlinal ridges and near the base of the slope basin (BSLB) (Figures 4), whereas absent or weak BSRs occur in slope basins; subhorizontal BSRs in basins have similar shallow dips to the sediment strata in some locations, presenting a challenge for BSR identification.

We have interpreted several double BSRs beneath the limbs of Ridge A and 4WCR (BSR2 and BSR3 in Figure 4) beneath an interpreted sliding feature deposit and seafloor-expressed head scarp, respectively (Figures 1 and S4). Similar to the main BSR, they show reversed polarity compared to that of the seafloor. Beneath Ridge A, the upper BSR (BSR2) shows strong reflection amplitudes, while at 4WCR the deeper BSR is the stronger reflection (Figure 4b) and shows continuous occurrence along the strike of the ridge. The double BSRs only exist where sedimentary strata crosscut the BSRs. Figures 4a and 4b show examples of this type of relationship where dipping strata crosscut the BSR and extend into the GHSZ. The common attribute of these reflections is that the extent of the "highly reflective segment" (HRS) is spatially limited. High reflectivity starts at or slightly below the BSR depth, crosscuts the BSR, and extends upward for some distance before fading into the background (Figure 1b).

We map the location and shape of the double BSRs in three dimensions (Figure 5a). We infer that, while the vertical separation between the double BSRs is not constant laterally, it is almost identical to the vertical depth separation of the paleo-seafloor and the modern seafloor after erosion and deposition occurred at 4WCR and Ridge A, respectively (Figures 5b and 5c).

4.2. Geologic Structures and BSR

We conducted seismic attribute analysis and correlated the results with anomalous lateral variations of the BSR subbottom depth (Figure 6). The BSR subbottom depth varies throughout the seismic volume, ranging

Figure 3. Interpreted (top) and original (lower) seismic sections from the 3-D seismic volume. These sections are representative of structure and processes dominating in the 3-D volume (locations in Figure 1b).

from 450 ± 25 mbsf (meters below sea floor) underneath the ridges to 260 mbsf underneath the slope basins. Predominantly long-wavelength BSR subbottom depth variations likely result from topographic effects and regional tectonic movements. On the other hand, localized, pronounced gas hydrate stability zone thinning is evident under the crest and the eastern limb of 4WCR and at the intersection of the BSR with BSLB strata. Furthermore, under the crest and eastern limb of the ridge, the GHSZ locally shallows along a NNE to SSW orientation, the same orientation as the inferred linear paleo-seep sites aligned at the seafloor (Klaucke et al., 2016; Figure 6b). A coherence attribute map extracted along the BSR (Figure 6d) reveals two low coherence zones, which coincide with the two zones with anomalously shallow BSRs: the NNE to SSW anomaly and its conjugate. The zone of low coherence correlates with zones of high sweetness and shallower BSR subbottom depth (Figure 6e).

To determine the locations and orientations of prominent structures, we extract seismic attributes in both cross-sectional view and map view at different subbottom depths (Figure 7). The HRSSs manifest themselves as high sweetness zones and are found in the lower half of the GHSZ under the ridge, below the BSR on the flanks of ridges, and in the western boundary of the slope basin. Figure 7 shows several examples where HRSSs intersect the BSR and extend upward along the same dipping horizon amid lower reflectivity layers in the background. HRSSs are generally associated with reversed polarity events beneath the BGHSZ (Figure 4c). Above the BSR, we observe mostly positive polarity events, but also zones where positive and reversed polarity reflections seem to interfere (Figures 4b and 4c), making polarity identification ambiguous.

Figure 4. West-to-east enlarged depth sections showing (a) Ridge A; (b, c) 4WCR; and (d) Slope basin east of 4WCR. The BSRs are shown as colored dashed lines; interpreted faults are shown in solid black lines; double BSR is marked with arrows. Black dashed line above the seafloor shows an anticline that has been inferred to have been removed by erosion. Paleo-seafloor is extrapolated from lithological horizons. Black boxes with white numbers highlight regions where wavelets have been extracted and enlarged in the inset figures.

Steeply dipping fault and fracture networks can be found in the hinge zones of both ridges. In map view there are small-scale low coherence lineations and large-scale N-S trending low coherence lineations under the ridge top (Figures 7b and 7c). The spatial relationship between the structural architecture and fluid migration pattern within the sediments is visualized by overlaying the coherency and sweetness attributes. The extracted coherence attribute along the seafloor horizon reveals N-S trending streaks of relatively low coherence that can be traced into the subsurface (Figures 7b and 7c). While these structural lineations are prominent in anticlinal ridges, they are rarely observed in the well-defined reflections inside the basins. Coherency maps show a NNW-SSE oriented fault underlying the slope basin east of 4WCR (Figures 8a and 8c). This fault intersects the BSLB and is characterized by an anomalously high-amplitude distribution further upward in its hanging wall (Figure 8g). Seismic horizons a few hundred meters below the seafloor also show patches of low coherence under the eastern limb of Ridge A and the western limb of 4WCR. These seismic features are spatially correlated with the zones with thinned BSR subbottom depths (Figure 6b).

