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Detection of free gas and gas hydrate based on 3D seismic data and cone penetration testing: An example from the Nigerian Continental Slope

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Abstract

We present a new method to characterize free gas, gas hydrates and carbonate concretions occurrence which are considered as high-risk factors for sub-sea developments in the Niger delta. This method is based on the combination of 3D seismic data to the geotechnical site characterizations using piezocone *CPTU* tests (Cone Penetration Test with additional measurement of the pore water pressure). A special processing of the 3D seismic data has enabled the determination of the interval compressional velocity. Using the effective-medium theory, velocity anomalies (negative and positive) within the first 15 m were translated in gas hydrate and free gas distribution. The calibration of the P wave velocity anomalies was done thanks to in-situ geotechnical testing carried out during two oceanographic surveys (2003 and 2004). Comparison between in-situ testing, recovered cores and the prediction of the gas and the gas hydrate distribution based on the compressional wave velocity have shown that 3D seismic data is a valuable tool to identify heterogeneous areas but the use of the piezocone was essential to discriminate between gas hydrate occurrences and carbonate concretions' presence. Furthermore, in-situ compressional wave velocity (V_p) measurements have clearly demonstrated what it was suspected from the 3D seismic data, the co-existence in the study area between gas hydrate and free gas.

Keywords: effective-medium theory; free gas; gas hydrate; Niger delta; piezocone

1. Introduction

A large number and variety of surveys have been carried out along the West African margin in recent years, in particular, due to the oil and gas industry. The continental slope off Nigeria is one of the areas where the occurrence near the seafloor of natural gas hydrates has been detected previously by several authors Hovland and Gallagher, 1997; Brooks et al., 2000). This type of gas hydrates accumulation is of special interest to industrial development because they are formed close to the seafloor and possibly could become one of the major risks to any future oil development. Any changes in bottom water temperature and/or in pressure generated by human activity on the seafloor (drilling, laying pipe lines) can destabilize hydrate layers, and potentially result in large landslides and soil failures. On the other hand, gas hydrate may be also at the origin of gas release within the sediment layer that can generate a dramatic

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modification of the engineering response of the soil. Free gas may increase the sediment compressibility, modify the shear strength of the soil (see Wheeler, 1988; Vanoudheusden et al., 2004 amongst others) and reduce the intrinsic permeability. Thus and for the safety of underwater developments, it is more and more frequently required to detect and quantify the free gas and gas hydrate occurrences within marine sediments.

This work was carried out within the framework of a joint research project (NERIS: *N*igeria: *E*valuation des *RIS*ques) between Ifremer and TOTAL. The main aim of this project is to define a protocol to characterize (detection and quantification) the gas and gas hydrates charged sediment corresponding to high-risk areas (geohazards) by using 3D-seismic data and in-situ geotechnical site investigation. While, the use of the 3D seismic data is fundamental to characterize at a regional scale, the heterogeneity and the extension of the gas and gas hydrate charged marine sediments, the in-situ geotechnical testing is essential to provide an accurate "truth" for calibration and verification.

In this work, the 3D seismic data available from industry were complemented during two NERIS surveys by different types of other geophysical and geotechnical data collected from the Nigerian continental slope. These data were acquired by using:

1. Different geophysical tools (swath bathymetry and associated imagery, deep towed high-resolution sub-bottom profiles, side-scan sonar images).
2. Piston coring used to collect sediment cores and gas hydrates samples.
3. In-situ geotechnical measurements using the Ifremer *CPTU* piezocone (Cone Penetration Test with additional measurement of the pore water pressure). A combination of two special cones (classical CPTU cone and sonic cone) was used.

2. Geological setting and seafloor features

The study area is located in the Gulf of Guinea on the West coast of central Africa, south of Nigeria and seaward of the modern Niger Delta (Fig. 1). The continental margin off the Niger Delta is undergoing deformation by gravity driven tectonism mainly initiated in response to rapid seaward progradation and to sediment loading of in the successive depocentres. Three regional structural styles are recognized Damuth, 1994) based on a plethora of studies (Stoneley, 1966; Hospers, 1971; Burke, 1972; Mascle et al., 1973; Delteil et al., 1974; Emery et al., 1975; Weber and Daukoru, 1975; Lehner and de Ruiter, 1977; Evamy et al., 1978; Whiteman, 1982; Galloway, 1986; Damuth and Link, 1987; Knox and Omatsola, 1989): (1) an upper extensional zone beneath the outer continental shelf characterized by extensive listric growth faults. Growth faulting is induced by load, compaction and differential subsidence resulting from huge sedimentation; (2) an intermediate translational zone beneath the continental slope characterized by shale diapirs and ridges dividing the slope into separate intraslope basins. These basins are filled with ponded sediments interbedded by turbidites, mass transport deposits and hemipelagic deposits; (3) a lower compressional zone beneath the lower continental slope and uppermost rise characterized by imbricate thrust structures (toe thrusts). These structural styles indicate that large portions of the thick sedimentary prism are slowly moving downslope by gravity gliding or sliding on decolement level, located within the "mobile shales" series, in a manner analogous to giant mass movements or mega-landslides.

Various studies from the Nigerian continental slope have shown different seafloor sedimentary features such as pockmarks, gas hydrates, slides, mud volcanoes and carbonate build-ups associated with fluid flow (Damuth, 1994; Cohen and McClay, 1996; Hovland et al., 1997; Haskell et al., 1999; Nissen et al., 1999; Brooks et al., 2000; Graue, 2000; Deptuck et al., 2003 amongst others). Heggland (2003) observed gas chimneys above hydrocarbon charged reservoirs. These chimneys are believed to result from hydrocarbon dysmigration along fault planes between source rocks of reservoirs and the seabed.

The study area (Fig. 1), from a tectonostratigraphic point of view, is within the translational zone (ridges and intraslope basins filled by turbidites among other deposits). The investigated area lies at water depths ranging from ~1100 to 1250 m and is characterized by numerous circular to sub-circular features, few m up to 700 m in diameter, and by numerous oblong patches Le Chevalier, 2002). Most of these features are located within a NW–SE trend area bounded by two lineaments clearly expressed on the bathymetry map (Fig. 1). The two lineaments (N1 and N3 — Fig. 2) correspond to deep-rooted normal faults, which delineate a graben collapsed zone linked to the axis of a subsurface anticline structure (Fig. 2).

The seafloor features display various shapes (Fig. 1): 1) a large scale circular depression about 110 m deep and 700 m in diameter interpreted as a giant pockmark; 2) typical small scale circular depressions, referred to as pockmarks (Hovland and Judd, 1988), which reveal different stages of development within disturbed sediments; 3) more atypical irregular structures on the seafloor, with a great variability in morphology, size (100–400 m in diameter) and acoustic characteristics. The distribution of