Three-dimensional seismic analysis of high-amplitude anomalies in the shallow subsurface of the northern Indus Fan: Sedimentary and/or fluid origin

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Three-dimensional seismic analysis of high-amplitude anomalies in the shallow subsurface of the Northern Indus Fan: Sedimentary and/or fluid origin

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We report on a detailed analysis of amplitude anomalies in three-dimensional (3D) seismic reflection data and their surrounding strata in the shallow subsurface of the northern part of the Indus Submarine Fan, Arabian Sea. Our analysis reveals the presence of distributary lobe complexes and a relict fluid migration system, including a buried mud volcano, linked to contractional anticlines overlying deep-seated strike-slip faults buried below the Indus slope. Building on a regional tectonic and stratigraphic framework, we have used a 3D seismic survey to map in detail the occurrence of high-amplitude anomalies in the shallow subsurface. We link these to gas hydrate and free gas accumulations hosted within distal distributary lobes deposited on the Indus slope and supplied by underlying focused fluid flow system along a fault zone. Our results suggest that the seismic amplitude anomalies may be classified as a weak “bottom-simulating reflection” (BSR) formed during a paleofluid flow event in the northern Indus Fan (~5–1.8 Ma). Present-day fluid influx is low.


1. Introduction

The fill of sedimentary basins can provide a record of Earth history and the effects of internal and external control on sedimentation. Seismic reflection data form an essential part of all modern studies to provide detailed insights into the processes that form marine basins, including large-scale tectonic elements, depositional bodies and structures related to the migration and storage of fluids. The latter are the results of physical and/or chemical processes (e.g., Cartwright, 2007).

Gas hydrates occur commonly along continental margins where a combination of low temperature and high pressure allows gas hydrates to be stable at the seafloor and up to hundreds of meters into the subsurface (Shipley et al., 1979; Claypool and Kvenvolden, 1983; Kvenvolden, 1993). Gas hydrates, also known as “clathrates”, are composed of frozen lattices of water containing a gas molecule in their center (Sloan, 1998). Gas hydrates are stable under favorable combinations of pressure-temperature conditions, as well as adequate gas composition and concentration (Sloan, 1998; Hyndman and Davis, 1992).

Seismic reflection profiles of marine sediments often show amplitude anomalies mimicking the seafloor known as a “Bottom-Simulating Reflections” [BSRs]. These are often caused by the interface between gas hydrate and free gas-bearing sediments [Shipley et al., 1979]. However, recent work and advanced methods of seismic acquisition in gas hydrate provinces, such as the Blake Ridge (US eastern seaboard) or Lake Baikal (Siberia), reveal that the absence of a BSR does not necessarily mean the absence of gas hydrates in the sediments [Paull et al., 1998; Vanneste et al., 2001]. The BSR is defined as a seismic reflection originating from the impedance contrast between a layer of sediment containing gas hydrate and a free gas layer below. The associated contrast from high to low velocity gives the BSR a polarity which is opposite to that of the seafloor reflection. The BSR mimics the seafloor, while its depth increases with the pressure gradient. As a result, the BSR usually cross-cuts sediment layers, although the angle of discordance can be very shallow.

In this paper, we report on an entirely seismic-based assessment of free gas and gas hydrate occurrences in an area of the Arabian Sea (NW Indian Ocean) where previously no BSR have been reported. We describe how these occurrences are related to the tectonic and stratigraphic setting and discuss possible controls on fluid migration and BSR occurrence in this new hydrate province.

2. Tectonostratigraphic Setting

2.1. Geological Setting

The Arabian Sea is located in the northwestern Indian Ocean and is defined by a variety of plate boundaries (i.e., passive margin, subduction zone, midocean ridge and transform plate boundary). The dominant sedimentary fea-
ture of the Arabian Sea is the Indus Submarine Fan or Indus Cone (dashed line in Figure 1). The northern Arabian Sea can be divided into four areas based on physiography and structural style [Gaedicke et al., 2002]: the Makran Accretionary Wedge, the Oman Abyssal Basin, the Murray-Owen Ridge system (MR, OR), the Pakistan-Indian Passive Margin. The Eurasian Plate overthrusting the Arabian Plate, forming a subduction accretionary wedge in the Makran Area (MAP in Figure 1). The Indian Plate has been in active continent-continent collision with the Eurasian Plate along the Indus-Yarlung Suture Zone since ~50 Ma [e.g., Beck et al., 1995; Rowley, 1996]. The Indian Plate is in a transform relationship with the Arabian Plate along the Owen Fracture Zone and the Chaman Fault onshore (OFZ and ONF in Figure 1) [Fournier et al., 2008]. The Murray Ridge (MR in Figure 1) forms the link between these two features and represents a transtensional structure because of its oblique orientation [Edwards et al., 2000]. The edge of the Indus Fan is uplifted along the Murray Ridge, which has prevented sediment flux from the Indus Delta into the Gulf of Oman since its initiation around 20 Ma. [Mountain and Prell, 1990].

