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A predictive numerical model for potential mapping of the gas hydrate stability zone in the Gulf of Cadiz

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ABSTRACT

This paper presents a computational model for mapping the regional 3D distribution in which seafloor gas hydrates would be stable, that is carried out in a Geographical Information System (GIS) environment. The construction of the model is comprised of three primary steps, namely: (1) the construction of surfaces for the various variables based on available 3D data (seafloor temperature, geothermal gradient and depth-pressure); (2) the calculation of the gas function equilibrium functions for the various hydrocarbon compositions reported from hydrate and sediment samples; and (3) the calculation of the thickness of the hydrate stability zone. The solution is based on a transcendental function, which is solved iteratively in a GIS environment.

The model has been applied in the northernmost continental slope of the Gulf of Cadiz, an area where an abundant supply for hydrate formation, such as extensive hydrocarbon seeps, diapirs and fault structures, is combined with deep undercurrents and a complex seafloor morphology. In the Gulf of Cadiz, the model depicts the distribution of the base of the gas hydrate stability zone for both biogenic and thermogenic gas compositions, and explains the geometry and distribution of geological structures derived from gas venting in the Tasyo Field (Gulf of Cadiz) and the generation of BSR levels on the upper continental slope.

1. Introduction

Gas hydrates are crystalline solids formed from water and hydrocarbon gases under low temperature and high pressure conditions. They are common world-wide in sediments of continental margins at water depths exceeding 300 m. Although controversial, an indirect seismic indicator of the base of the gas hydrate stability zone (GHSZ) is the bottom simulating reflector (BSR) (Miller et al., 1991), which has a high amplitude and reverse polarity, and is located below a seismic “blanking” facies (Andreassen et al., 1995). The importance of evaluating the hydrate stability field on seafloors lies in the fact that the massive dissociation of hydrates generates major slumps and pockmarks inducing geological risks (Campbell, 1991; Bagirov and Lerche, 1998; Bouriak et al., 2000).

A large number of pockmark-like structures (Baraza and Ercilla, 1996; Somoza et al., 2000, 2003; León et al., 2001, 2006), mud volcanoes bearing gas hydrates (Ivanov et al., 2000; Somoza et al., 2000, 2003; Standnitskaia et al., 2001; Mazurenko et al., 2002), and authigenic carbonate crusts and slabs have been reported along the continental slope (Díaz-del-Río et al., 2003; Magalhães et al., 2004; Mata et al., 2005) and have revealed the intense activity of hydrocarbon seeps in the Gulf of Cadiz on both the Iberian and African margins (Ivanov et al., 2000; Somoza et al., 2000; Gardner, 2001). These hydrocarbon seepage structures are especially frequent in an area named the Tasyo Field (Somoza et al., 2003), which is warmed by the Mediterranean outflow water (MOW). BSR levels have also been detected below the upper continental slope (Somoza et al., 2000; Casas et al., 2003; Depreiter et al., 2005).

Several quantitative models can be found in the literature for calculating the hydrate stability field in the seafloor. They calculate the theoretical hydrate stability field from equations deduced from

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its composition and infer their results from physical characteristics obtained from geophysical surveys. One of these types of models, transient models, are based on the conservation of energy (Sloan, 1998; Mienert et al., 2001, 2005; Sultan et al., 2004). Transient models are often conceptually simpler and easier to model the GHSZ 3D occurrence below seafloor as the only equation that they need to solve is that of energy conservation in transient regime. They consider the GHSZ as a function of temperature and pressure, and some of them take into account changes in oceanographic conditions that show rises and falls in the GHSZ related to changes in sea level or bottom water temperature (e.g. Vogt and Jung, 2002; Sultan et al., 2004; Mienert et al., 2005).

The regional and wide-extend 3D prospecting of the GHSZ, by the above models and methodologies, entails the difficulty of the punctual solving the GHSZ thickness and infer the results over a wide-extend area. The use of gridded datasets of the physical parameters controlling the formation of gas hydrate is a useful solution for the GHSZ 3D prospecting in several continental margins; Europe (Miles, 1995), India where there is applied an implementation of a C-program (Rao, 1999), and China Sea (Wang et al., 2006). Nevertheless, incorporation of new parameter for the system, spatial variability of parameters, actualization of new data in real time, simulation of conditions, and assessment of the uncertainty of the model and propagation error of the parameters due to algebra processes of the gridded dataset, entails an added difficulty not easy solution. This paper proposes a methodology inside a GIS environment that provides a useful solution to the difficulties above mentioned. Proposed model presents an added value to the geographical application of transient models of the hydrate stability field, managing of 3D dynamic variables such as seafloor temperature and the geothermal gradient, and introducing the gas hydrocarbon composition in the model as a boundary of the hydrate nucleation in the sub-seafloor. These parameters can be especially important in controlling the distribution of hydrates in areas with variable seawater temperatures caused by deep water undercurrents, such as the loop current of the Gulf of Mexico (Milkov and Sassen, 2001), the Mediterranean outflow undercurrent in the Gulf of Cadiz (Gardner et al., 2001) and the Congo continental slope (Sultan et al., 2004). Furthermore, the spatial variation in the sub-seafloor temperature gradient is a key control of the thickness of the GHSZ, especially in areas with anomalous heat flows related to focused fluid venting such as mud volcanoes or carbonate mounds. In addition, GIS technology allows large 3D data sets to be managed by a logical and mathematical function for solving geographical problems.

