Application of Outcrop Analogues in Carbonate Reservoir Characterization and Modeling: Multiscale and Multidisciplinary Approaches*

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Search and Discovery Article #51084 (2015)**
Posted April 6, 2015

*Adapted from oral presentation given at AAPG Geoscience Technology Workshop, Carbonate Plays around the World – Analogs to Support Exploration and Development, New Orleans, Louisiana, February 4-5, 2015

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ABSTRACT

Outcrop analogues are key elements in the understanding of reservoir architecture and heterogeneities. Indeed, subsurface data often represent an extremely small fraction of the reservoir complexity. This is specifically true for carbonate reservoirs that exhibit a high degree of heterogeneity, whatever the scale of investigation. Working on subsurface data without the benefits of relevant outcrop analogues and application of geological principles based on field observations may, therefore, lead to important misinterpretation of well or seismic data. The aim of this presentation is to illustrate different application of outcrop analogue studies: definition of conceptual relationships between several geobody types; quantitative characterization to describe the dimensions and geometry of geobodies; user cases to calibrate modeling parameters and to design modeling workflows.

This presentation mainly focuses on a multidisciplinary approach applied on the Mississippian Madison Formation, outcropping in several locations in the Bighorn foreland Basin (Wyoming, USA), as a thick (up to 400 m) carbonate series. It shows a large variety of sedimentary facies and environments (from supratidal sebkha to deep subtidal) and a polyphased diagenetic history (that successively involved marine, meteoric, and basinal fluids). The quantitative approach carried out in this study has enabled use of the sedimentological and diagenetic data in a modeling workflow to reproduce both facies and diagenetic trends in a static reservoir model and to account for reservoir property changes due to the diagenetic overprint. The SIS and nested geostatistical algorithms used in this study enabled us to perform joint modeling of the sedimentary facies and the diagenetic overprint. This study demonstrates our ability to account, during the reservoir modeling process, for the heterogeneities both in the sedimentary facies distribution and in the subsequent diagenetic imprint.

The Madison Formation is also an analogue of natural fractured carbonate reservoir. Tight carbonate reservoirs are often highly fractured, with high heterogeneities in terms of fracture distribution, hierarchization, and connectivity. In the Sheep Mountain anticline (Wyoming, USA),
sedimentary facies are organized into three types of elementary facies sequences showing different vertical evolutions of their petrophysical properties. These are controlled by the combined influence of the initial sedimentary facies and subsequent diagenetic evolution. In parallel, three main sets of fractures (related to the Sevier and Laramide compressive pulses and to the folding of Sheep Mountain) have been described at three scale orders. The series may, therefore, be described as an imbricated set of mechanical units, the distribution and characteristics of which are controlled by (1) initial texture; (2) early diagenetic overprint at small-scale; (3) overall facies stacking pattern, and (4) the large-scale fold curvature. Sheep Mountain outcrops therefore provide a good spatial representation of the carbonate reservoir heterogeneities from the micro- to the field scale, illustrating the complexity of fractured-carbonate reservoirs. It also highlights the major influence of mechanical stratigraphy on fracture distribution, connectivity and style, a conclusion that can be used for reservoir characterization and modeling by generating Discrete Fracture Network (DFN) for each mechanical unit, thus modifying the hydraulic properties controlling fluid flow and hydrocarbon migration pathways.

Innovative approaches are presented on complementary case studies to illustrate the use of outcrop analogs for new challenging topic. The recent discovery of hydrocarbons in microbial carbonate reservoir facies along the South Atlantic margins raised many questions on the origin and the distribution of nonmarine microbial carbonates. Based on different outcrop studies of lacustrine series (Argentina, Southeast France, Greece), it is possible to propose quantitative rules that can be used as basic building blocks for modeling workflows at both basin scale (stratigraphic modeling) and reservoir scale (stochastic simulation). Recent advances in 3D photogrammetry enable the integration of 3D numerical outcrop models in modeling workflows. These 3D models are particularly useful in the case of sedimentary systems with complex sedimentary architectures, and allow the collection of 3D virtual outcrop data that provide important constraints for the building of surface models and quantitative parameters or relationships (spatial characteristics / length scales…).

To conclude, outcrop analogues provide essential data for the understanding of the subsurface. Nevertheless, as no perfect analogue exists, there will never be an absolute certainty provided by outcrops. It is, therefore, important to critically assess the problems and objectives to know how far one can rely on analogues.

References Cited


**Website**

Application of outcrop analogues in carbonate reservoir characterization and modeling: Multiscale and multidisciplinary approaches

Heterogeneity at all scales!!

Butler R., Virtual Seismic Atlas

1 km - 10 km

1 m - 100 m

10 µm - 10 mm

1 cm - 10 cm
Carbonate reservoirs are unique!!

