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Testing geological assumptions and scenarios in carbonate exploration: insights from integrated stratigraphic, diagenetic and seismic forward modeling

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Abstract

Carbonates are considered complex, heterogeneous at all scales, and unfortunately often poorly seismically imaged. We propose a methodology based on forward modelling approaches to test the validity of common exploration assumptions (e.g. chronostratigraphic value of seismic reflectors) and of geological interpretations (e.g. stratigraphic correlations, depositional and diagenetic architecture) that are determined from a limited amount of data. The proposed workflow includes 4 main steps: 1) identification and quantification of the primary controls on carbonate deposition and the prediction of the carbonate stratigraphic architecture (through stratigraphic forward modelling), 2) identification of diagenetic processes and prediction of the spatial distribution of diagenetic products (diagenetic forward modelling), 3) quantification of the impact of diagenesis on acoustic and reservoir properties, and 4) computation of synthetic seismic models based on various scenarios of stratigraphic and diagenetic architectures and comparison with actual seismic. The likelihood of a given scenario is tested by quantifying the

misfit between the modeled versus the real seismic. This workflow illustrates the relevance of forward modelling approaches for building realistic models that can be shared by the various disciplines of carbonate exploration (sedimentology, stratigraphy, diagenesis, seismic, geo-modelling and reservoir).

Introduction

Carbonate rocks are the results of interacting biological, geological and physico-chemical processes, often over a long period of time. Stratigraphic forward modeling has been demonstrated to be a powerful tool to quantify the controlling parameters (sea level, subsidence, carbonate production, transport...) on siliciclastic and carbonate system architectures and to challenge fundamental concepts of stratigraphy (Burgess et al., 2006; Warrlich et al., 2008; Montaggioni et al., 2015; Spina et al., 2015). There is room for methodologic improvement in exploration of carbonate prospects, particularly by better integrating naturalistic and quantitative approaches. We aim therefore at proposing a robust methodology enabling carbonate explorers to test the validity of commonly-used assumptions (e.g. chronostratigraphic value of seismic reflectors) and of poorly-constrained geological interpretations by integrating the widest span of available data (cores, thin-sections, well-logs, laboratory acoustic and petrophysical measurements...) and by using stratigraphic, diagenetic and seismic forward modelling (Fig.1). Typical exploration tasks that are addressed by the present approach are: 1) verifying and testing stratigraphic well-correlations, 2) revealing the stratigraphic architecture of carbonate systems, 3) developing scenarios of diagenetic evolution and diagenetic architecture, and 4) reservoir property prediction.

As illustrated in Fig.1, the methodology is an iterative loop with successive forward modeling and verification steps. In step 1 a stratigraphic forward model is built by integrating all the available geological data (well-logs, cores, thin-sections, seismic), geological concepts derived

from outcrop analogues and regional tectonic history (e.g. Bosence and Waltham 1990; Warrlich et al., 2008; Kolodka et al., 2016; Montaggioni et al., 2015). The resulting 3D stratigraphic grid is then an input to step 2 which consists in a diagenetic process-based forward modeling. In step 2, diagenetic processes are simulated thus leading to a grid populated by diagenetic facies and associated petrophysical properties (porosity, permeability and mineralogy) (e.g. Paterson et al., 2008; Whitaker et al., 2014; Cantrell et al., 2015; Berra et al., 2016). The grids of porosity and mineralogic composition from step 2 is used in step 3 as an input to rock physics equations for computing P- and S-wave velocities and bulk density. A synthetic seismic model is computed from the velocity and density models by using a simple convolutional model. Finally, Step 4 consists in the comparison between the modeled and real seismic to assess the robustness of the chosen exploration hypotheses (e.g. Eberli et al., 1994; Shuster and Aigner, 1994; Cacas et al., 2008). In conclusion, this loop can be considered as a more objective approach (although manually through incremental sensitivity experiments) to test geological scenarios by minimizing the misfit between the modeled synthetic seismic and the actual seismic data. The comparison between synthetic and actual seismic is therefore expected to help the geoscientists to better predict the dimensions of geological bodies, the stratigraphic architecture, the diagenetic trends and the petrophysical heterogeneities.

