Title: *Hedberg Research Conference on Fundamental Controls on Flow in Carbonates: Request for Travel Support for Post-Doctoral Fellows*

Final Report

Reporting Period Start Date: 02/01/2012
Reporting Period End Date: 0 1/31/2013

Laura J. Pyrak-Nolte
April 2013
DOE Award: DE-SC0007504

Department of Physics
1396 Physics Building, Room 166
525 Northwestern Avenue
West Lafayette, Indiana 47907-1396

Table of Contents

1. Project Summary

Carbonate reservoirs pose a scientific and engineering challenge to geophysical prediction and monitoring of fluid flow in the subsurface. Difficulties in interpreting hydrological, reservoir and other exploration data arise because carbonates are composed of a hierarchy of geological structures, constituents and processes that span a wide spectrum of length and time scales. What makes this problem particularly challenging is that length scales associated with physical structure and processes are often not discrete, but overlap, preventing the definition of discrete elements at one scale to become the building blocks of the next scale. This is particularly true for carbonates where complicated depositional environments, subsequent post-deposition diagenesis and geochemical interactions result in pores that vary in scale from submicron to centimeters to fractures, variation in fabric composition with fossils, minerals and cement, as well as variations in structural features (e.g., oriented inter- and intra layered - interlaced bedding and/or discontinuous rock units). In addition, this complexity is altered by natural and anthropogenic processes such as changes in stress, fluid content, reactive fluid flow, etc. Thus an accurate geophysical assessment of the flow behavior of carbonate reservoirs requires a fundamental understanding of the interplay of textural and structural features subjected to physical processes that affect and occur on various length and time scales.

To address this complexity related to carbonates, a Hedberg conference on "Fundamental Controls on Flow in Carbonates" was held July 8 to 13, 2012, to bring together industry and academic scientists to stimulate innovative ideas that can accelerate research advances related to flow prediction and recovery in carbonate reservoirs. Participants included scientist and engineers from multiple disciplines (such as hydrology, structural geology, geochemistry, reservoir engineering, geophysics, geomechanics, numerical modeling, physical experiments, sedimentology, well-testing, statistics, mathematics, visualization, etc.) who encompass experience as well as the latest advances in these multi-faceted fields. One of the goals was to include early career scientists and engineers (post-doctoral fellows, assistant professors, etc.). With this grant 10 early career scientists and engineers were supported to attend the conference. This reports contains a brief overview of the conference and the list of support participants supported by this grant. Full details of the outcomes of the conference are given in the publication found in the Attachment section of this report.

1. Introduction

Carbonate reservoirs contain approximately 50% of the world's hydrocarbon resources (Roehl & Choquette, 1985) but are challenging to produce due, in part, to their lithologic and structural heterogeneity. A small increase (1-2%) in recovery from these reservoirs will make a substantial difference to global hydrocarbon production and could extend substantially the life of mature fields. However, this requires an in-depth understanding of flow behaviors and processes on various length and time scales, and significant advances in geologic and flow simulation methods.

Nurmi et al. (1990) observed that heterogeneity in physical properties occurs on all length scales in carbonate reservoirs, i.e., from the micro-scale to the reservoir scale. The physical properties of carbonate rock are strongly influenced by the rock fabricthat depends on the depositional environment, organic activities, diagenetic and tectonic processes (Figures 1 & 2). The fabric of carbonate rock is often classified based on the major constituents, pore space, fractures and styolites (Durrast & Siegesmund, 1999). The major constituents in the rock (e.g., fossils, ooides, etc) and the packing and cementation of these constituents result in heterogeneity in physical properties at multiple scales. The most common form of heterogeneity is layering caused by a variation in porosity (Nurmi et al., 1990). The thickness of the layers can vary, and porosity within a layer may also vary. The variation in porosity among layers leads to anisotropic behavior in the hydraulic, mechanical and seismic properties of carbonate rocks. On the reservoir scale, carbonate reservoirs exhibit heterogeneity but may not exhibit any known anisotropic model because of interlaced as well as discontinuous rock units with various orientations caused by the depositional environment (e.g., Figure 2).