At Ridge A, faults appear to accommodate normal offsets with throws of up to 15 m (Figure 4a), whereas beneath 4WCR, faults and fractures are associated with a more complex geometry, including curved-to-crosscutting relationships. High reflection amplitudes associated with fault zones can be seen in the form

Figure 5. (a) Depth map of the observed double BSRs beneath Ridge A and 4WCR. (b) Vertical separation between BSR2/BSR3 and BSR. (c) Cutout showing BSR (red arrow) and double BSR (blue arrow) underneath Ridge A. Major depositional sequences are marked as colored fields. (d) Cutout showing BSR (red dashed line) and double BSR (blue dashed line) underneath 4WCR. Inferred paleo-seafloor is shown as a black dashed line. The vertical depth range between the paleo BSR and the current BSR is almost identical to the vertical depth range between the paleo-seafloor (black arrows with red head) and the original shape of the seafloor before erosion and deposition occurred at 4WCR and Ridge A, respectively.

of high sweetness spots in the lower half of the GHSZ beneath 4WCR and the western limb of Ridge A (Figure 7). The former coincides with a zone where high P wave velocity and high-resistivity strata were found (Berndt et al., 2019). We found high-amplitude reflections at both the limbs of the ridges and in the apex of the fold where we have interpreted fracture zones and ridge-top normal faults. We can visually link the fault zones to a confirmed cold seep site at the seafloor (Figures 4c and 7a; Berndt et al., 2019).

We observe BSR shoaling up to 15 m along the margin of the slope basin (Figure 4d). In this region, the seafloor topography is gentle, the BSLB dips to the northeast (Figure 8d), and the BSR shoals locally in the updip direction. In addition, high-amplitude slope basin reflections occur below the BSR (Figures 8f and 8g). Interestingly, the high-amplitude reflections do not extend across the BSLB from slope basin strata to the underlying anticline to the west (Figure 8e).

In summary, we have identified three zones of geological structures: (1) under the crest of the anticlinal ridges; (2) in the limbs of the ridges; (3) and along the intersection of the BSR with the BSLB strata. We interpret complex fault patterns, dipping sedimentary strata, high reflection amplitudes below or above the BGHSZ, and localized BSR shoaling.

4.3. Heat Probe Measurements and BSR-Derived Geothermal Gradients

Comparing seafloor heat probe data with BSR-based thermal data can help to test whether the modern BSR subbottom depth is in equilibrium. Geothermal gradient and heat flux from heat probe measurements are shown in Figures 9 and S1. At the 4WCR, the background gradients range from 28.0–39.0°C km^{−1} while

Figure 6. (a) BSR depth map; (b) BSR subbottom map; (c) extracted sweetness along BSR horizon; (d) extracted coherence attribute along BSR; and (e) coherence and sweetness attributes extracted along BSR horizon. Black arrow in (b) marks the orientation of observed paleo-seep sites in our survey area that are oriented in the direction of the Yung-An lineament (Klaucke et al., 2016). Green dashed lines in (e) highlight a zone of anomalous coherence and sweetness at the eastern limb of 4WCR. Black dashed lines mark the slope basin boundary.

the gradient at the seep site was as high as $51.7^{\circ}\text{C km}^{-1}$. Along the BSLB, gradients range from $52.2\text{--}55.9^{\circ}\text{C km}^{-1}$ and dropped to $48.1^{\circ}\text{C km}^{-1}$ in the basin east of 4WCR. Along the western flank of Ridge A, gradients range from $61.4\text{--}66.9^{\circ}\text{C km}^{-1}$ and decrease westward to $55.0\text{--}58.0^{\circ}\text{C km}^{-1}$.

Heat probe measurements fall within the range of the BSR-derived temperature field, improving confidence of our analysis. Discrepancies between the heat probe and the BSR results are usually less than 11% but can vary between 0.6% and 31% (Figure S2). In the case of the BSR-derived thermal data (Figure 9), the geothermal gradients at the seafloor on 4WCR show lower geothermal gradients (approximately $-4.0^{\circ}\text{C km}^{-1}$), except for significantly increased geothermal gradients ($+9.3^{\circ}\text{C km}^{-1}$) beneath the active seep site. In addition, heat probe measurements at the seafloor close to the edge of the slope basin were $+0.7$ to $+4.0^{\circ}\text{C km}^{-1}$.

