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Sea-level change and free gas occurrence influencing a submarine landslide and pockmark formation and distribution in deepwater Nigeria

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ABSTRACT

A series of pockmarks observed at the seabed matches well the perimeter of a large submarine landslide, called NG1, located on the outer shelf and continental slope of the Eastern Gulf of Guinea. NG1 extends over 200 km^2, is covered by a 120-m thick sedimentary layer which tapers downslope, and has an internal structure clearly identified in 3D seismic data consisting of three adjacent units on the upper continental slope. The pockmarks above NG1 have a diameter of several tens of meters and reveal distinct origins: (1) linked to >500 m deep fluid reservoirs, (2) rooted in NG1 internal discontinuities between NG1 units, and (3) well above NG1, superficially rooted in a regional conformity (D40), which marks the lowest sea level of the Marine Isotope Stage 6.

The regional stratigraphic pattern of the study area is composed of muddy sedimentary sequences separated by correlative conformities and transgressive condensed units of coarser grain size. Mud-confined coarser-grained units constitute transient gas reservoirs favoring lateral gas migration and formation of pockmarks rooted in the condensed units. The buried NG1 landslide modifies the layered structure of the sedimentary column providing (1) overall, a barrier to fluid migration, and (2) localized pathways for fluid migration. The triggering factor for the formation of pockmarks above NG1 can be the variation of hydrostatic pressure driven by relative sea-level fall during Marine Isotopic Stages 6 and 2 and consequent gas exsolution and fluid flow. We anticipate our result to be a starting point for understanding the role of gas seeps on climate change worldwide. Furthermore, gas release intensifies during lowstands with relevant implication on global warming after ice ages.

1. Introduction

Since the 1970s, studies of the ocean floor have revealed the presence of pockmarks on passive and active continental margins worldwide. Pockmarks are described as circular or near circular depressions, generally 10–200 m in diameter and some tens of meters in depth, but they may reach 1.5 km in diameter and 150 m in depth (Pilcher and Argent, 2007). When pockmarks are observed in vertical section (seismic profile), they are associated with a vertical chimney under the depression (Hustoft et al., 2007). In seismic sections, chimneys are characterized by either an interruption of seismic reflectors due to the gas charge (wipe-out zone) (Hovland, 1983, 1991; Rao et al., 2001), or by an inflection of seismic reflectors (Hovland et al., 1984) corresponding to a velocity pull down effect or to a deformation of sedimentary layer where fluids migrate.

Since the first study about pockmarks (King and MacLean, 1970), where they were considered as randomly distributed features at the seafloor, their understanding has evolved. It is now widely accepted that pockmarks represent the morphological signature of fluid seepage (Hovland et al., 1984), where fluid may be biogenic and/or thermogenic gas (Rogers et al., 2006) or water (Harrington, 1985). During recent years, there has been much interest in the study of pockmarks because they represent potential pathways for important quantities of gas from sediments to the oceans (e.g. Vogt et al., 1999; Paull et al., 2002; Ussler et al., 2003; Dimitrov and Woodside, 2003; Hovland et al., 2002, 2005; Gay et al., 2006a).

The discovery of pockmark alignments has shown that their spatial organization may be the result of fluid seepage from underlying sedimentary structures such as fault systems, channels, mud volcanoes, mud diapirs, and glaciogenic deposits (e.g. Eichhubl et al., 2000; Pilcher and Argent, 2007; Forwick et al.,

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2009). The spatial distribution of pockmarks suggests that all the discontinuities affecting the sedimentary column represent potential drains for fluid flow, and that simple diffusion through the sediments cannot explain such structures (Abrams, 1992; Brown, 2000). Today it is recognized that pockmarks can be subdivided in two groups: non-random pockmarks, when their spatial distribution is related to identified buried geological features, and random pockmarks, when it is not (Pilcher and Argent, 2007).

The mechanisms behind pockmark formation are still poorly understood. Some hypotheses and conceptual models about pockmark formation have been proposed by various authors (e.g. Josenhans et al., 1978; Hovland, 1987; Gay, 2002; Cartwright et al., 2007; Andresen et al., 2008; Cathles et al., 2010). Josenhans et al. (1978), Hovland (1987), and Gay (2002), for example, propose schematic models of pockmark formation involving gas pressure in a transient fluid reservoir, local sedimentation, and action of bottom currents, but are insufficient to have a comprehensive view of all factors governing fluid expulsion.

Many studies suggest the possible implication of mass transport complexes in pockmark development (Trincardi et al., 2004; Bayon et al., 2009; Plaza-Faverola et al., 2010; Sun et al., 2012), but the role of a landslide in the distribution and formation of pockmarks has never been the central subject of a study. The Eastern Niger Submarine Delta (ENSD; Fig. 1), situated in deepwater "Niger Delta", deserves attention because (1) there is significant evidence for fluid migration at the seabed (Bayon et al., 2007, 2011; Sultan et al., 2007b, 2010, 2011; Riboulot et al., 2011a); (2) the sedimentation is affected by gravity processes (Sultan et al., 2007a; Garziglia et al., 2010; Ker et al., 2010; Riboulot et al., 2012); (3) the age and main controlling parameters of regional sedimentation for the late Quaternary are known (Riboulot et al., 2012).