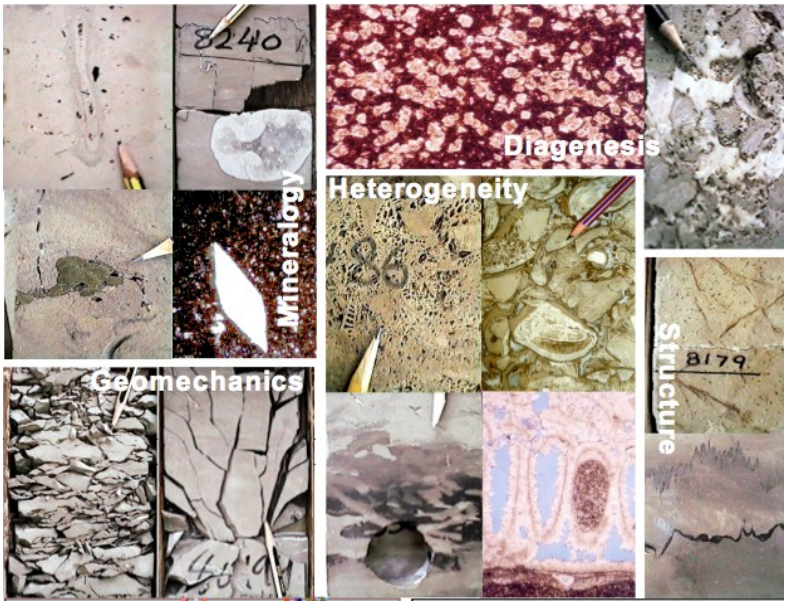

Figure 1. The complexity of carbonate reservoirs arises from processes related to mineralogy, sedimentology, diagenesis, structure, geomechanics and flow processes [scaweb.org, 2000].

One of the fundamental problems in reservoir engineering, hydrology and geophysics is the difficulty of relating properties and processes at one scale to properties and processes at other scales. This is known as the "upscaling" problem. What makes this problem difficult is that length scales associated with physical structure and processes are often not discrete, but overlap, preventing the definition of discrete elements at one scale to become the building blocks of the next scale. One source of concern in upscaling hydraulic in carbonate reservoirs are the range of structural scales (i.e., submicron pores

in fossils, pores, micro-cracks, vugs, fractures, joints, faults, etc.) because they occur on all length scales either singly or as sets, and they are easily perturbed by natural (e.g., earthquakes) and/or induced processes associated with subsurface projects (e.g., production). In addition, these structural features are subject to dynamic geomechanical and geochemical alterations that occur during hydrocarbon production from changes in pore pressure, in-situ stress, fluid chemistry, closing/opening of existing discontinuities as well as the generation of fractures, all of which impact reservoir permeability and geophysical monitoring. These structural and physical problems pose a significant challenge to numerical simulation of fluid flow in carbonate reservoirs.

In additional to structural controls on flow, geochemical controls of flow in carbonates include (1) dissolution and/or precipitation of minerals that affect porosity, and (2) the wettability of the rock. Studies have shown that carbonates can exhibit neutral, mixed or preferential wettability to oil (e.g. Austad et al., 2008). The wettability of the rock affects capillary pressures, saturations, electrical conductivities and seismic wave propagation, i.e., wettability affects not only fluid distributions in the reservoir but also the geophysical interpretation of fluid distribution prior to and during production.
Addressing these and other challenges requires collaborations between scientist and engineers from such diverse fields as hydrology, structural geology, geochemistry, geophysics, geomechanics, statistics, computational sciences, mathematics, visualization, sedimentology, and the use of a wide range of approaches (e.g., numerical modeling, theoretical developments, physical experiments, well-testing, filed work, etc.).

