3D Integrative gas hydrates geological modeling. Hydrate Ridge (Cascadia accretionary prism, Oregon)

Modelización geológica 3D de hidratos de gas. Hydrate Ridge (prisma de acreción de Cascadia, Oregon)

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Abstract: *Predicting the spatial distribution of gas hydrates is challenging due to the complex geological and geochemical processes controlling their formation and stabilization. We present a research project aiming to improve the understanding of how these factors interact to control gas hydrates by using three-dimensional numerical models. The main objective is to forecast the 3D distribution of gas hydrates and their evolution throughout geological time by applying a workflow including two phases. Phase I focuses on building 3D geological models that capture the structural and sedimentary heterogeneity of the subsurface. In Phase II, these models are used as inputs to construct petroleum systems models that simulate pressure-temperature evolution and gas hydrate distribution and concentration. The models are built in Petrel E&P and PetroMod® (Schlumberger). We selected the study area of Hydrate Ridge, located in the Cascadia accretionary complex (offshore Oregon), in which gas hydrates occur. The project will try to answer questions such as: To what extent the sedimentary heterogeneity affects the distribution and stability of gas hydrates, and could control the presence of the bottom-simulating reflector (BSR) and variations in its amplitude? How long does it take for gas hydrates to form and dissociate throughout the geological history of a basin?*

Keywords: *Gas hydrates, 3D facies modeling, petroleum systems modeling, gas hydrate stability zone, sedimentary heterogeneity*

Resumen: Predecir la distribución de hidratos de gas es complejo debido a los múltiples procesos y factores geológicos y geoquímicos que controlan su formación. Presentamos un proyecto de investigación que tiene por objetivo comprender mejor la interacción de dichos factores mediante el uso de modelos numéricos 3D. Así, el objetivo principal es predecir la distribución 3D de hidratos de gas y su evolución a lo largo del tiempo geológico mediante la aplicación de un flujo de trabajo que incluye dos fases. La Fase I se centra en la construcción de modelos geológicos 3D que reproduzcan la estructura y capturen la heterogeneidad sedimentaria del subsuelo. Durante la Fase II, los modelos geológicos son usados para la construcción de modelos de sistemas petroleros que permitan simular los campos de presión y temperatura así como la distribución y concentración de hidratos de gas resultante. Estos modelos son construidos usando Petrel E&P y PetroMod® (Schlumberger). Como caso de estudio se ha seleccionado la región de Hydrate Ridge, situada en el prisma de acreción de Cascadia (costa afuera de Oregon), donde hay acumulaciones de de hidratos de gas. La consecución de los objetivos permitirá dar respuesta a cuestiones como: ¿hasta qué punto la heterogeneidad sedimentaria afecta a la distribución y estabilidad de los hidratos de gas, a la presencia del *bottom-simulating reflector* (BSR) y variaciones en su amplitud? ¿Cuánto tiempo geológico se requiere para la formación y disociación de los hidratos de gas?

Palabras clave: Hidratos de gas, modelización 3D de facies, modelización de sistemas petroleros, zona de estabilidad de los hidratos de gas, heterogeneidad sedimentaria.

INTRODUCTION

Understanding gas hydrate accumulations and their spatial distribution is an important topic from academic and industrial perspectives. Recently, multiple efforts have investigated the relationship between dissociation of gas hydrates and climate change. Part of the current global warming is related to gas hydrate dissociation and methane release, a strong greenhouse gas. Gas hydrates are also associated with seafloor instability, a potential marine geohazard. In addition, significant progress has been recently made on the technologies for exploration and production of gas hydrates. Although still in its infancy and not commercial, methane hydrates could contribute to natural gas supply in the future. Using natural gas as a source of energy provides a cleaner option than other fossil fuels (such as coal or liquid *hydrocarbons) and is an attractive option to limit greenhouse emissions during the transition to renewable energies in the coming decades. Gas hydrates could also be used in other industrial applications, for example, for Carbon Capture and Sequestration (CCS), which will be required to reduce CO_2 atmospheric concentration to meet the 2 degrees maximum warning as established in the Paris Agreement.*

In gas hydrate crystals, small gas guest molecules are encaged within water cavities. These crystals are formed and are stable at high pressure and low temperature; and require enough gas supply (from both thermogenic and/or biogenic origins) to be generated. Gas hydrates occur mostly in offshore sediments in the continental margin and in onshore permafrost regions. Other factors, such as sediment type (lithology, grain size, texture, etc.), petrophysical properties (porosity, permeability), geographic location, salinity of the interstitial water and the presence of other gases, also control the formation, stability and distribution of gas hydrates.

