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Initiation of gas-hydrate pockmark in deep-water Nigeria: Geo-mechanical analysis and modelling

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ABSTRACT

A review of recent literature shows that two geomorphologically different types of pockmarks, contribute to gas seepage at the seafloor. Type-1 pockmarks are defined as seafloor craters associated to fluid seepage and are the most classical type referred to as "pockmarks" in the literature. In contrast, Type-2 pockmarks reveal a complex seafloor morphology that may result from the formation/decomposition of gas hydrates in underlying sedimentary layers.

Interpretation of very-high-resolution seismic data, sedimentological analyses and geotechnical measurements acquired from the Eastern Niger Submarine Delta reveal that Type-2 pockmarks are associated to the presence at depth of a conical body of massive gas hydrates. Based on acquired data, theoretical analysis and numerical modelling, it was possible to propose a novel geo-mechanical mechanism controlling the irregular seafloor deformations associated to Type-2 pockmark and to show that pockmark shapes and sizes are directly linked to the initial growth and distribution of sub-seafloor gas hydrates. The study illustrates the role of gas hydrates formation in the fracturation, deformation of the subsurface sediment and the formation of Type-2 pockmarks.

1. Introduction

Pockmark formation, associated with gas (free or dissolved) and gas hydrates, often found in continental slope environments represents an overlooked mechanism possibly responsible for the transfer of large quantities of gas from seafloor sediments into the ocean and ultimately into the atmosphere, potentially contributing to atmospheric warming (e.g. Chand et al., 2012; Leifer and Judd, 2002; Solomon et al., 2009). The identification of pockmarks is therefore an important aim for industries to choice the location of the deep-water infrastructures. The sedimentary deformations linked to gas hydrates are poorly known but their localization are crucial because the modifications of pressure/temperature conditions near from gas hydrates could provoke sedimentary instabilities that may generate tsunamis.

Since the first study about pockmarks (King and MacLean, 1970), where they were considered as randomly distributed craters at the seafloor, many efforts have been made to understand the evolution of these structures. It is now widely accepted that pockmarks represent the morphological signature of fluid seepage through the seafloor (Fig. 2a; e.g. Hovland et al., 1984, 2005; Judd and Hovland, 2007), and can form organized arrays when the fluid they expel comes from underlying organized structures (e.g. Eichhubl et al., 2000; Forwick et al., 2009; Pilcher and Argent, 2007). Recent studies have evidenced sub-surface three-dimensional irregular depression morphologically different from classical pockmarks but resulting from fluid seepage linked to dissociation/dissolution of gas hydrates bearing underlying sedimentary layers (Fig. 2b; Davy et al., 2010; Sultan et al., 2010, 2014).

Davy et al. (2010) and Sultan et al. (2010) have named the subsurface sedimentary deformations related to gas hydrates, gas escape features and pockmarks, respectively. Macelloni et al. (2012) and Simonetti et al. (2013) have observed similar features in the Gulf of Mexico and the seafloor depressions over gas hydrates have been mentioned as craters. Riboulot et al. (2011) consider these features as pockmarks and have made a classification to make a distinction between two different features: (1) the conical depressions, commonly described in literature, are named Type-1 pockmarks and (2) the hydrate-bearing depressions are classified as Type-2 pockmarks (Fig. 2). Sultan et al. (2010) propose a detailed model controlling the morphology evolution of the herein called Type-2 pockmark by the formation/decomposition of gas hydrates. According to Sultan et al. (2014), rapid gas hydrate growth and slow hydrate dissolution are the main mechanisms leading

