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Seismic attributes for identifying gas-hydrates and free-gas zones: application to the Makran accretionary prism

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The most commonly used marker for gas-hydrates is a bottom simulating reflector or BSR on seismic section. The BSR is not a lithological interface but a physical boundary between the gas-hydrates bearing sediments above and free-gas saturated sediments below. From visual inspection of seismic section, it is hard to demarcate the zones of gas-hydrates and free-gas laden sediments. At many places in the world, BSRs have not been observed but gas-hydrates have been recovered by drilling. Again, BSRs have been identified but no gas-hydrates have been found by drilling. Therefore, we need to study certain attributes to ascertain whether a BSR is related to gas-hydrates or to identify gas-hydrates without a BSR. It is also necessary to demarcate the zones of gas-hydrates and free-gas bearing sediments. Here we compute the reflection-strength, instantaneous-frequency and seismic 'blanking' or reduction in seismic amplitudes from a seismic data set in the Makran accretionary prism and demonstrate that these attributes can be used as important indicators for the exploration of gas-hydrates and free-gas. Presence of gas-hydrates increases the seismic velocity and causes amplitude 'blanking' due to cementation. The landward decrease in 'blanking' window above the BSR implies that the thickness of gas-hydrates bearing sediments decreases landward. Underlying free-gas saturated sediments have lower velocities than host sediments and exhibit high reflection strength due to variation in gas saturation. Presence of free-gas is also indicated by 'shadows' in the instantaneous frequency plot. High reflectivity and low frequency 'shadows' over a large time window below the BSR show a large thickness of alternate gas-rich and gas-poor strata. Coupled with these attributes, the velocity anomaly superimposed on the seismic section shows the lateral extension of gas-hydrates and free-gas bearing sediments.

Introduction

Gas-hydrates are ice-like crystalline solids made up of water and hydrocarbons (mainly methane). These are formed at high pressure ($>5\text{MPa}$) and low temperatures ($<15^\circ\text{C}$) when pore fluids are saturated with gas molecules, and are typically found in the outer continental margins within sediments up to few hundred meters below the seafloor at water depths exceeding 500 m and in the permafrost regions within depths ranging from 130 to 2000 m (Henriet and Mienert, 1998; Kvenvolden, 1998; Sloan, 1998; Paul and Dillon, 2001; Max, 2003; Milkov et al., 2004; Taylor and Kwan, 2004). Gas-hydrates are attracting the global attention due to their widespread occurrences in nature, potential as future major energy resource and role in environmental hazards. One volume of gas-hydrates releases ~ 164 volumes of methane and 0.8 volume of fresh water at standard temperature and pressure. Dissociation of gas-hydrates releases methane (green house gas) to the atmosphere causing global warming, and reduces the sediment strength resulting in slope failure, or seafloor instability. Methane stored within and trapped as free-gas below the hydrate-bearing sediments exceeds the fossil fuel (crude oil, natural gas and coal) reserves of the world (Booth et al., 1996; Klauda and Sandler, 2005). The carbon in global gas-hydrates is speculated to be 10,000 gigatons, which is two times the carbon content in worldwide fossil fuels (Kvenvolden, 1998; Sloan, 1998). According to Makogon et al. (2007), production of gas from 15% of global gas-hydrates reserve can meet the world's energy requirement for the next 200 years at the current rate of energy consumption. Therefore, identification and quantification of gas-hydrates are very essential for evaluating the energy potential and appraising the hazard assessment.

The common method for identifying gas-hydrates in the sub-oceanic sediments is mapping an anomalous reflector, known as the bottom-simulating reflector or BSR on a seismic section (Paul and Dillon, 2001; Max, 2003; Lu and McMechan, 2004; Kou et al., 2007). The BSR typically mimics the shape of seafloor, shows opposite polarity with respect to the seafloor reflection, cross-cuts dipping strata. However, BSRs have not been observed on seismic section at many places in the world but gas-hydrates have been recovered by drilling (Finley and Krason, 1986; Westbrook et al., 1994; Wood and Ruppel, 2000; Ashi et al., 2002; He et al., 2006). They are not found by sampling even if BSR has been identified on seismic sections in the Bering Sea. Therefore, we explore other proxies for ascertaining whether a BSR is related to gas-hydrates and for identifying gas-hydrates without any BSR.