This paper presents a predictive numerical model for regional mapping of the thickness of the GHSZ. The principal contribution of this model are: (a) the understanding of the hydrocarbon gas composition as a mathematical function and the variables that control the hydrate nucleation as inferred surfaces for the estimation of the GHSZ 3D thickness; (b) the solution of the GHSZ 3D thickness based on a transcendental function, which is solved iteratively in a GIS environment; and (c) implementation of the uncertainty assessment and propagation error in the work processes of the model. The 3D geographical solution of the GHSZ establishes a GIS methodology for the 3D spatial inference of hydrates by incorporating real data such as bottom seawater temperatures, swath bathymetry, geothermal gradient values and hydrocarbon composition.

Furthermore, to validate this model, an area of the Gulf of Cadiz (Fig. 1) was selected as a case study. The Gulf of Cadiz is an area with a complex regime of cold and warm underwater currents, fluid flow and thermal anomalies, which control the hydrate stability field. The model explains the distributions and geometry of several geological structures related to gas venting in the Gulf of Cadiz and the presence of BSR levels on the upper continental slope of the Gulf of Cadiz. It is also applicable to other, simpler areas such as passive continental margins.

2. Regional setting

The Gulf of Cadiz is the western approach to the Strait of Gibraltar, where the interchange of Atlantic and Mediterranean waters takes place (Lacombe and Lizeray, 1959). Here the Mediterranean outflow water (MOW), ranging from 12.5 °C to 14 °C, flows below the North Atlantic surficial water (NASW) warming the seafloor in the process (Ochoa and Bray, 1991). The circulation pattern of the MOW is very complex: the Coriolis effect pushes it to the NW on the upper slope and the MOW becomes separated into several branches that move along submarine canyons and channels of the middle and upper continental slope (Hernández-Molina et al., 2003). At 900–1000 m depth, the MOW rises off the bottom and moves toward Cape San Vicente, intercalated between the North Atlantic deep water (NADW), ranging from 3 °C to 8 °C, and the North Atlantic central water (NACW), ranging from 12 °C to 16 °C (Ochoa and Bray, 1991) (Fig. 1).

Geologically, the Gulf of Cadiz is located at the westward front of the Betic–Rifian Arc, in the easternmost sector of the Azores–Gibraltar segment of the Africa/Eurasia collisional plate boundary (Dewey et al., 1989) (Fig. 1). It has a complex geological history and has undergone several episodes of rifting, compression and strike-slip motion since the Triassic (Maldonado et al., 1999). In late Tortonian times (11.2–7.1 Ma), westward migration of the Alboran domain associated with the formation of the Betic–Rifian Arc forced the emplacement of a large sedimentary body in the Gulf of Cadiz (e.g. Bonnin et al., 1975). During the final stages of accretion of the Betic–Rifian Arc and the emplacement of thrusting units, gravitational sliding of mobile shale and salt stocks formed a giant complex of mass-wasting deposits, generally known as the Guadalquivir allochthonous unit (GAU) (Medialdea et al., 2004), which reached as far west as the Horseshoe and Seine abyssal plains (Fig. 1). This feature appears in seismic sections as a chaotic, highly diffractive body with high amplitude reflections, consisting of a mixture of Triassic, Cretaceous, Paleogene and Neogene sedimentary units overlying the Palaeozoic basement (Maldonado et al., 1999). The GAU is responsible for diapirism of huge volumes of mud and salt of Triassic units and under-compacted Early–Middle Miocene plastic marls (Maldonado et al., 1999; Medialdea et al., 2004).

Throughout this area, widespread venting of hydrocarbon-rich fluid and mud diapirism are observed as numerous mud volcanoes (e.g. Gardner, 2001; Ivanov et al., 2000; Somoza et al., 2002; Van Rensbergen et al., 2005), carbonate mounds and ridges (Díaz-del-Río et al., 2003), and pockmarks (Baraza and Ercilla, 1996) (Figs. 1 and 2). These are related to the lateral compression from the Africa–Eurasia convergence, which promotes migration of fluid to the surface. In the NE sector of the Gulf of Cadiz, several NE–SW oriented diapiric mud ridges occur, topped by carbonate chimneys and crusts (Díaz-del-Río et al., 2003; Somoza et al., 2003; Fernández-Puga, 2004). Gas hydrates have been sampled in mud volcanoes (Mazurenko et al., 2002; Pinheiro et al., 2003) and have been detected geophysically as BSR-like reflectors (Casas et al., 2003; Depreiter et al., 2005) (Fig. 1). Hydrates and hydrocarbon gases sampled from mud volcano sediments include both biogenic and thermogenic components (Blinova and Stadnitskaia, 2001; Mazurenko et al., 2003; Stadniskaia et al., 2006).

3. Predictive model of the gas hydrate stability zone

3.1. Proposed model

Natural gases in marine sediments result from thermogenic or biogenic formation within the seabed soil (Davie and Buffett, 2003).