Hydrothermal Karst Process-Like Modelling of Palaeozoic Complex Mound Reservoir from Kazakhstan*

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Search and Discovery Article #50588 (2012)
Posted April 9, 2012

*Adapted from extended abstract prepared for oral presentation at AAPG Annual Convention and Exhibition, Long Beach, California, April 22-25, 2012 AAPG©2012

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Abstract

Carbonate mounds are reported throughout the stratigraphic scale from the Proterozoic to the Present. They developed on continental margins or intra-platform environments, in water depths ranging from 10 to 1000 m, and they represent targets for hydrocarbon exploration. In Kazakhstan (Figure 1), recent discoveries of giant hydrocarbon accumulations have generated renewed interest in these distinctive carbonate deposits (Grigor'yeva, 1992; O'Hearn et al., 2003; Lapointe and Glass, 2010). An understanding of ancient (Lapointe et al., 1999) and recent carbonate mounds systems provides a tool to appraise potential hydrocarbon-bearing subsurface mound carbonates as well as provides a complement to classic outcrops studies (De Mol et al., 2007; Foubert and Henriet, 2009; Foubert et al., 2008).

The comparative analysis of mound evolution – focusing on early to late diagenetic processes, products and patterns – in the recent and ancient deposits provides new insights into reservoir porosity and permeability. In these carbonate reservoirs, heterogeneity is primarily driven by diagenetic patterns and karst processes are one of the most critical diagenetic phases for carbonate reservoir development.

Objectives

Static and dynamic models are used to assess the reservoir potential. These models are populated by integrating data from core, well log and field analogues. The primary control on reservoir quality is related to hydrothermal processes that follow faults and synsedimentary fracture corridors developed during deposition, resulting in a strong vertical control on enhanced porosity and permeability. Depositional facies provide minor contributions to the distribution of porosity and permeability. These concepts are integrated into a geologic model by applying a dedicated karst modeling tool, developed in-house by TOTAL, to model these hydrothermal karst processes using nested stochastic simulations.

Pre-Caspian Basin Mound Complex

Carbonate mud mounds have been extensively studied in the past (Bridges et al., 1995; Vennin et al., 2007; Riding, 2000; Stemmerik, 2003).

A mound is not a unique container but an envelope resulting from the coalescence or aggradation of multiple smaller mounds.

The Lower Permian Mound Complex of Kazakhstan exhibits vertical and lateral heterogeneity due to the amalgamation and coalescence of carbonate bioherms (boundstones) and their related deposits. These carbonate bioherms commonly form dome-shaped bodies, ranging from 20-60 m high and extend laterally from about 500 m to 1 km. They are commonly capped by relatively shallow, skeletal grain-supported deposits and draped by deeper bioclastic sediments.

The model proposed by E. Vennin (1997; 2002; 2005) for the Tratau Hill Mound (Russia) (Figure 2) provides a scenario for complex mound development using seismic interpretation, core data, and analogues.

1. The sedimentological model refers to the seismic interpretation, hard data from cores and the above discussed analogues. The model considers a general mound system, made of scale, with interbedded of-mound or intermound or draping over the mound of crinoidal pack-grain (packstone) facies.
2. Faults and neptunian dykes may only be present either at the periphery of the buildups or developed inside with possible rejuvenation during late tectonic phases.
3. These preferred pathways allow hydrothermal and/or TSR fluids to flow along fault planes and preexisting discontinuities, such as bedding (mound envelopes), facies changes, stylolites, fractures, faults, meteoric karst-related pores to cavities.

Synsedimentary fissures and fractures, seen as neptunian dykes (Figure 2 - Van Laer, 1983; Vachard et al., 1987; Vennin, 2002), are distinctive sedimentary features of the Tratau Mound. The tectonically induced evolution of fractures reveals two-stage timing of dyke formation and stages of filling identified from the biostratigraphic data. These works facilitated the process identification from Lower Permian Mound from Kazakhstan.

Circulation of fluids of different chemical composition and temperature leads to mixing water corrosion (Bogli, 1964; Wigley and Plummer, 1976), with the fluids following the faults, fractures and the sedimentological discontinuities. The mixing is also controlled by the convection in the system (free or forced convection). The fluids are either exotic fluids coming in the platform from the basin deposits, fluids coming through faults from the Devonian platform or fluids related to hydrocarbon migration.

Karst Modeling Tool

Mapping of the actual reservoir remains critical for predicting the best distribution of porosity and permeability and the prognosis of future production well locations, particularly for horizontal or highly deviated wells. Jacta software, used for that purpose, is a toolbox allowing the quantification of subsurface uncertainties. Based on nested stochastic simulations, it integrates all uncertainties from structural to reservoir properties and quantifies their impact on final volumes. The Karst modeling module developed in-house is dedicated to integrate complex karstic features in the reservoir model. Based on sedimentological knowledge and stochastic algorithms, it allows the construction of karst conduits or chambers from various origins: meteoric, mixing or hydrothermal.