Each individual steps of the proposed workflow will be discussed and illustrated by a well-constrained Lower Cretaceous (Aptian) carbonate platform case study from Abu-Dhabi (UAE). The reservoir in this case study is a typical carbonate low-angle ramps that developed along the Tethyan margin during the Early Cretaceous. In such Aptian tropical carbonate ramp systems, rudist bivalves are considered as a major component of the carbonate factory (Steuber et al., 2005). The studied Aptian carbonate system from Abu Dhabi (Yose et al., 2006) is composed of three main architectural elements (Figures 1 and 2): a lower retrogradational

interval (Sequences 1 and 2), an overlying aggrading interval (Sequence 3) and prograding wedges (Sequence 4 and 5).

Step 1: Carbonate forward stratigraphic modeling

Carbonate process-based forward stratigraphic modeling consists in a numerical simulation of stratigraphical and sedimentological processes with the aim of predicting a stratigraphic architecture and facies distribution (see Fig.2). The simulations were performed with the stratigraphic forward model software DIONISOS (Granjeon, 1997; Granjeon and Joseph, 1999). This software allows to analyze the principal factors controlling the development of both carbonate and siliciclastic systems mainly at basin scale (10 to 100 km) and over time durations ranging from 10 kyr to 100 Myr (e.g. Burgess et al., 2006; Montaggioni et al., 2015). The general workflow of the forward stratigraphic modeling approach is summarized in Figure 2. The initial bathymetry is an input of the model. At each time step, DIONISOS simulates three main stratigraphic processes: (1) variations of accommodation space; (2) the sediment supply; (3) the transport of sediment. Accommodation space is simulated using subsidence maps and a eustatic sea-level curve. In this study, only in situ marine carbonate production is simulated for sediment supply. The carbonate production depends on several factors, substratum, water depth, water energy, nutrient supply, light intensity, temperature and salinity. These factors affect growth rates of carbonate. Carbonate production is commonly associated with the light intensity, with high carbonate production in the upper few meters of depth and an exponential decrease with depth (Bosscher and Schlager, 1992). In the DIONISOS software, carbonate production is simulated by three main parameters: (1) the maximum growth rate curve that is modulated by (2) water depth and (3) wave energy. Sediment transport is simulated with a generalized modified diffusion equation, replicating at the basin scale sediment shift in the direction of water flow. DIONISOS uses two empirical equations based on slope gravity-

driven diffusion and water mass-driven diffusion equations (Granjeon, 1997). Sediment dispersal is mainly simulated with a diffusion equation (e.g. Quiquerez et al., 2004; Williams et al., 2011).

The major inputs of the DIONISOS modeling approach are: 1) the initial paleotopography, 2) the eustatic curve, 3) subsidence maps, 4) carbonate production rates curves (with water depth and time), 5) parameters related to water energy and sediment transport (prevailing wind direction, fetch, wave energy...) 6) time length and time increment. Once the geological parameters have been set, the numerical simulation starts by simulating and stacking paleoenvironments through time and space thus resulting in a 3D grid of the stratigraphic architecture of the carbonate system (Fig.2, 2). The final step consists in a quality control (QC) (Fig.2, 3) of the modeled stratigraphic architecture against the real seismic to check that the main seismically interpretable features are modeled (e.g. progradations, shelf boundaries).

The key geological parameters used for the process-based forward stratigraphic of the Lower Cretaceous case study are summarized below (Table 1):

- *Initial paleotopography*

The model area a represent square of 80x80 km² and grid point spacing is 1 km wide. This surface correspond to the size of a hydrocarbon field in the United Arab Emrirates in the Shuaiba formation (Yose et al., 2006). The initial paleotopography was derived from the published paleogeographic maps (Yose et al., 2006). However, the simulation tests demonstrated the need to add a global tilt of 0.02° on initial topography in order to reproduce the overall progradation pattern, the shelf dimensions and slope gradients of the series (Fig.3). This tilting is probably related to a differential burial of the margin towards the basin. This tilt

is comparable with the slope difference between the interior craton and the recent Arabian Gulf (Williams et al., 2011).