Carbonate sedimentary facies

Large diversity of composition and texture linked to their biogenic origin

Multi-scale Reservoir heterogeneities

Successive diagenetic events

Strong chemical reactivity and large diversity of reaction (Dissolution, precipitation recrystallization)

Fractures

Large diversity of scale, connectivity and filling
“Soft data”
- Conceptual relationships between, stratigraphic, paleoenvironmental, structural contexts…
- …distribution and morphologies of microbialites.
Outcrop studies for pre-salt problematics

- « Hard data »: Compilation of database of geological (dimensions, connectivity, mineralogy…) and statistical / geostatistical parameters (VPCs, lateral continuity…)

Tests to simulate different lateral continuity of microbialite build-ups. (Yacoraite Fm., Argentina).
3D outcrop modeling

3D outcrop models
- Assessment of geometries, lateral continuity...
- Integration in modeling workflows
- Database of 3D outcrop models (SAFARI, Smart Analogue...).
An example of 3D virtual outcrop (photogrammetry)

Serraduy outcrops
Graus-Tremp Basin
Spain
Outline of the presentation

- **Outcrop analogues provide plenty of data…**
  - Various relevance depending of the analogue and the problematic
  - Usable for subsurface

- **Illustrate a complete workflow of characterization and modeling of an outcrop analogue, based on an integrated approach implying:**
  - Sedimentological, diagenetic and fracturing pattern characterization, used to...
  - ... populate a reservoir model through *stochastic joint modeling of sedimentary facies and diagenesis*, and ...
  - ... to look at relationships between *facies-diagenesis and fracturing pattern*.

- **Focus on the Mississippian Madison Formation, outcropping in several locations in Wyoming (USA).**
The case study

- Madison Formation (Mississippian; Wyoming)
  - Thick (up to 340 m) carbonate series
  - Outcropping in Laramide structures (Bighorn foreland Basin)
  - Reservoir in subsurface

Sheep Mountain Anticline
Geological context

5 study sites:
- WRC: Wind River Canyon
- SH: Shell Canyon
- SM: Sheep Mountain
- SC: Shoshone Canyon
- CF: Clark's Fork Canyon

- **Sevier thin-skin compressive phase (Cretaceous):**
  - Formation of micro-structures associated to N90-N110 compressive stress

- **Thick-skinned Laramide orogeny (Late Cretaceous-Eocene):**
  - Differentiation of numerous sedimentary basins (such as the Bighorn Basin) throughout the Wyoming.
  - Formation of NW-SE tectonic structures, such as basement cored arches (Sheep Mountain, Shoshone Canyon)
Sonnenfeld (1996): A 2\textsuperscript{nd} order sequence, itself composed of six 3\textsuperscript{rd} order depositional sequences which are formed by numerous "high frequency cycles"
Methodology and datasets

- **Sedimentology**
  - 6 Logged sections
  - High resolution stratigraphic correlations

- **Diagenesis**
  - 300 thin sections
  - C/O/Sr isotope analysis
  - Major and trace elements quantified analysis (SEM coupled with a QUANTAX EDS & WDS detector)

- **Fracturing**
  - 8 km of scanlines.
  - More than 3000 bed-confined fractures and 1000 persistent measured fractures.

5 study sites:
- WRC: Wind River Canyon
- SH: Shell Canyon
- SM: Sheep Mountain
- SC: Shoshone Canyon
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Complementary well data (bibliographic):
- TC: Torchlight
- GL: Garland
- EB: Elk Basin

Modified from Love et Christiansen (1985)
Sixteen sedimentary facies organized in shallowing-upward small-scale cycles (supratidal, intertidal, subtidal) deposited on an homoclinal ramp
An example of supratidal shallowing-upward cycle:
**Facies**

An example of (deep) subtidal shallowing-upward cycle:

<table>
<thead>
<tr>
<th>Echelle</th>
<th>Structures sédimentaires</th>
<th>Lithologie</th>
<th>Textures</th>
<th>Env. Séd.</th>
<th>Supratidal</th>
<th>Subtidal</th>
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<td>Mudstone</td>
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<td>Rudstone</td>
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</tbody>
</table>

**Oolitic grainstone**

**Bioturbated dolo-Mudstone**
Correlation and geological model
**Modeling workflow**

**SEDIMENTARY DATA**
- 5 sections informed in facies
- 9 sedimentary facies
- 3 sequences (units)
- A depositional model (spatial relationships between facies)

**GEOSTATISTICAL PARAMETERS**
- Matrix of proportions and lithotype rules for each of the three units

**FACIES SIMULATION**

- Grid divided in 6 units
- 60 km long for 60 km wide
- Cell size: 1 km long, by 1 km wide, by 50 cm high
- Proportional layering

**Non-stationary Plurigaussian algorithm**

**Stochastic modeling including different steps:**
- Gridding and layering
- Calculation of simulation parameters
- Simulation using plurigaussian algorithm (variogram-based model).
The series have been split into 6 modeling units, and corresponding grids, following the sequence stratigraphic framework.