This modeling approach leads to horizontally driven and vertically driven cave developments controlled by all the existing heterogeneities and particularly those related to the tectonic events. The resulting complex reservoir is unique, and its modeling is achieved through these specific geomodeling tools that were internally developed within TOTAL to cope with the karst distribution and to take into account the geological uncertainty associated to that model (Lapointe and Massonnat, 2008; Labourdette and Lapointe, 2012).

Hydrothermal karst morphology is related to predominant vertical fluids flowing through discrete vertical flow paths and moving horizontally away along discontinuities or high permeability layers (Figure 3). The karstic development is then modeled as vertical and horizontal conduits and more diffuse karst zones.

The modeling is achieved through different steps (Figure 4):

1. Definition of the karst zone around fault network.
2. Removal of low-permeable zones restricting fluid flow.
3. Vertical and horizontal conduit simulation and associated petrophysical properties.
4. Diffuse karst zone creation.
5. Matrix petrophysical properties co-simulated with the distance from the fault network.

Conduit diameters for the karst conduits and vug size for the diffuse karst are provided as inputs to the modeling. Conduit seeds are stochastically distributed at the base of and along the fault network. The conduit development is driven by the matrix permeability, and the vertical conduits are never developed at the same location. Horizontal branching conduits are controlled by a matrix permeability thresholding. Diffuse karst is then propagated around the conduits.

Conclusions

This 3-D approach leads to horizontally driven and vertically driven conduits, cave and diffuse karst developments, controlled by all the existing heterogeneities and particularly those related to the fracturing events (synsedimentary and/or tectonic in origin). The resulting complex reservoir is unique, and its modeling is achieved through the specific Karst geomodeling tool that had to be internally developed within TOTAL to cope with the karst distribution and to take into account the geological uncertainty associated to that model.

The overall results are a karst distribution following geological concepts. The Jacta environment allows the multiple realizations that bracket the reservoir uncertainties, particularly those related to the karst development.

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Figure 1. Location of North Caspian Basin.

