Proceedings of the 7th International Conference on Gas Hydrates (ICGH 2011), Edinburgh, Scotland, United Kingdom, July 17-21, 2011.

3-D NUMERICAL MODELING OF METHANE HYDRATE DEPOSITS

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ABSTRACT

Within the German gas hydrate initiative SUGAR, we have developed a new tool for predicting the formation of sub-seafloor gas hydrate deposits. For this purpose, a new 2D/3D module simulating the biogenic generation of methane from organic material and the formation of gas hydrates has been added to the petroleum systems modeling software package PetroMod®. Typically, PetroMod® simulates the thermogenic generation of multiple hydrocarbon components including oil and gas, their migration through geological strata, and finally predicts the oil and gas accumulation in suitable reservoir formations. We have extended PetroMod® to simulate gas hydrate accumulations in marine and permafrost environments by the implementation of algorithms describing (1) the physical, thermodynamic, and kinetic properties of gas hydrates; and (2) a kinetic continuum model for the microbially mediated, low temperature degradation of particulate organic carbon in sediments. Additionally, the temporal and spatial resolutions of PetroMod® were increased in order to simulate processes on time scales of hundreds of years and within decimeters of spatial extension.

As a first test case for validating and improving the abilities of the new hydrate module, the petroleum systems model of the Alaska North Slope developed by IES (currently Shlumberger) and the USGS has been chosen. In this area, gas hydrates have been drilled in several wells, and a field test for hydrate production is planned for 2011/2012. The results of the simulation runs in PetroMod® predicting the thickness of the gas hydrate stability field, the generation and migration of biogenic and thermogenic methane gas, and its accumulation as gas hydrates will be shown during the conference. The predicted distribution of gas hydrates will be discussed in comparison to recent gas hydrate findings in the Alaska North Slope region.

Keywords: gas hydrates, 3D modeling, reaction kinetics, methane generation, Alaska North Slope

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INTRODUCTION

With the basic aim of predicting exploitable gas hydrate deposits and quantifying the global gas hydrate inventory, the main objectives of the SUGAR subproject A4 "Numerical modeling and spatial characterization of gas hydrate deposits" are: i) modeling the spatial and temporal distribution of sub seafloor hydrates; ii) constraining the major control parameters of hydrate formation; and iii) developing a new tool for 3-D prediction of gas hydrate deposits. With this aim, and as a first attempt to train a commercial 3D basin modeling software to calculate the formation of gas hydrate accumulations, additional functionalities simulating the biogenic generation of methane from organic material at low temperatures and the formation of gas hydrates has been added to PetroMod®.

PetroMod® is a software package for the petroleum systems modeling in 1D, 2D and 3D, including the thermogenic generation of oil and gas, and the secondary degradation of oil into gas. A major topic of research and development for PetroMod® is to implement unconventional petroleum systems such as gas hydrates, shale gas, etc. A new tool to predict gas hydrate formation is included in the most recent version of PetroMod® (2011.1), covering the 4 main factors that contribute to the formation of gas hydrates in the petroleum gas hydrate systems: i) gas hydrate pressure-temperature stability conditions; ii) gas sources; iii) gas migration; and iv) suitable host sediment or reservoirs [1].

Much effort has been made to estimate the gas hydrate extraction potential in the Northern Alaska region since 1972 when a drilling, coring and production test was carried out in the Northwest Eileen State-2 well in the Prudhoe Bay Field [2]. In 2008, this lead to a complete assessment of the technically recoverable gas hydrate resources on the North Slope of Alaska by the U.S. Geological Service (USGS), estimating a total of 85.4 trillion cubic feet of methane (under standard temperature-pressure conditions) stored in potentially recoverable gas hydrates. The assessment is based on a total petroleum system study, including the characterization of hydrocarbon source rocks, reservoir rocks, and hydrocarbon traps, which make this area one of the most accurately studied gas hydrate systems.

In order to provide a new instrument for the prediction of gas hydrate accumulations, here we present the new "gas hydrate" tool in PetroMod®. The availability of the full 3D geological model of the Alaska North Slope developed by the IES (currently Schlumberger) and the USGS, as well as recent publications about the gas hydrate distribution in this area provide the necessary means to validate and calibrate the new gas hydrate module.

NEW DEVELOPMENTS IN PETROMOD®

The PetroMod® software package fully integrates seismic, stratigraphic and geological interpretations into multi-dimensional simulations of thermal, fluid-flow and petroleum migration history in sedimentary basins. PetroMod® is primarily used in hydrocarbon exploration, but has also proven to be a valuable tool in research applications.

