Gas hydrate pingoes: Deep seafloor evidence of focused fluid flow on continental margins

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ABSTRACT
Gas hydrates in the shallow subsurface form one of the largest reservoirs of methane in the global organic carbon cycle. Seafloor seeps and associated features represent the venting points of methane released from the shallow lithosphere to the hydrosphere and atmosphere. Here we document the discovery of seep-related seafloor mounds in the Kwanza Basin, offshore Angola, and employ high-resolution three-dimensional seismic analysis to unravel the subsurface plumbing system and the origin of mounds. Mounds with distinct morphologies and geophysical signatures illustrate different development stages associated with the formation and dissociation of shallow gas hydrate, linked to thermogenic fluid migration along salt diapir flanks draining deeply buried salt minibasins. The mounds are more than an order of magnitude larger than previously described submarine hydrate pingoes, and comparable to hydraulic pingoes commonly found in terrestrial periglacial environments, suggesting hydrate volumes of individual mounds up to $1.1 \times 10^6 \text{ m}^3$ (equivalent to $2.0 \times 10^6 \text{ m}^3$ of methane gas). The interpretation of seismically well-defined seep-related seafloor mounds brings new insight to the occurrence and development of concentrated near-surface gas hydrate accumulations and their relationship with thermogenic fluid migration and host sediment properties along continental margins.

INTRODUCTION
Natural gas hydrates are commonly found along continental margins and polar regions, under which intermediate pressure (1–12 MPa), low temperature (<300 K), and adequate gas concentrations facilitate the formation of clathrate hydrates (Kvenvolden and Lorenson, 2001; Sloan and Koh, 2008). Natural gas hydrates and associated methane seeps along continental margins play important roles with regard to seabed ecology (Judd and Hovland, 2007), continental slope instability (Sultan et al., 2004), and contribution to the global organic carbon cycle (Kvenvolden, 2002) for which gas hydrate accumulations are considered both for their economic importance (Milkov and Sassen, 2002) and for their potential role in past and future climate change (Maslin et al., 2010). Although gas hydrates have been widely recognized from reflection seismic images in the form of bottom-simulating reflection (BSR) (Shipley et al., 1979), and to a lesser extent from direct observations, the use of high-resolution three-dimensional seismic data brings new insight to the occurrence of gas hydrate and associated relationship with venting points and deep plumbing systems.

This study presents the discovery of seep-related seafloor mounds and their underlying plumbing systems in the Kwanza Basin, offshore Angola, supporting previous suggestions that gas hydrate pingoes do exist in the submarine realm (Kvenvolden and Hoverd, 2006). Detailed seismic interpretation of their nature illustrate different development stages associated with the formation and dissociation of shallow gas hydrate, as well as their links to deep-rooted plumbing systems enhancing thermogenic fluid migration. Volumetric calculations are used to evaluate the significance of hydrate pingoes with regard to shallow gas hydrate accumulations and methane vents along continental margins.

STUDY AREA
The Angolan continental margin represents a natural laboratory to study shallow fluid flow and seep-related features based on the coincident presence of key elements including numerous active petroleum systems, abundant hydrocarbon seepage, and available high-quality three-dimensional seismic data (Fig. 1). Deep source rocks (Burwood, 1999) and shallower organic-rich sediments (Berger et al., 2002) provide important sources for thermogenic and biogenic fluids, in addition to pore fluid expelled by sediment compaction. Favorable stratigraphic and structural evolution (Brownfield and Charpentier, 2006) has created preferential fluid flow pathways. Stratigraphic intervals including permeable carbonates and sandstones allow lateral and updip fluid migration, whereas structural deformation associated with salt tectonics have resulted in numerous seal bypass systems enhancing cross-stratal fluid migration with the presence of growth faults in the extensional domain and salt diapirs and related faulting in the contractual domain (Andresen et al., 2011; Brownfield and Charpentier, 2006; Gay et al., 2007). Recognized hydrocarbon potential along the South Atlantic continental margins has generated an explosive growth in deepwater exploration (Brownfield and Charpentier, 2006). Acquisition of high-quality three-dimensional seismic data and numerous studies in the Lower Congo Basin, and to a lesser extent in the Kwanza Basin, have helped to recognize the widespread occurrence of past and present fluid flow phenomena (Andresen et al., 2011; Gay et al., 2007), including the widespread occurrence of gas hydrates (Cunningham and Lindholm, 2000).

