3D modelling of carbonates: Techniques and applications at different scales and processes

3D modelling has emerged as an important tool to tackle the quantitative study of carbonates at different scales. Applications are in the fields of carbonate sedimentology, structural geology, reservoir characterization and analogue modelling and include, for instance, volume assessment, calculation of growth rates and precipitation rates, study of depositional geometries, distribution of facies and rock properties, evaluation of heterogeneity, forward modelling of sedimentation and diagenetic processes, reaction transport modelling and characterization of sub-surface reservoirs (e.g., Blendinger et al., 2004; Adams et al., 2005; Aigner et al., 2007; Qui et al., 2007; Borgomano et al., 2008; 2020; Kenter et al., 2008; Warrlich et al., 2008; Palermo et al., 2010; Tomás et al., 2010; Williams et al., 2011; Amour et al., 2013; Franceschi et al., 2015; 2016; Kolodka et al., 2016; Tomassetti et al., 2018; Petrovic 2020; Brandano et al., 2020). A number of techniques, such as 3D seismics, photogrammetry, LIDAR, hyperspectral imaging, CT scanning are now able to provide an invaluable, easily accessible quantitative three-dimensional information on carbonates bodies from micron to kilometre scales. Software development has proceeded in parallel, and sophisticated tools for the interpretation and management of an ever-increasing volume of digital data are available. These data are used in the fields of carbonate sedimentology.

This special volume gathers sixteen contributions from the academia and the industry presenting a number of case histories on 3D modelling of carbonate bodies. They reflect the broadness of today's modelling approaches and are a sample of the developments and ongoing research carried out with 3D digital techniques on carbonates.

Seven papers of the special issue study carbonates in 3D by combining classical field work and new emerging digital acquisition techniques.

Jablonska et al. show an example from the Gargano Promontory (Cretaceous Apulian margin) in southern Italy, where large discordant breccia bodies deposited in slope-to-basinal settings. Such depositional architecture may have significant implications for fluid-flow migration and compartmentalization of tight carbonate reservoirs. The paper combines field mapping and UAV-based Structure from Motion (SfM) Photogrammetry with 3D Virtual Outcrop Models (VOM) to build the breccia bodies exposed on inaccessible cliffs. The obtained VOM are used to characterize the size and shape of these sedimentary bodies and provide insights that support the interpretation of the breccias complex as the result of sidewall collapse produced by solution along a wide fault damage zone.

The paper by ***Larssen et al.*** describes a workflow integrating multi-scale outcrop data from fieldwork and geo-referenced Digital Outcrop Models (DOMs) to collect sedimentological-structural data and to investigate the natural fracture network of the Upper Permian carbonate-dominated succession in Norway. Exploiting observations and data from the 3D models provide a better understanding of the heterogeneity in fracture characteristics, an element that could help in the characterization of subsurface reservoirs in similar geologic bodies. The results in the Upper Permian carbonates suggest that fracture porosity is highly sensitive to fracture aperture and density, but not to fracture length.

Inama et al. integrate Digital Outcrop Modelling techniques and field mapping to investigate the architecture of a Middle Triassic carbonate platform in the Italian Dolomites. The platform crops out extensively but direct investigation in many of its parts is prevented by the exposition conditions. By using the advanced UAV Digital Photogrammetry techniques, the authors reconstruct a high-resolution 3D model of the entire outcrop (2 Km^2). This allows comprehensive characterization of the geometry and distribution of structural and depositional surfaces. These data, integrated with direct field measurement and observations, revealed the presence of two superimposed prograding carbonate bodies (Cassian I and II), that represent two high-stand phases, and whose sedimentary evolution and architecture was partly controlled by synsedimentary normal faulting.