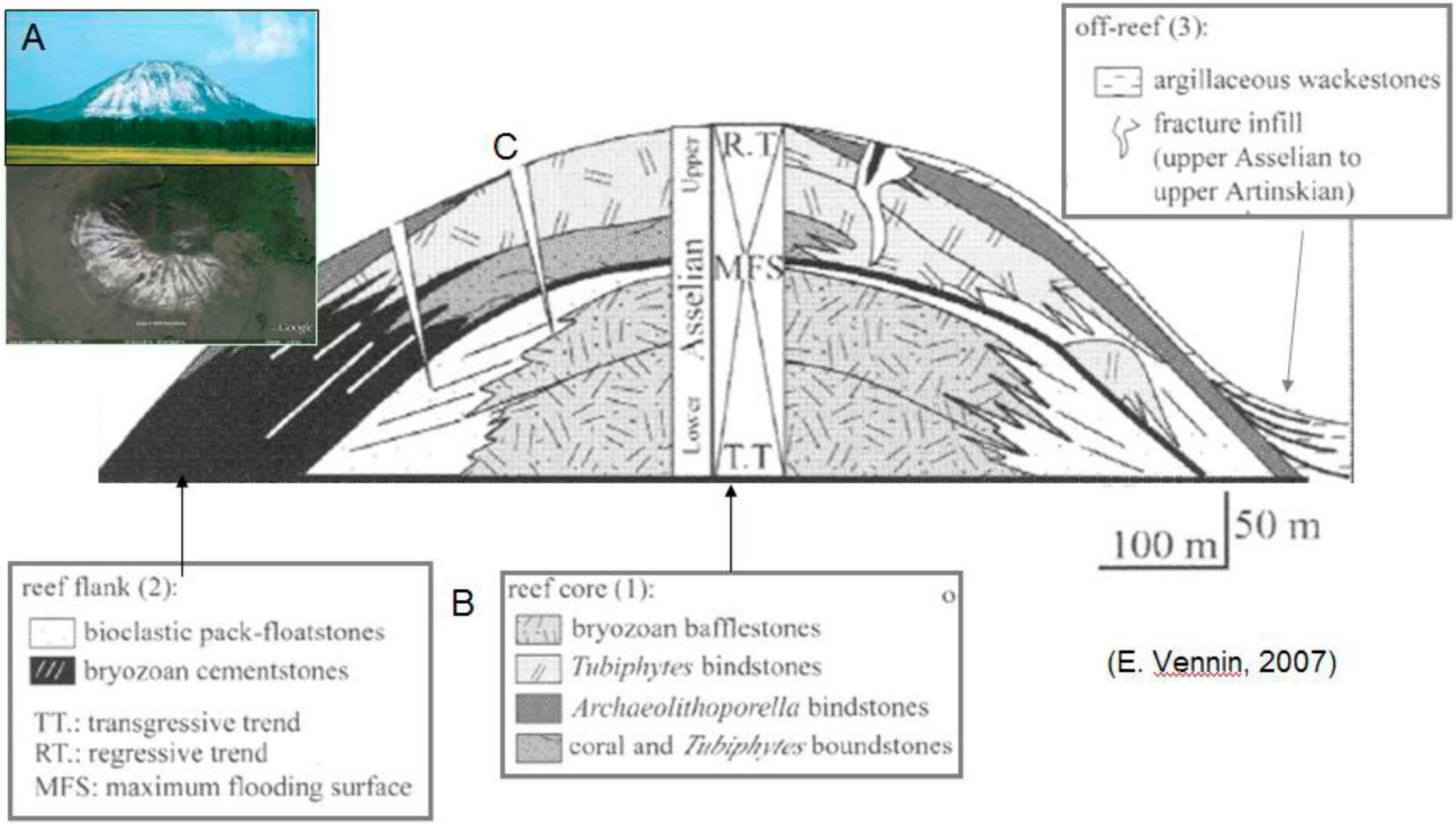

Figure 2. Tratau Hill, Lower Permian mound complex, Sterlitamak area, Russia (CIS). A. General view. B. Stratigraphic analyses. C. Distribution of the neptunian dykes through time with mound complex evolution.