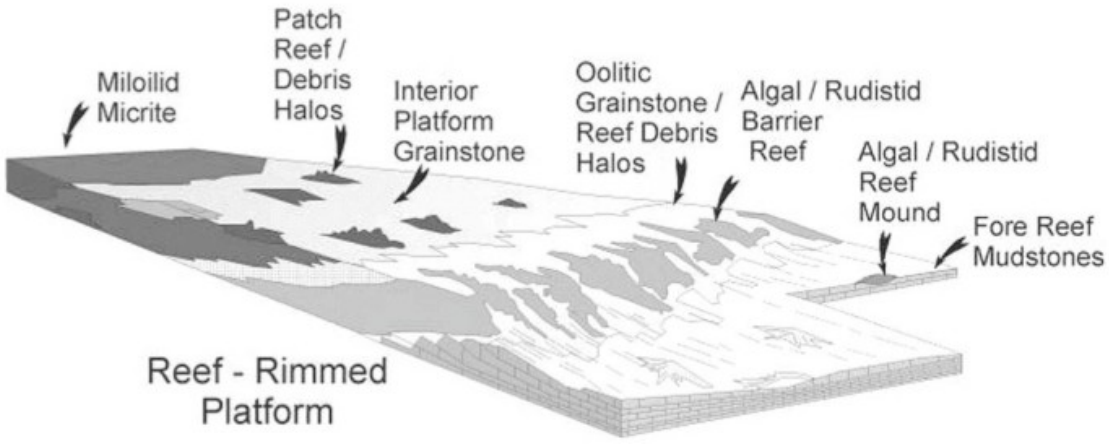

Figure 2. Schematic diagram illustrating the facies on a carbonate shelf or platform taken from [Montgomery et al., 2002]

3. Conference Overview

The Hedberg conference on Fundamental Controls of Flow in Carbonates was held July 8th -13th 2012 at the Dolce Fregate conference center to the east of Marseilles, France. The primary purpose of this Hedberg conference was to stimulate innovative ideas and joint industry-academic ventures that can accelerate research advances related to flow prediction and recovery in carbonate reservoirs. The conference conveners and organizing committee (Table 1) represent an international mix of academic and industry

researchers. The conference was focused on four technical themes (see section 2.1) and also included a field trip. A key advantage of the conference location was the access to Cretaceous outcrop analogs for Middle East carbonate reservoirs that provided access to a range of rock types, structures and diagenesis. All conference participants attended the field trip to ensure that rocks were not neglected, to stimulate discussion and to provide a reality check for those involved with modeling or those who may have no prior exposure to carbonate rock outcrops.

Table 1. Conveners and Organizing Committee

Name	Institution	Name	Institution
Sebastian Geiger, Convener	Heriot-Watt University	Susan Agar, Convener	ExxonMobil
Giovanni Bertotti	Technical University of Delft	Olivier Gosselin	Total
Fiona Whitaker	University of Bristol	Gareth Jones	ExxonMobil
Gary Hampson	Imperial College	Constantine Tsingas	Saudi Aramco
Stephan Matthai	Montan University of Leoben	Mike Sullivan	Chevron
Joyce Nielson	University of Aberdeen	Juliette Lamarche	University of Provence
Laura Pyrak-Nolte	Purdue University	Charlie Kerans	Bureau of Economic Geology, U of Texas

The five-day conference consisted of non-parallel oral and poster presentations. There were four days of presentations, discussion and breakout sessions and one day in the field. Prior to the conference, a website was used to enable conference participants to learn more about each other. This help to promote early identification of complementary interests, skills and ideas. The conference started with a broad theme to encourage multidisciplinary engagement and participation by researchers who are not necessarily involved in "classic" fields related to carbonate reservoirs. The first half of the conference was dedicated to bringing people up to speed on different research areas and capturing thoughts from leading scientists on what they considered to be promising future research directions. By the start of the third day, participants were charged with defining teams to develop research proposals. In this way, the conference quickly focused down to evaluate a set of research objectives. A primary objective was to define promising, new research directions that can stimulate novel research programs around the globe, stimulating industry-academic collaboration. These research directions are given in the publication in the attachment section of this report.

