Processes Affecting the Depth of the Gas Hydrate Stability Zone in the Accretionary Prism Offshore Taiwan

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***Abstract*—Several geological processes introduce a discrepancy between the geothermal gradient derived from heat probe measurements on the seafloor and gradients derived from gas hydrate-related bottom-simulating reflectors (BSRs) at a few hundred meters below the seafloor. We use a wide-spread BSR offshore SW Taiwan in 3D seismic data and an in-situ thermal probe dataset, in addition to 3D finite element modeling, to study these processes, including topographic effects, fluid advection, and landslides. Topographic effects make the geothermal gradient lower on the ridge and higher under the flanks. Fluid advection from depth warms up the shallow crust through some conduits like faults, fissures, and mud diapirs. Landslides reset the seafloor temperature and generate temperature pulses that will take thousands of years to propagate to the BSR depth. To study regional crustal thermal structures we need to correct these effects. On the other hand, we could use these effects to better select gas hydrate prospects.**

Keywords—Taiwan; gas hydrate; BSR; geothermal gradients; accretionary prism

I. Introduction

Information regarding depth of the gas hydrate stability zone is among the most important parameters for gas hydrate studies. Such depth is related to P-T condition of shallow sediments at several hundred meter sub-bottom depth. Shallow thermal structures of the seafloor are usually measured in-situ using thermal probes [1]. In addition, temperature fields at a few hundred meters sub-bottom depth can be inferred from a Bottom-Simulating Reflector (BSR) on seismic profiles [2], which is related to the base of the gas hydrate stability zone. However, these two datasets are not necessary to be consistent. The processes causing such discrepancy are still unclear. Here we use a dense grid of 2D seismic profiles and three 3D seismic cubes, in addition to in-situ heat probe measurements, to study the processes causing such discrepancy offshore Taiwan accretionary prism.

II. Temperature at the BSR and BSR-based Heat Flow

We have collected extensive 2D and 3D seismic datasets offshore SW Taiwan [3]. These seismic data show widespread BSRs. Using the Hamilton equation we have converted the BSR sub-bottom depth from two-way travel time to depth [4]. We also measured the water depth. By combining the water depth and the BSR sub-bottom depth, we derived the hydrostatic pressure at the BSR. Such pressure was applied to a methane hydrate phase boundary to derive the temperature at the BSR. We also measured the seafloor temperature [5]. Using the temperature difference between the seafloor and the BSR and the BSR sub-bottom depth, we have derived more

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than 2000 geothermal gradients. We also measured the thermal conductivity of the sediments in this region. By multiplying the geothermal gradient and the thermal conductivity we derived the BSR-based heat flow.

On a regional scale, the heat flow is highest at the toe of the accretionary prism. The heat flow decreases toward the ridge of the prism. Both in-situ measurements and BSR-based method gave similar results. This is consistent with the heat flow pattern in other subduction zones around the world [6], showing the effect of the subducting plate cooling the over-riding plate.

On a local scale, the heat flow is expected to be similar because the temperature field usually varies smoothly over large distances, thus it does not show abrupt changes within short distances. However, for the shallow part of the seafloor, topographic effects are strongly influencing the temperature field. Heat tends to escape from depth to the seafloor through the shortest path. As a result, more heat will be focused into the valleys of the bathymetry. And the heat flow is lower on the ridges. Such topographic effects cause the BSR sub-bottom depth to be deeper under the ridge, and shallower under the flanks of the ridge.

III. 3D Finite Element Thermal Modeling

To simulate the effects of 3D bathymetry on heat flow patterns, we conducted 3D finite element thermal conductive modeling using the bathymetric data from this region.

We first imported high-resolution bathymetry data into the finite element model. We then assigned an average seafloor temperature. The four sides of the model are insulated. We have tried to assign different temperature at the bottom of the model, representing different regional geothermal gradients. We picked a bottom temperature that gives a good temperature fit between the BSR-based temperature and the numerically modelled temperature under gentle slope or under flat regions where the topographic effects are minimum. The output of the modelling is a 3D temperature field of the area of the seismic cube that only considers the conductive heat transfer taking into account the topographic effects.