- *Eustasy and subsidence*

The eustatic variation used the short term Haq (2014) reference curve. (Fig.2).

The subsidence maps are derived from the equation:

$\Delta S = (\Delta T + \Delta W) - \Delta E$ for each sequence boundary. Where Δ represents a variation between time n and time $n+1$, S is the subsidence, T is the cumulated sediment thickness, W is the paleo-water depth and E is eustasy. In this study, the average rate of subsidence ranges from 10 to 40m/My (Fig.2).

- *Carbonate production*

On the basis of core and outcrop studies, three main paleoenvironmental domains have been defined (inner-platform, outer-platform and basin) and corresponding carbonate production rates have been estimated (Yose et al., 2010; Maurer et al., 2010). These are the “building blocks” for DIONISOS numerical simulation. The values of carbonate production are defined for each paleoenvironmental domain as follows (Fig. 2):

$$P_L = P_{ref} \cdot P_{bathy.L} \cdot P_{wave.L}$$

P_L is the carbonate production rate by paleoenvironment, P_{ref} is the production of reference (maximum, production capacity), $P_{bathy.L}$ is the bathymetric coefficient and $P_{wave.L}$ takes into account the influence of water energy.

P_{ref} ranges from 100 to 500 m/Myr for inner and outer platform and from 20 to 80 m/My for basinal domain (Schlager, 2005) (Table 1).

P_{bathy} characterizes the changes in carbonate production with water depth. In this study, carbonate production is considered as a function of light intensity (Bosscher and Schlager,

1992). Moreover, the chosen curve has been shown to be consistent with the growth of rudist platforms (Pomar 2001). The pelagic production rate is constant along the water column (Fig. 2).

Pwave is a parameter that modulates the effect of wave energy on carbonate production. Carbonate production is effective for wave-energy ranging from 50 and to $\text{kW}\cdot\text{m}^{-1}$ in platform environments, and for wave-energy lower than $50 \text{ kw}\cdot\text{m}^{-1}$ in basinal setting.

Step 2: Diagenetic forward modeling

The 3D stratigraphic grid from Step 1 serves as an input for the diagenetic forward modeling. Based on the understanding of the diagenetic processes and data analysis of the studied area, a paragenetic sequence is built. To achieve that, each sedimentary facies simulated by DIONISOS is associated to a diagenetic transformation and an original permeability-porosity value. The definition of the original porosity and permeability values is based on the analysis of the depositional fabrics.

The diagenetic overprint modeling is performed on a lattice gas automata used to mimic the diagenetic fluid flows and to reproduce the diagenetic processes (Planteblat et al., 2012; Planteblat, 2013). This algorithm mimics the diagenetic fluid flows, physico-chemical processes and subsequent rock by-products. The fluid flow is characterized by a particle displacement following either advective and/or dispersive movements. The particle displacement is controlled by the diagenetic reaction speed (dissolution/precipitation) and the initial depositional facies distribution and petrophysical properties. The fluid rock interaction is characterized by a reaction index impacting the petrophysical properties and mineralogical composition.

The diagenetic history of the Lower Cretaceous case study is characterized by multiple episodes of calcite cementation/dissolution and mechanical compaction (not simulated in this