The paper by ***Khanna et al.*** combines UAV photogrammetry, morphometric analysis and geostatistics to study depositional features of Upper Cambrian microbial-build-ups outcropping in Central Texas (USA) considered potential analogs of subsurface hydrocarbon reservoirs in microbial carbonates. Drone photogrammetry produces fine-resolution base maps that are used for performing morphometric analysis including Ripley's k, univariate, multivariate, and grouping. The results demonstrate that at different scales (from few decimetres to hundreds of metres), clustering and the spatial organization of microbial-buildups is non-random.

Thomas et al. use drone photogrammetry integrated with structural and geostatistical modelling to create a metre-scale geological model of prograding oolitic clinoforms of a Bathonian carbonate platform exposed in a quarry in France. They perform an accurate line-drawing correlation and detailed architecture analysis on inaccessible areas. The authors are thus able to identify a platform transect from the tidal flat to slope and provide a good analogue example for reservoir micro-porosity and secondary porosity associated with dedolomitization.

The paper of ***Gianolla et al.*** presents a 3D geological model of an Anisian-Ladinian carbonate platform-to-basin system in the Dolomites of Italy whose deposition was in part coeval to volcanic activity. Their 3D model is based on georeferenced field data collected over a seismic size area and mapped on high resolution Digital Terrain Model derived from LIDAR, and on geological cross sections. Results allow highlighting how carbonate bodies and structural elements were influenced by the volcanic event.

Janocha et al. investigate a Carboniferous succession exposed in the High Arctic archipelago of Svalbard. The stratigraphy exhibits intervals of paleokarst breccias formed by gypsum dissolution. The authors integrate digital outcrop modelling and 2D ground penetrating radar (GPR) to extrapolate external irregular paleokarst geometries beyond the 2D outcrops and directly and indirectly link lithofacies characteristics to GPR facies reflectors.

3D modelling finds large application in the effort of predicting reservoir quality and properties as well as in depicting the high degree of lateral and vertical heterogeneities that can characterize both carbonate and siliciclastic systems. Regarding this issue, four papers in the special volume deal with the forward stratigraphic modelling and reaction transport modelling applied to the study of the architecture and distribution and characters of diagenetic features in carbonate geobodies.

In the paper of ***John et al.***, forward stratigraphic modelling has been used to constraining the stratal architecture and pressure barriers in the subsalt Lower Carboniferous Serpukhovian carbonates in the Karachaganak Field (Northern Kazakhstan), which is characterized by a complex facies architecture and reservoir compartmentalization. In this context, the salt body causes seismic attenuation effect resulting in poor imaging of the carbonates and high uncertainty in their stratigraphic stacking pattern. By using diffusion-based numerical modelling coupled with a sensitivity analysis, the authors illustrate how the application of forward stratigraphic modelling, in particular, can be the best solution to mimic, through a range of numerical elaborations, the biological, chemical and physical process of deposition of sediments.

The paper of ***Gratacós et al.*** illustrates the use of the stratigraphic forward modelling to identify and quantify the complex interplay between carbonate production, sea level and terrigenous clastic sediment supply and to explore the physical, chemical and biological processes controlling facies distribution in time and space in an Aptian carbonate platform top-to-basin succession outcropping in the Maestrat Basin (Eastern Iberia).

Hamon et al. apply an integrated approach based on stratigraphic forward modelling, using the software DionisosFlow, and reactive transport modelling, to analyze the development of a mixed siliciclastic-carbonate sedimentary system and its diagenesis, and to evaluate the mineralogical transformations and resulting changes in petrophysical properties occurred during early diagenesis. The authors realized their work using the realistic case study of the Oligo-Miocene succession of Carry-le-Rouet, South-East of France. This succession is characterized by a complex pattern of bioclastic, bioconstructed and siliciclastic deposits. Several exposure surfaces are associated with meteoric diagenesis. Simulated diagenetic trends are globally coherent with petrographic observations.

