

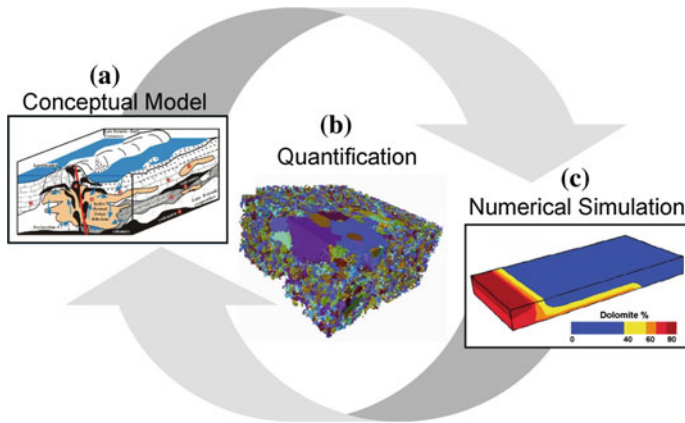
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## Preface

The starting point of the worldwide interest in “Diagenesis”—especially for carbonate rocks—can be traced back to 1975, when R. Bathurst published the book entitled “Carbonate Sediments and their Diagenesis” including the famous statement: “*Carbonate rocks are as much the products of diagenesis as they are of primary deposition*”. Alteration of sedimentary rocks after sediment deposition due to various processes of diagenesis is crucial in reshaping their mineralogical and petrophysical properties. The petroleum industry, since that early time, needed workflows and means to understand and predict the heterogeneous flow properties of reservoir rocks. Henceforth, a considerable amount of research work has been dedicated to the investigation of diagenetic processes, environments and products. Diagenetic processes are inherently related to the rock–fluid interactions and attract multi-disciplinary researchers. This is quite demonstrated by the wide spectrum of the nature of published work on diagenesis and by the difficulty in integrating all aspects related to diagenesis research.

Sedimentologists have extensively described the results of diagenetic processes (“diagenetic phases”) in surface-exposed rocks and subsurface well cores across the planet. The aim was set at matching processes and products, and being able to come up with conceptual models that would allow at least constraining the geometry/dimension as well as the fluid flow history of the altered rocks. In addition, since the 1970s and the original paper of Choquette and Pray (1970)—entitled “Geologic nomenclature and classification of porosity in sedimentary carbonates”—efforts were spent to understand the impact of diagenesis on porosity and permeability of carbonate rocks.

To date, classical diagenesis studies make use of a wide range of descriptive methods and analytical techniques converging into conceptual models that explain specific, relatively time-framed, diagenetic processes, and deduce their impacts on carbonate reservoir rocks (e.g. Nader et al. 2004; Nader et al. 2008). Currently used techniques combine petrographic (conventional, cathodoluminescence, fluorescence, scanning electron microscopy with energy dispersive spectrometer—SEM/EDS and 3D computed tomography, CT), geochemical (major/trace elements, stable oxygen and carbon isotopes, strontium isotopes, Mg and clumped isotopes) and fluid inclusion analyses (microthermometry, Raman spectrometry, crush-leach analysis, laser ablation), providing independent arguments to support or discard any of the proposed models. More recently, the use of basin modelling is



**Fig. 1** From conceptual to numerical modelling of diagenesis, quantifying diagenetic phases remains essential. **a** Conceptual studies of diagenesis—for example hydrothermal or high-temperature dolomitization (HTD; Nader et al. 2004, 2007). **b** Quantification methods—e.g. micro-computed tomography (micro-CT) image analyses (De Boever et al. 2012). **c** Numerical simulations of diagenetic processes such as reactive transport modelling of dolomitization (e.g. Consonni et al. 2010)

employed (e.g. Fontana et al. 2014; Peyravi et al. 2014) to support the burial history evolution (including temperature and pressure boundary data) and the proposed paragenesis (i.e. the sequence of diagenetic phases in chronological order). Still, conceptual models lack exact dating frameworks (or specific timing constraints for the described processes). They are qualitative and do not yield quantitative data to be directly used by reservoir engineers for rock-typing and geological modelling (Nader et al. 2013). New analytical techniques (e.g. U/Pb for dating) and advances in numerical modelling may provide better tools for achieving time-constrained, quantitative diagenetic studies. The operational workflow that aims at predicting the impact of relevant diagenetic processes on reservoir properties, henceforth, consists of three main iterative stages (Nader et al. 2013): (i) constructing a conceptual diagenesis model, (ii) quantifying the related diagenetic phases and (iii) modelling the diagenetic processes (Fig. 1).