Figure 1. Location map with the main morphological features of the Arabian Sea. The black box shows the area covered by the reflection seismic data. The dashed dark line is the fringe of the Indus Fan (adapted from Kolla and Coumes [1987]; Droz and Bellaiche [1991]). The bathymetry is from the GEBCO compilation [British Oceanographic Data Centre, 2003]. Scientific boreholes are from ODP Leg 117 (black dots) and DSDP Leg 23 (gray dots). White dots on the axis of the Indus Fan mark the location of sonobuoy data used by Bachman and Hamilton [1980]. Zones of BSR previously identified on reflection seismic are striped bodies along the Indian Margin (after Rao et al. [2002]). Major structural features are abbreviated as follows: MR: Murray Ridge; OR: Owen Ridge; OFZ: Owen Fracture Zone; GOO: Gulf of Oman; MAP: Makran Accretionary Prism; SR: Shelia Ridge; CR: Carlsberg Ridge; CLR: Chagos-Laccadives Ridge; LR: Laxmi Ridge; MF: Minab Fault. Map projection: WGS 84.
located between the continental shelf of offshore Pakistan and the Murray Ridge in a region of tectonic transpression in the crystalline crust (Figure 1). The seafloor extends from water depths of 1040 to 1325 m with a dip of 0.6–0.7 degrees.

The study area consists of two contrasting tectonic regimes. To the northeast the area is bounded by extensional growth faults on the continental shelf and to the northwest by strike-slip faults that define the plate boundary along the western edge of the Murray Ridge (Figure 2). The study area represents a combination zone between these two areas showing deep-seated strike-slip faults overlain by thin-skinned contractional features (Figures 2 and 3). Throughout most of the Cenozoic the Indian Plate was moving northward faster than the Eurasian Plate, thus creating sinistral transform displacement along the Murray Ridge [Figure 2; Edwards et al., 2000; Kukowski et al., 2000].

The Cenozoic sedimentary record along the Pakistan passive margin can be subdivided into ten major sequences based on seismic stratigraphic principles (Figure 3). The stratigraphic interval covered in this study corresponds to the upper part of the Indus Megasequence of Droz and Bellaiche [1991]. The base of the studied interval (green on Figure 3) is dated as top Middle Miocene (Tortonian 11.6 ± 0.5 Ma) based on seismic stratigraphic studies and biostratigraphy from borehole data along the continental shelf. The top of the studied interval (light blue on Figure 3) is dated as Upper Miocene to Recent [Kolla and Coumes, 1987; Gaedicke et al., 2002; Clift et al., 2002]. Isochore mapping of sediments between the base of the Plio-Pleistocene and the seafloor reveals two major depocenters in the study area (Figure 2). West of the present day shelf break in water depths of around 200 m, a shelf edge delta of 0.4–0.7 s two-way travel time (TWT) thickness is mapped out. This delta is associated with an inner slope distributary lobe complex (0.3–0.4 s TWT thickness) that is laterally confined by the topographic low associated with the previously deposited Indus channel-levee system C [Deptuck et al., 2003] and the edge of the Murray Ridge (dashed lines in Figure 2). The expression and significance of the distributary lobe complex is described and analyzed in the following section.

2.2. Documented Fluid Flow and BSRs in the Arabian Sea

In the global inventory of natural gas hydrate occurrences of Kvenvolden and Lorenson [2001], two major locations on the margins of the Arabian Sea are identified, as inferred from the presence of BSRs in the shallow subsurface (Figure 1). These two provinces are located offshore the Indian Continental Slope [Veerayya et al., 1998; Rastogi et al., 1999; Rao et al., 2002] and the Makran
3. Data and Methodology

The upper sedimentary section of the Indus Fan has been imaged by several hydrocarbon exploration multichannel reflection seismic surveys (MCS) since the 1970s [Naini and Kolla, 1982; Kolla and Coumes, 1987; McHargue and Webb, 1986; Droz and Bellaiche, 1991; Deptuck et al., 2003]. The seismic data used for the current study are two-dimensional (2D) and 3D multi-channel, post-stack, time-migrated reflection seismic data (Figure 2). The seismic data displays used here are zero phase, SEG normal polarity, i.e., black peak indicating an increase in acoustic impedance ["American polarity", Brown, 1996]. The seismic migration velocities vary spatially, based on normal moveout velocity analysis. Within the study interval (0–500 ms TWT below seafloor) the interval velocity ranges between 1500 and 1750 ms⁻¹.

4. Seismic Data Analysis—Methodology

The 2D and 3D seismic data in this study have been interpreted using standard seismic stratigraphic techniques [Mitchum et al., 1977; Vail et al., 1977] based on reflection terminations and seismic facies reflection characteristics. Recognition of continuous seismic reflections and their relation to the geometry of individual seismic reflections (terminations) allows the seismic volume to be divided into chronostratigraphic packages. Using these techniques, a framework of eight seismic surfaces has been used to define four seismic packages in the study interval. These packages are used to analyze depositional elements [Posamentier and Kolla, 2003], amplitude anomalies and detect bright spots [Heggland, 1997]. This type of seismic analysis is com-
monly used in scientific and petroleum exploration to highlight potential geohazards and fluid occurrences in the vicinity of proposed borehole locations [Sharp and Samuel, 2004].