Figure 7. Sweetness and coherence attributes extracted from seismic cube: (a) sweetness attribute across the volume; (b, c) coherence and sweetness attributes extracted from depth-projected seafloor horizons 150 and 250 mbsf. Note that high sweetness values are pronounced underneath the crest of 4WCR and the limbs of 4WCR and Ridge A. Prominent lineations of low coherence are faults/fractures affecting the hinge zone of 4WCR and Ridge A.

higher than the BSR- based geothermal gradient. Interestingly, these discrepancies occurred updip from the observed pronounced BSR deflection toward the seafloor and the increased geothermal gradients at the intersections with the BSLB. Farther to the north, where there is no local shoaling of the BSR, heat probe geothermal gradients are lower than the BSR-derived geothermal gradients (approximately -3.0 to $-1.4^{\circ}\text{C km}^{-1}$). At Ridge A, near the edge of the slope basin boundary to its west, seafloor geothermal gradients from heat probes are elevated by $+2.8$ to $+12.8^{\circ}\text{C km}^{-1}$ compared with the BSR-derived thermal gradients. We also compared temperature gradients from BSR 2 underneath Ridge A with heat probe data and found a temperature gradient discrepancy of less than 1%.

4.4. Geothermal Modeling: Revealing Clear BSR Depth Anomalies

To assess local temperature variations as a result of focused fluid flow, we have built a 3-D thermal model and studied the likelihood of lithological or structural hydraulic conduits for such fluid flow. We first subtracted our 3-D steady-state conductive only numerical model of field temperature, including topographic effects, from the BSR-derived temperature fields to reveal clear BSR depth anomalies at these sites (Figure S3). The regional topography lead to decreased geothermal gradients along the ridge crest, whereas higher geothermal gradients occur along flank depressions (Figure S3d; Blackwell et al., 1980). Using a geothermal gradient of $0.043^{\circ}\text{C m}^{-1}$ (Figure 2a), we found the best fit between BSR-derived temperatures and the theoretical temperature field. The geothermal gradient from the BSR-derived temperature field

Figure 8. (a, b) Inline and crossline illustrating the main processes in the adjacent slope basin of 4WCR. Pronounced shoaling of the BSR (dashed red line) is observed at the edge of the slope basin boundary. Spatial appearance of the fault cutting through the base of the slope basin (BSLB) is highlighted by a solid black line. (c) Coherence attribute extracted along the BSLB. (d) BSLB depth contour map. Preferred direction of fluid migration (black arrow). The small arrows are derived from the median gradients of the structure (spaced every 200×150 m), which shows the preferred direction of free gas migration. (e) Extracted RMS attribute over a window 100 m below the BSR. Amplitudes are clearly pronounced in sedimentary units of the basin, while sedimentary strata of the ridge are less affected. (f, g) Amplitude map along horizon H1 and H2, highlighting accumulation of high reflection amplitudes below the BSR in areas where BSR is shoaling.

and the theoretical temperature field can be seen in Figure S3. Temperature discrepancies of up to 15–20% can be found locally. Highest BSR-based positive temperature anomalies occur within the apex of 4WCR where we observed a high concentration of amplitude anomalies (Figures 4a and 4c).

We show derived geothermal gradients, in conjunction with (1) seismic data along one inline (Figure 10); (2) a crossline over the eastern limb (Figure 11); (3) another crossline over the slope basin (Figure 12); (4) and in the map view (Figure 13). We compare temperature anomalies directly to geological structures perpendicular to and along strike and to the extent of amplitude anomalies in the gas hydrate system. In inline-sectional view, the 3-D numerical model has similar geothermal gradient patterns to that derived from the BSR (Figure 10). Under Ridge A, heat probe data are consistent with geothermal gradient

Figure 9. BSR-derived geothermal gradient with geothermal gradients from heat probe measurements (circles). The star marks the approximate location of the active seep site at the ridge crest.

derived from modern BSR2. Under 4WCR, however, heat probe data are consistent with the geothermal gradient derived from the proposed paleo BSR3. For Figure 11, we applied a shift in the temperature gradient to improve the fit with the observed short-wavelength shoaling of the BSR in a cross line across the eastern limb of the 4WCR where the BGHSZ is pierced by HRSS. Our geothermal modeling shows that BSR shoaling at the intersection with the slope basin does not occur along the entire western boundary of the slope basin but only in the southern part (Figures 12 and 13), in the updip direction of the slope basin strata.

