# Role of Gas Hydrate and its Migration Pathways in Submarine Slope Failures: East Indian Margin

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## Abstract

Gas hydrates from the continental margin settings are mostly confined to continental slopes and it is an established fact that their dissociation might trigger submarine slope failures. The present study is carried out to investigate such a scenario in the Krishna Godavari basin where there are proven gas hydrate deposits. We interpret a fault that is generated below the bottom simulating reflector as a result of free gas overpressure in the shale deposits. Gas column height calculated for the KG basin is 51 m and shows that the gas zone is critically over pressured and any further increase in the gas column can potentially trigger slope failure.

# Role of Gas Hydrate and its Migration Pathways in Submarine Slope Failures: East Indian Margin

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**Abstract**

Gas hydrates from the continental margin settings are mostly confined to continental slopes and it is an established fact that their dissociation might trigger submarine slope failures. The present study is carried out to investigate such a scenario in the Krishna Godavari basin where there are proven gas hydrate deposits. We interpret a fault that is generated below the bottom simulating reflector as a result of free gas overpressure in the shale deposits. Gas column height calculated for the KG basin is 51 m and shows that the gas zone is critically over pressured and any further increase in the gas column can potentially trigger slope failure.

## 1 Introduction

Gas hydrates are naturally occurring ice-like crystalline solids where methane gas molecules are trapped within the cages of the water molecules (Sloan, 1998). Gas hydrates are formed in the continental margins and permafrost regions where they encounter suitable pressure and temperature conditions and are considered as the cleanest energy resource for future generations (Yin et al., 2019). The stability conditions for gas hydrates are met within a few meters from the seafloor and thereby they are restricted to the continental shelf and continental slopes (Sain et al., 2012). They are formed under high pressure and low-temperature conditions and any changes in either of them would result in the dissociation of gas hydrate and thereby releasing the water and gas. This over pressured can potentially trigger seafloor instabilities and cause slope failures.

Slope stability studies carried out initially (Terzaghi, 1956) by concluded that the submarine instability was due to gravity and might be caused due to Earthquakes or the rapid accumulation of sediment in gentle slopes. Gas accumulations can also affect slope stability (Hornbach et al., 2008) and can trigger slope failure and/or submarine landslides. A statistical chart of 14 triggering factors for slope instabilities was prepared by studying 366 subsea slope instabilities (Hance, 2003). The study listed shallow gas or natural gas hydrate is one of the major factors influencing the seafloor stability. Many submarine slope failures in hydrate-bearing sedimentary deposits might be directly triggered, or at least primed, by gas hydrate dissociation which eventually turns into a landslide. The storegga slide is one such large submarine landslide that occurred at southwestern Norway resulting in a Tsunami leading to a significant runup to the height of 30-35 feet (Kristian et al., 2006). This landslide occurred due to the combined effect of gas hydrate dissociation and earthquake. Although about 68 % of the Black sea is suitable for the formation of gas hydrates, the BSRs are found only in a few areas out of the 5000 locations where the gas flares were recorded. There are three slumps in the vicinity of the S2 canyon in the Black Sea, called Slump A, slump B and slump S2 (Hillman et al., 2018). Among them slump A is the oldest, S2 slump is recent. The average height of the headwall scarp at the recent S2 slump is approximately 25 m resulting in an estimated volume of 0.36 $km^2$ of sediment being removed in this slope failure event proving that the dissociation of gas hydrate makes the slope unstable and causes slope failures. The major landslides from prehistoric to today have reported that the gas hydrates act as a trigger or as an initiator for landslides.

In the Krishna Godavari basin, recent studies (Ramprasad et al., 2011) have shown the evidence of sliding and slumping in upper slope regions, caused due to the presence of gas/fluid within the regional faults, coupled with rapid sedimentation. KG basin is known for characteristic shale diapirism (Dewangan et al, 1999) and as shale is highly porous but impermeable; the overpressure would eventually create hydro fractures or faults to migrate through it, which can potentially initiate a slope failure. The rate of sedimentation is huge till the water depth of 750m and these observations motivate studies on the slope stability, which are carried out for a seismic line in the KG basin.

## 2. Methodology:

### 2.1 Data:

The study is carried out along a 18 km long 2D seismic line, acquired in the KG basin. The water depth at this location is approximately 1050 m. Well NGHP-01-10A, drilled by National Gas Hydrate Program Expedition 01 has shown evidence of massive gas hydrates as fracture-fill (Collett et al., 2007). The drill site NGHP-01-10A is approximately 8 km from our study area and we have used the log data (density, porosity) from this site in our computations, owing to lack of drill hole within our study area. The water depth at this well site is approximately 1038m.