3.1 Technical Themes

The conference focused on four technical themes to help define long-term challenges related to flow in carbonates that require new and collaborative research directions. A selection of industry case studies was used to address components within one or more of the technical themes. These served to reinforce areas where knowledge is thin or lacking and to build a common knowledge platform for meeting participants with diverse

backgrounds. Sharing case studies with academic participants helped them to identify areas in which their research is relevant while industry participants benefited from novel academic insights that have not been conditioned by industry experience. We achieved our goal to have post-doctoral and other early career participants that were relevant to each theme.

1. **Fundamentals**– This theme focused on the fundamental physics and chemistry that control flow behavior and recovery in carbonate reservoirs from the pore- to field- scale. This theme included laboratory measurements and experiments, theoretical and numerical modeling studies and addresses topics including but not limited to: the evolution and distribution of wettability in carbonates, matrix-fracture interactions, and multiphase flow in rocks with wide variations in porosity and wettability.
2. **In-situ Monitoring of Flow –** The second theme encompassed the application of novel geophysical methods (including seismic, resistivity, gravity, magnetic and X-ray computer tomography) for real-time monitoring of flow in carbonates as well as subsurface experiments (for example tracers) that offer the potential to gain new insights to flow phenomena. This theme tackled questions concerning the theoretical and practical challenges for geophysical monitoring as well as the value and potential limitations of subsurface flow experiments.
3. **Prediction & Uncertainty** – This theme addressed our current knowledge of geologic characteristics of carbonate reservoirs and ways to predict them. A strong emphasis was placed on the geologic processes controlling the links among sedimentologic, structural and diagenetic features in carbonates and the value of understanding these processes to predict flow paths among them. Novel approaches for characterization and gauging uncertainty such as multipoint statistics, geomechanical modeling, probabilistic methods, Bayesian statistics, and novel seismic techniques were included. Discussions examined prediction at different scales and over different stages of Exploration, Development and Production.
4. **New Geologic and Flow Simulation Techniques** – This theme explored novel methods for geologic modeling and flow simulation, placing a strong emphasis on emerging methods in academic circles that have yet to penetrate the industry arena. Modeling approaches included efficient methods to develop outcrop analogs, reactive-transport modeling in deformed carbonates, and next generation flow simulation methods. Participants explored paradigm shifts that help to streamline data acquisition, modeling and flow predictions.

3.2 Conference Format

The conference format was designed to promote a novel set of interactions to stimulate paradigm shifts. One of the goals, that was particularly relevant to post-doctoral fellows and early career scientists, was to open new opportunities to researchers seeking to learn more about how their research relates to the challenges of predicting flow in carbonate (and possibly unconventional) reservoirs. A further aim was to raise awareness of the new cross-disciplinary skill sets that individuals need to solve problems related to flow prediction in carbonate reservoirs.

The conference was designed to promote dialogues, the exchange of ideas and develop collaboration among a diverse set of participants in terms of discipline and experience. The key differentiators of this conference from other carbonate workshops were

(1) Specific processes and experienced facilitators were used to promote dialogues between geoscientists and engineers, and between industry and academic researchers, and between new and experienced participants.
(2) An emphasis on innovation (i.e., the translation of ideas into economic value) was supported by professional techniques to stimulate novel ideas and to explore potential collaborations.
(3) Key research questions and hypotheses were prioritized such that, if addressed, will be most likely to result in improved hydrocarbon recovery.
(4) An exciting vision for research around the globe was developed that sets stretch goals for academic-industry research collaboration, shaping the future oil and gas industry
(5) The recognition of critical skill sets that are needed to address these long-term challenges. With this knowledge, early-career researchers are now better equipped to establish effective cross-disciplinary and academic-industry teams.