The simulation shows that the topographic effects are large, some can perturb the geothermal gradients for more than 150%. Some of the BSR-based geothermal gradients are consistent with the modelled geothermal gradients, suggesting that topographic effects can change the sub-bottom depth of the gas hydrate stability zone.

There are some cases where the modelled temperature is lower than the BSR-based temperature. This suggests that the temperature at the BSR is higher than expected from the temperature field that has been corrected for the topographic effects. Such exceptions usually occur near structures, including the toe of the accretionary prism, as shown in Fig. 1, and faults, fissures, and mud diapirs, as shown in Fig. 2.

IV. Interpretation

Strong water explusion can occur at the toe of the accretionary prism. The porosity of the incoming sediments is usually large before they get incorporated into the trench. Once the sediments enter the convergent zone, the strain from the tectonic stress will reduce the porosity, and cause the pore fluid to be expelled. Such fluid migration to the seafloor will increase the heat flow, thus leading to shallower BSR, e.g. that in Fig. 1. We interpret that these instances are the results of warm fluid migrating from depth to the shallow crust.

We also found another example of focused fluid migration perturbing the temperature field inside a mud diaper. Fig. 2 shows that, by comparing the BSR-based temperature with the model temperature at the BSR, we found a 2 to 3°C temperature increase. We interpret that this mud diapir is active and material is being transported upward by diapirism. We also measured abnormally high in-situ heat flow at the seafloor both above the diapir and at the toe of the accretionary prism.

In addition to topographic effect and fluid migration effects, we have documented a possible transient temperature change due to a recent submarine mass-wasting event, as shown in Fig. 3. Submarine landslides move seafloor sediments causing perturbation of the sub-bottom temperature field that will take time to return to temperature equilibrium.

Rapid sedimentation processes can also affect the thermal structure of the crust. The BSR sub-bottom depth in Fig 3 is very shallow in the upslope zone while the sub-bottom depth is very deep under the newly deposited area in the downslope zone. Such large changes in BSR sub-bottom depth and the BSR-based temperature cannot be explained by topographic effects alone. We interpret that we have imaged an example of recent landslide. The temperature field is not back to equilibrium due to the lag time of the thermal pulse from the new seafloor surface to reach the BSR depth. It will take about 3000 years for the temperature perturbation to propagate from seafloor to 300 meter below seafloor [7]. Another possibility is that the temperature changes due to the changing seafloor bathymetry have already propagated to BSR depth, but it takes additional time for the base of the gas hydrate stability zone to respond to the temperature changes.

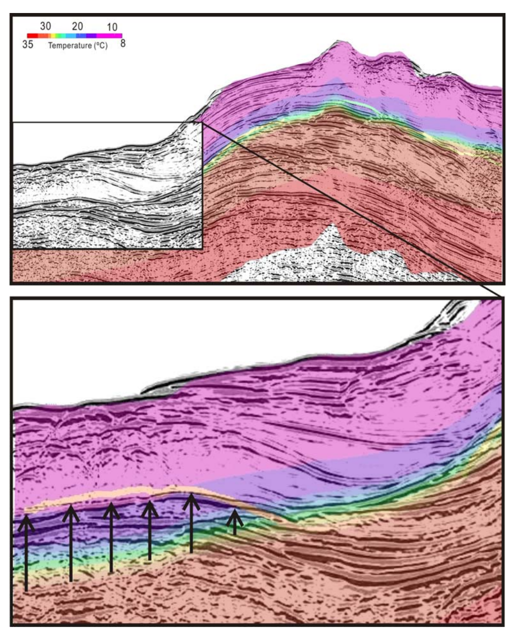

Fig. 1. The BSR becomes very shallow at the toe of the accretionary prism, suggesting advective heat transfer from fluid flow. The color in the background shows the temperature field calculated numerically from the finite element methods that only take into account of conductive heat transfer. The arrows show the difference in temperarure between the model-base temperature and the temperature derived from the BSR (the yellow line).