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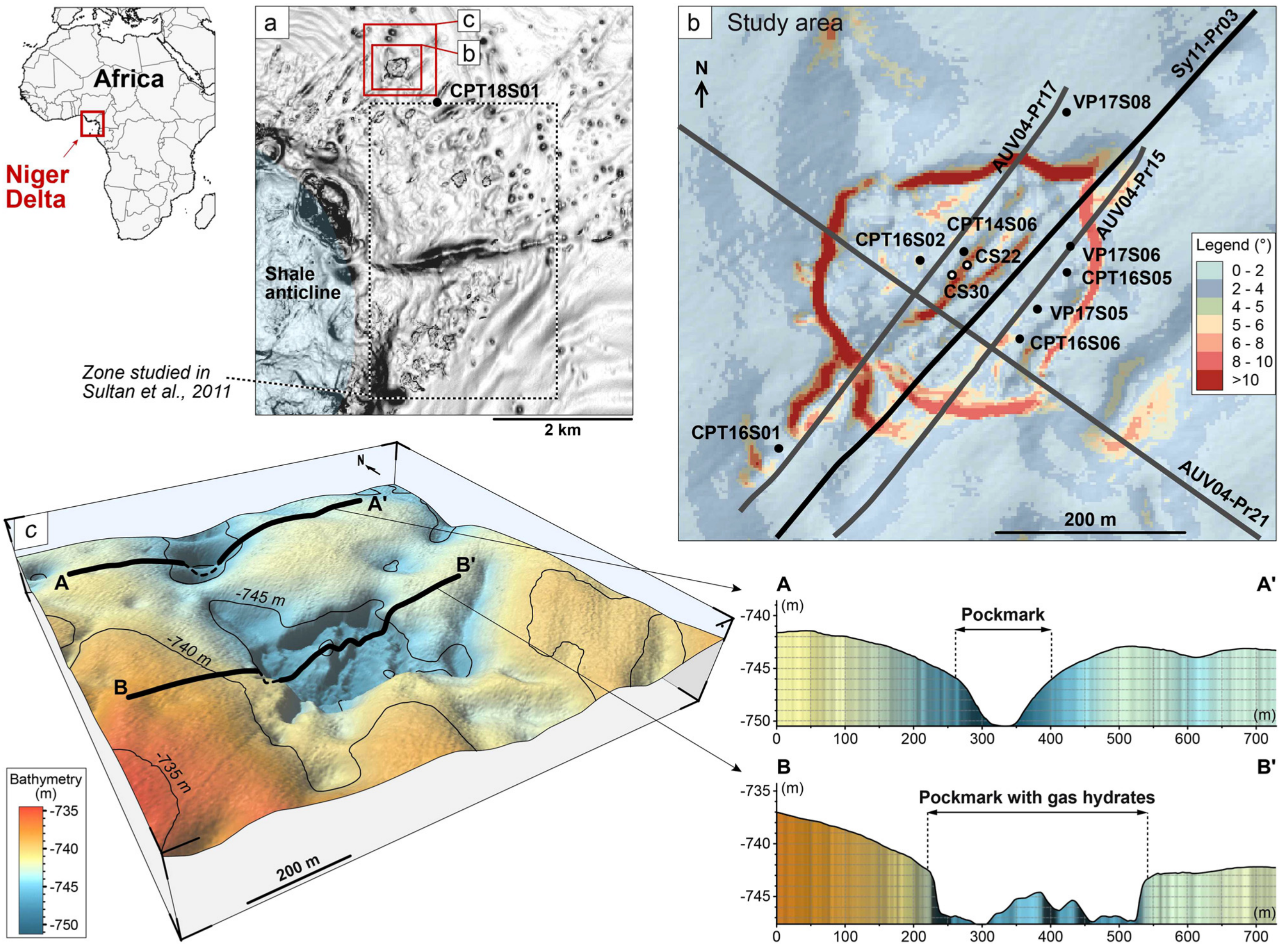

Fig. 1. a: Location maps of the area of interest presenting the seafloor morphology with the dip map derived from the bathymetry (horizontal resolution: 3 m). We study a small area located at the north of the area studied in Sultan et al. (2011). b: The location of all data used in this study (HR seismic profiles, cores and geotechnical data) is projected on the seafloor dip map. c: The 3D view of the area of interest shows two types of seafloor deformations and the location of two bathymetric profiles. The bathymetric profiles AA′ and BB′ correspond, respectively, to a Type-1 pockmark and a Type-2 pockmark.

to the development of Type-2 pockmarks and sub-seafloor architecture. Davy et al. (2010) suggest that the size of these Type-2 pockmarks linked to the presence of gas hydrates depends on slumping and translation along the overpressured BGHS that may have contributed to their morphology. Imbert and Ho (2012) propose a conical shape failure generated by gas hydrate formation to explain 1 km-diameter paleo-funnel-shaped collapse features. Although the above studies open an essential way forward in our understanding of Type-2 pockmarks, they are lacking a precise description of the geo-mechanical process triggering the sedimentary deformation due to gas hydrate formation. The main aim of the present work is to identify the key mechanical process connecting gas hydrate formation to the initiation of sub-surface sediment fracturing and deformation.

The Eastern Niger Submarine Delta (ENSD; Fig. 1), situated in deep-water "Niger Delta", deserves attention because it is an active area for the oil industry and, apart from pockmarks expressed at the seafloor (e.g. George and Cauquil, 2007), many seep-related seafloor features have been recently described as a consequence of gas hydrates decomposition (e.g. Sultan et al., 2014). The ENSD is therefore an important source of hazards for deep-water infrastructures and a suitable site to study the potential link between gas hydrate and sub-surface deformation features. In this work we focus on a specific area, where very high resolution bathymetry data reveal a Type-2 pockmark (Fig. 1). Based on the combined analysis of very high resolution (VHR) seismic lines, sedimentological and geotechnical data, we investigate the pockmark to define a conceptual model describing the mechanical process at the origin of the sedimentary deformation observed above gas hydrates. Finally, we use numerical modelling to check assumptions and working hypotheses about the link between pockmarks shape and the gas hydrate formation and distribution.

2. Background

2.1. The eastern Niger Submarine Delta

The study area concerns a sub-surface deformation feature named "pockmark" situated on the northern flank of the shale-cored anticline EB named and described in Riboulot et al. (2012) and it lies at 750 m water depth. It is located in the ENSD, on the continental margin off the Niger Delta, on the middle continental slope dominated by folding and faulting in response to rapid sedimentation rates and shale remobilization (e.g. Morley and Guerin, 1996). Indeed, major structural faults have been identified beneath the pockmark and described in Ruffine et al. (2013) and Sultan et al. (2011). These vertical discontinuities constitute gas migration pathway from the deep structure to the upper sedimentary layers. The late Quaternary interval of the ENSD consists of a stack of mud-dominated sedimentary sequences separated by coarse-grained planktonic foraminifera and other sand-size particles marked by high amplitude reflectors in seismic data (D10 to D40; Fig. 3; Riboulot et al., 2012). After burial, the layers with grain