The ability to achieve many of the goals of the conferences requires strong integration of geoscience and engineering perspectives on carbonate reservoirs. This integration

(1) Provided geoscientists with a better understanding of how reservoir engineers think and what they consider to be important. Geoscientists participants are now better positioned to "tune" their research to high-impact factors for flow predictions.
(2) Provided reservoir engineers with a better understanding of how geoscientists perceive the impacts of carbonate reservoir geology on flow. Reservoir engineers and flow modelers are now positioned to frame questions, to evaluate uncertainties and consider paradigm shifts in their approach to flow modeling.
(3) Identified emerging methods and novel connections that offer potential uplift for characterization and flow modeling of carbonate and potentially unconventional reservoirs.
(4) Improved knowledge of key geologic features that control flow in carbonate reservoirs, the ways by which these can be identified, quantified and modeled for a given oil or gas field.
(5) Strengthen interest in (a) shaping industry researchers to develop the necessary skills to cross the geoscience – reservoir-engineering divide, (b) developing academic programs to establish multi-disciplinary capabilities in future industry employees and consultants.

A full description of the outcomes of the conference is given in the publication found in the Attachment section of this report.

3.3. Early Career Participants Supported

Table 2 contains a list of the early career participants, their institution and the amount of support received to attend the conference. The funds were used to reimburse a portion of the costs (flight, other transportation, lodging and food costs).

Table 2. List of early career participants funded by this grant, their institutions and the amount of support.

Early Career Participants	Institution	Amount
Philippe Leonide *Assistant Professor*	University of Marseille, France	$1200
Masa Pradonovic *Assistant Professor*	University of Texas, Austin, TX	$1175
Enrique Gomez-Rivas *Post-doctoral Fellow*	Dept. of Geosciences, Univ. of Tubingen, Germany	$925
Peter Fitch *Research Fellow*	Imperial College, London, UK	$925
Simon Emmanuel *Senior Lecturer*	Institute of Earth Sciences, Hebrew University of Jerusalem, Israel	$1175
David Healy *Senior Lecturer*	School of Geosciences, King's College, University of Aberdeen, UK	$750
Iryna Malinouskaya *Post-doctoral Fellow*	Univ. of Pierre & Marie Curie (UPMC), Paris, France	$775
Charlotte Garing *Post-doctoral Fellow*	University of Montpelier, France	$775
Francois Fournier *Lecturer*	University of Marseille, France	$1150
Cees van der Land *Post-doctoral Fellow*	University of Edinburgh, UK	$1175

4.0 References

Austad T, Strand S, Madland MV, Putnervold T, Korsnes R, Seawater in chalk: An EOR and compaction fluid. SPE Reservoir Evaluation and Engineering, 11(4), 648-654, 2008.

Durrast, H. and S. Siegesmund, Correlation between rock fabrics and physical properties of carbonate reservoir rocks, International Journal Earth Sciences, 88, 392-408, 1999.

Montgomery, S. L., Petty, A. J. and P. J. Post, James Limestone, northeastern Gulf of Mexico: Refound opportunity in a Lower Cretaceous trend, AAPG Bulletin, v. 86, no. 3 (March 2002), pp. 381–397

Nurmi, R., Charara, M., Waterhouse, M. and R. Park, Heterogeneities in carbonate reservoirs: detection and analysis using borehole electrical imagery, Geological Society, London, Special Publications, 48, 95-111, doi:10.1144/GSL.SP.1990.048.01.09, 1990

Roehl, P. O. and Choquette, P. W., Carbonate Petroleum Reservoirs. Springer-Verlag, New York, (1985) pp 622.

http://www.scaweb.org/assets/pdf/scal-2000_carbonates-.pdf

5. Attachment: Publication of Conference Outcomes

The attachment section contains the following selected publication that gives an overview of the conference results.

'AAPG Bulletin, v. 97, no. 4 (April 2013), pp. 533–552

Attachement removed due to copyright