case). Such mechanical and chemical processes occurred from shallow burial until deep burial stages. The paragenetic sequence is based on a comprehensive study (e.g. petrographic observation, isotope, well logs) where 20 diagenetic events were identified among which several of minor importance (low impact on reservoir properties) (Alsharhan, 1995). Only the dissolution phases related to major exposures during sea level drops were modeled since they were shown to have had a dominant impact on porosity and pore space evolution (Alsharhan and Kendall, 2003; Russell et al., 2002). The numerical modeling is realized by the downward infiltration, from the major unconformities, of a virtual meteoric fluid characterized by a saturation index (with regards to calcite) and a percolation velocity (Step1-3 Fig.5). The numerical simulations are repeated with different fluid parameters until fitting the modeled secondary porosity development with the observed data. The reactivity of the fluids is dependent on the mineralogical composition associated with each sedimentary facies. The output of the simulation is a 3D porosity grid for the carbonate system. The spatial distribution of porosity obtained by diagenetic forward modeling is mainly controlled by: 1) the saturation index of the dissolving fluid with regards to calcite, 2) the initial 3D distribution of depositional facies & associated petrophysical properties, and 3) the location of two surface boundaries: the exposure surface at the top and the water table position at the bottom.

Step 3: Seismic forward modeling

The diagenetic processes of carbonates affect the mineralogical fractions, the porosity, the pore microstructures and grain arrangement. Step 3 is mainly based on the quantification the impact of diagenetic transformations and resulting pore types on the acoustic properties. Fundamental factors controlling the acoustic properties of rocks (P- and S-wave velocity, bulk density) effective stress, source frequency, mineralogy, porosity, pore microstructure and fluids (nature and saturation). A major goal of rock physics is to define quantified relationships linking

velocities and bulk density with such fundamental controlling factors. In carbonate rocks, the diversity and complexity of pore structures, as well as their common heterogeneity make the definition of such relationships difficult (Eberli et al., 2003; Fournier et al., 2011; Borgomano et al., 2013). In order to model the impact of porosity and pore type on the acoustic properties of carbonate rocks, we used a set of two parameters called EPAR (Equivalent Pore Aspect Ratios: α_K and α_μ), which represents a quantitative index of the pore network architecture that is independent of pore volume and mineralogic composition (Fournier and Borgomano, 2009; Fournier et al., 2011). The integration of laboratory and/or well log acoustic measurements and detailed petrographic observations on thin-sections and under SEM allowed the calibration of α_K porosity and α_μ -porosity trends for selected diagenetic transformation. The impact of a diagenetic transformation on velocities is therefore characterized by a change in α_K , α_μ and porosity. The diagenetically-modified velocities are computed from the changed values of α_K , α_μ and porosity and by using Differential Effective Medium computations (e.g. Mavko et al., 1998). By such an approach, we are able to convert a porosity model into a velocity model, by considering assumptions on the nature of the dominant pore types and on the diagenetic processes that controlled the porosity evolution of the carbonate system. Various synthetic seismic models, related to various diagenetic scenarios can be therefore be computed and compared with actual seismic (Fig.6).

The interpretation of a dataset of 214 ultrasonic velocity and porosity measurements from Lower Cretaceous carbonates provided a well-constrained velocity–porosity transform (Fig.7) and allowed the quantification of the impact of pore type and diagenetic history on velocities (Fournier et al., 2011; Fournier et al., 2014). EPAR (α_K and α_μ) parameters are used to link the diagenetic transformations and associated pore network evolution with the elastic properties. Three categories of dominant pore type have been discriminated by means of EPAR: 1) microporous limestones (low α_K and $\alpha_\mu < 0.22$), 2) intergranular and moldic pores (intermediate

α_K and α_μ), and 3) vuggy limestones (α_K and $\alpha_\mu > 0.3$). Additionally, three velocity–porosity trajectories related to distinct diagenetic pathways have been quantified: 1) EPAR preserving micro-scale cementation of micrite, 2) no-EPAR-preserving dissolution with moldic pore development and 3) EPAR-preserving sparry calcite cementation of molds.

Step 4: Modeled vs Actual seismic

Once the velocity and density cubes are obtained by forward modeling approaches, the impedance cube is calculated and a synthetic reflectivity cube can be computed by means of a convolutional model and by using zero-phase Ricker wavelet of frequencies ranging from 10 to 40 Hz. The comparison between the modeled and actual seismic should provide significant insights into typical production topics such as: 1) the geological meaning of seismic reflectors in highly diagenetized carbonate reservoirs, 2) the stratigraphic architecture of the carbonate reservoir, and 3) spatial distribution of petrophysical properties in the carbonate reservoir, 4) lateral variations of depositional and diagenetic facies, 5) the identification and interpretation of diagenetic overprints on seismic expression in carbonate reservoirs.