DATA AND METHODS
This study was carried out using high-resolution three-dimensional seismic data, with an

Figure 1. A: Location of study area along the Angolan continental margin, including main subbasins (LCB—Lower Congo Basin; KB—Kwanza Basin; BB—Benguela Basin), major tectonic elements (SMC—seamount chain [dark gray circle]), previous fluid flow studies, gas hydrate distribution based on bottom-simulating reflection (BSR), and location of cold-water coral mounds. B: Two-dimensional seismic profile A–B (location in Figs. 2 and 3) illustrating the main tectonostratigraphic framework of the contractional domain dominated by minibasins, salt nappes, and salt diapirs forming broad bathymetric highs, and enhancing thermogenic fluid migration and associated seep-related seafloor mounds (M6 shown in Figs. 2 and 3). Alb—Albian; K—Cretaceous; P—Paleogene; N—Neogene; Q—Quaternary.
inline and crossline spacing of 12.5 m, covering an area of 3000 km² in water depth ranging from 630 to 1750 m. The seismic data are zero phased with positive amplitude represented by a red, orange, or yellow peak, and negative amplitude represented by a light blue to dark blue trough, respectively characterizing an increase and decrease in acoustic impedance. A dominant frequency of 40 Hz gives a vertical resolution (Δz) of ~11.5–15.5 m, assuming seismic velocities between 1800 and 2500 m/s.

Mound morphology is described based on a depth-converted seafloor map with a resolution of 12.5 m and assuming a seismic velocity of 1500 m/s for seawater. Seafloor amplitude is employed to define variations in seafloor sediment density and/or seismic velocity. Negative amplitude anomalies are interpreted as the result of free gas in surface sediments (Evans et al., 2007), as opposed to positive amplitude anomalies generally associated with the occurrence of denser sediments, hardgrounds, precipitated authigenic carbonates, shell debris, or gas hydrates (Judd and Hovland, 2007; Roberts, 2001). BSR interpretation is based on the recognition of particular seismic reflections with seafloor-reversed polarity, generally mimicking the seafloor topography with salt diapirs (Figs. 1B, 2A, and 3A). Detailed face expression of underlying salt diapirs and broad bathymetric highs representing the seafloor (1°–2°) and the presence of numerous characterised by a gently west-southwest–dipping SEAFLOOR MOUNDS AND BSR (GHSZ) (Sloan and Koh, 2008).

The bathymetry within the study area is characterized by a gently west-southwest–dipping seafloor (1°–2°) and the presence of numerous broad bathymetric highs representing the surface expression of underlying salt diapirs and salt nappes (Figs. 1B, 2A, and 3A). Detailed mapping of one of these diapir-related bathymetric highs at depth between 850 and 1000 m revealed the presence of small protruding seafloor mounds of 80–300 m in extent and 5–40 m in height (Figs. 2 and 3A; Fig. DR1 in the GSA Data Repository). Generally circular to elliptoidal in plan view, their morphologies vary from smooth, well-rounded, steep-sided mounds (9°–16°) (M1, M2, M6) to rough, uneven, gently dipping mounds (3°–10°) (M4, M5, M7, M8) (Table DR1 in the Data Repository). All mounds are characterized by a lack of internal structures and the absence of basal reflection corresponding to the regional seafloor. Apart from the distinctive occurrence of mounds, the surrounding seafloor is fairly smooth and featureless, although a few additional features can be noted, including pockmarks, fault scarps, and mounds around mounds M1 and M7 (Fig. 2A; Fig. DR1).

Seafloor amplitudes are of moderate strength over the broad bathymetric high as the result of Late Cretaceous–Paleogene, overcompacted rocks cropping out at the seafloor, in comparison to relatively low amplitudes associated with Quaternary sediments in surrounding minibasins (Figs. 1B and 3B). The local occurrence of distinct, moderate to high amplitude anomalies that generally coincide with mound locations may suggest the presence of hardgrounds, authigenic carbonates, chemosynthetic community shell debris, or gas hydrate commonly associated with cold seeps (Roberts, 2001) (Fig. 3B).

The presence of strong, discontinuous reflections with negative polarity and crosscutting relationships to stratigraphic reflections in the shallow subsurface (40–70 mbsf) are comparable to BSR (Shipley et al., 1979), however, somewhat different from continuous BSR commonly observed in similar deepwater settings (850–1000 m water depth) where BSR is often relatively deeper (~250–300 mbsf) (Lucazeau et al., 2004; Cunningham and Lindholm, 2000). The occurrence of discontinuous BSR may represent discrete gas accumulations trapped below hydrate-bearing frozen sediment within high-permeability sedimentary layers or highly fractured fault zones (Singh et al., 1993; Crutchley et al., 2010). Thinning of the GHSZ can be associated with either bottom water temperature variations or thermal gradient anomalies in the shallow subsurface. Considering the likely constant bottom water temperature (~4 °C) in this setting, thinning of the GHSZ is attributed to enhanced thermal conductivity of salt and warm fluid advection linked to deep-rooted plumbing system along salt diapir flanks and related faulting (Serié et al., 2011; Lucazeau et al., 2004) (Figs. 1B and 3A).