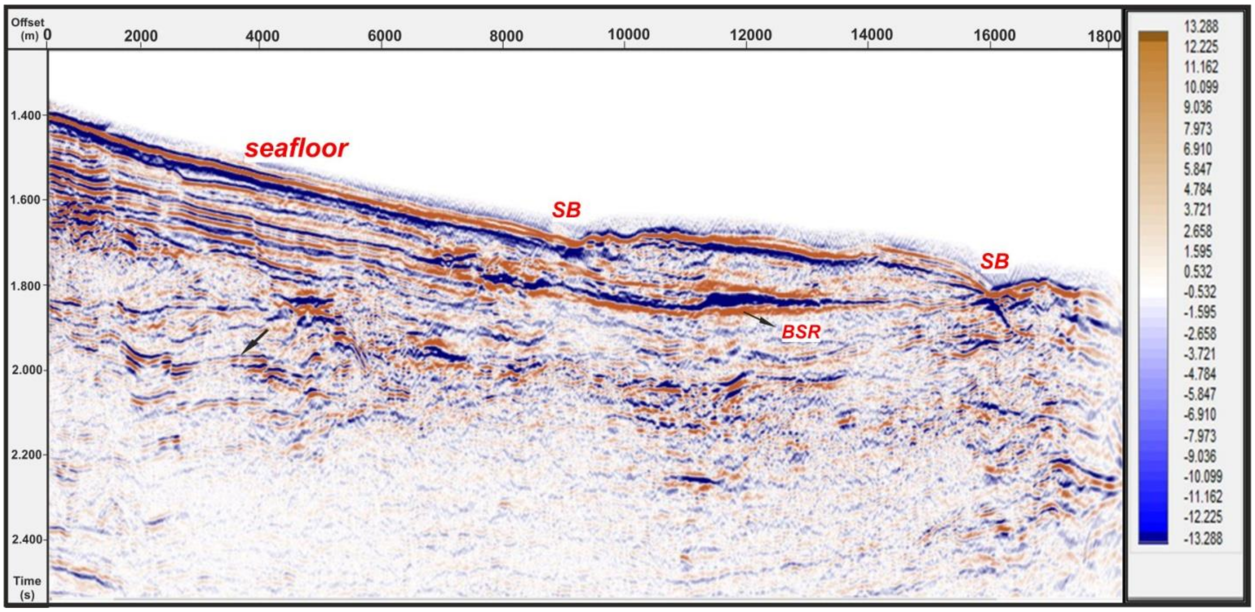


**Figure 1.** Time-migrated 2D seismic line of our study area showing seafloor reflection, BSR (Bottom simulating reflector) and SB (Slope break) marked in the figure.

### 2.2 Seismic Data Processing:

Seismic data processing was carried out using Paradigm software. Data were sampled at 2ms and a total of 1512 CDPs with an interval of 12.54 m are used in this study. A trapezoidal filter with corner frequencies 7, 10, 110 & 120 has been applied to the data to remove the noise component and a spiking deconvolution is applied to enhance the continuities of the event by shaping the embedded wavelet. Normal move-out correction is applied using the velocities obtained from vertical velocity analysis and subsequently, the dip move out correction is applied. Finally, pre-stack time migration is carried out to collapse the diffractions and move the dipping reflections to their true subsurface positions. The seismic image obtained after the processing is shown in (Fig.1).

### 2.3 Seismic Interpretation:

A high amplitude reflector mimicking the seafloor and having a reverse polarity occurs at 1.6 s in the time section (~160mbsf). This reflection is interpreted as the bottom simulating reflector or BSR. The obtained depth is in agreement with the depth of gas hydrate occurrence at NGHP drill site NGHP-01-10A. To ascertain the BSR and free gas zones we have computed the seismic attributes, namely the reflection strength and instantaneous frequency. Reflection strength attribute also called Envelope, is the phase independent view of amplitudes, having its maximum value at phase points other than peaks or troughs of the trace (Taner et al., 1979). The layers that contain trapped gas often generate strong reflections, due to the high impedance contrast. Such enhanced reflections are observed near and below the BSR (Fig.2). Abrupt termination of reflection strength near the faults is also observed. The instantaneous frequency attribute is useful in the identification of gas zones. Free gas attenuates high-frequency component and the regions that show such attenuation are indicative of gas presence (Satyavani et al., 2008). We interpret that two faults, A & B are generated as a result of overpressure in the gas zone (Fig.4). Fault A which is in the up-dip direction of the slope has a gentle fault slip but it might not be acting as a fluid/gas migration pathway. Fault B extends almost upto the seafloor and we interpret that the break in the seafloor (B) might have been caused due to the rapid migration of critically over pressured gas along this fault. This interpretation is further corroborated by the presence of mass transport deposits (MTD) on the down slope.