Figure 10. (a) Comparison of the geothermal gradient from BSR and heat probe with the results from 3-D numerical model along extracted inline 1,140. (b) The corresponding seismic image showing the subseafloor strata and structures. Note high discrepancies in geothermal gradient are observed underneath the crest of 4WCR and the edge of the slope basin boundary. We interpret these discrepancies as caused by fluid migration. (c–e) Enlarge seismic sections marked by solid black boxes in (a) that highlight prominent fluid flow patterns in the survey area.

Figure 11. (a) Comparison of geothermal gradient derived from BSR and theoretical 3-D numerical model results along extracted cross line 3,430. (b) The corresponding seismic image shows the theoretical temperature field and BSR-derived temperatures. The BSR is annotated by the colored circles. The location of the profile is shown in Figure 1b.

5. Discussion

5.1. Using Temperature Data and Thermal Modeling to Detect Zones of Focused Fluid Flow

The high-resolution 3-D seismic data reveals a widespread BSR, which allows dense sampling of BSR-based temperature field data (3.125 by 3.125 m bin spacing) over 4WCR at subbottom depths of a few hundred meters. A comparison of the thermal probe data set, 3-D steady-state conductive-only numerical modeling of the temperature field and the BSR-derived temperature fields show that the lateral change of BSR subbottom depth at the intersection with structural and lithological discontinuities not only reflects the bathymetric effects but also localized temperature perturbation on different spatial scales (from tens to hundreds of meters) (Figures 8 and 13). We interpret these perturbations as evidence of focused fluid flow along these conduits into the GHSZ. At 4WCR, updip fluid migration in the slope basin strata results in

Figure 12. (a) Comparison of geothermal gradients derived from the BSR and theoretical 3-D numerical model results along extracted cross-line 3,930. (b) The corresponding seismic image shows the theoretical temperature field and BSR-derived temperatures. The BSR is annotated by the colored circles. The short-wavelength shoaling of the BSR is highlighted with a blue double sided arrow. The location of the profile shown is in Figure 1.

coherent BSR depth anomalies on the southern part of the slope basin. Furthermore, at the ridge crest, the short-wavelength temperature anomalies are most pronounced around the seep site, consistent with the interpretation of active fluid flow. It is also possible that part of the temperature field is not in equilibrium due to rapid geological processes.

Each of the described individual structures and BSR depth anomalies are not always stand-alone indicators of fluids flowing into the GHSZ. However, these perturbations are proximal to other fluid indicators from the attribute analysis (e.g., sweetness attribute; Figure 7), which supports our interpretation that focused fluid flow is present in these regions (Crutchley et al., 2014; Hornbach et al., 2012; Pecher et al., 2010; Plaza-Faverola et al., 2014).

Figure 13. (a) Difference between the modeled steady state and observed 3-D temperature fields. Note the clear shoaling (warm colors) of the BSR near the known seafloor vent site as well as at the eastern limb of 4WCR and the edge of the slope basin boundary. (b) Thermal gradient discrepancies between the modeled temperature field and the temperature field derived from BSR2 and BSR3.

Geochemical age dating of carbonates in the region (Feng et al., 2018) suggests that venting can be intermittent but there are few geophysical data sets documenting such processes. In this study, there are a few vent sites where heat probe data are not consistent with the BSR-based data. Although gas flares have not been present at multiple inactive vent sites along the lineation proposed by Klaucke et al. (2016), carbonates have been sampled, showing us evidence for venting in the recent past. Despite this intermittency, we see a shallower BSR along this lineation without clear velocity pull-ups above the BSR, suggesting a high-temperature anomaly at the BSR depth. In addition, an active vent site near the crest of the 4WCR shows a high heat flow probe geothermal gradient and a lower BSR-based gradient (Figure 9). We interpret these conditions to be a result of intermittent venting events, indicating that the temperature field between the seafloor and the BSR is still in transient stage.

5.1.1. Uncertainties in Estimating the 3-D Temperature Field

We observe discrepancies between the modeled and observed BSR-derived temperature field over large parts of the survey area. Perturbations due to any environmental factors that alter the near-surface temperature and pressure field may influence the stability conditions of gas hydrates and result in a shift of the BGHSZ. However, uncertainties in the BSR-derived temperature field, including errors associated with the depth-dependent velocity, porosity, thermal conductivity, and possible errors in picking the BSR-subbottom depth, can also affect possible heat flow scenarios. Most of these uncertainties have been discussed in detail in previous studies, such as Chi and Reed (2008). Here, we briefly address these uncertainties.