The difficulty in predicting the spatial distribution of gas hydrates mainly lies in the complex geological and geochemical processes that control their formation and stabilization. In the project presented herein, we aim to better understand the interaction of these factors by using three-dimensional numerical models of temperature and pressure fields. The main objective of the project is to build 3D models capturing lithology, porosity and permeability; and, subsequently, use these as inputs to build basin and petroleum systems models to ultimately forecast the 3D distribution of gas hydrates and to assess how they evolve throughout geological time. To develop the project, we selected the study area of Hydrate Ridge, where the presence of gas hydrates was demonstrated.

METHODOLOGY

The workflow followed in this project is twofold (Fig. 1):

a) Data conditioning, data analysis, and 3D geological modeling. This step includes the analysis and interpretation of seismic and well data covering the area of interest, the construction of detailed 3D geological models reproducing the large-scale stratigraphic and structural framework, and finally simulating detailed sediment facies and petrophysical property distributions. These models will be built using Petrel E&P (by Schlumberger), and integrate seismic stratigraphy and seismic attribute analysis.

b) Pressure-Temperature simulation, scenario testing and output analysis. In this phase, we will model the gas hydrate system in 3D and its evolution over geological time using the 3D geological models created in Phase I as input in PetroMod® (Schlumberger) to reproduce the processes that control hydrate formation.

Until now, only a few recent contributions using basin and petroleum systems modeling tools to predict gas hydrate occurrence have been published (e.g. Burwicz et al., 2017; Kroeger et al., 2017); and only the work by Fujii et al. (2014) has included facies changes to constrain the modeling of gas hydrate distribution. Building and analyzing the predictions from the models will allow us to address the following questions:

a) To what extent geological heterogeneity (i.e., faults, facies, geometry of sedimentary bodies, porosity and permeability contrasts, etc.) controls the distribution and stability of gas hydrates? And what is the amount of heterogeneity represented in the geological model required to accurately predict gas hydrate distribution?

b) How long does it take for gas hydrates to form and dissociate throughout the geological history of a basin?

c) Under which settings and conditions (e.g., bathymetry, bottom water temperature, salinity, geothermal gradient) could marine platforms at medium latitudes such as in Spain (e.g. Mediterranean Sea or Atlantic Ocean) host gas hydrates?

d) How source rock kinetics influence gas hydrates generation and concentration?

e) Could basin modeling techniques be used to forecast hazardous submarine slides (e.g., pore pressure modeling)?

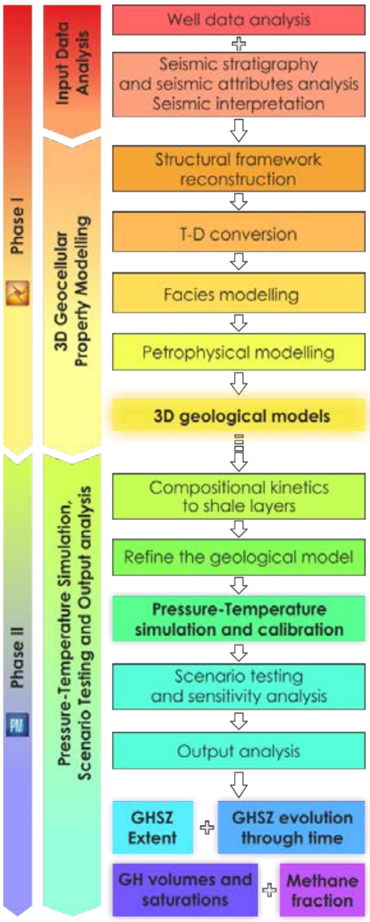

FIGURE 1. Proposed workflow for the 3D integrative geological modeling of gas hydrates. Phase I includes the data analysis and interpretation followed by the construction of the 3D high-resolution geological model. Phase II aims at modeling the gas hydrate distribution. GH stands for gas hydrates and GHSZ for gas hydrate stability zone.