[18] The 3D reflection seismic data set was processed to extract geometric seismic attributes, such as coherency. This attribute is used to enhance recognition of coherent events and emphasize discontinuities such as faults and stratigraphic surfaces, such as unconformities. Root Mean Square (RMS) amplitude between horizons was computed and used to detect the occurrence of anomalous amplitudes. In the shallow subsurface such anomalies may be caused by lithological changes (e.g., sand vs. mud, or carbonates vs. siliciclastic sediments), diagenetic changes or fluids (e.g., hydrocarbons). Hydrocarbon gas in shallow porous sediments is detected by high-amplitude reflections and the absorption of high-frequency components of the underlying seismic section [e.g., Castagna et al., 2003]. A spectral frequency analysis was carried out along 2D sections within the 3D seismic volume in order to understand the effect on the amplitude of the reflections of sediment versus fluid charging of the layers (discussed below).

5. Seismic Observations of High-Amplitude Anomalous Reflections

[19] A seismic stratigraphic interpretation of the seismic data allows for the definition of eight continuous seismic reflections in the shallow subsurface (H1-8; Figures 4A and 4B). Integration with the regional framework shows that these horizons correspond to the Upper Miocene to Plio-Pleistocene of the Indus Megasequence (Figure 3).

[20] High-amplitude “soft” anomaly reflections are found between Horizons H5 and H7 horizons on the 3D seismic data (Figures 4A and 4B). These discontinuous reflections occur at 200–400 ms TWT below the seafloor (Figure 5). They have opposite polarity to the seafloor reflection, which indicates a negative acoustic impedance contrast, thus indicating a change to lower velocity and density below these “soft” reflections.

[21] Three traces along an amplitude seismic section have been extracted and displayed to emphasize the amplitude signature of the anomalous reflections (Figure 5). Traces 2 and 3 show high-amplitude anomalies of negative value around 1.8 s TWT, whereas on Trace 1 no such high amplitude is observed for the laterally equivalent reflection. The wavelets of these negative amplitudes display a 90° phase shift, as compared to the zero phase wavelet at the seafloor. The wavelets of these negative amplitudes display a 90° phase shift, as compared to the zero phase wavelet at the seafloor. Such a response would be expected from a soft (gas-bearing) porous layer with a thickness around the tuning thickness, i.e., ~10 m with a dominant frequency ~38 Hz (Figure 6) and assuming a velocity of 1500 ms⁻¹ for the gas-bearing interval below the hydrate layer [cf. Holbrook et al., 1996].

[22] The geometry of the high-amplitude anomalous reflections are different from the surrounding background
reflections, as they cut through coherent parallel reflections (Figures 4A and 4B). On a N–S oriented seismic section these anomalous reflections show a specific arrangement in being organized in a “roof-tile” geometry, i.e., shallowing upward from the South to the North (Figures 5 and 7). The “step” between each of the “roof-tiled” reflections is indicated by black arrows in Figure 5.

Frequency extractions were performed for three intervals covering an area below the anomalous reflections, the high-amplitude anomalous reflections themselves, and the interval between the anomalous reflections and the seafloor (black boxes on Figure 6C). The 2D plot presented here (Figure 6) summarizes a full 3D evaluation of frequency variation both along horizons and across specific intervals. The three intervals display peak frequencies of 25, 38 and 50 Hz from base to top. The individual frequency domains and peak frequencies for each interval are shown in Figure 6A. A spectral analysis was performed on windows of 200–400 ms along 300 traces. A second spectral analysis was performed for reference on laterally equivalent intervals where there were no anomalous reflections (gray boxes on Figure 6C). For the shallow interval above the anomalous reflections to seafloor, a slight change is observed toward higher frequencies (Figure 6A). Those intervals laterally equivalent to the anomalous reflections show a slight lowering of peak frequency. This is associated with a decrease in the high-frequency content and an increase in low-frequency content within the area of the high-amplitude anomalous reflections (Figure 6A). The interval below the anomalous reflections shows a significant drop in high-frequency content, but no change in peak frequency because there is no change in the low-frequency content (Figure 6A).

Absolute amplitude values have been extracted for each of these peak frequencies (Figure 6B). The anomalous reflections have absolute amplitude values 2.5 times greater than the surrounding intervals. The absolute seismic amplitude within those areas, which are laterally equivalent to the anomalous reflections but have no anomalous reflections is 0.4 times the amplitude of the anomalous reflections (Figure 6B).