It can be applied in new exploration areas, where only few data are available, as well as in already explored areas where problems such as source-reservoir correlations, seal efficiencies, and overpressure systems are investigated in order to obtain the most accurate prediction of timing and location of petroleum generation, expulsion and migration processes (Figure 1).

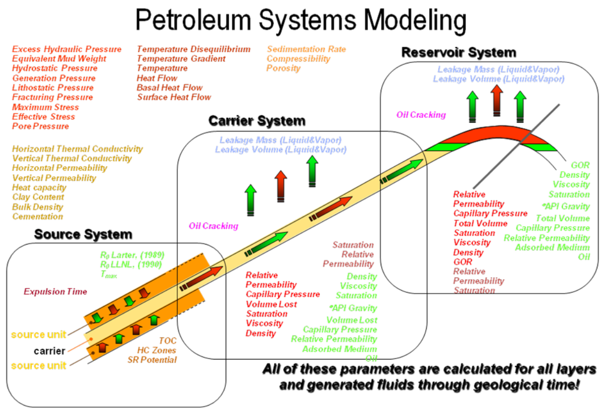

Figure 1. Sketch of the petroleum systems modeling followed in the PetroMod® software package, showing the main parameters calculated for the sediment layers and fluids through time.

PetroMod® includes several methods to simulate fluid migration: Flowpath (buoyancy driven), Darcy flow (overpressure driven), invasion-

percolation (capillary pressure driven), and a hybrid Darcy/flowpath. The whole petroleum migration modeling is fully PVT-controlled with multi-component relationships using flash calculations.
To develop the new gas hydrate tool in PetroMod® the software has been extended with:

- routines for the physical and thermodynamic properties of gas hydrates;
- kinetic formulation for the formation and dissociation of gas hydrates through time;
- kinetic formulation of biogenic methane generation;
- numerical improvements to achieve a higher temporal and spatial resolution.

The physical properties of gas hydrates that are considered include density, thermal conductivity, and heat capacity. The software contains some default values derived from the classical gas hydrate literature (e.g. [3]) (Figure 2). Methane hydrate stability and solubility are calculated with the set of equations provided by Tishchenko [4], which consider pressure, temperature, and salinity of the pore water. At present, the default value of salinity for these calculations is the average seawater salinity (35 ‰). Further developments of the software will include the dissolution and diffusion of chemical species in pore water.

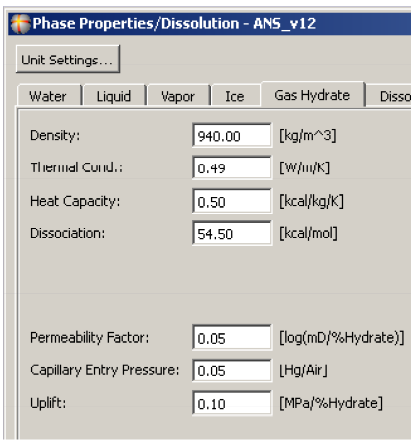

Figure 2. Phase Properties command window in PetroMod® 2011.01.

PetroMod® automatically calculates the formation and dissociation of gas hydrates via the dissolved methane phase. Thus, methane gas first dissolves and then forms hydrate while dissociation follows the opposite path. Consequently, hydrate formation is based in the concentration difference of methane with respect to the gas phase and the thermodynamically stable hydrate phase.
In the new kinetic formulation for the microbial generation of methane from the degradation of organic matter at low temperature, the degradation rate of organic matter by Middelburg [5] was adopted (Equation 1): the organic matter degradation rate (R_{POC}) is a function of the total organic carbon content (TOC) and the alteration time for organic matter since entering the sediment column (age).

$$R_{POC} = 0.16\ (age)^{-0.95}\ TOC \qquad (1)$$

In order to consider the short term processes as well as the high spatial variations that characterize the gas hydrate geological systems, the spatial and temporal resolution in PetroMod® have been refined. Thus, the thickness of a geological layer can be set to a minimum value of 0.1 meters, while the minimum time step between two calculations can be reduced to 100 years (0.0001 Ma).
In order to save computational time, the user can choose the geological formations where gas hydrates will form, as well as the different kinetic reactions that lead to the formation of methane within each sedimentary facies, including the biogenic methane generation through the degradation of organic matter at low temperatures.
The results of the model calculation can be shown as an overlay of the gas hydrate stability (differentiating permafrost and marine conditions) and its evolution over time. The calculated gas hydrate accumulation mass can easily be displayed for each time step either for the entire model volume or for discrete geological layers.