Presence of gas-hydrates and free-gas changes the sediment properties in different ways, which can be recognized by various seismic attributes like amplitude blanking (Lee and Dillon, 2001), reflection strength and instantaneous frequency (Taylor et al., 2000; Berndt et al., 2004; Chopra and Marfurt, 2005; Satyavani et al., 2008). Gas-hydrates in the sediments pore spaces homogenize the physical properties in the sediments and thereby decrease the seismic impedance contrasts between units within gas hydrate-bearing sediments, resulting in reduction in seismic reflection amplitudes or blanking (Lee and Dillon, 2001). On the other hand, free-gas in the pore spaces reduces the seismic velocity considerably and hence changes the impedance contrasts across the sedimentary strata (Taylor et al., 2000) with high and low concentration of gas resulting in strong reflectivity. As gas-charged sediments highly absorb the seismic energy, they exhibit 'shadows' in the instantaneous frequency plot (Taylor et al., 2000). We calculate these attributes from a seismic data set in the Makran accretionary prism where BSR has been identified (Minshull and White, 1989; Sain et al., 2000) and qualify whether the BSR is related to gas-hydrates and free-gas. Gas-hydrates studies are still in the nascent stage and a lot needs to be carried out for the investigation of gas-hydrates. Status of global and Indian gas-hydrates research and development are available in a recent review paper by Sain and Gupta (2008).

Study area

The study area (Fig.1) lies in a region of convergence where the oceanic lithosphere of the Arabian plate subducts beneath the continental lithosphere of the Eurasian plate (Minshull et al., 1992). The sediments in the Makran accretionary prism are sandy in nature (Fruehn et al., 1997; Sain et al., 2000). The sediments entering the deformation front of the Makran accretionary prism consist of about 4 km thick lower section, interpreted to be the Himalayan Turbidites derived from the Indus fan to the east (Kopp et al., 2000) together with an upper 3 km thick section of the Makran Sands derived from the north. The Makran Sands lie unconformably above the Himalayan Turbidites and are themselves covered by a thin layer of shelf deposits.

Figure 1. Location of the study area in the Makran Accretionary Prism. One north-south seismic line is shown along with bathymetry contours.

Material and methods

Existence of gas-hydrates and free-gas across a BSR can be established by studying various seismic attributes like the amplitude blanking, reflection strength and instantaneous frequency, etc. Pure gas-hydrates have much higher seismic velocities than those of the pore fluids and shallow host sediments. Presence of gas-hydrates reduces the impedance contrast by filling the pore spaces of sediments (Shipley et al., 1979; Dillon et al., 1993; Lee et al., 1993; Kou et al., 2007) and makes sediments transparent to the passing seismic energy. This phenomenon can be studied by observing reduction in seismic amplitudes or blanking in gas-hydrates bearing sediments. The amplitude variation within a time window from the seafloor to a depth below the BSR can be examined by computing the absolute value of reflectance as

$$A_i \text{ (dB)} = 20 \log_{10} |(A_i/A_0)| \quad (1)$$

where A_i is the amplitude at i^{th} sample point in the time window and A_0 is the reference amplitude. A_i is converted into decibel (dB) scale and then plotted against time. To investigate the amplitude blanking phenomenon, amplitudes at each sample (A_i) of CDP (common depth point) traces are picked and scaled with regard to A_0 .

Presence of even small amount of free-gas below the BSR reduces the compressional seismic velocity appreciably and hence decreases the seismic impedance (velocity * density) (Yilmaz, 1987). On the other hand, gas-hydrates in sediment increases the seismic velocity and hence the seismic impedance. Therefore, if we analyze reflection strength attributes, both the existence of BSR and free-gas below the BSR can be well characterized in seismic sections. The energy decrease of a seismic wave depends on the number of wave cycles along its travel path. For a particular region of high attenuation, shorter wavelength (high frequency components) energy will be preferentially attenuated. Since the gas-charged sediments highly absorb the seismic energy, free-gas bearing sediments exhibit a low frequency shadows (Yilmaz, 1987) below the BSR. Since gas-hydrates cement the pore spaces of sediments, the hydrates bearing sediments allow the seismic waves to pass through them and are associated with less attenuation.