A three dimensional analysis of the extent of each of the “roof-tile” anomalous reflections was carried out. As shown by the RMS amplitude extraction across the interval H5–H7, a significant occurrence of relatively high-amplitude values occurs in the shallow subsurface (red to green on Figure 7A). This high-amplitude anomaly is located in the center of the 3D seismic survey (Figure 7A).
anomaly extends up to 15 km from north to south and more than 5 km from west to east. A detailed analysis of this interval amplitude anomaly map was performed in order to understand the relationship between each individual anomaly (Figure 7B). Each high-amplitude anomaly was picked as an individual reflection (labeled 1 to 14 in Figure 7B). A schematic SW–NE projected profile shows that the geometry of these anomalies is a “roof-tile” organization of enhanced “soft” reflections [negative reflection coefficient] that shallow toward decreasing seabed depth (Figure 7C). Anomalous reflection number 1 shows the greatest lateral extent along a SW–NE axis. This reflection conforms in most places to Horizon H5. Anomalous reflections 2 to 5 shallow up from SW to NE and toward Horizon H7 in the northeast.

Figure 7. Location of high-amplitude anomalies in the shallow subsurface in interval H7–H5. (A) RMS amplitude extraction map is shown; low-amplitude values are in blue, and high-amplitude values are from green to yellow. (B) Detailed contours of individual high anomalies are shown. Note the SW to NE relay trend between the anomalies. (C) Seismic picks used for individual amplitude anomaly analysis are shown. The plots on the side of the figure represent the predicted base of hydrate stability (BGHS). (D) The profile of projected individual anomalies along a SW–NE orientation illustrates the “roof-tile” organization of the high-amplitude anomalies especially between 1 and 7. Map projection: UTM zone 42.
The “roof-tile” organization, the discordant relationship with the sedimentary background reflections, and the high “soft” amplitude of the high-amplitude anomalies suggest a non-stratigraphic origin for the anomalous reflections.

5.1. Depth of Anomalies Versus Base of Hydrate Stability

To test a potential relationship between the occurrence of the high-amplitude anomalies and the hydrate layer we plot the depth to the base of the gas hydrate stability (BGHS) zone (Figure 7C). The parameters used for this prediction were the temperature in the water column from the NOAA-NGDC World Ocean database 2005 at http://www.nodc.noaa.gov/OC5/WOD05/pr_wod05.html, Sloan’s [1998] free gas/hydrate phase boundary for sea water approximation with different gas composition φ1 (100% methane) and φ2 (96% methane and 4% ethane) and geothermal gradient of 30 and 50°C/km. A range of geothermal gradients was selected from a regional review of published measurements from the Western Indian Margin [Khan and Raza, 1986; Pollack et al., 1993]. Hydrostatic pressure is assumed to increase linearly with depth in the sediments. Predicted water depths to the BGHS (φ1 and φ2) varied between 1400 ms TWT (1050 m for water velocity of 1500 m/s) and 1720 ms TWT (1290 m). Using a geothermal gradient of 30°C/km depths to the BGHS range from 135 to 305 ms TWT below seafloor (Figure 7C). However, for a geothermal gradient of 50°C/km, the BGHS will range from 245 to 535 ms TWT. The depth below seafloor at which high amplitudes occur in the 3D survey area is observed to lie between 180 and 300 ms TWT. These values are in agreement with a predicted BGHS using a geothermal gradient of ~30°C/km. Therefore the top of the high amplitude observed can be interpreted as the base of the gas hydrate phase in the sediments, while the underlying bright event would be free gas.

5.2. Depositional Versus Fluid-Hydrate Origin of the Discordant High-Amplitude Anomalies

The anomalous reflections that are the focus of this paper are characterized by a marked amplitude increase when compared to stratigraphically equivalent surrounding events on the seismic data (Figures 4–6). The polarity of the anomalous events is opposite to that of the seabed reflection and is thus indicative of a negative acoustic impedance contrast (Figure 5; i.e., “soft”).

The depth below seafloor to the top of the anomalous reflections ranges from 180 to 300 ms TWT for shallower and deeper water, respectively (Figure 4). Using a range of interval velocities from 1600 to 1700 m/s, the estimated depth below seafloor ranges from 150 m to 250 ± 5 m. This range of velocity and depth is in agreement with the velocity function estimated by Bachman and Hamilton [1980] that was derived from sonobuoy data in the Indus Fan.

The local increase of amplitude along the anomalous reflections (i.e., bright spots), the reverse polarity of the anomalies from the seafloor reflection, the amplitude shadow under the anomalies, and the low-frequency shadow beneath the high-amplitude anomalies all match the criteria of Brown [1996] for recognition as potential “hydrocarbon indicators”, albeit of limited extent and thickness. The cross-cutting nature of the high-amplitude reflection is the most important diagnostic feature in the identification of fluid contact reflections rather than stratigraphic contacts [Brown, 1996]. From a velocity perspective, such anomalies of negative acoustic impedance contrast are due to a high-velocity contrast from fast to slow media. Such a drastic change could be due to a change in lithology or fluid content in porous space. For example a gas-charged layer would decrease the seismic velocity by 20% [Sheriff, 1975; Hilterman, 2001], and therefore be represented by a negative acoustic impedance contrast.