The paper by ***Corlett et al.*** describes the application of a 3D geocellular modelling in carbonate systems. 3D geocellular model is often used to reconstruct subsurface hydrocarbon reservoirs in siliciclastic depositional systems, where rock properties are strongly facies-controlled. On the contrary, in carbonate systems depositional and diagenetic history needs to be considered in order to successfully model reservoir properties. The authors illustrate a workflow in which 3D geocellular modelling is applied considering the outcrop analogue of the Hammam Faraun Fault Block, in the Gulf of Suez (Egypt). Sedimentological, petrophysical, diagenetic, and structural information are integrated into a single database and analyzed. Results demonstrate how simple algorithms can be used to capture the geometries of diagenetically controlled geobodies.

Another application of the 3D modelling in carbonate systems is pore-scale modelling by using the 3D microCT-scan technique to evaluate the porosity network and features such as cementation stages.

The paper by ***Bonomo et al.*** illustrates the application of 3D micro-CT scan analyses to reconstruct in three-dimension the geometry and spatial distribution of the real connected porosity, cementation and fluid circulation of the Plio-Pleistocene Calcarenite di Gravina (southern Italy) deposits and investigates the relationship between bioturbation and texture, porosity, permeability and cementation.

Also the paper of ***Matonti et al.***, illustrates the application of 3D microCt-scan to the characterized if the influence of depositional and diagenetic processes on the petroacoustic signature of the heterozoan and photozoan carbonates of the Cape Range Group of the northern Carnavor Basin (NW Australia). The Authors integrate the use the 3D micro-CT scan with numerical forward modelling to quantify the link between carbonate producers, nature of pore types and acoustic properties for a given diagenetic history of distinct carbonates types. They emphasize that the establishment of such links is fundamental in forward modelling since it makes it possible to convert depositional facies into acoustic properties in function of different diagenetic contexts.

The last part of the special issue groups papers dealing with basin and reservoir modelling. Contributions investigate the relation of porosity/permeability to fractured reservoirs and apply different geostatistical approaches to assess the hydrocarbon distribution within carbonate reservoirs.

The paper of ***Zambrano et al.*** assesses the contribution of metre-scale fractures (macrofractures) to the porosity and permeability in a porous carbonate reservoir analogue at the microscale. The authors create dual-porosity/permeability (DP/P) models at the microscale through the integration of different methods of 3D imaging such as, high-resolution synchrotron X-ray microtomography (SR micro-CT) and Structure from Motion (SfM) photogrammetry.

Trippetta et al. test and discuss the accuracy of different modelling solutions, both deterministic (using Kriging) and stochastic (using Sequential Gaussian Simulation- SGS) in the analysis of a large publicly available dataset on hydrocarbons distribution in the Majella Mountain reservoir (central Apennines, Italy).

The paper of ***D'Ambrosio et al.***, instead, discusses the crustal model of an area of the Apennine orogen comprised between the Central Adriatic and Central Apennine orogen/foredeep/foreland system (Italy). The Authors carry out 2D structural restoration and 3D modelling to contrast/compare thick-skin vs thin-skin model and investigate which model could better explain the current known hydrocarbons in the petroleum system of the study area.

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Laura Tomassetti[a,*], Marco Franceschi[b], Beatriz Bádenas[c], Sara Tomás[d], Jeroen Kenter[e]

[a] *Dipartimento di Scienze Della Terra, Sapienza University of Rome, Italy*
[b] *Dipartimento di Matematica e Geoscienze, University of Trieste, Italy*
[c] *Department of Earth Sciences, University of Zaragoza, Spain*
[d] *Institute of Geosciences, University of Potsdam, Germany*
[e] *TOTAL CSTJF, Pau, France*

[*] Corresponding author.
E-mail addresses: laura.tomassetti@uniroma1.it (L. Tomassetti), mfranceschi@units.it (M. Franceschi), bbadenas@unizar.es (B. Bádenas), stomas@geo.uni-potsdam.de (S. Tomás), jeroen.kenter@total.com (J. Kenter).