Thus, the study of instantaneous frequency enables us to differentiate the free-gas containing sediments from the gas-hydrates bearing sediments. Reflection strength and instantaneous frequency can be computed using the formula given by Taner et al. (1979).

A north-south seismic stack section (Fig. 2) with landward increasing CDPs between 4200 and 4750 shows a strong BSR at 2.8 to 2.85s two way traveltimes (TWT) beneath the seafloor with water depth of 2.3s TWT in the Makran margin (Minshull and White, 1989; Minshull et al., 1992; Sain et al., 2000). Low velocity zone associated with the presence of free-gas beneath the BSR is mapped by synthetic seismogram modelling (Minshull and White, 1989). The 24-fold seismic data with offset range of 200-2650 m has been reprocessed using the commercial seismic data processing software (ProMax-2D). Dominant frequency in the data is ~35 Hz. The spherical divergence correction ($1/(\text{time} \times \text{velocity}^2)$),

Figure 2. The seismic stack section showing the seafloor reflection at ~2.3s TWT and the BSR at ~2.85s TWT.

minimum phase spiking deconvolution, detailed velocity analysis at every 10th CDP or 225 m intervals and trace equalization have been carried out before the stack (Ostrander, 1984). Hydrophone array attenuation is corrected using the function of Sheriff and Geldert (1995). No source array correction is applied because it can be considered as a point source (Sain et al., 2000).

Reflectance of the seismic data across the BSR are calculated using the expression (1) to study the blanking, a characteristic feature of gas-hydrates bearing sediments. To investigate the amplitude blanking, amplitudes at each sample (4 m interval) for six consecutive CDP traces are picked at two locations between CDPs 4375 to 4380 and 4400 to 4405. The maximum value of the picked amplitudes of the seafloor among six CDPs is scaled to 0.4 with respect to reference amplitude (A_0), and the reflectance are shown in Figure 3. A five-

Figure 3. (a) Amplitude analysis for the CDP's 4375-4380 and (b) 4400-4405. Dots represents the amplitude at each 4 ms TWT of each CDP and the solid line represents the moving average variation of reflectance across the BSR.

point moving average of reflectance (i.e. over a moving window of 16 m) is taken and the solid line represents the variation of reflectance against the TWT. The blanking or reduction in seismic reflection amplitudes is clearly observed on the reflectance attribute plot along with its vertical extension. We do not see the amplitude blanking so clearly on the normal seismic section (Fig. 2).

The reflection strength (Fig. 4) and instantaneous frequency (Fig. 5) of the seismic data are estimated using the appropriate modules of ProMax software. The high reflectivity

and low instantaneous frequency attributes characterize the presence of free-gas and its vertical extension below the BSR. The plot of instantaneous frequencies exhibits a shift to lower frequency (yellowish blue) beneath the BSR. Presence of a number of gas-rich/gas-poor strata mask the noticeable frequency drop beneath the BSR. The velocity anomaly (Fig. 6) computed using the Dix's formula from semblance analysis is superimposed on seismic stack section. This shows the lateral and vertical extension of high velocity hydrate- and low velocity gas-bearing sediments and correlates well with the computed reflection strength and instantaneous frequency attributes.