In order to establish whether the mapped anomalous reflections are caused by lithologic change in sedimentation, fluid charge (overpressured pore waters or hydrocarbons), or a combination, the location of sedimentary bodies have been studied in an attempt to discriminate amplitude changes due to lithologic changes from those due to potential fluids such as water or free gas within porous space.

6. Discussion

6.1. Tectonic Activity

If the anomalous reflections represent porous layers hosting fluids including free gas beneath a sealing gas hydrate layer, then it is interesting to look at the location of the anomalous reflections in relation to deeper structures, as these could give an indication of fluid migration pathways. The anomalous reflections discussed here are located above a detached contractional anticline, formed above an area of transtensional faulting in the basement (Figure 8).

Figure 9A shows an RMS amplitude map of the interval containing the anomalous reflections, and shows the location of all the shallow anomalous reflections in the area. A deeper antclinal structure at the level of Horizon H1 (Figure 8) is shown in the TWT structure map (Figure 9B). This structure trends N–S and has an associated en echelon fault system. The faults displayed on Figure 9B have been mapped using a coherency attribute along Horizon H1 and verified using vertical displays of regular amplitude data. The underlying seismic basement structure is shown in the TWT structure map (Figure 9C). Major faults affecting the seismic basement were extracted from a coherency attribute of the seismic basement. An en echelon system is depicted by three major faults trending NW–SE and NNE–SSW. Three domains or blocks (α, β and γ; Figures 9C and 9D) can be inferred from the fault geometry. The basement contains two transtensional structures related to the NNE–SSW extension and NW–SE compression (blue lows in the center of Figure 9C). Figure 9D shows a compilation of all the mapped seismic features: the shallow high-amplitude reflections, the contours of the underlying antcline in the Horizon H1, together with associated faults and the major faults cutting the seismic basement. It is clear from this compilation that the anomalous reflections are located above the H1 anticline controlled in turn by a major basement fault. This strongly suggests fluid migration from near the seismic basement through the Cenozoic cover sequences and occasionally breaching the paleoseafloor as mud volcanoes.
6.2. Sedimentologic and Fluid Escape Features

In order to further investigate the origin of the shallow, high-amplitude anomalies, we analyzed the stratigraphically-equivalent depocenter using a combined thickness-amplitude-coherence approach, facilitated by the high-quality 3D seismic data set:

1. The TWT thickness of the interval containing the anomalous reflections reveals the location of the main sedimentary depocenter (Figures 10A and 10D).

2. Extraction of RMS amplitudes between continuous stratigraphic horizons is used to locate the high-amplitude anomalies within two stratigraphic intervals: H5–H6 and H6–H7 (Figures 10A and 10D). Most of the high RMS values correlate with the negative amplitude. The location of the amplitude anomalies is first analyzed with reference to the position of mapped sedimentary bodies.

3. In order to visualize the depositional bodies making up the depocenters identified from the thickness maps an isoproportional coherency slice was extracted for each interval to recognize specific depositional events (Figures 10B and 10E). Coherence is generally interpreted to image the stratigraphic and structural context, as well as potential hydrocarbon occurrences [Bahorich and Farmer, 1995].

Looking at the TWT thickness and RMS amplitude maps together (Figures 10A and 10D) allows us to propose a potential relationship between the depocenters and individual amplitude anomalies. To test whether the amplitude anomalies are compatible with sedimentary or structural variations we use the coherency attribute to map variations in the internal structure of a given stratigraphic interval (Figures 10B and 10E). The three “independent” observations are summarized in a blended surface (Figures 10C and 10F) for each stratigraphic interval of interest. In this manner we can address a composite “geological” answer to the potential origin of the anomalous seismic reflection observed in the shallow subsurface.

The thickness of interval H5–H6 is 27–117 ms. Three domains are highlighted by the isochore of that interval, a NW and SW region where the contours are gradually thinning, a NE–SW diagonal depocenter delimited to the NW by the 60 ms TWT contour, and an eastern region where the main depocenter shows an isolated triangular shape that is thick to the east and thins toward the SW (Figure 10A). The geometry of the two depocenters resembles lobate features; one elongated lobe to the east measuring some 21 × 8 km and a more triangular-shaped depocenter measuring 15 × 8 km. The interval H5–H6 shows relatively high RMS amplitude values in the central part of the 3D data volume (green-red-yellow colors in Figure 10A). The relatively high-amplitude anomaly is located in the central domain, whereas the surrounding RMS amplitude mostly shows relatively low values (blue to light green in Figure 10A). Two faults are also depicted on the RMS amplitude map cutting across interval H5–H6. These show high amplitude values along a NW–SE axis (H.A.F. in Figure 10C). The anomalies are associated with the termination of the strike-slip faults (Figure 4). As in interval H6–H7, the most coherent patch correlates to the highest-amplitude anomaly (Figure 10B).