### 2.4 Calculation of critical gas pressure necessary to initiate the fault slip:

The passage of free gas through the Hydrate stability zone (HSZ) has been demonstrated in high flux regimes globally, whereas in low flux regimes the Hydrate stability zone (HSZ) has been largely considered as an impermeable barrier to the migration of free gas. In the KG basin, folding and faulting is reported (Ramprasad et al., 2011) at the sites of steep topography (water depth <750m) as a result of shale diapirism and it is proposed that these faults act as conduits for fluid/gas migration, in turn leading to sliding/slumping of the seafloor. In our study area, the water depth is ~ 1050m and at these depths, the sedimentation rate is relatively less (Dewangan et al, 1999) and the seafloor has a gentle topography, indicating that sedimentation might not influence the slope stability here. Sedimentary structures may influence the build-up of overpressure by focusing fluid flow and forcing migration of fluids, e.g., in sediment waves or along faults (Elger et al., 2018). The seismic section in the present study shows that the BSR is commonly disrupted by gas injection through the fault into the HSZ. This situation is quite similar to the that observed in Black ridge crest (Gorman et al, 2002), where the methane gas is transported upward through the HSZ to a level limited only by the availability of permeable pathways. The instantaneous frequency attribute computed for the present dataset shows high-frequency attenuation along fault B, but not fault A. Therefore, we infer that fault A is not an active pathway, whereas fault B, is possibly a potential pathway. The over pressured gas from the gas zone might have passed through fault B, disrupting the BSR and the gas is injected into the overlying sediments through the gas hydrate stability zone, causing a zone of reduced reflectivity in underlying gas below the BSR. The vertical and lateral transport of gas in the sediments above the BSR might have destabilized the slope and caused the seafloor breaks, shown as SB Fig 4. The mass transport deposit (MTD) in this region extends up to 5-8 km approximately, indicating a significant lateral flow. Fault A has a gentle fault slip but cannot be treated as migration pathway for the passage of overpressure from the gas zone as it does not show significant anomaly in the instantaneous frequency plot (Fig.3).

The fault reactivation in the hydrate provinces in a sedimentary basin depends on the gas column height below the BSR, wherein the thickness of the free gas zone required for the fault reactivation is calculated as a function of BSR depth and sediment properties (Hornbach et al., 2004). According to the model, the gas column thickness generally increases with the depth of BSR for the passive margin basin and remains constant for the active margin basin. In the present study, we calculated the free gas column height necessary to initiate the fault slip for fault A using the method explained by Hornbach et al., 2004.

The critical gas pressure necessary to initiate the fault slip is calculated using the following formula:

$$Pcrit = \left[\frac{\sigma v+\sigma h}{2}\right] + \left[\frac{\sigma v-\sigma h}{2}\right]\left[\frac{1+cos2\theta-sin2\theta}{\mu}\right] + \frac{c}{\mu} - Pw \qquad \text{-------- (1)}$$

where,

*Pcrit* is Critical gas pressure.

$\sigma_v$ is vertical stress

$\sigma_h$ is horizontal stress

$\Theta$ is fault dip angle

$\mu$ is a coefficient of sliding friction

*C* is cohesion

$P_w$ is hydrostatic pressure of water and each of these terms is calculated as explained below:

The fault dip angle (Θ) is measured from the seismic section and is found to be ~ 70 °

The Cohesion of the shallow sediments (C) is assumed to be zero (Hornbach et al., 2004)

Coefficient of sliding friction μ is calculated using the formula

$\mu = \tan(90-2\Theta)$

The vertical stress is calculated from eq.2 using the bulk density of 1.7gm/cc (at the BSR) from the well NGHP-01-10A

$$\sigma_v = \rho g h \quad \text{--------- (2)}$$

where,

ρ is the bulk density from the well log data

g is the acceleration due to gravity

h is the depth up to BSR from the seafloor.