High concentrations of gas hydrate above the BSR can lead to unexpected high velocities (Hornbach et al., 2012) and, thus, the shoaling of the BSR. We observe geophysical indicators for high concentrations of gas hydrates beneath the anticlines that can lead to unexpectedly high velocities. However, BSR shoaling is unlikely to be related only to higher hydrate saturation, as that would require unreasonable hydrate saturations, which is not supported by seismic data (Berndt et al., 2019). In addition, we do not see a clear velocity pull-up in the strata directly above the shoaling BSR or below.

OBS derived P wave velocities imply errors of up to ± 150 m/s for the interval just above the BSR (Berndt et al., 2019). We found that, for a 5–15% error in estimating the BSR subbottom depth, the BSR-based temperatures and geothermal gradients will only change approximately 0.1 – 0.25°C and 0.5 – 5°C km^{-1} , respectively, which is relatively small. This is because the BSR subbottom depth error will also be mapped into the error in the hydrostatic pressure estimates, which in turn will change the estimated BSR temperature; this thus compensates for the effect that resulted from errors in BSR subbottom depth in estimating the geothermal gradient (Chi & Reed, 2008).

The numerical modeling in this study assumes a homogenous sedimentary section, but the thermal properties of the sediments (e.g., thermal conductivity) will be heterogeneous at different spatial scales. Although thermal conductivity is strongly dependent on porosity, decreasing porosity with depth does not significantly affect bulk conductivity between seafloor and the BGHSZ for most settings (Hillman et al., 2018; Villinger et al., 2010). However, complex structural styles and sedimentary processes like those that characterize the Taiwan accretionary prism can result in stark thermal conductivity contrasts with depth. For example, thrust faulting resulting in older, more compact rocks with higher conductivity overlying younger rocks with lower conductivity. This increased thermal conductivity and the advection terms of the upward moving hanging wall block can result in a generally higher heat flow in the anticline, which would manifest itself as long wavelength temperature anomaly in our geothermal model. However, cooling from the downgoing footwall will counteract this high heat flow (Molnar & England, 1990). At 4WCR, heterogeneous lithology may result in variations of the thermal gradient, although the extent of this is difficult to estimate, because the local lithostratigraphy is poorly constraint. In this study, our aim is to reduce the topographic effects on temperature field without introducing too many parameters and additional uncertainties.

5.2. Structural Control on Fluid Migration Into the Gas Hydrate Stability Zone

5.2.1. Gas Migration Into the Gas Hydrate Stability Zone Along Faults and Strata

Thrust faults and bedding-parallel fluid flow allow gas migration toward the BGHS at anticlinal ridges: for example, (1) offshore of Taiwan (Lin et al., 2008; Liu et al., 2006); (2) at Hikurangi Margin, NZ (Barnes et al., 2010; Crutchley et al., 2011; Pecher et al., 2010); (3) at Nankai Margin (Ashi et al., 2002; Henry et al., 2002); and (4) at the Makran accretionary prism (Ding et al., 2010; Smith et al., 2014). Fluid flow across the BGHSZ, however, is generally believed to be more difficult due to the reduced permeability of the overlying hydrate-bearing sediments. Several flat spots underneath the BSR have been documented in this region (Chi et al., 1998), showing that gas hydrates can trap gas underneath them. Flexural extensions during anticlinal folding and ridge uplift (Morley, 2007) could help form a highly saturated hydrate system under the ridge by allowing fluid to ascend through the GHSZ (Crutchley et al., 2013; Tréhu et al., 2004; Weinberger & Brown, 2006).

We propose a fluid flow model (Figure 14) in which fluids migrate along the thrust fault or the limbs of the anticline and accumulate underneath the apex of folding where they are likely trapped by the permeability contrast of the gas hydrate layer. Normal and strike-slip faults from depths underneath the anticlinal ridges may provide additional hydraulic conduits (Klaucke et al., 2016). The conjugate low coherence and reflection amplitude anomaly extracted from the BSR horizon (Figure 6) correlate with zones of elevated temperature anomalies (Figure 13a) in directions consistent with the fault orientation depicted in geomorphic studies (Liu et al., 2004).

In gas hydrate systems, interconnected gas columns underneath the BGHSZ on the order of tens of meters, in addition to dissociation of hydrate, may be sufficient to generate pore pressures approaching lithostatic pressure (Flemings et al., 2003; Hornbach et al., 2004) causing migration into the hydrate stability zone. At greater pore pressures, hydraulic fractures may form in the overlying sediment, providing high-permeability conduits into the GHSZ. The gas below the GHSZ would then flow into the fracture, migrating upward, potentially filling subhorizontal permeable layers in the GHSZ, and ultimately forming gas hydrates. The correlation between high amplitude reflections, fractures in the hanging wall, and the seep site at the crest (Figure 7) is consistent with our interpretation that concentrated gas hydrate deposits have formed from focused fluid migration into the GHSZ.