While most of the concepts of diagenetic processes operate at the larger, basin scale, the description of the diagenetic phases (products of such processes) and their association with the overall petrophysical characteristics of sedimentary rocks remain at reservoir (and even outcrop/well core) scale. Hence, “upscaling” becomes another major challenge for sedimentologists and reservoir engineers in the coming decades. Recently, massive work has been undertaken to propose methods capable of defining representative elementary volumes (REV) of carbonate reservoir rocks. REV’s would then be used to represent the whole rock type at various scales (reservoir and basin scales).

Between the years 2000 and 2003, I worked, during my Ph.D. project (KU Leuven, Belgium), on the “Dolomitization Problem” as one of the significant processes of diagenesis in carbonate rocks (Nader 2003). About 50 % of the

world's known carbonate reservoirs are in dolostones. Based on my local field knowledge, I have investigated the Jurassic dolostones that are exposed in Lebanon (part of the Jurassic carbonate platform on the southern margin of the Neo-Tethys ocean) and ascribed them to conceptual models (eogenetic reflux and mesogenic high-temperature fracture-associated) invoking the fluid flow characteristics and rock–fluid interactions (Nader et al. 2004). From 2003 to 2007, I have extended this work upon my appointment as assistant professor at the American University of Beirut (Lebanon) by further studying the Jurassic hydrothermal dolomitization fronts and the Cretaceous sabkha-style dolostones in Lebanon (Nader et al. 2006, 2007). I have also supervised projects on diagenesis of carbonate rocks (Doummar 2005), hydrocarbon assessments based on petrography and geochemistry of source rocks (Al Haddad 2007), and diagenesis of sandstones Bellos (2008).

In 2007, I joined IFP Energies nouvelles (*Institut Français du Pétrole* at that time), and I worked first within the “Reservoir Characterization” mega project and Enhanced Oil Recovery Joint Industry Project. Most of my work at that time concerned with characterization of diagenetic phases and their relationship with reservoir properties. This involved field investigation of some of the world-class outcrops of hydrothermal dolomites (e.g. Ranero, Spain; Apennines, Italy; e.g. Shah et al. 2010, 2012; Swennen et al. 2012), as well as studies of actual oilfields and outcrop-analogues (e.g. Gashsaran oilfield, Iran). Other than characterization studies, I got myself involved in upgrading analytical methods for petrography and fluid inclusion analyses as well as X-ray diffraction quantifying methods and atomic absorption spectrometry of mixed dolomite/calcite samples. This was the beginning of quantitative diagenesis workflows for carbonate rocks at IFPEN (e.g. Turpin et al. 2012).

I have started applying numerical modelling to dolomitization as of the first years I spent at IFPEN. We tried to model hydrothermal dolomitization fronts with ArXim-Coores<sup>TM</sup> (coupled geochemical and transport reactive software packages). Geostatistical modelling was also applied to the Ranero hydrothermal fault-associated dolomites by coupling Fraca<sup>TM</sup> and GOCAD software packages.

In 2009, we embarked on larger-scale studies of diagenesis, concerning basin-scale processes. Fluid inclusion analyses across the Apennines Jurassic platform as well as the petrographic and mineralogic investigations of the Cretaceous Mannville tight sandstones gave a larger framework for the investigated diagenetic processes (Deschamps et al. 2012). At that time, I initiated my second Ph.D. project which consisted of a basin-scale diagenesis study of the Permo-Triassic Khuff carbonates in the United Arab Emirates (Fontana et al. 2010, 2014). I was also involved in the CAPSARK project (BRGM, IFPEN, GeoGreen), which aimed at proposing sites for CO<sub>2</sub>-storage in the Kingdom of Saudi Arabia. This project allowed me to undertake a comprehensive stratigraphic and structural geology review at the scale of Saudi Arabia (Jaju et al. in press).

In 2010, two new aspects of diagenesis research were added to our ongoing projects. The first consisted in developing more advanced techniques on quantifying diagenetic phases by means of 2D and 3D image

analyses with micro-CT and MATLAB<sup>TM</sup> tools. We became capable of quantifying diagenetic phases from high-resolution scans of thin sections and 3D scanned rock samples. The postdoctoral project of Eva de Boever, which I have conceived, allowed us also to link the micro-CT approach to (reactive) Pore-Network Modelling to establish a possibility to model dissolution of carbonates or precipitation of anhydrite based on 3D scanned images at the scale of plugs (De Boever et al. 2012). The second aspect of diagenesis also concerned quantifying techniques, but at a larger, reservoir scale. Here, we benefited from collaboration with the Petroleum Institute in Abu Dhabi (UAE) in order to analyze a huge petrographic and petrophysical database across an oilfield (Morad et al. 2012). We constructed maps showing the proportional distribution of diagenetic phases (such as dolomite and anhydrite) and relative abundance of cements, such as syntaxial calcite overgrowth (Nader et al. 2013). Such maps were essential and preceded geostatistical modelling (with CobraFlow<sup>TM</sup>) which helped in illustrating the reservoir heterogeneity based on quantitative diagenesis at the oilfield scale (MSc. Thesis of Morad 2012). Henceforth, I have put together a workflow whereby quantifying tools (such as 2D/3D image analyses) can be used to achieve quality control on industrial petrographic and petrophysical data, and then statistical analyses of the data sets are done by EasyTrace<sup>TM</sup> software before undertaking geostatistical modelling with CobraFlow<sup>TM</sup>.