FUTURE WORK: CALIBRATION OF THE NEW GAS HYDRATE TOOL IN THE ALASKA NORTH SLOPE MODEL

Geological Setting

The Alaska North Slope area extends from the National Petroleum Reserve in Alaska (NPRA) on the west through the Arctic National Wildlife Refuge (ANWR) on the East, and from the Brooks Range to the U.S. offshore boundary located 3 miles north of the coastline (Figure 3).
Geologically, the Alaska petroleum province evolved through various tectonic stages: passive

margin, rift, foreland basin, and foreland fold and thrust belt. Rift-related structures and the lower cretaceous unconformity trap the migrated components in the main oil and gas accumulations (green and red areas in Figure 3). In addition, other stratigraphic traps that developed during extensional and compressional tectonic regimes show significant importance of the Jurassic through Cenozoic shelf and turbidite sequences [6].

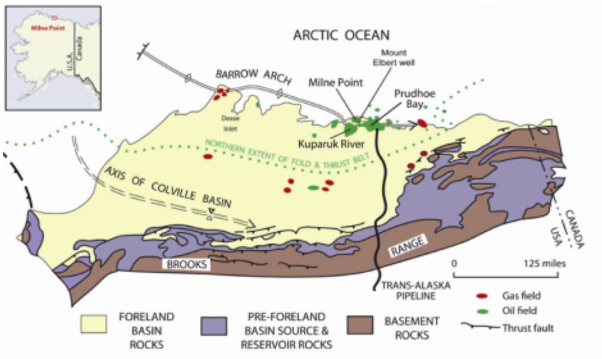

Figure 3. Geological setting of the Alaska North Slope area [7].

All the known and inferred gas hydrates occurrences at the Alaska North Slope are in reservoirs of the Brookian sequence (Cretaceous to Holocene) [1]. Studying the well-log data from more than 400 wells in the North Alaska Slope revealed the existence of two main gas hydrate accumulations: Eileen and Tarn.

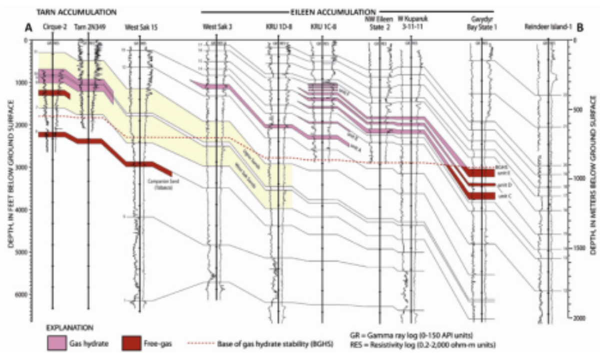

Figure 4. Well-log cross-section showing lateral and vertical extent of the Eileen and Tarn gas hydrate accumulations and the associated underlying free-gas zones in the Prudhoe Bay and Kuparuk River fields.

In the Eileen accumulation, the gas hydrate reservoir consists of six sedimentary units (A to F) composed of fine-grained to very fine-grained sands and coarse silt with minor amounts of interbedded sands, ranging from a depth of 325 m down to the base of the gas hydrate stability field [7] (Figure 4). The Tarn gas hydrate accumulation ranges from a depth of 200 to 450 m.

Gas hydrate stability field

Based on the thermal and pressure data collected at 148 North Slope wells, Collett et al. [1] published a distribution map of the gas hydrate stability zone (Figure 5). Geothermal gradients were derived after high-resolution temperature measurements in 46 wells and the depth of the ice-bearing permafrost sediments in 102 wells, with values ranging from 1.5 to 5.2 ºC/100 m. The values were combined and extrapolated for the entire area.

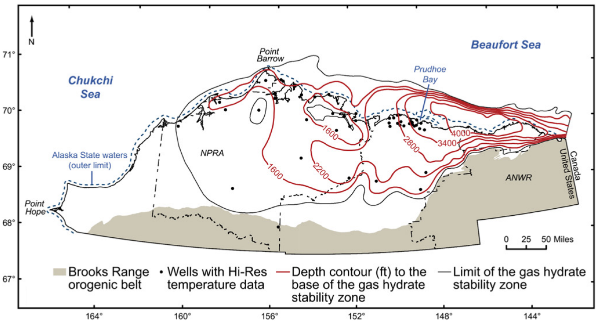

Figure 5. Map of the depth of the base of the gas hydrate stability zone in the Alaska North Slope area [1].