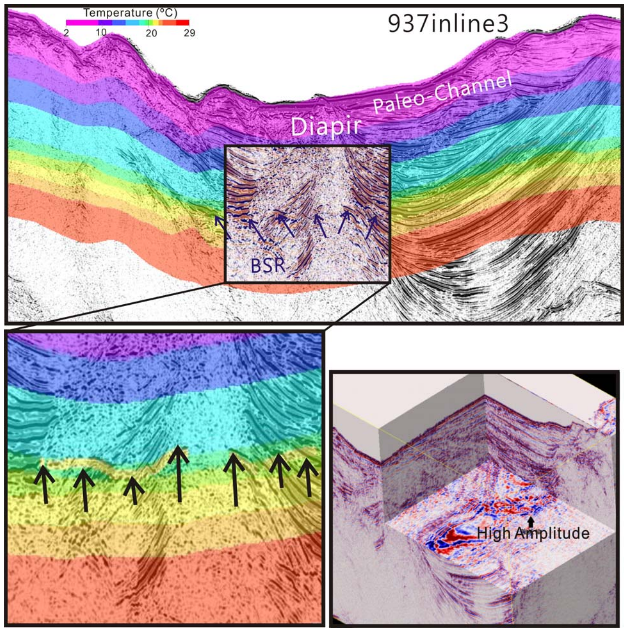

Fig. 2. An example of shallow BSR under a diapir. The advective heat transfer from the diapir increases the temperature by 2 to 3 ºC. We also see high amplitude reflectors inside the diapir.

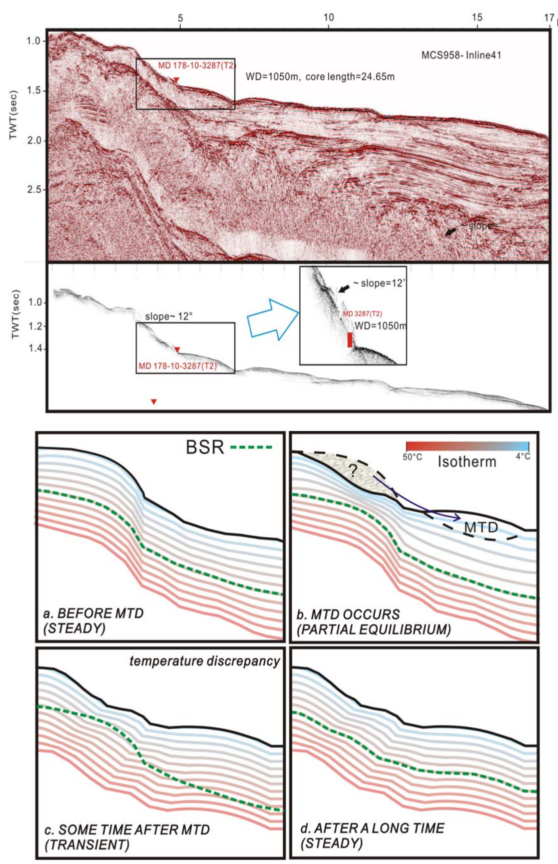

Fig. 3. We see very shallow BSR sub-bottom depth under the slope and deeper BSR subbottom depth in region under a possible mass-transport deposit (MTD) site. The seismic diffractions show an irregular surface caused by mass-wasting processes. The MTD causes rapid removal and deposition of surface material, which perturbs the temperature of the seafloor. It will take time for the temperature perturbation to go back to equilibrium state. It might also take time for the BSR to respond to the temperature changes.

V. Conclusions

By using the BSR-based temperature field, we constrain the sub-surface temperature over a wide area offshore southwestern Taiwan. By comparing these data with surface heat flow measurments and interpreting high-quality 2D and 3D seismic reflection data, we can document several geological processes that affect the thermal structures of the shallow crust. Such knowledge is important for gas hydrate reservoir simulations. Our results also suggest that the in-situ thermal probe data are important for studying the thickness of the gas hydrate stability zone, but when interpreting the data one needs to consider possible processes, including topographic effects, fluid flows, and landslides that might have affected the thermal structures at greater depths. On the other hand, the BSR-based temperature field provides valuable additional temperature information at sub-bottom depths of several hundred meters, and marks the PT condition at the base of the gas hydrate stability zone. The results from this study will help to better understand the fluid migration patterns of some gas hydrate prospect sites and the temperature condition of the reservoirs.

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