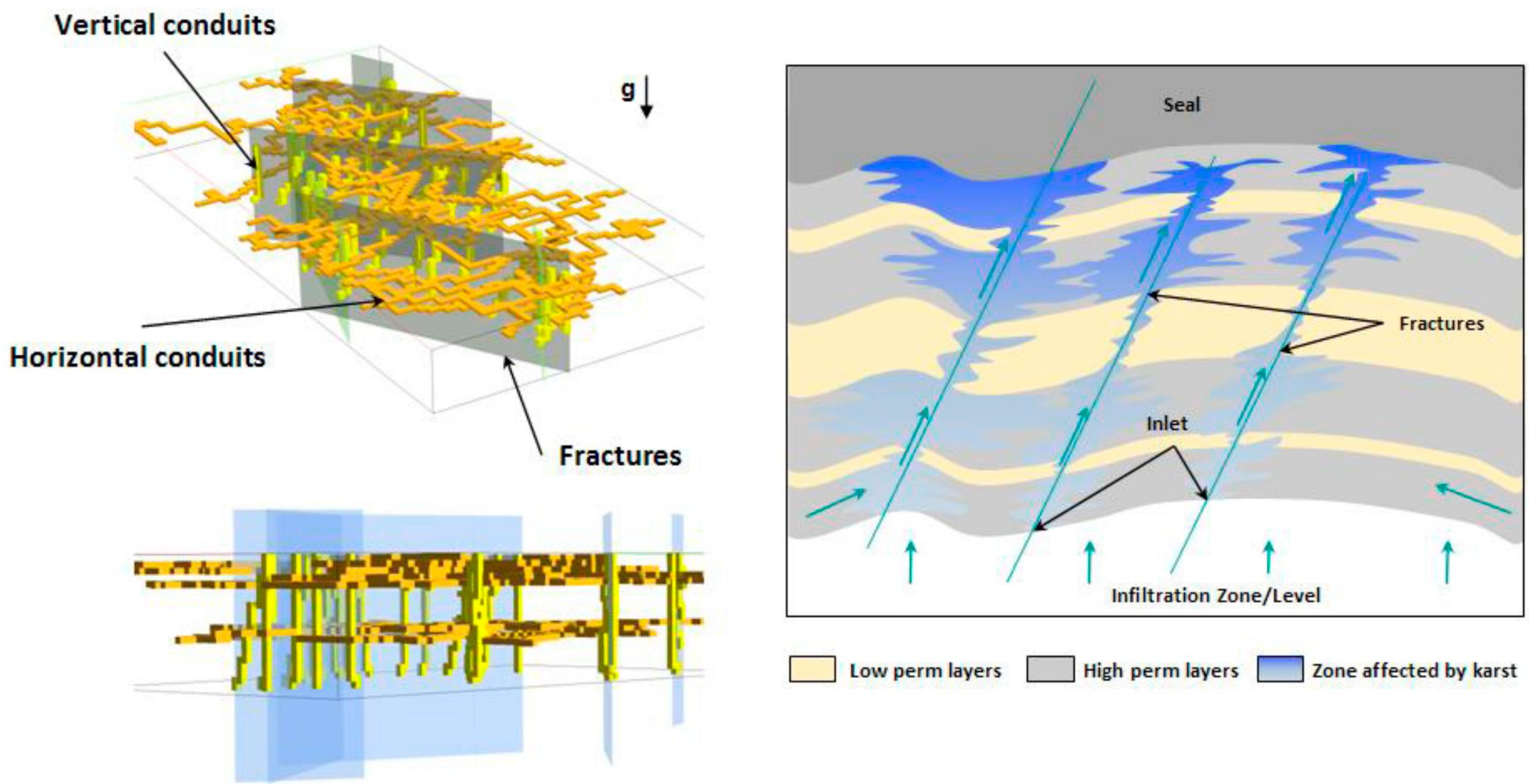

Figure 3. Karst model principles. Hydrothermal karst morphology of vertical and horizontal conduits.

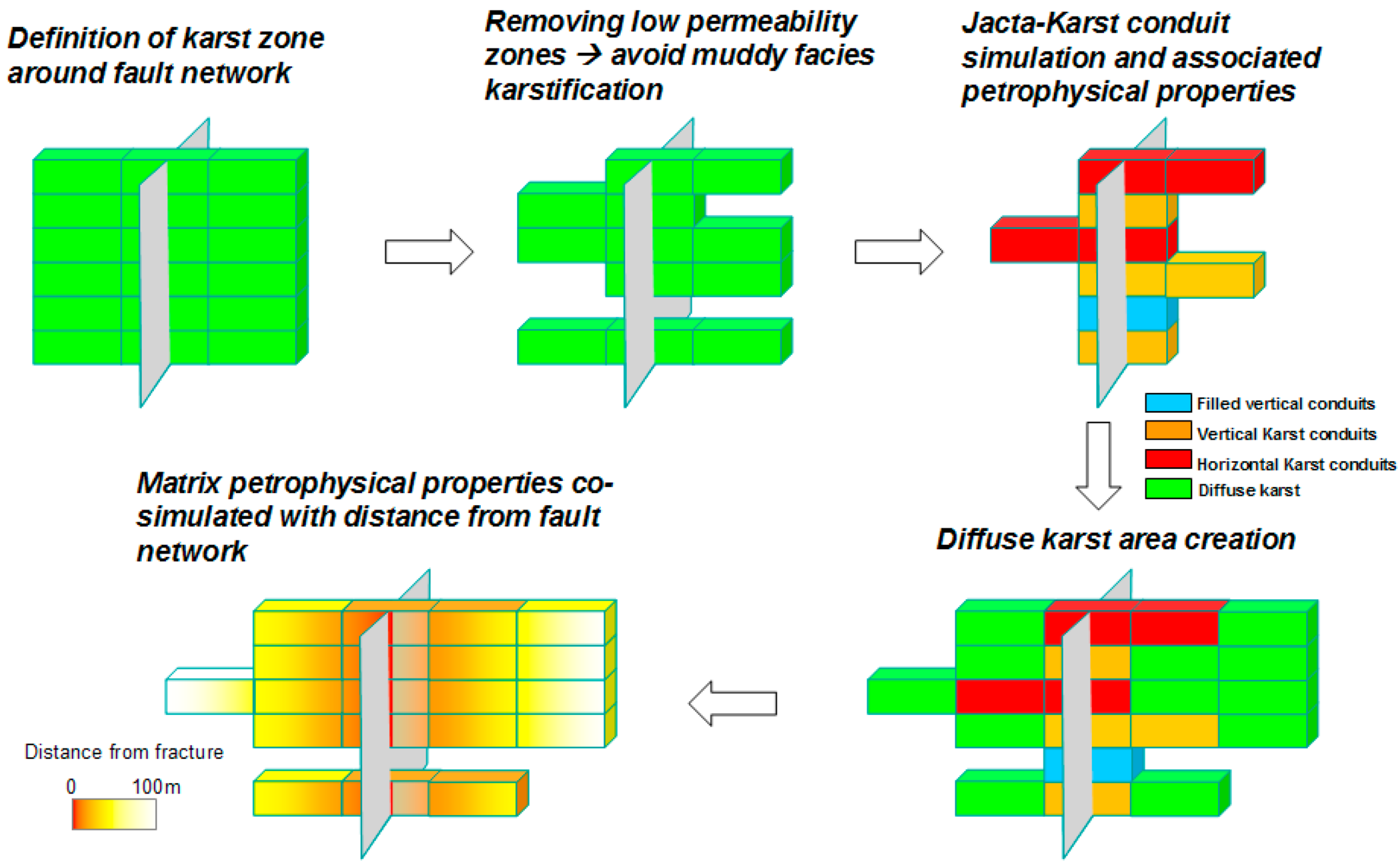

Figure 4. Karst modeling workflow.