Horizontal stress is calculated using the poroelastic formulation (Eq.3), where the poisons ratio at BSR (V) is assumed to vary from 0.466 to 0.477. (Hamilton, 1979).

$$\sigma_h = \frac{\nu}{(1-\nu)} + \alpha \left[\frac{(1-2\nu)}{(1-\nu)}\right] [P_w + P_g] \quad \text{----------(3)}$$

$P_w$ and $P_g$ are hydrostatic pressures of water and gas

α Biot coefficient of effective stress and for unconsolidated sediments, it is given as,

$$\alpha = \frac{-184.05}{1+\exp[\varphi + \frac{0.5646}{0.09425}]} + 0.99494 \quad \text{----------- (4)}$$

For consolidated sediments

$$\alpha = 1 - (1 - \varphi^{3.8}) \quad \text{------------ (5)}$$

Biot coefficient of effective stress α is calculated using the correlation method where the porosity value at a suitable depth is taken to calculate the Biot coefficient (Luo et al., 2015). Using eq.4, the biot coefficient is estimated at about 0.99.

### 2.5 Calculation of critical gas column height:

$$hgas = \frac{Pcrit}{\rho * g} \qquad \text{------------------------ (6)}$$

*where,*

*hgas* is the gas column height.

*Pcrit* is the critical pressure of gas necessary to initiate the fault slip

ρ is the density of gas below the BSR.

*g* is acceleration due to gravity.

## Results:

From the above equations, we have calculated vertical stress (lithostatic pressure) as 2.66Mpa and Horizontal stress as 2.02Mpa. The Critical gas pressure necessary to initiate fault slip is 0.88Mpa (fault dip angle of 70 degrees and cohesion as zero). The critical gas column height is found to be 51 meters.

In general, depth from the seafloor to BSR (m) increases as the gas column thickness increases (Hornbach et al**,** 2004), as shown in Fig 5. However, this assumption is true for all the passive margin basins but not for active tectonic basins. In the active margin basin, the gas column thickness is constant irrespective of the depth of the BSR. One possible explanation for thin FGZs in active tectonic settings is that they are often characterized by water phase overpressures, which reduces the gas column height required to initiate slip (Flemings et al., 2003). From Fig 5, it is noticed that most of the global passive basins are within the grey region indicating that the faults are critically pressurized and prone to mechanical failure if the gas column height exceeds the critical value. The gas column height in the present study is ~ 51m at critical gas pressure. The same is superposed in Fig. 5 and is shown in green color. It is noticed that this point is also in the grey area, and conforms to the general observations from passive settings. This observation implies that fault A is within the range of mechanical failure and might get activated if the gas column thickness exceeds this critical value (~51 m). The resulting gas flow in high pressures can potentially trigger a submarine slope failure/submarine landslide.