THE HYDRATE RIDGE CASE STUDY

Hydrate Ridge is located 85 km offshore the Oregon state (USA), at water depths between 600 m and 1500 m. The ridge is approximately 30 km long and 15 km wide, and is part of the Cascadia accretionary complex, which formed in response to the oblique subduction of Juan de Fuca plate beneath the North America plate (Tréhu et al., 2003) (Fig. 2A).

Hydrate Ridge is a structurally and stratigraphically complex region. Seismic data show a shallower seismic part corresponding to sediments that were folded and uplifted, and which unconformably overly deeper lower frequency incoherent reflectors, interpreted as highly deformed accretionary complex material (Tréhu et al., 2003). In the slope basin located to the east of the ridge, dipping and continuous seismic reflectors, which alternate with seismic facies without internal reflectivity, are found. The main lithologies described for the slope sediments are: stratified clay and clayey silt interbedded with fine- and coarse-grained sand, glauconite sand, diatom-bearing silty clay, ash-rich sand, volcanic ash, and pebble-sized mudclasts in deformed clay matrix, and authigenic carbonate. These deposits are early to late Pliocene to Holocene (<0.8 Ma) in age.

A bottom simulating reflector (BSR) identified in almost the entire area of interest at depths between 68 and 200 mbsf (meters below sea-floor) suggest the occurrence of gas hydrates (MacKay et al., 1994; Tréhu et al., 2003; Bangs et al., 2005, 2011; Crutchley et al., 2015). This was confirmed by sediment samples acquired during Ocean Drilling Program (ODP) Leg 146 (Kastner et al., 1995) and Leg 204 (Tréhu et al., 2003). A second, weaker BSR, which is 20 – 40 m below the primary BSR mainly in the western flank of the southern ridge, was interpreted as remnants of a BSR under past P-T conditions (Bangs et al., 2005). The gas in the hydrates is from both biogenic and thermogenic origins, and variable concentrations of gas hydrates were estimated throughout the ridge (Tréhu et al., 2004). Highly hydrate saturated zones with contents up to 30 – 40% of the pore space (20 – 26% of total volume) occur in the upper tens of meters below the seafloor near the southern summit (SHR in Fig. 2B) have been associated with gas vents (Bangs et al., 2011; Crutchley et al., 2015). Above the BSR at the northern summit, at least 10% of pore space is occupied by gas hydrates (Kastner et al., 1995). In the rest of the zone, gas hydrate concentration is generally <2%. Abundant massive hydrates at the seafloor were discovered near the southern ridge summit (Tréhu et al., 2004), and a 50-m-high carbonate structure on the seafloor (i.e. the Pinnacle) located about 700 m southwest of the southern summit has been associated with focused methane seepage (Crutchley et al., 2015).

The dataset used in this project comprises two high-resolution 3-D seismic cubes covering an area of 4 km by 12 km

