Geological controls on the gas hydrate system of Formosa Ridge, South China Sea

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***Abstract*—Formosa Ridge is one of many topographic ridges created by canyon incision into the eastern South China Sea margin. The northwestern termination of the ridge is caused by beheading of the ridge due to a westward shift of the canyon that originally formed to the eastern flank of Formosa Ridge. Below Formosa Ridge a bottom simulating reflector (BSR) exists. Its depth below sea floor coincides with the theoretical base of the gas hydrate stability zone and the reflection has reverse polarity suggesting that it is caused by free gas below gas hydrate accumulations. The BSR is ubiquitous but shows significant variations in depth below sea floor ranging from 150 ms TWT (or approximately 180 m) underneath the incised canyon in the north to up to 500 ms (or approximately 460 m) underneath the crest of Formosa Ridge. Predominantly this depth variation is the result of topography on subsurface temperature, but comparison with the average BSR depth underneath the surrounding canyons suggests that recent canyon incision in the north has perturbed the thermal state of the sediments. Formosa Ridge consists of a northern half that is dominated by refilled older canyons and a southern half that consists mainly of contourite deposits. However, judging by the reflection seismic data this difference in origin seems to have little effect on the distribution of gas hydrate.**

Keywords—gas hydrate; sedimentary systems; heat flow

I. Introduction

Gas hydrate is an ice-like substance stable at high pressure and low temperature [1]. Gas hydrate forms from free gas that combines with water molecules resulting in a substance called clathrate. As the gas stored in gas hydrate is primarily methane, gas hydrate has been identified as a potential future energy source. In particular countries that do not have a large amount of other fossil fuels are keen to develop gas hydrate as an alternative means to satisfy their energy demand. Therefore, there is a lot of interest in establishing how much gas hydrate is present in continental margins, how it is distributed and how quickly it forms and distintegrates as pressure and temperature conditions change. Gas hydrate has also been identified as a potential agent in slope destabilization, and as a threat to global warming. For all these reasons we conducted a cruise on the german research vessel Sonne in 2013 to understand the underlying geological processes that control the distribution and dynamics of gas hydrates off Taiwan. The seas SW off Taiwan are an excellent study site for gas hydrate investigations as a lot of background information is available and the area allows to compare the effect of structural deformation on gas hydrate processes [2].

Here, we report on the results of the 3D-seismic investigation of one of the study sites – Formosa Ridge (Fig. 1). The objective is to determine the influence of geological controls on the distribution of free gas and gas hydate within Formosa Ridge.

II. P-Cable 3D seismic data

The P-Cable system delivers high-resolution 3D data at a fraction of the cost and operating requirements of full-scale industry 3D acquisition, making it a feasible and attractive option for academic surveys. The system used in this study consisted of 12 streamers attached to the cross cable that is towed perpendicular to the ship's steaming direction (Figure 2A). The cube covers a surface area of 30 km^2 (12 km long in-lines by 2.5 km long cross-lines). The source consisted of one 210 in^3 GI gun towed at a depth of 4 m 15 m behind the vessel. It was fired at 5 s intervals. Data were sampled at 1 ms and revealed a dominant frequency of ~100 Hz. Processing of the 3D seismic data included navigation corrections using direct wave travel times, frequency filtering, and 3D time migration with water velocity.

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comprising most of the ridge within the gas hydrate stability zone (Fig. 2d).