From the isoproportional coherency slice analysis (pseudostratigraphic; Figure 10B) the three domains resolved from the amplitude analysis are also recognized, with one lying to the NW with a low-coherency signature, one south of this with a relatively high-coherency signature and one to the east with moderate to low coherency. When these regions are tied to the seismic facies (Figures 4A and 4B), the highly coherent part of interval H5–H6 can be seen to be related to a continuous and concordant seismic facies, while the low to moderate coherency area is related to areas of isolated chaotic facies surrounded by otherwise more

![Figure 8. Seismic line indicating shallow anomalous reflections (HAA), detached anticline, and basement structure. See Figure 2 for location.](image-url)
concordant continuous seismic facies. In this interval the coherency seems to delineate two separate distributary lobes. The thickness of interval H6–H7 is 14–120 ms TWT (Figure 10D), within which we highlight two main domains: a western domain where contours gradually thin to the west and an eastern domain where the main depocenter thickens to the NE and thins toward the SW. The geometry of the main depocenter resembles a lobate feature measuring 21 km in the NNE–SSW direction and 12 km in the NW–SE direction. Interval H6–H7 shows relatively high amplitudes in the eastern part of the 3D seismic survey, whereas the western domain is mostly linked with relative low amplitude values (Figure 10D). The highest-amplitude anomaly occurs at the transition from the core to the edge.

Figure 9. Results from a detailed analysis of the 3D seismic data set. (A) TWT structure map (seconds TWT) of the seafloor morphology superimposed on the RMS amplitude of the anomalous reflection interval between horizons H7 and H5. (B) TWT structure map of horizon H1 where dotted white lines show the extent of anomalous amplitude reflections and faults extracted from coherency attribute along the seismic horizon. (C) TWT structure map of the seismic basement and faults extracted from the coherency attribute along the seismic horizon. (D) Composite of anomalous amplitude interval RMS extraction map (from Figure 9A), antlcline time structure map at horizon H1 (contours from Figure 9B) and coherency at this horizon, and basement structure map and superposition of faults from basement (from Figure 9C). The three tectonic blocks related to the strike slip setting are α, β, and χ. Map projection: UTM zone 42.
Figure 10
of the main depocenter, equivalent to the 75 ms TWT contour (green and red color in Figure 10D). The most coherent patch is correlated to the highest-amplitude anomaly (white on Figure 10E). The positive amplitudes are indicative of high acoustic impedance bodies, possibly related to diagenetic processes and cementation, whilst the negative anomalies are likely associated with fluid overpressure or the presence of gas in porous sedimentary layers.

[42] Using the isoslice coherency (Figure 10E) two distinct domains similar to those seen in the amplitude analysis are also observed, with a highly coherent signature to the west and a moderate to low coherency to the east. When the coherency is tied to the seismic facies (Figures 4A and 4B), the highly coherent part of Interval H6–H7 is seen to be related to a seismic facies of concordant reflection geometries, while the poorly to moderately coherent area is associated with a more chaotic seismic reflection configuration. We highlight the low-high coherency transitions with thin black lines in Figure 4. The seismic attribute analysis outlines the geometry of a depositional distributary lobe complex located on the paleoslope of the margin basinward of a shelf edge delta located to the northeast of the 3D survey area (Figures 2 and 3).

[43] This combined analysis of sediment thickness, RMS amplitudes, coherency maps and seismic facies, allows us to constrain the potential origin of the shallow subsurface anomaly. In Interval H5–H6, about one quarter to one third of the amplitude anomaly overlaps with the western part of a large eastern depocenter, but the remainder of the anomaly falls outside of the depocenter, suggesting that this anomaly is largely due to an anomalous fluid composition, rather than a specific lithology change (Figure 10C). In Interval H6–H7, we note a first-order relationship between the extent of the high-amplitude anomaly and the western side of the main depositional lobe (Figure 10F). The main amplitude anomaly located in the southwest occurs at a transition from chaotic to concordant reflections, as imaged by the coherency map. Therefore development of this amplitude anomaly may be related to the presence of a thicker depositional body, which could serve as a reservoir for fluids possibly including free gas and gas hydrate.

[44] Evidence of fluid migration includes pockmarks that are observed between Horizon H5 and just below the seafloor (Figures 10B and 11). These pockmarks are elongated and trend NW–SE, paralleling the slope contours. The size of the largest pockmark is 300 × 600 m. These fluid escape structures are found in the center of the anomalous reflection package (Figures 10B and 10C) and are located along the crest of the anticline observed on the time structure map of Horizon H1 (Figure 9B). Fluid escape structures are spatially correlated with the underlying strike-slip faults, suggestive of a genetic link (Figure 9B). The stratigraphic position of these features suggests initiation around the end of the Miocene to the Pliocene transition (∼5 Ma), potentially extending to as young as the Pleistocene (>1.8 Ma (Figures 3 and 11).