Closer to the seafloor, the lack of subhorizontal HRS (Figure 4c) suggests that gas migration is mostly subvertical even though seafloor seepage does occur (Berndt, 2013). A highly reflective patch of the

Figure 14. Schematic 3-D view of the 4WCR gas hydrate system. Gas-charged fluids migrate through the base of the gas hydrate stability zone along the strata and fault system. Fold asymmetry and shallow fluid flow results in preferential hydrate formation in the limbs of the ridges. Deep reaching fault structures beneath the ridge can act as fluid flow conduits toward shallower depths. (a) Sea floor erosion and related temperature perturbation lead to a downward shift of the BGHSZ. Free gas beneath the BGHSZ will transform into gas hydrates due to the downward movement of the BGHSZ, resulting in a high concentration of gas hydrates. (b) Depositional processes at the seafloor lead to the formation of a double BSR. Sedimentation drives gas hydrate recycling. In (a) and (b), t0 depicts a stage prior to pronounced sedimentation or erosion; t1 shows a period just after this event has occurred; and t2 indicates the effect of that change in P-T conditions has on the hydrate stability conditions and the BGHSZ.

seafloor west of the active seep site contains massive carbonates based on video observations (Berndt, 2013), but no gas flares have been found in hydroacoustic data. The fluid flow system underneath these carbonates might be intermittent because gas hydrate may periodically clog the vertical flow pathways feeding the seafloor vent.

It is not clear whether the high amplitudes adjacent to the normal faults under the crest are highly saturated with hydrates or with a mixture of free gas and hydrates as the polarity of these seismic events is ambiguous (Figure 4c). Velocities derived from OBS data from this site are high and are likely related to hydrate occurrence (Berndt et al., 2019). Nonetheless, given the evidence of active venting at the seafloor, it is likely that there is free gas within the GHSZ. Moreover, based on our geothermal modeling, we expect relatively high rates of fluid flow underneath 4WCR. The ratio between hydrates and free gas in the stability zone is still unknown.

5.3. Lithological Control on Fluid Migration Into the Gas Hydrate Stability Zone

5.3.1. Fluid Flow Along Dipping High Permeable Sequences

Anticlinal fluid flow along both flanks might be different due to the fold asymmetry. The longer backlimb might have collected more gas (Laird & Morely, 2011), which is in our cases the eastern and western limbs of 4WCR and Ridge A, respectively.

The high-amplitude dipping reflections usually intersect the BSR in the backlimb of the anticlines (Figure 6)—features that may indicate stratigraphically controlled fluid migration toward the hydrate system from greater depths (Figure 10d). HRSs below the BSR are likely the result of gas within the strata, while HRSs above the BSR are likely due to high hydrate saturation (Boswell et al., 2012, 2016; Crutchley et al., 2015, 2019; Taladay et al., 2017). Drilling results (Boswell et al., 2012; Taladay et al., 2017; Tréhu et al., 2004) suggest that HRSs in sandy sediments with the same polarity compared to the seafloor are more likely to contain a high saturation of gas hydrates. Boswell et al. (2016) identified large positive amplitude anomalies within anticlines associated with high gas hydrate saturations (>40%) in coarse grained sediments, similar to those amplitude anomalies seen at 4WCR. Such deeply buried, sand-rich turbidite deposits are promising geologic targets for offshore gas hydrate exploration (Taladay et al., 2017). The turbidite deposits in our study area were likely generated near Penghu Canyon (Klaucke et al., 2016; Lin et al., 2014); however, overconsolidated mud rocks are expected to also constitute the background lithology at 4WCR (Bohrmann, 2018; Lundberg et al., 1992).

HRSs are not necessarily related solely to gas hydrate-bearing sediments (Boswell et al., 2012, 2016). They can also form by porosity reduction through diagenetic effects or by lithological effects between muds and water-bearing sands. However, if these two processes are important, it is not clear why the imaged HRSs from this study are always near the BSR. Additional geological or geophysical evidence would assist in clarifying these ambiguities.

5.3.2. Focused Fluid Flow Along the Edge of the Slope Basin Boundary

We propose that there is fluid flow in the inclined strata of the slope basin and that there are interactions where the BSR intersects the BSLB. Layer-constrained fluid flow can occur along the inclined beds of the slope basins (Ding et al., 2010; Wang et al., 2017). The changing focused fluid flow direction can be inferred from the high BSR-derived temperature anomalies near the BSLB, in addition to high seafloor thermal gradients and a shallow sulfate-methane interface (Chen et al., 2014; Yang et al., 2006) where the BSLB crops out on the seafloor (Figure 8).