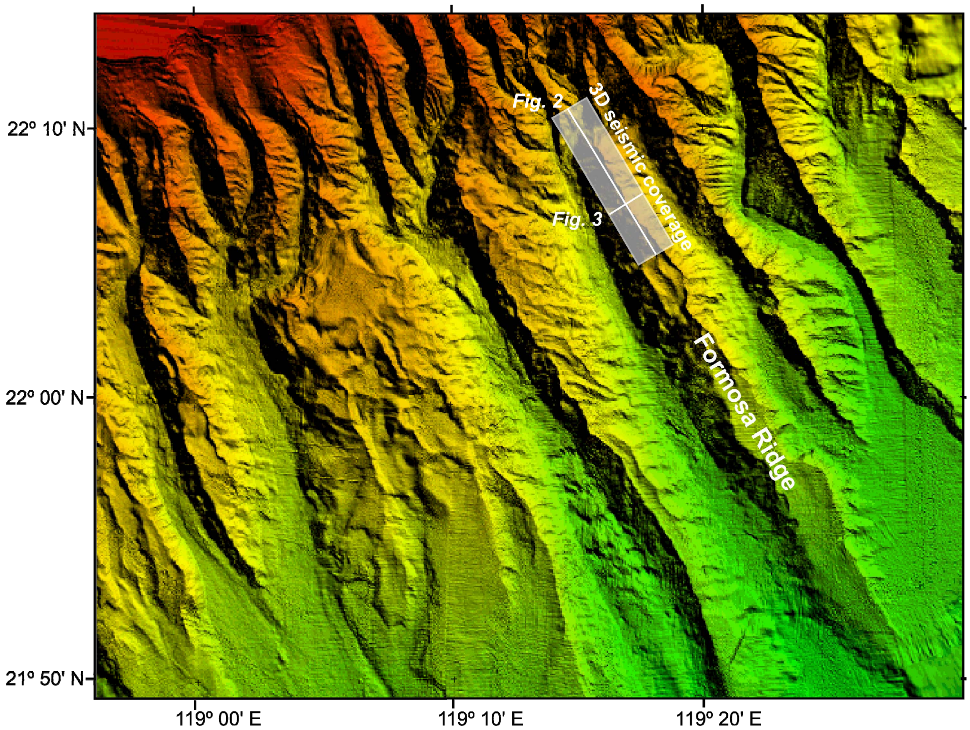

Fig. 1. Location of the study area at the northern end of Formosa Ridge. Water depth ranges from 200 m (red) to 2800 m (green).

III. Results

Formosa Ridge is approximately 30 km long and 5 km wide (Fig. 1). In the West, East and North the ridge is bounded by up to 700 m deep canyons. Its flanks are steep with slope angles exceeding 30 degrees. The study area is located in the northern 8 km of the ridge. In this area two summits exist. Both are approximately at 1050 m water depth. The deepest part of the study area is approximately 2600 m deep. The seismic data show an almost continuous BSR underlying Formosa Ridge (Fig. 2). The BSR varies in sub-bottom depth from 150 ms below the incised canyons to 500 ms two-way travel time (TWT) below the crest of the ridge. This BSR is only interrupted below the southern summit where a seismic amplitude anomaly reaches from the sea floor down to the BSR. On both sides of this amplitude anomaly the BSR bends upward (Fig. 2c). East of the southern summit there is a second BSR below the regional BSR (Fig. 3).

The 3D seismic data reveal the internal structure within Formosa Ridge. Within the northern half of the study area there are at least seven nested unconformities cutting into eachother (Fig. 2b). These unconformities form elongated depressions that strike in N-S direction. Frequently, they are associated with high amplitude anomalies in the deepest parts. The seismic facies within the depressions formed by the unconformities is horizontally layered with some undulations.

The southern part of the study area lacks such unconformities. Instead the sedimentary reflectors show lateral thickness variations on a wave length of more than 1 km comprising most of the ridge within the gas hydrate stability zone (Fig. 2d).

IV. Discussion

The new 3D seismic data reveal a prominent bottom-simulating reflector (BSR) which is underlying most of the ridge (Fig. 2). The high amplitudes and its reversed polarity show that the BSR is caused by free gas in the pore space and the observation of the BSR is direct geophysical evidence for gas hydrates within the overlying sediments. The wide-spread occurrence of the BSR implies an efficient gas advection system within the ridge. The depth of the BSR below the sea floor is greatest below the summit of the ridge and shallowest below the floor of the submarine canyon in the north of the ridge. This pattern should be expected simply because of the sea floor morphology which allows the sediments to cool from both sides within the ridge leading to a downward shift of the gas hydrate stability zone. However, the particularly shallow depth of the BSR below the canyon in the North of approximately 200 m below the sea floor may be evidence for recent incision of the canyon and a gas hydrate system that is outside steady-state conditions (Fig. 2a). Other evidence for a dynamic past of the gas hydrate stability conditions is the observation of a double BSR below the central eastern part of the ridge (Fig. 3). The occurrence of double BSR has often been attributed to past changes in the temperature and pressure conditions that control the depth of the gas hydrate stability zone leaving gas hydrate in a critical state below the gas hydrate stability zone [3]. These hydrates may remain meta-stable for a significant length of time.

