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The character and amplitude of ‘discontinuous’ bottom-simulating reflections in marine seismic data

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ABSTRACT

Bottom-simulating reflections (BSRs) identified in seismic data are well documented; and are commonly interpreted to indicate the presence of gas hydrates along continental margins, as well as to estimate regional volumes of gas hydrate. A BSR is defined as a reflection that sub-parallels the seafloor but is opposite in polarity and cross-cuts dipping sedimentary strata. BSRs form as a result of a strong negative acoustic impedance contrast. BSRs, however, are a diverse seismic phenomena that manifest in strikingly contrasting ways in different geological settings, and in different seismic data types.

We investigate the characteristics of BSRs, using conventional and high resolution, 2D and 3D seismic data sets in three locations: the Terrebonne and Orca Basins in the Gulf of Mexico, and Blake Ridge on the US Atlantic Margin. The acquisition geometry and frequency content of the seismic data significantly impact the resultant character of BSRs, as observed with depth and amplitude maps of the BSRs. Furthermore, our amplitude maps reinforce the concept that the BSR represents a zone, over which the transition from hydrate to free gas occurs, as opposed to the conventional model of the BSR occurring at a single interface.

Our results show that a BSR can be mapped in three dimensions but it is not spatially continuous, at least not at the basin scale. Rather, a BSR manifests itself as a discontinuous, or patchy, reflection and only at local scales is it continuous. We suggest the discontinuous nature of BSRs is the result of variable saturation and distribution of free gas and hydrate, acquisition geometry and frequency content of the recorded seismic data. The commonly accepted definition of a BSR should be broadened with careful consideration of these factors, to represent the uppermost extent of enhanced amplitude at the shallowest occurrence of free gas trapped by overlying hydrate-bearing sediments.

1. Introduction

Bottom-simulating reflections (BSRs) identified in seismic data are well documented, and have been used to indicate the presence of gas hydrates in continental slope environments since they were first identified at the Blake Ridge in the 1970s (Bryan, 1974; Shipley et al., 1979). BSRs are defined in seismic data as reflections that sub-parallel the seafloor, cross cut dipping sedimentary strata, and in the case of hydrate related BSRs, are opposite in polarity to the seafloor (Guerin et al., 1999; Holbrook et al., 1996; Shipley et al., 1979). The majority of documented BSRs are interpreted to be the result of a negative impedance caused by the transition from gas hydrate bearing sediments above the base of gas hydrate stability (BGHS), to free gas bearing sediments below (Haacke et al., 2007; Max and Dillon, 1998; Petersen et al., 2007; Shedd et al., 2012). The shallowest occurrence of gas is dependent on the local supersaturation of methane within a local gas stability zone (Xu and Ruppel, 1999). In the literature the term bottom-simulating reflector is sometimes used, rather than bottom-simulating reflection. A reflector is a physical boundary at which a reflection occurs; whereas the BGHS or top of free gas is a physical horizon off which seismic energy reflects, forming a BSR, therefore the term bottom-simulating reflection is more accurate. In a seismic profile we observe reflections, which can be described in terms of attributes such as amplitude. Such properties cannot be assigned to a reflector.

Previous studies have proposed several primary geological controls on the presence of free gas below the BGHS, and therefore

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the observation of a BSR. These are, the pressure and temperature conditions, the rate of tectonic uplift of the seafloor, lithology and the rate of upward fluid flux (Chapman et al., 2002; Haacke et al., 2007; Shedd et al., 2012; Wood and Gettrust, 2000).

The location of the BGHS is dependent primarily on pressure and temperature conditions, which are unlikely to vary dramatically across localized scales (Clennell et al., 2000; Wood et al., 2008). Porewater salinity and gas composition are also controlling factors, and these may vary locally, resulting in the formation of pluming BSRs, such as are observed in the Gulf of Mexico (Clennell et al., 1999; Liu and Flemings, 2007; Shedd et al., 2012). Other factors including grain surface effects and pore size may have a more limited impact on the position of the BGHS (Daigle and Dugan, 2014). The interaction of these factors determines the thermodynamic state, growth kinetics, spatial distribution and growth state of gas hydrate (Clennell et al., 1999). Although the definition implies that a BSR must be 'bottom simulating', a BSR will only mirror the seafloor in areas where the temperature conditions (isotherms) are dominated by conduction, not advection.

Nevertheless, BSRs are commonly used to interpret the presence of gas hydrate and/or free gas in many different settings (Bünz et al., 2003; Hornbach et al., 2008; McConnell and Kendall, 2013), although the exact nature of these parameters are often not clearly understood, and gas hydrate occurrences have been documented in the absence of BSRs (Haacke et al., 2007; Majumdar et al., 2016; Paganoni et al., 2016). Such complicating factors have motivated this review of the physical nature of the characteristics of BSRs. As described by Shedd et al. (2012) there are three types of BSR that are attributed to the presence of gas hydrates and can be characterized in seismic reflection data; continuous (Fig. 1a and b), discontinuous (Fig. 1c and d), and pluming BSRs. Continuous BSRs are the classic feature, characterized by a continuous, coherent event that cross-cuts primary stratigraphy, a typical, well known example would be the Blake Ridge (Shipley et al., 1979). In some regions continuous BSRs are relatively rare, in the Gulf of Mexico, for example, the most common is discontinuous. Unlike the continuous BSR, a discontinuous or segmented BSR is characterized by spaced anomalous seismic events that are generally parallel to seafloor bathymetry (McConnell and Kendall, 2013; Shedd et al., 2012). Pluming BSRs are characterized as a continuous reflection that does not follow seafloor geomorphology, but are bowed towards the seafloor as a result of significant, locally constrained increases in heat flow related to strong vertical fluid flux (Shedd et al., 2012). Pluming BSRs occur as small scale, localized anomalies; as such, these features will not be discussed further in this study.