- Grid 60km x 60km – cell 1km x 1km x 50cm.
Simulation parameters

Sedimentary lithotypes present in the unit

Vertical Proportion Curves
(Vertical succession and distribution of facies in a modeling unit)

Truncation rules
(Possible vertical and lateral facies transitions)

Matrix of Proportions
(3D vertical AND horizontal trends)
Resulting simulations for sedimentary lithotypes
Modeling workflow

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FACIES SIMULATION

UNIT 1

DIAGENETIC IMPRINT SIMULATION
Eogenetic phases have the most important influence on the petrophysical properties. Porosity occlusion in grainstones and porosity development in bioclastic wackestones.

Fracturing has a major impact on the hydraulic properties of the Madison reservoir.
Different early diagenetic pathways depending of the sedimentary facies

- Isopachous rims and/or syntaxial calcite cementation (marine phreatic) in oolitic and crinoid-rich facies.
- Mosaic/blocky calcites associated to shallow burial.

dolomicrosparite: sebkha-type dolomite (D1).
- Initial subtidal bioclastic wackestones are dolosparite: Reflux dolomitisation (D2).
How to integrate diagenesis data?

**Diagenetic class (imprints):**
A typical sequence of diagenetic phases that affected one sedimentary facies

<table>
<thead>
<tr>
<th>DIAGENETIC PHASES</th>
<th>D1</th>
<th>D2</th>
<th>D3</th>
<th>D4</th>
<th>D5</th>
<th>D6</th>
<th>D7</th>
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<tr>
<td>Early lithification</td>
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<td>Dolomitisation (dolomicrite)</td>
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<td>Isopachous calcite rims</td>
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<td>Syntaxial calcite cement</td>
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<td>Dolomitisation (dolosparrite)</td>
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**Diagenetic imprints:**
- X: Presence
- Dec.: Decrease
- Inc.: Increase
- X: Presence
- ??: Unknown
How to integrate diagenesis data?

- **Association laws** between sedimentary facies and diagenetic imprints, based on thin section analysis and counting (around 400).

**Nested SIS simulation:**

Diagenetic classes are not simulated but distributed in each simulated sedimentary facies.
The sedimentary heterogeneity is smoothed by diagenesis. The diagenesis increases the sedimentary heterogeneity.

Resulting simulations for diagenetic imprints:

The different Facies/Diagenesis couples may be associated with $K/\Phi$ properties.

PGS Simulation sedimentary facies

SIS Simulation diagenetic imprint
Three main sets of fractures
(Bellahsen et al. 2006; Amrouch et al. 2010)

Set I: N110-130E dated from the Sevier Orogeny (Cretaceous)
Mechanical units

- 6-8 km (cumulative length) of scanlines
- More than 3000 bed-confined fractures and 1000 persistent measured fractures
- Allow us to recognize 3 orders of mechanical units.

Mechanical unit (MU): one or several stratigraphic unit(s) with homogeneous mechanical properties. MU boundaries are limits of vertical persistence of a selected type of fractures (Laubach et al., 2009).
Fracture density is structurally controlled, but persistence is stratigraphically controlled.


**Mechanical units MU2**

**Types of fractures:**
- Set I: Shear band zone
- Set III: through-going vertical fracture

**MU2 boundaries:**
- Major facies changes

**Number of fractures / m**
- Few
- N45E Frac.

**Mechanical Unit thickness vs. FI**
- 0.8 F/m
- 0.17 F/m
Mechanical units MU2 (backlimb)

- **Lithologic control ↔ Seq. Strat.**
  - Shallowing and progradational phase dominated by grainy limestones → Increase of fracture density.

- **Impact of seq. boundaries**
  - SBs (solution collapse breccias) show sliding along bed boundaries. → Local increase of fracture density.

Fracture density and persistence reflect a faciologic and structural control.
Types of fractures:
Bed-confined fractures, poorly connected.

MU3 boundaries:
Bedding or small-scale cycles boundaries.
Mechanical units MU3 (backlimb)

**Lithologic control ↔ Seq. Strat.**
- Shallowing and progradational phase dominated by grainy limestones → Increase of fracture density.
- Transgressive phases, dominated by homogeneous dolomitized Mst./Wst. → Low fracture density.

**Various types of fractures**
- Dolomitized porous facies: diffuse fractures
- Cemented grainstones: Well organized, well marked linear fractures.

**Facies and early diagenetic control on the fracturing pattern**
Integration in modeling workflows

- Construction of synthetic (1D) Discrete Fracture Network, based on the outcrop data:
  - Representation of the different orders of fractures and MU, and their connectivity.
  - Used to extract equivalent $K$ and $\Phi$, to be combined with facies and rock matrix properties.
  - Improvement of fluid flow simulation.

- If mapping of fractures is available, 3D DFNs may be constructed.

Green: Persistent N110-130
Brown: N130
Yellow: Bed confined, N45
Concluding remarks

- Analogues may be used at different scale and stage of reservoir characterization and modeling process.

- Outcrop analogues provide essential data for the understanding of the subsurface…
  - Hard data: Quantitative parameters/database…
  - Soft data: Conceptual models, laws…

- THE outcrop analogue doesn’t exist
  - Critically assess the problems and objectives to know how far one can rely on each analogue.
Thank you for your attention
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