Some minor faults across the BSLB might allow fluid flow from greater depth to enter into the slope basin. A fault crosses the BSLB and reaches down to at least 400 m below (Figure 8a). Bright reflections in its hanging wall indicate a potential fluid migration pathway and support the notion that at least some of the gas in the slope basin is from below the basin (Figure 8g). Interpreted gas-charged layers are only observed above the BSLB; hence, it seems that the free gas is of shallow origin within the basin. However, the thermal anomaly requires large amounts of advection over time from depths, and thus an additional gas source. As such, fault in the slope basin may contribute to fluid flow across the BSLB in some specific zones. The advection of deeper-sourced gas is considered favorable for gas hydrate prospects (Boswell et al., 2016). However, Berndt et al. (2019) found that high gas hydrate saturation zones are mostly beneath the anticlines, rather than in the slope basins.

In summary, we have found fluid flow along the margin of the slope basin. The BSLB acts as a conduit located between the anticline strata and basin sediment fills, focusing methane charged fluids toward the seafloor. Such features may enhance the saturation of gas hydrate at localized sites.

5.4. Sedimentary and Fluid Flow Processes Governing Double BSR and Hydrate System Dynamics

Multiple hypotheses have been proposed to explain double BSRs, including diagenetic processes, regional environmental changes such as sea level fluctuations, rapid uplift, and the presence of higher-order hydrocarbons (Andreassen et al., 2000; Bangs et al., 2005; Pecher et al., 2017; Zander et al., 2017). We interpreted that the double BSRs at our sites are mostly due to surficial sedimentary processes.

All of the multiple BSRs show negative polarity compared with that of the seafloor, showing decreased acoustic impedance below the BSRs. Thus, the diagenetic process, which should increase the acoustic impedance with depth, is likely not a driving factor in this case (Berndt et al., 2004). The BSRs are converging (Figure 5), instead of showing a direct-current (DC) shift, toward the west and east at Ridge A and 4WCR, respectively. Therefore, long wavelength perturbations caused by sea level change or regional uplift are also unlikely to be the cause of the double BSRs.

It is possible that the observed double BSRs are due to thermogenic gas flow from a deeper source. Higher-order hydrocarbons, such as ethane or propane, lead to the formation of structure II hydrates (Sloan, 1998), which are stable at higher temperatures than methane hydrate and can therefore form a BSR below the methane hydrate stability zone. However, a comparison between predicted hydrostatic pressures and BSR-derived temperatures to the phase boundaries containing different proportions of methane and ethane show that double BSRs underneath Ridge A are unlikely caused by admixing gas compositions (see Text S5 and Figure S5). The double BSRs are laterally smooth and follow the (paleo)bathymetry—features that we do not expect to see from a BSR caused by admixing of different gas compositions (Pecher et al., 2017; Plaza-Faverola et al., 2017), which should instead have a more DC shift occurrence related to the modern bathymetry.

Instead, we propose a model where the double BSRs are primarily the result of rapid seafloor processes that alter the hydrate stability conditions at depth. Our preference of this model is based on the good correlation between laterally varying vertical depth separation of the double BSRs and the vertical depth separation of the paleo-seafloor and the modern seafloor after erosion and deposition occurred at 4WCR and Ridge A, respectively (Figures 5 and S4).

At 4WCR, the possible planar sliding surface at the seafloor suggests localized rapid erosion (Figures 1 and S4). Erosion of the seabed will alter the pressure and temperature conditions and therefore hydrate stability. Rapid erosion leads to a rapid temperature decrease on the newly exposed seafloor and can cause temperature perturbations that propagate downward with a velocity related to the thermal diffusivity of the sediment; this would subsequently cause the vertical downward shifts of the BGHSZ. Pressure changes caused by erosion, however, will occur more quickly as the overburden is removed and potentially result in destabilization of the hydrate below (Hornbach et al., 2003). Depending on the BSR subbottom depth and the kinematic properties of the hydrate system, it might take 10,000 years for the hydrate systems to totally adjust to new P-T conditions (Bangs et al., 2010; Kinoshita et al., 2011).

Erosion of a few tens of meters of seafloor might result in a high concentration of gas hydrates at different subbottom depths between the double BSR. Once the temperature at the paleo BGHSZ depth has readjusted and the BGHSZ shifted downward, the free gas beneath will begin to form hydrates.