A fourth type of BSR, known as diagenetic BSRs, form as the result of diagenetic boundaries in siliceous sediments where sediment density increases with depth, most commonly due to the transformation of biogenic silica (opal-A) to opal-CT (Berndt et al., 2004; Davies and Cartwright, 2002; Goldberg et al., 1987). The acoustic impedance associated with the relative change in density results in a prominent reflection with the same polarity as the seafloor; this reflection follows an isothermal gradient, and therefore parallels seafloor topography (Davies and Cartwright, 2002; Lee et al., 2003). This is unlike BSRs caused by free gas and/or gas hydrate, where the reflection is the opposite polarity of the seafloor reflection.

Herein, we characterize BSRs associated with the presence of gas hydrate in three locations to understand the impact of hydrate and free gas saturation, geological characteristics, and acquisition parameters of the seismic data on the appearance of BSRs in marine seismic data. The Blake Ridge on the US Atlantic margin, although by no means the largest hydrate occurrence worldwide, is perhaps the most well-known, (e.g. Gorman et al., 2002; Hornbach et al., 2008, 2003; Markl et al., 1970). We selected this site as it is the textbook example of a continuous BSR, and multiple seismic datasets have been acquired in the area. Our other two locations, the Terrebonne mini-basin and the Orca Basin, provide classic examples of discontinuous BSRs in the northern Gulf of Mexico. The Terrebonne mini-basin has been the site of several previous gas hydrate studies (Boswell et al., 2012b; Frye et al., 2012), most notably the Joint Industry Project (JIP) II in 2009, when two wells were drilled and logging-while-drilling (LWD) data were acquired. Both the Terrebonne mini-basin and the Orca Basin are being evaluated as proposed drill sites in the Gulf of Mexico Generation of Methane [GOM]^2 project, currently under review by the International Ocean Discovery Program (IODP), and multiple seismic data sets have also been acquired at each of these sites.

In each of these locations we use 3D seismic data to map out and characterize the BSR, producing depth and amplitude maps. In addition, at the Terrebonne site, we use high-resolution 2D seismic data to investigate the differences associated with data acquisition geometry and frequency content on the characteristics of the mapped BSR. Mapping BSRs in 3D seismic data allows us to determine the potential areal extent of gas hydrate occurrence, which, in combination with well data, is a valuable tool in constraining volumetrically the quantity of methane hydrate in a region (Hornbach et al., 2008). Mapping BSRs using 2D seismic data with a higher frequency content, provides enhanced stratigraphic detail near the base of hydrate stability, indicated by BSRs that have a distinct character, which also provides a critical tool for defining the location and disposition of hydrate in sedimentary layers (Haines et al., 2014). One of the primary factors that determine how a feature is imaged in seismic data is the frequency content of the data, and the corresponding resolution. The resolution of seismic data refers to the minimum separation of two features at which they can be resolved as multiple interfaces (Bulat, 2005; Hyndman and Spence, 1992; Wood et al., 2008). The lateral resolution of the data, commonly referred to as the Fresnel zone, is defined for vertically traveling waves as the area within which the reflected waves interfere constructively, resulting in energy being averaged and coherently reflected back towards the receiver (Wood et al., 2008; Yilmaz, 2001). The size of the Fresnel zone is dependent on the wavelength of the seismic signal and the depth to the reflector. In this study, we refer to conventional 3D data, with a typical frequency content in the 10–80 Hz range and high-resolution data in the 80–250 Hz range (Chapman et al., 2002; Petersen et al., 2007; Wood et al., 2002; Wood and Gettrust, 2000).

We present maps of BSRs derived from 3D seismic data, including previously unpublished amplitude maps. The results highlight the significant influence that seismic acquisition geometry and frequency content have on the resultant BSR characteristics, and call into question the widely accepted definition of a BSR. The BSRs in our study areas do not fit the definition as they do not consistently follow seafloor bathymetry, and depending on the resolution of the seismic data, they are not characterized as discrete reflections.

1.1. Geological setting

The seabed morphology of the northeast Gulf of Mexico is characterized by salt-bounded mini-basins, typically infilled by Miocene–Pleistocene strata (Diegel et al., 1995; Frye et al., 2012; Pilcher and Blumstein, 2007). The geomorphology of these mini-basins is due to the coeval processes of relative salt rise on the flanks, and subsidence at the center (Diegel et al., 1995; Worrall and Snelson, 1989). The Terrebonne and Orca Basins

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