In 2011 and 2012, I had the opportunity to work as a geology consultant at the Ministry of Energy and Water in Lebanon at the time of the preparation for the first Lebanese offshore licensing round. I discovered basin-wide reflection seismic data (2D and 3D) and their major importance, not only for hydrocarbon exploration assessment but also for stratigraphic and structural studies. At that time, Petroleum Geo-Services (PGS) and Spectrum Geo Ltd. were busy acquiring 2D and 3D seismic surveys covering the whole Lebanese offshore exclusive economic zone (EEZ; exceeding 19,000 km<sup>2</sup>). I learned about the wealth of data provided by these surveys in the frontier gas-bearing Levant Basin (Nader 2011, 2014a). I have initiated three Ph.D. projects based on such seismic data and fieldwork onshore Lebanon. These projects are to be integrated, and cover the stratigraphic (Hawie et al. 2013), structural (Ghalayini et al. 2014) and petroleum (Bou Daher et al. 2014) aspects of Levant Basin. Having established the basin-scale framework for the Levant Basin research with various European academic and industrial partners, I am looking forward eventually to tackle reservoir-scale studies once exploration well data will be made accessible.

Upon my return to IFPEN (end of 2012), I worked on extending my research network over the Eastern Mediterranean region (including new Ph.D. projects offshore Cyprus; Ph.D. projects of N. Papadimitriou and V. Symeou, 2014–2017). Additional 2D and 3D seismic interpretations were carried out on the first seismic profiles onshore Lebanon and the Messinian salt in the Levant Basin, respectively. Numerical modelling of diagenesis also took a considerable part of my work, including geostatistical modelling at the reservoir-scale and geochemical reactive transport modelling of dolomitization. We developed simple examples of rock-water geochemical simulations with ArXim. For instance, geochemical modelling can provide

simple estimations of porosity destruction or enhancement in the freshwater lens during carbonate platform growth. Such modules can be eventually plugged in forward stratigraphic modelling tools (e.g. DionisosFlow<sup>TM</sup>) and help in predicting the effect of diagenetic processes during the growth of a carbonate platform. The eventual goal for geochemical RTM is the predictive modelling of diagenetic processes and their impacts on reservoir properties. They ought to be used as tools to question certain scenarios and to infer about the sensitivity of specific parameters.

Today, we have an operational workflow for proposing conceptual models of diagenetic processes based on studying surface-exposed rocks and well cores. We are able to quantify the diagenetic products in carbonate rocks with various techniques and on varying scales. In addition, we have the possibility to use distinct software packages for numerical modelling. I have been involved in all aspects of this workflow by undertaking and supervising research projects on plug, reservoir and basin scales.

On a more global level, the way forward, seems evident to me as the integration of workflows at different scales. I would like to improve such integration by planning research projects that go from a basin scale (using seismic data, outcrop-analogues, well cores, etc.) to a reservoir scale, and eventually the plug scale. Such integration will bring more constraints on the boundary data, better validation for models, and less uncertainty.

This book is based on the thesis I have defended on the 19 March 2015, for acquiring my Habilitation diploma (HDR) at the Université Pierre et Marie Curie (UPMC, Sorbonne Universities, Paris, France), and about 12 years of research work—mainly on carbonate rocks. The present book composed of five chapters. First, an introductory chapter outlines the general topics of diagenesis (i.e. characterization, quantitative diagenesis and numerical modelling) that will be further investigated in this work. Three chapters follow consecutively bringing appropriate emphasis on the actual state of the art and the future perspectives for each of these three topics, respectively. In addition, future development trends are discussed at the end of each chapter. Chapter 5 presents major conclusions and general perspectives, which are grouped in five sections (i.e. characterization techniques, quantitative methods, modelling workflows, integration of modelling workflows and the way forward). It is my belief that the larger, basin-scale picture is of importance to carbonate rock diagenesis studies, as it provides the broader framework for fluid migrations and can help in setting the boundary conditions for reservoir-scale studies. This contribution aims to highlight the multi-scale aspect of diagenesis and provide a road map for future research projects (including techniques, workflows and tools).

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