DISCUSSION: POSSIBLE ORIGIN OF THE MOUNDS

Detailed seismic interpretation shows a correlation between seafloor amplitude anomalies, BSR, and seafloor mounds of distinct morphologies. The absence of extrusive features such as mud flows or mud cones, and negative amplitude anomalies associated with the extrusion of fluidized sediment and gases, discount a possible interpretation of extrusive processes forming mud mounds, mud volcanoes (Evans et al., 2007; Kopf, 2002), and liquid hydrocarbon seepage forming asphalt volcanoes (Valentine et al., 2010). Positive amplitude anomalies, commonly associated with the presence of hardgrounds, authigenic carbonates, and chemosynthetic community shell debris, could be attributed to the formation of carbonate or cold-water coral mounds. Offshore Angola, such structures are generally characterized by a circular to elongated shape not exceeding 300 m in width, stretching 1.0–1.5 km in length, and up to 30 m in height, and are usually defined by internal reflections downlapping onto a clearly defined reflection corresponding to the paleoseafloor (Le Guilloux 2008).
Gas hydrate pingoes, also known as hydrate mounds, have been globally observed in numerous tectonic settings; offshore California (Paull et al., 2008), Nigeria (Cunningham and Lindholm, 2000), Japan (Freire et al., 2011), Canada Cascadian Margin (Chapman et al., 2004), and Beaufort Sea (Paull et al., 2007). The concept of gas hydrate pingoes is poorly constrained due to the limited understanding of their formation process in comparison to their terrestrial analogue found in periglacial environments (Pissart, 1985). Hydrate pingoes are generally formed with the growth of hydrate in the shallow subsurface, with the exception of pingo-like features associated with gas hydrate dissociation and subsequent sediment extrusion (Paull et al., 2007). The formation of massive hydrate in the very shallow subsurface requires high fluid flux to maintain high methane concentration within seafloor sediment and surface water in order to prevent gas hydrate dissociation (Egorov et al., 1999; Xu and Ruppel, 1999), and is usually associated with a supply of thermogenic hydrocarbons (Lu et al., 2007). The presence of high fluid flux from thermogenic origin is strongly suggested in the present study area, considering the deep-rooted plumbing system along salt diapir flanks and related faulting (Figs. 1B and 3A).

Distinct mound morphologies and geophysical signatures may illustrate different development stages associated with the dynamic formation and dissociation of shallow gas hydrate (Fig. 4B). The well-rounded mounds (M1, M2, M6) with relatively strong BSR are interpreted as pingo-like structures. Following the nucleation of gas hydrate within relatively high-permeability and porous sedimentary layers, high fluid flux along faults and inclined stratigraphic carriers will maintain the formation and expansion of shallow gas hydrate, causing the overlying sediments to swell. The rough, uneven, and gently dipping mounds associated with weak BSR (M3, M4, M5, M7, and M8) are interpreted as collapsed pingo structures, resulting from insufficient fluid flux, or temperature variations linked with fluid advection, causing gas hydrate dissociation and subsequent fluid release at the seafloor. Relatively

Figure 3. A: Two-dimensional seismic profile C–D illustrating mound geometries, discontinuous bottom-simulating reflection (BSR), and deep plumbing system (uninterpreted profile in Fig. DR2 [see footnote 1]). B: Seafloor maximum-amplitude map including depth contour interval (20 m), outline of exposed older sedimentary rock, and seismic profiles A–B and C–D. C: BSR minimum-amplitude extraction within a 36 ms two-way traveltime window around the depth of the observed BSR.

Figure 4. A: Schematic representation of deep-rooted plumbing system along salt diapir flanks and related faulting enhancing thermogenic fluid migration and subsequent formation of gas hydrate pingoes. B: Gas hydrate pingo formation and collapse associated with the nucleation, formation, and dissociation of gas hydrate likely due to variation in fluid flux, composition, and temperature. BSR—bottom-simulating reflection.
strong seafloor amplitudes are mainly present around collapsed mounds and may be attributed to remnant gas hydrate lenses, hardgrounds, and authigenic carbonates associated with surface sediment disruption and seepage.

A basic volumetric estimation based on the simple geometric relationship observed at the seabed, assuming all of the positive relief is entirely attributed to hydrate expansion and minor precipitation of authigenic carbonates, suggests hydrate volumes of individual mounds up to 0.7–1.1 × 10^5 m^3 of pure hydrate (equivalent to 1.3–2.0 × 10^5 m^3 of gas at standard temperature and pressure; Sloan and Koh, 2008). This is a relatively small amount compared to global estimates of submarine gas hydrate volumes of 1.0–5.0 × 10^15 m^3 (Milkov, 2004) and marine cold seep emissions of 2.5–3.5 × 10^9 m^3 of methane per year (Kvenvolden and Lorenson, 2001). Nonetheless, the evidence presented here suggests a link to a deep plumbing system and the near-surface occurrence of consolidated sediments as a result of salt remobilization, and brings new insights for the significance of deep-sourced hydrocarbon fluids and host sediment properties controlling gas hydrate formation and manifestations of fluid venting along continental margins.

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