For the Lower Cretaceous case study, the seismic interpretation of the stratigraphic architecture of the reservoir is significantly improved after performing the proposed carbonate exploration integrated workflow. For example, the prograding pattern of the platform is clearly imaged both in section and time slice (synthetic seismic) enabling to locate the best facies to drill (rudists & corals) (Fig. 8). In addition, the amplitude of the seismic reflector associated to sequence boundaries can vary laterally depending on the intensity of dissolution. As a consequence the proposed approach makes possible to track facies changes and diagenetic boundaries from seismic data.

Potential and limitations of the methodology

The proposed carbonate exploration integrated workflow is an interdisciplinary approach combining sedimentology, diagenesis, rock physics and forward modeling that aims at improving the seismic interpretation of carbonate systems. It gives a scientific framework to study the impact of stratigraphic architecture, facies variations, diagenesis and rock petrophysical properties on the seismic expression of carbonate reservoirs. The proposed methodology allows to perform sensitivity tests (Fig. 10) on stratigraphic & diagenetic scenarios, sequence stratigraphic concept, controlling factors or to answer relevant scientific questions, critical for exploration and production studies. Such approaches are also useful in carbonate exploration and production studies for modeling complex stratigraphic architectures, to generate facies maps away from well-control, to assess the controlling factors and to guide the seismic interpretation when sparse control-point data are available.

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Figure captions

Fig.1: Integrated methodology for carbonate exploration based on stratigraphic, diagenetic and seismic forward modelling. Legend for facies is given in figure 2. The seismic profile and stratigraphic architecture model (step 4) is modified from Yose et al. 2006).

Fig.2: Carbonate forward stratigraphic modeling workflow. The depositional model is derived from Yose et al. (2006) and the sea-level is extracted from Haq (2014).

Fig.3: Influence of initial paleotopography on carbonate stratigraphic architecture.

Fig.4: Lower Cretaceous carbonate producers as a function of P_{Bathy} & P_{Wave} , modified after Granjeon (1999), and Bosscher and Schlager (1992).

Fig.5: Diagenetic forward modeling of meteoric dissolution processes below major unconformities.

Fig.6: Seismic forward modeling using the Seismo-Diagenetic workflow

Fig.7: Velocity-porosity pathways as a function of diagenetic transformations (modified after Fournier et al., 2014)

Fig.8: Comparison of synthetic and actual seismic

Fig.9: Application domain of the integrated carbonate exploration workflow

Fig. 10: Sensitivity test of transport-related parameters on stratigraphic architecture

Table 1: List of the parameters used in simulation. (For detailed discussion and references see text).

Parameters	Values / processes / references
Run time	125.5 – 118 (7.5 Ma)
Time step	0.1 Ma
Cell size	1 km
Area of simulation	80 x 80 km
Stratigraphic simulation	
Eustatic curve	Haq, 2014
Subsidence	30 to 60 m/Ma
Inner Platform, maximum production rate	300 m/Ma
Outer Platform, maximum production rate	500 m/Ma
Outer Shelf, maximum production rate	200 m/Ma
Basin, maximum production rate	100 m/Ma
Erosion	0
Water-driven transport K (diffusion coefficient)	0 à $3 \cdot 10^{-3} \text{ km}^2 \text{ kyr}^{-1}$
Wave action depth	10 to 20 m
Wave progradation angle	N30 to N70
Diagenetic simulation	
Particle displacement	Percolation
Reaction Nature	Dissolution & precipitation
Porosity & Permeability	Russell et al. 2002
Seismic simulation	
Vp	Fischer et al., 1997
Vs	Fischer et al., 1997
Density	Fischer et al., 1997

Table 1: List of the parameters used in simulation. (For detailed discussion and references see text).