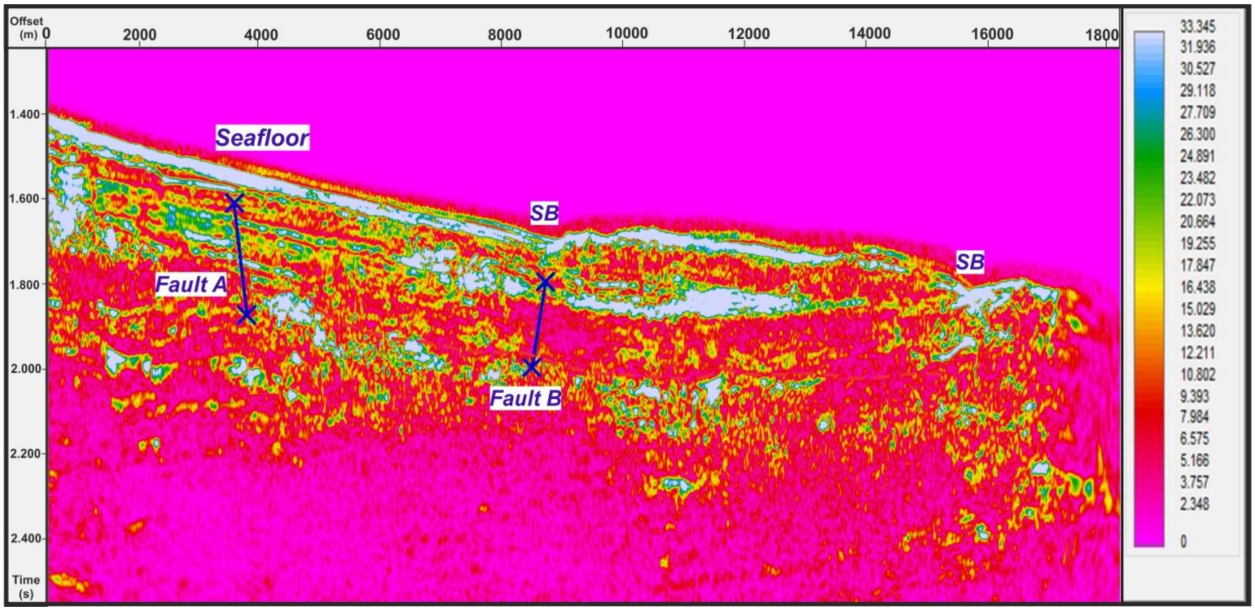


Figure 2. Reflection strength attribute showing the high amplitude reflections in the BSR.

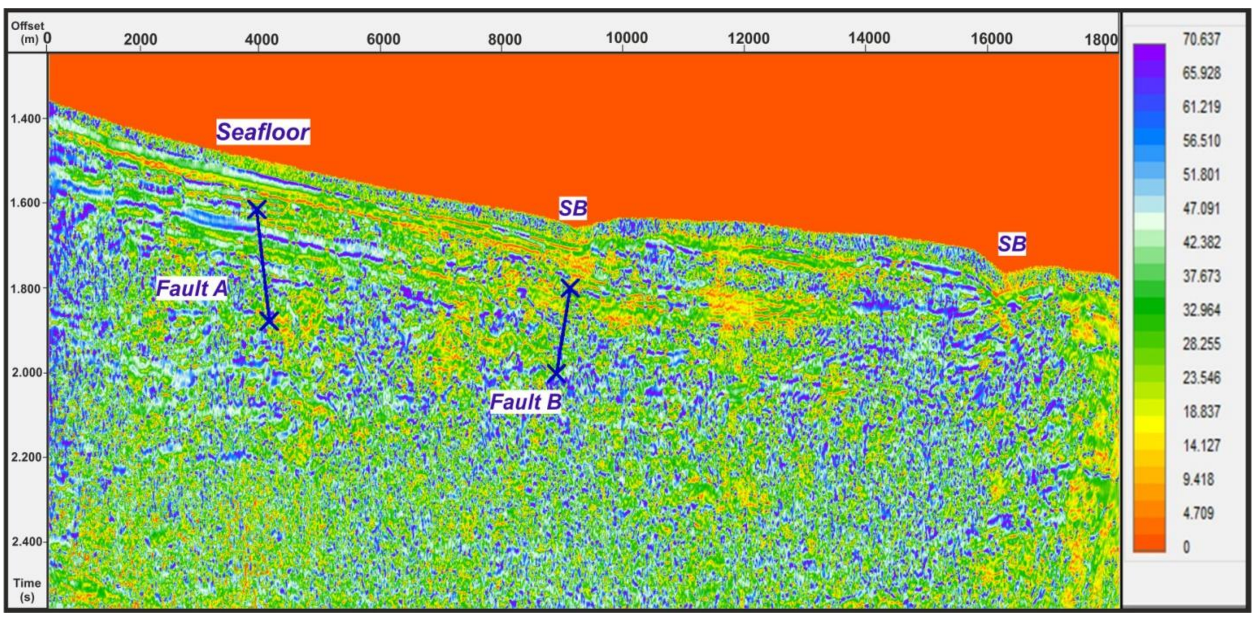


Figure 3. Instantaneous frequency attribute showing the low-frequency anomalies in the gas zone. The upper part of Fault B passes through the gas zone, characterized by low-frequency anomaly (red). A similar signature is not seen at Fault A and it passes through the mid-frequency range (blue).