The 3D seismic data reveal the fluid conduit to the seep site that fuels the chemosynthetic ecosystem at the southern summit of Formosa Ridge [4]. The data show that fluids and gas rise to the surface at least from the base of the gas hydrate stability zone. Seismic attribute anomalies and interrupted seismic reflections show that the fluids are ascending almost vertically in a seismic pipe structure. Several high-amplitude anomalies between the BSR and the sea floor show that there are accumulations of free gas inside the gas hydrate stability zone below the seep. As gas should normally form hydrate at these pressure and temperature conditions it is likely that there is a dynamic three-phase equilibrium that allows co-existence of free gas, water, and gas hydrate within the sediments.

The 3D seismic data also provide information on the sediment facies that constitute Formosa Ridge. Undulating

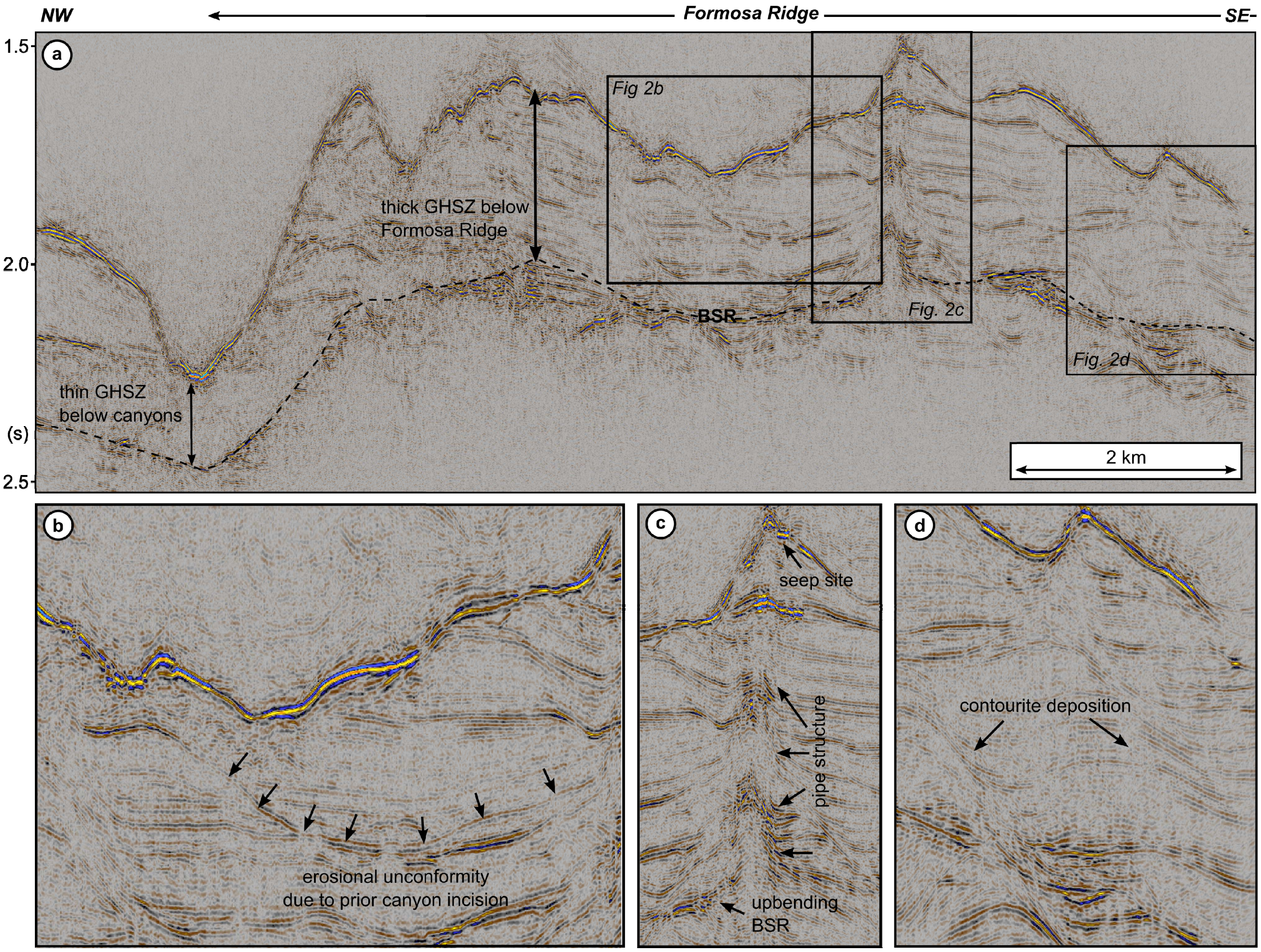

Fig. 2. 3D seismic cross-section along the Formosa Ridge axis. Fig.2a shows the overall sub-bottom depth variation of the BSR which indicates the strong thermal control on the gas hydrate system. Fig. 2b shows one of the unconformities that are caused by previous canyon incisions. Fig. 2c. is a cross-section through the pipe structure underneath the southern summit of Formosa Ridge with the site of chemosynthetic ecosystems above. Fig. 2d shows the seismic character of the sediment waves in the southern part of the study area. The black boxes in Fig. 2a indicate the position of the seismic examples in Fig 2b-d. The location of the line is shown in Fig. 1.

seismic reflections and laterally variable thickness of the seismic units are clear indications that bottom currents have controlled sedimentation along this part of the margin for most of the time during which the ridge has developed (Fig. 2d). Thus it is likely that the bulk of the ridge consists of fine-grained sediments. However, the 3D seismic data also show prominent unconformities that can be traced laterally and are conclusive evidence for repeated episodes of canyon incision and infill (Fig. 2b). They suggest that the present day sedimentation regime, which forms the margin is not new. High-amplitude seismic reflection strength anomalies at the deepest points of the unconformities may represent sand deposits within the thalwegs of former canyons. Where these occur within the gas hydrate stability zone, i.e. above the BSR, such sand deposits may be promising targets for gas hydrate exploration as they would have much higher permeability than the surrounding fine grained sediments.