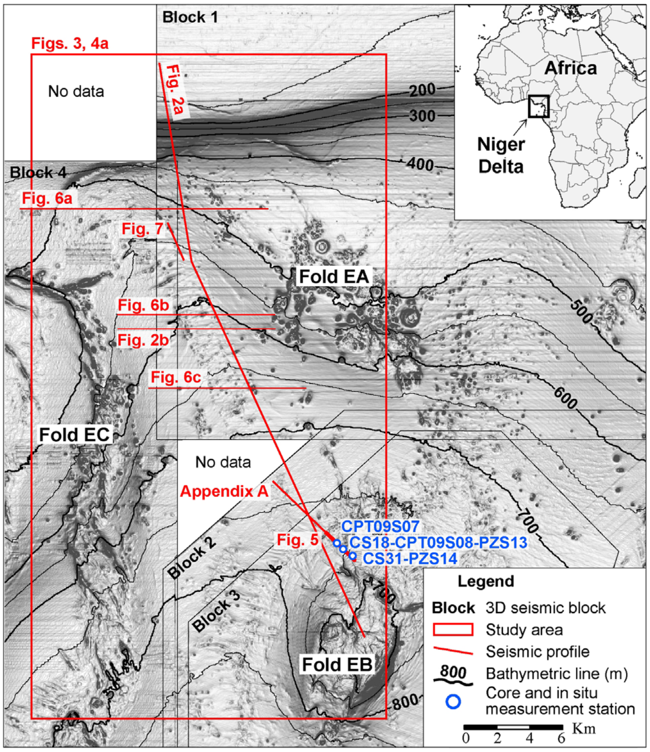

Fig. 1. Location map of the Eastern Niger Submarine Delta. The seafloor dip map of the study area with 50-m spaced bathymetric contour has a 25 m horizontal resolution (modified from Riboulot et al., 2012). This map is generated from seismic seabed picking with Sismage software provided by Total. The red lines and boxes are the figure location presented in this paper. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

The upper-most five depositional sequences of the ENSD were formed during the last ca. 500 kyr BP, in response to glacial/interglacial fluctuations driven by 100-kyr Milankovitch cycles. Fluid seepages are expressed at the seabed by the presence of pockmarks, gas hydrates, mud volcanoes and carbonate constructions (e.g. Damuth, 1994; Cohen and McClay, 1996; Hovland and Gallagher, 1997; Brooks et al., 2000; Graue, 2000; Deptuck et al., 2003; Sultan et al., 2007, 2010).

This study presents the influence of the overall stratigraphic organization of the ENSD and of a buried landslide on fluid migration and pockmark generation. Based on the combined analysis of industrial 3D seismic data, scattered 2D seismic lines, sedimentological and geotechnical data (Cone Penetration Tests with pore pressure measurements, CPTu) a conceptual model is proposed to present the age of sedimentary units hosting pockmarks, to explain the origin of pockmarks from transient reservoirs at sequence boundaries and to assess the role of a landslide versus gas seeps.

2. Regional setting

2.1. The Niger Delta

The continental margin off the Niger Delta, named 'Niger Delta' by oil companies (e.g., Damuth, 1994; Corredor et al., 2005 among others), "Niger Delta complex" (Oomkens, 1974) or "Greater Niger Delta area" (Morley et al., 2011) is undergoing gravity-driven deformation due to the presence of a mobile substratum at the base of the sediment fill (Damuth, 1994; Bilotti and Shaw, 2005; Corredor et al., 2005). This substratum is formed by Early Tertiary overpressured shale deformed since the Oligocene (Wiener et al., 2006).

The continental shelf of the "Niger Delta" is characterized by an extensional zone dominated by large offset listric normal faults (synthetic and antithetic) (Damuth, 1994; Morley and Guerin, 1996). The upper and middle continental slope represent a translational zone (Damuth, 1994) dominated by folding and faulting in response to rapid sedimentation rates and shale remobilization (Doust and Omatsola, 1990; Morley and Guerin, 1996). As the thick stratigraphic column slowly moved downslope (Morley and Guerin, 1996), the lower slope is characterized by a compressional zone (Damuth, 1994) dominated by a series of linear toe-thrusts forming a fold-and-thrust belt. On the Nigerian continental slope, fluid seepage activity is expressed by the presence of pockmarks, gas hydrates, mud volcanoes and carbonate build-ups (Damuth, 1994; Cohen and McClay, 1996; Hovland and Gallagher, 1997; Brooks et al., 2000; Graue, 2000; Deptuck et al., 2003; Sultan et al., 2007a,b, 2010; Riboulot et al., 2011a).

2.2. The Eastern Niger Submarine Delta

The study area is on the continental shelf and slope of the ENSD, roughly 65 km offshore, between 150 and 800 m water depth, and it covers 2350 km^2. Three prominent structural folds are formed by shale-cored anticlines expressed by collapse normal faults faintly discernable at the seabed (folds EA, EB, EC, Fig. 1). These shale-cored folds delimit a large corridor where submarine landslides and fluid-migration features are present.

The ENSD consists of a stack of mud-dominated sedimentary sequences separated by marked erosional surfaces on the continental shelf (D10, D20, D30, D40 and D50 from bottom to the top; Fig. 2a). The shelfal unconformities, formed during sea level falls and lowstands, correspond seaward to correlative bounding conformities that have regional extent. The conformities are