Results and discussion

Figure 3 displays the absolute value of reflectance that shows the amplitude blanking immediately above the BSR. The drop in reflectance of about 33 dB for CDP's 4375-4380 (Fig. 3a) and about 26 dB for CDP's 4400-4405 (Fig. 3b) with reference to the reflectance values at BSR and seafloor strongly suggests the presence of gas-hydrates above the BSR. It is also noticed that the zone of blanking is wider for CDP's 4375-4380 (~150 ms TWT) than for CDP's 4400-4405 (~50 ms TWT), indicating that the thickness of gas-hydrates bearing sediments decreases as the CDP number increases towards the land. It is to be stated that the amplitude blanking is a non-definitive parameter in quantifying the amount of gas-hydrates in absence of other information but is a good indicator for identifying gas-hydrates in sediments (Lee and Dillon, 2001; Kou et al., 2007). However, by studying the reflectance attribute, we can provide a qualitative estimate of gas-hydrates in terms of thickness variation of hydrate-bearing sediments. Very prominent blanking is observed almost up to the seafloor from BSR on the seismic section in the Blake Ridge area (Holbrook et al., 1996). The blanking, observed on the section in the study region of Makran accretionary prism is not that prominent. Results of ODP leg 164 demonstrate that the pronounced blanking at the Blake Ridge is mainly caused by the homogenization of fine-grained clay-rich sediments. Since the sediments in the Makran accretionary prism are sandy in nature (Fruehn et al., 1997; Sain et al., 2000), the observed blanking is attributed to the presence of gas-hydrates that cement the pore spaces of sediments. Nevertheless, both regions show high reflectivity

Figure 4. Reflection strength plot for CDP's between 4200-4750.

Figure 5. Instantaneous frequency plot for CDP's between 4200-4750.

beneath the BSR indicating sedimentary strata containing variable concentration of free-gas below the BSR.

Gas-hydrates, by filling the pore spaces of sediments, reduce the permeability in the hydrates-bearing sediments and act as seal that traps free-gas in the underlying dipping strata. The reflection strengths are sensitive to changes in acoustic impedances and thus stratigraphic horizons that contain trapped free-gas in variable concentration beneath the hydrates bearing sediments generate strong reflections or 'bright spots'. Figure 4 exhibits the reflection strengths of the gas-hydrates and free-gas bearing sediments in the Makran accretionary sediments. The enhanced reflections observed below the BSR are quite thick (200-350 m). We ascribe the enhanced-reflectivity zone below the BSR to the gas-rich and gas-poor dipping sedimentary strata, as has been interpreted by Andreassen et al. (2003) for free-gas bearing Norwegian sedimentary formations below the BSR.

The low frequency anomaly beneath the BSR correlates well with the high reflection strength of the free-gas containing sediments, evidence of which is further supported by the low-velocity zone (Fig. 6) derived using the semblance velocity analysis and full-waveform inversion results (Sain et al., 2000). A semblance plot in velocity analysis at CDP 4380 has been shown in Fig. 7 depicting the low velocity zone below the BSR. Our interpretation is consistent with the drop in instantaneous frequency for the seismic data below the BSR in the Blake Outer Ridge (Taylor et al., 2000) and the mid-Norwegian Margin (Berndt et al., 2004), which is explained by the free-gas absorbing the high-frequency component of the seismic energy.

The lack of gas-hydrates fails to diminish the impedance contrast between layers. Presence of gas-hydrates may be apparent via the amplitude blanking analysis. But, presence of free-gas trapped below the hydrated sediments produces significant effects on reflection

Figure 6. Semblance interval velocity superimposed on the seismic stack section.

Figure 7. A semblance plot in velocity analysis shows seafloor, BSR and low velocity gas zone below the BSR.

strength and instantaneous frequency plots, and hence helps to identify BSR.

Conclusions

Various seismic attributes like amplitude blanking, reflection strength and instantaneous frequency can be used as important tools for identifying and qualifying gas-hydrates and free-gas across a BSR. These attributes can be used at places where BSR is not observed

on seismic section but various other geological, geochemical or microbiological parameters indicate the probable occurrences of gas-hydrates. Strong reflectivity observed below the BSR is attributed to the alternate layers of gas-rich and gas-poor dipping sedimentary strata or gas accumulations. This is also supported by the absorption of high frequencies in the instantaneous frequency plot. Though the amplitude blanking is not so obvious on the seismic section, the reflectance attribute plot demonstrates the phenomenon. The attribute plot also provides a measure of gas-hydrates in terms of thickness

variation. The study shows that the thickness of the gas-hydrates bearing sediments decreases from 150 to 50 ms TWT at CDP 4375 to 4405 towards the land. The high reflectivity zone (> 200 ms TWT) below the BSR indicates that the free-gas containing sediments in the study region are quite thick, of course the actual thickness depends on the seismic velocity.

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