[45] Looking beyond the area immediately surrounding the amplitude anomalies yields further insights into the fluid plumbing system of the area. Figures 10C, 10F and 11 illustrate the expression of fluid flow from the deeper parts of the basin toward the shallow subsurface by the occurrence of a buried mud volcano located to the south of the study area. A ~50 ms tall and ~750 m wide mud volcano sits on top of a >500 ms deep diatremal structure that appears to emanate from a contractional anticline bisected by a steep fault (Figure 11). The root of the mud volcano system appears to be located near the top of the acoustic basement where it is overlain by Paleocene mudstones at a depth of ~4.7 s TWT (~3 s TWT subseafloor). The mud volcano is occurring at the interval H5–H7 and is draped by sediment between Horizon H7 and the seafloor, allowing the timing of its activity to be constrained. The first mud eruption above Horizon H7 (Figures 3 and 11) could be related to sediment remobilization at the end of the Middle Miocene (>11–5 Ma). The last mud eruption observed within the 3D survey may predate 5 Ma and lasted until ~2 Ma, but is not as young as the last pockmark observed.

6.3. Fluid Migration—Potential Origin

[46] The physical relationship between likely fluid migration pathways and geophysical evidence (such as folds, faults, mud volcanoes and pockmarks) and the location of the inferred gas and gas-hydrate related BSRs leads us to suggest that the shallow amplitude anomalies are most likely related to a relatively recent (5.0–1.8 Ma) episode of fluid migration from the deep sedimentary section of the basin (Figure 11). This period of fluid expulsion may relate to overpressuring caused by accelerated Plio-Pleistocene sedimentation in the Arabian Sea [Métivier et al., 1999; Clift et al., 2002]. Rapid Plio-Pleistocene sediment loading is also associated with mud volcanism and fluid expulsion in the Song Hong-Yinggehai Basin of the South China Sea [Clift and Sun, 2006].

[47] The high-amplitude velocity anomalies start at the same level as the last stage of flow from the mud volcano

Figure 10. Depocenter amplitude coherence analysis of shallow anomalous reflections in the shallow subsurface. (A) RMS amplitude extraction between horizons H6 and H5, isochore contours by steps of 5-ms TWT for the interval between horizons H5 and H6. (B) Coherency extraction along isoproportional (pseudostratigraphic) horizon in interval H5–H6 showing stratigraphic signature of slope lobes fan, faults, pockmarks (P.), and mud volcano (M.V.). Faults are highlighted by their low coherency due to their offset in the NW and SW areas (dark thick black lines in Figure 10B). (C) Composite image of coherency, high-amplitude values from RMS, and depocenter in interval H6–H5 to emphasize correlation between information (high amplitudes along faults—H.A.F). (D) RMS amplitude extraction between horizons H7 and H6, isochore contours by steps of 5-ms TWT for the interval H6–H7. (E) Coherency extraction along isoproportional (pseudostratigraphic) horizon in interval H7–H6 showing stratigraphic signature of slope lobe fan, faults, and mud volcano (M.V.). (F) Composite image of coherency, high-amplitude values from RMS, and depocenter in interval H6–H7 to emphasize correlation between information. Map projection: UTM zone 42.
The seismic amplitude anomalies migrate upwards, progressively crossing the stratigraphy (SSE to NW of Figure 11), and are amplified each time an anomalous reflection passes over a fault or anticline.

Our study suggests that the shallow anomalous reflections are related to a BSR between a gas hydrate and a thin free gas zone potentially fed by deeply-sourced fluid flow. However, a shallow biogenic origin cannot be ruled out in this area. Recent petroleum exploration drilling by Shell confirmed our prediction that the gas layer is thin. Similar observations have been made in many other continental margins where tectonic features are buried under sedimentary basins, such as in the Makran [White, 1977], deep-offshore Niger Delta [Cunningham and Lindholm, 2001], Blake Ridge [Taylor et al., 2000], Amazon Fan [Tanaka et al., 2003], and the Møre Basin offshore Norway [Bünz et al., 2003].

In the context of the northern Indus Fan the amplitude anomalies investigated here do not constitute a prominent, “classic” BSR. However, all of the conditions exist for the presence of a gas hydrate (water depth over 1000 m, 5–7°C temperature at the seafloor, and evidence for free gas in sediments). This implies that a “weak” BSR might exist, even if the supply of methane is low or even absent following a fluid migration episode some time in the past. This type of BSR has already been suggested and observed in well-documented hydrate provinces such as Blake Ridge [Holbrook et al., 1996; Paull et al., 1998] and Lake Baikal [Vanneste et al., 2001]. As suggested by Haacke et al. [2007], hydrates can occur in a passive margin setting with low geothermal gradient and low pressures, without the