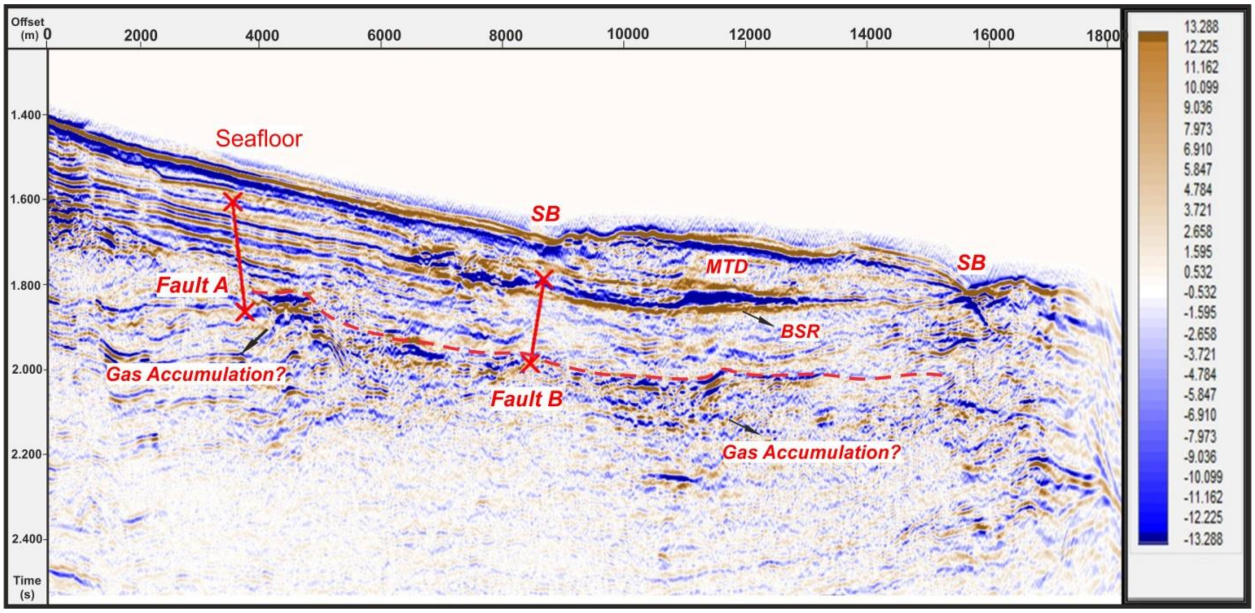


Figure 4. Interpreted seismic section showing the fault traces for Fault A and Fault B. The possible zone of gas accumulation is the region below the red dashed line. BSR-Bottom simulating reflector, MTD-Mass transport deposit and SB-Slope break

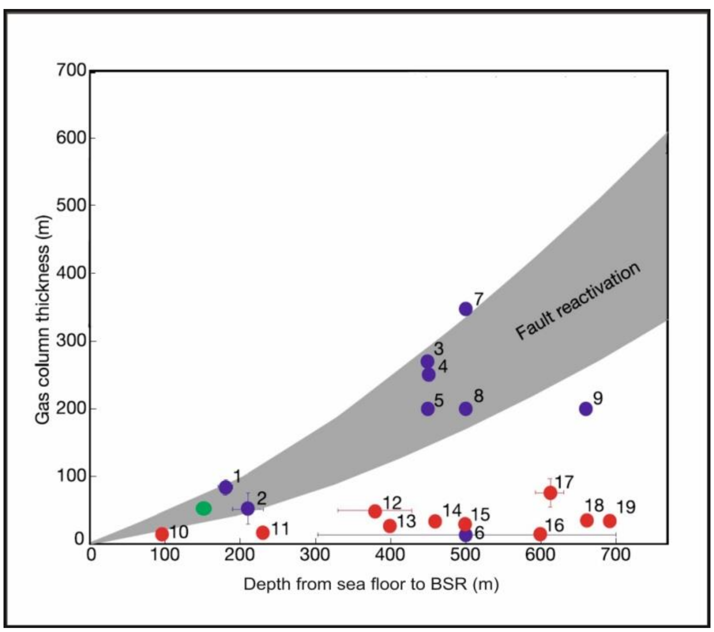


Figure (5): Depth from sea floor to BSR (m) versus gas column thickness (m). The gas column thickness for the KG basin is shown in green. Blue symbols (numbered 1–10) show gas column thickness below BSRs at several hydrate provinces in passive margin basin settings. Red symbols (10–19) show gas column thickness below BSRs at hydrate provinces in compressional settings (Hornbach et al, 2004).

## 4 Conclusions

We conclude that faults act as primary migration pathways in our study area. Fault B is developed due to overpressure and passes through the BSR and the hydrate stability zone. The gas migration along this fault resulted in the lateral and vertical focused flow of gas, causing seafloor collapse at SB. Fault A is critically pressurized due to the gas below the BSR and can undergo mechanical failure if the gas zone thickness exceeds the critical value of 51m. However, the small disruptions in the BSR and vertical injection of free gas suggest that the overpressure of the free gas zone below the BSR can be a reason for possible slumping and sliding.

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