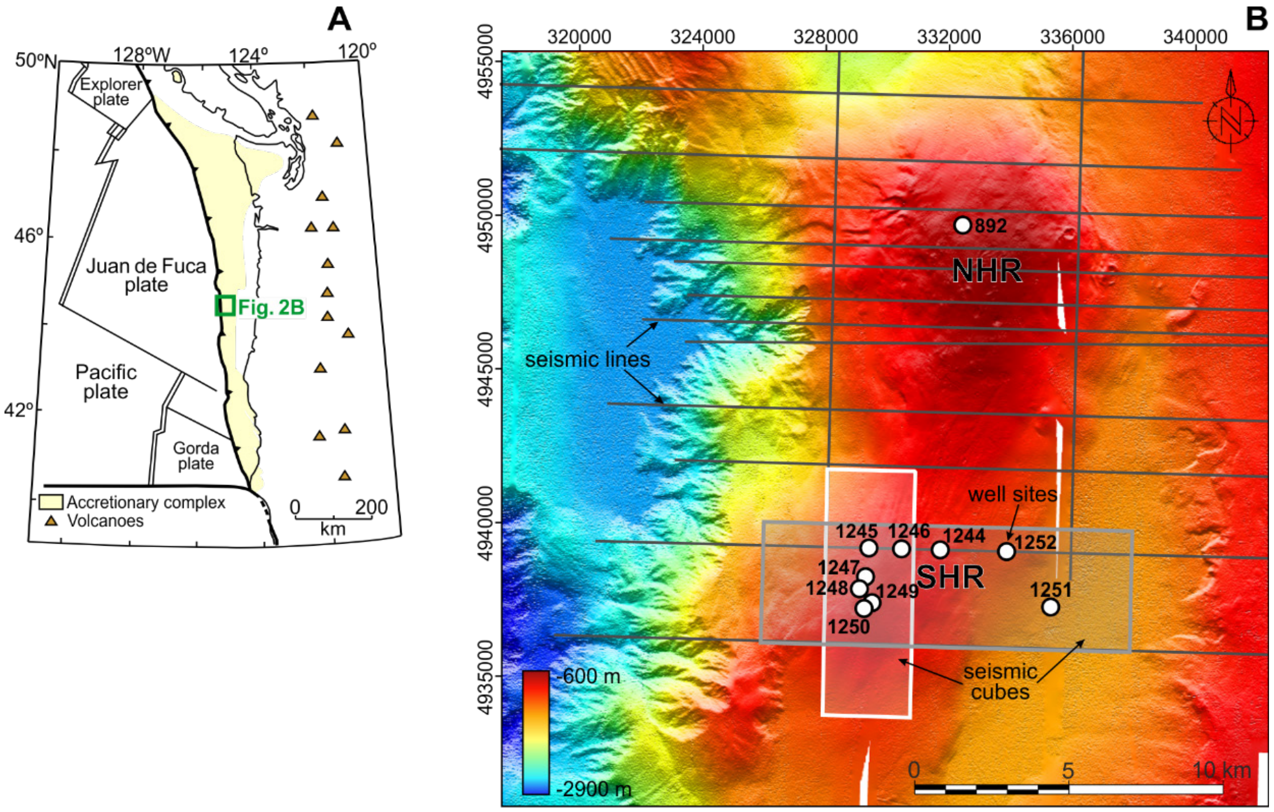

FIGURE 2. A) Tectonic map of the Cascadia subduction zone, where Hydrate Ridge is located. The extent of the accretionary complex is indicated. The green box shows the area of Fig. 2B. Modified from Tréhu *et al.* (2003). B) Bathymetric map along Hydrate Ridge with the location of the dataset used in the project (10 wells, 2 seismic cubes and 14 seismic lines) (coordinates are in UTM84, Zone 10N). NHR and SHR stands for North Hydrate Ridge and South Hydrate Ridge, respectively.

and 2.8 km by 8 km, fourteen 2-D seismic lines (with a total length of 327 km), and data from ten ODP Expedition well sites (sites 892 and 1244 to 1252). Through the 3D reconstruction and modeling of the structure and the sedimentary heterogeneity in Hydrate Ridge and in the slope basin to the east, and the subsequent application of the petroleum system modeling, answers to the following specific questions will be sought:

a) When gas hydrates formed and how many gas hydrate systems exist?

b) Is the change in the BSR amplitude and in the distribution, texture and chemistry of the hydrate recorded in the Hydrate Ridge with regards the slope basin to the east associated with sedimentary facies changes and/or structural controls?

c) Why is there less free gas beneath the BSR at southern Hydrate Ridge than beneath northern Hydrate Ridge (cf. Tréhu et al., 2003)?

d) How did the massive hydrate near the seafloor in the summit formed?

e) Did gas hydrates partially dissociate in Hydrate Ridge as consequence of bottom water temperature increase since the Last Glacial Maximum? If so, did the gas migrate back into the gas hydrate stability zone to reform hydrates, as suggested by Bangs et al. (2005), or could the gas be released to the ocean?

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