The fact that there is no significant change of BSR character from the area dominated by the refilled submarine canyons as compared to the area that is dominated by sediment waves suggest that the style of sedimentation does not influence significantly the formation of hydrate at a later stage. Possibly the sediments are not too different. The slight undulations of the reflections in the canyon infill may suggest that they were also influenced by bottom currents just as the contourites in the southern part of the study area. Probably most of Formosa Ridge consists of fine grained sediments except for the thalweg of some of the older canyons which may consist of sand as indicated by the higher seismic amplitudes.

V. CONCLUSIONS

Geomorphologically Formosa Ridge is an erosional structure as opposed to the compressional ridges of the active margin farther to the southeast. The ridge is made up of sediment wave deposits in the southern half of the study area and by infilled canyons in its northern half. Thus, the two halves of the ridge are of different geological origin and possibly of different age.

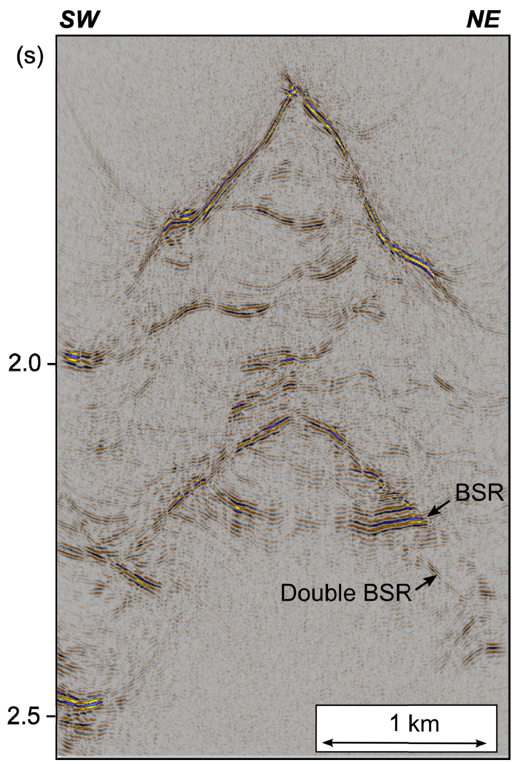

Fig. 3. 3D seismic cross-section across the Formosa Ridge showing the characteristics of a weak double BSR east of the southern summit of Formosa Ridge. The location of the line is shown in Fig. 1.

There is ample evidence for gas hydrates in the entire ridge as a hydrate-related BSR is present everywhere. We attribute the significantly different depth of the BSR below the seafloor primarily to topographic effects on the thermal state of the ridge. However, there are indications that recent canyon incision has perturbed the thermal state of the sediments leading to even shallower BSR depth below the northern canyon.

The different geological origin of different parts of the ridge does not seem to affect the distribution of gas hydrate very much as the BSR exists everywhere and is of similar amplitude.

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