Alaska North Slope model

As a first test case for validation of the new hydrate module in PetroMod®, the recently developed petroleum systems model of the Alaska North Slope has been chosen (Figure 6). The model reconstructs and evaluates the development of the individual petroleum systems, burial history, and thermal evolution, as well as migration, accumulation, and preservation of hydrocarbons [6].

The stratigraphic model contains five hydrocarbon source rock units, namely the Kekiktuk coals, Shublik source rocks, Kingak-K1 source rocks, Gamma Ray Zone, and Hue shales. The dominant oil and gas reservoir units are the Kemik and Kuparuk sandstones and the Sag River and

Ledge/Ivishak formations [6]. In order to build the model, source rock characteristics, such as the distribution of original total organic carbon (TOC) and hydrogen index (HI), were adopted from the literature (e.g. [8]). In order to reduce the complexity of the model, the hydrocarbons were combined afterwards to one oil component and one gas for each source rock.

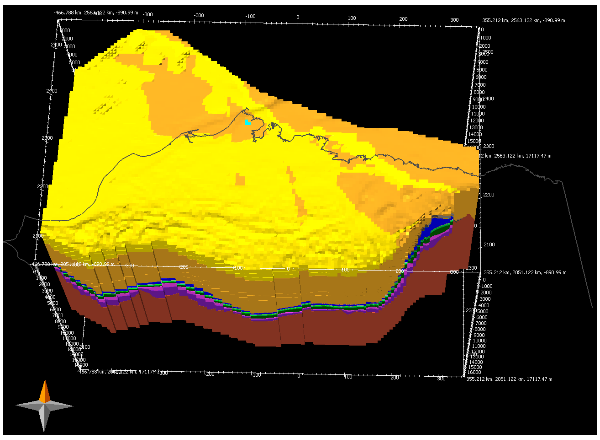

Figure 6. Petroleum system model of the Alaska North Slope implemented in PetroMod®.

Several preliminary model runs for the Alaska North Slope geological model in PetroMod® allowed the calculation of the current gas hydrate stability (Figure 7). This allowed to constrain the physical conditions according to the available thermal information. The resulting map shows that gas hydrates are stable almost in the entire Alaska North Slope area and a distinction between hydrate occurrences under marine and permafrost conditions is possible.

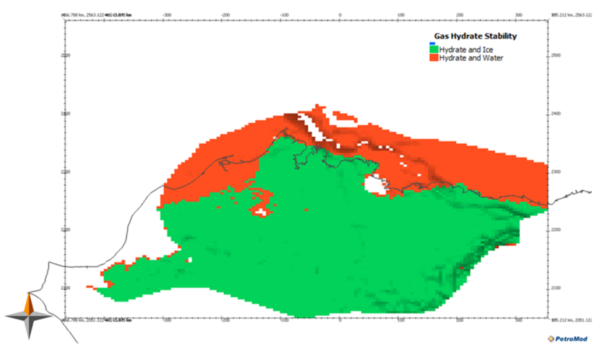

Figure 7. Gas hydrate stability zones for marine and permafrost conditions at the Alaska North Slope model, calculated with PetroMod®

CONCLUSIONS and ONGOING WORK

A new tool to predict the basin-wide formation and distribution of gas hydrates over geological times has been developed and implemented into the petroleum systems modeling software PetroMod®. So far, the module includes the physical, thermodynamic and kinetic properties of gas hydrates as well as the biogenic generation of methane at low temperatures. Additionally, the spatial and temporal resolution of the numerical grid has been increased up to 0.1 m and 100 years.

The new gas hydrate tool allows the study of the evolution of the gas hydrate stability field over time, the generation and migration of biogenic and thermogenic methane, and its accumulation in high permeability deposits.

The application of the new "gas hydrate" module of PetroMod® in the Alaska North Slope area shows that gas hydrates are actually stable in almost the entire region. Several new results, such as the calculated gas hydrate distribution and the main gas migration pathways will be presented during the conference. The evolution of the permafrost zone and the gas hydrates stability zone during the geological history, as well as their influence on trapping the hydrocarbons since the Pilocene [1] will also be discussed.

ACKNOWLEDGEMENTS

This work was conducted within the SUGAR subproject A4 funded by the German BMBF Geothechnologien programme (grant no. 03G0687A).

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