**Figure 11.** Seismic section showing the detailed tectonostratigraphic context of the high-amplitude anomalous reflections and associated fluid migration pathways. The shallow interval is displayed on top to show details of the fluids and sediment remobilization. Two anticlines are crossed by this seismic section, a buried mud volcano located above faults that cross-cut the southern anticline is the first clear evidence for fluid migration through the entire Cenozoic succession during the early Pleistocene (~H5 time). It is possible that continued fluid flow from this system has fed the anomalous reflections located updip in the northern anticline via stratal migration through the middle Pleistocene interval (H5–H7). The core of the anomalous reflections is disrupted by a pockmark showing evidence of fluid evacuation at the paleoseafloor. The latest episode of fluid expulsion appears to be midway between horizons H7 and H8, i.e., late Pleistocene. See Figure 2 for location.
presence of free-gas under the hydrate/free-gas stability limit (weak or no BSR).

[50] A hydrate recycling model allows us to relate the potential hydrate layer to a past major release of thermogenic methane from the deeper part of the basin as suggested by the observation of a mud volcano and pockmarks [Kvenvolden and Barnard, 1983; Haacke et al., 2007]. Such a gas release could have been stored in potential reservoirs, such as the depositional lobe complexes imaged in the shallow subsurface, and subsequently recycling has occurred at the BHSZ, consuming most of the free-gas beneath the BHSZ. Alternatively, the paleofluid migration system may have acted as a valve for any residual methane present in the source, allowing this to escape in a steady “trickle”, and resulting in minimal gas under the anomaly today.

[51] The evidence for a paleofluid migration system is clearly imaged by the seismic data, but the origin of the shallow gas cannot be pinpointed without biogeochemical analyses. Elsewhere in the Arabian Sea analyses from Deep Sea Drilling Program (DSDP) Leg 23 showed that gas measured in the shallow subsurface is mostly related to biogenic methanogenesis [Claypool and Kvenvolden, 1983]. A biogenic signature is common for most gas measurements in shallow sediment of hydrate provinces even if a strong link to thermogenic methane can be suggested, based on direct evidence and expulsion modeling. This relationship may suggest that any thermogenic gas migrating toward the surface in anything but catastrophic events is likely to be altered by biogenic processes, leading to a biogenic signature even for gases that have a thermogenic origin.

[52] Figure 12 shows a schematic comparison of the potentially deep origin of the fluids and their migration toward the shallow subsurface, as well as associated shallow, high-amplitude anomalies (BSRs) observed in the northern Indus Fan and in the deep offshore Niger Delta on the West African margin [Cunningham and Lindholm, 2001]. The two areas are characterized by different tectonic regimes and varying quantities of mobile mud substrates, but in both cases the shallow manifestation of fluid flow is similar in that BSRs are located on top of contractional structures. These anticlinal structures allow fluids, including methane gas, to migrate laterally and upward toward the hydrate stability field where they can be stored in a subhydrate reservoir, incorporated into the hydrate cap, or vented to the surface.

[53] In our study area the top of the anomalous reflection interval is interpreted to mark the BHSZ (Figure 12). The location of the shallow anomalous reflections in the northern Indus Fan is controlled by the stratigraphic dip and regional pinch out of the first infill sequence on the Murray Ridge playing a potential origin for fluids (dark gray interval in Figure 12). Deep-seated tectonic processes and overlying detached contractional folds and faults are also important in providing the deep-seated plumbing system for...
a highly focused, shallow, fluid-flow system, as evidenced by mud volcanism, pockmarks and the antcline-hosted BSR (Figure 12). The present day observation of high-amplitude anomalies and BSRs could also be related to a present day low volume flow of gas. The source could either be from deeper parts of the basin or from methane biogenesis activity. The role of diagenetic processes as potential origins for these gases must be tested by direct measurement.

7. Conclusions

[54] This study documents for the first time the occurrence of high-amplitude anomalous reflections in the shallow subsurface of the upper Indus Fan, northern Arabian Sea. We conclude from analysis of a high-quality 3D seismic data set that the anomalies are related to the occurrence of potential gas hydrate overlying a thin accumulation of free gas within distal distributary lobe of sands or even more porous muds. The anomalous reflections are organized in a “roof-tile” geometry, the top of which parallels the seafloor. The resulting BSR is not as strong, continuous, or discordant as classical cross-cutting BSRs seen elsewhere, such as in New Zealand or Hydrate Ridge. This might be due to the stratigraphy being subparallel to the seafloor, and partly due to the minor amount of gas found under the hydrates. However, the sublith of the BSR does not preclude its value in the assessment of the hydrate occurrence and shallow fluid flow systems of the area. The northern Indus Fan BSR is conspicuously confined to an antcline east of the Murray Ridge and is linked with a buried mud-volcano fed from the older Cenozoic succession that onlaps the Murray Ridge, and which may be buried sufficiently to have reached source rock maturity. The absence of a widespread BSR in an area, which is well within the gas hydrate stability zone suggests that this is a low-flux province relying on focused fluid flow systems and lateral redistribution in the shallow subsurface.

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