At Ridge A, there is evidence of a seafloor slump deposit above the double BSRs (Figures 1 and S4). Slumping deposition occurs on shorter time scales than typical submarine deposition, which occurs too slowly to generate double BSRs, despite altering the depth of the BGHSZ (Bünz et al., 2003; Crutchley et al., 2019; Paull et al., 1994). Rapid depositional processes on the seafloor cause the temperature to gradually increase at the paleo-BSR subbottom depth, causing upward shifting of the modern BGHSZ (e.g., Zander et al., 2017). If hydrates exist just above the paleo-BGHSZ, the upward shifting of the BGHSZ will dissociate the hydrates into free gas and favors the development of interconnected gas columns that drive fluids back into the GHSZ to re-form as gas hydrates (i.e., hydrate recycling; Crutchley et al., 2019; Paull et al., 1994). The free gas underneath the modern BGHSZ will then gradually increase the reflection amplitude of the modern

BSR. If a very large excess pore pressure was generated by rapid hydrate dissociation (Xu & Germanovich, 2006), upward shifting of the BGHSZ was possibly temporarily delayed until excess pore pressure is allowed to dissipate by fluid flow.

The double BSRs might imply that there is gas below both BSRs at two different subbottom depths. If that is the case, it is unclear why the gas in the stability zone did not form hydrates. Some possibilities include a lack of water in the strata or that the system is still transient. Another less likely possibility is that hydrate saturation is high enough to cause acoustic impedance contrast without the help from free gas.

While we are only just beginning to realize how prevalent these features may be along convergent plate boundaries, our analysis suggests that seafloor processes can cause dynamic hydrate systems and affect BSR and double BSR occurrences. The bathymetric data from off SW Taiwan show numerous signs of erosion and slumping on the flanks of the anticlinal ridges (Klaucke et al., 2016; Liu et al., 1997). The repeated formation and dissociation of hydrate in such a dynamic environment likely cause interactions between fluid flow patterns and the three-phase hydrate system, which may capture hydrocarbons in massive quantities.

6. Conclusions

Using data from 4WCR, we have obtained the first high-resolution estimate of the 3-D distribution of fluid migration patterns and gas hydrate occurrence under a ridge near the toe of the accretionary prism off SW Taiwan. We propose three zones of active localized fluid flow: (1) the core of the anticline; (2) the backlimb of the anticline; and (3) along the BSLB. Concurrently, results from 3-D thermal modeling suggest that long-wavelength lateral temperature variation from topographic effects due to thermal conduction is also strong.

We interpret that the double BSRs formed as a result of either rapid depositional events or rapid mass wasting/erosional events on the seafloor. The former seems to contribute to dissociation of gas hydrates at the paleo-BGHSZ and a shallower modern BGHSZ. In contrast, the latter contributes to the formation of gas hydrates below the paleo-BGHSZ, leading to a deeper modern BGHSZ. We propose that upward shifting of the BGHSZ at Ridge A has dissociated hydrates and generated additional interconnected gas that is migrating upward into the modern BGHSZ. In addition, the downward shifting hydrate stability zone at 4WCR is resulting in the transformation of gas below the paleo BSR into hydrates. Free gas might still exist between the modern BSR and paleo-BSRs due to either a lack of water in pore space or the concentration of hydrate inhibitors (e.g., salt) slowing hydrate formation. Hydrate saturation might increase at these double BSR sites through such repeated processes. Future studies of double BSRs in transient systems might help constrain how gas hydrate systems respond to PT perturbations.

It has been suggested that the most promising gas hydrate prospects are interbedded sandshale sequences or strata-bound fracture-filling gas hydrates that are associated with high fluid flux in regional anticlinal structures. Our results from 3-D seismic data provide a detailed, spatially constrained example of temperature disturbances at the hundreds-of-meter scale along the margin of a slope basin due to the presence of fluid flow. The slope basin boundary is an additional feature that increases geologic complexity and can enhance the saturation of gas hydrates at localized sites.

Based on newly available data sets and analyses presented in this work, we propose that rapid sedimentary processes on the seafloor can affect pressure and temperature field under the seabed, causing dynamic responses of the hydrate system. As a result, transient or even multiple BSRs can form, hydrate saturation may fluctuate with localized formation or dissociation, and there is an increased potential of gas venting. How much influence of such surficial process on hydrate distribution, saturation, and methane emission should be studied in the future.

Data Availability Statement

The data are stored at PANGAEA repository (<https://doi.pangaea.de/10.1594/PANGAEA.913192>, <https://doi.pangaea.de/10.1594/PANGAEA.913795>, and <https://doi.pangaea.de/10.1594/PANGAEA.913796>).

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