Figure 1

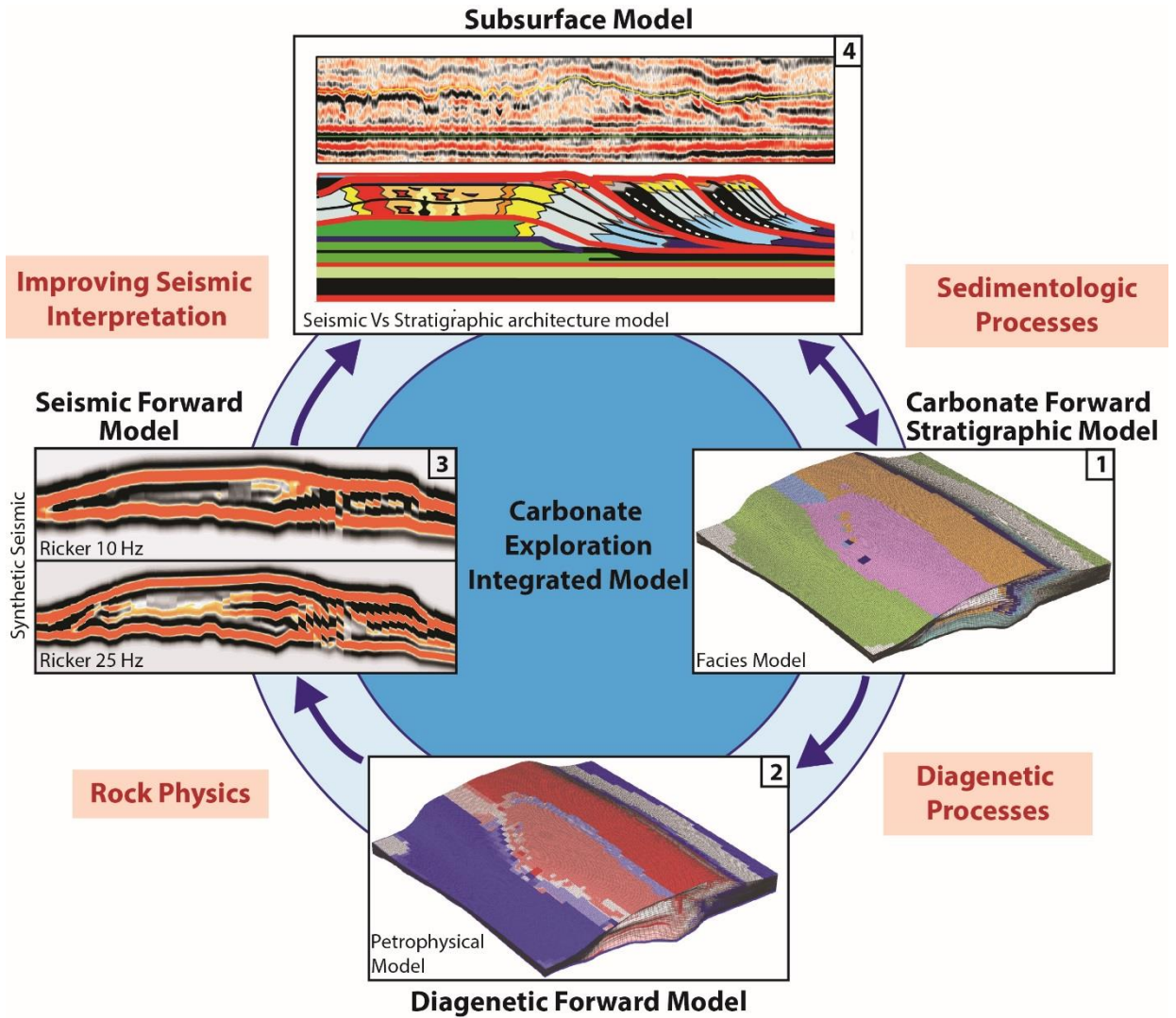


Figure 2

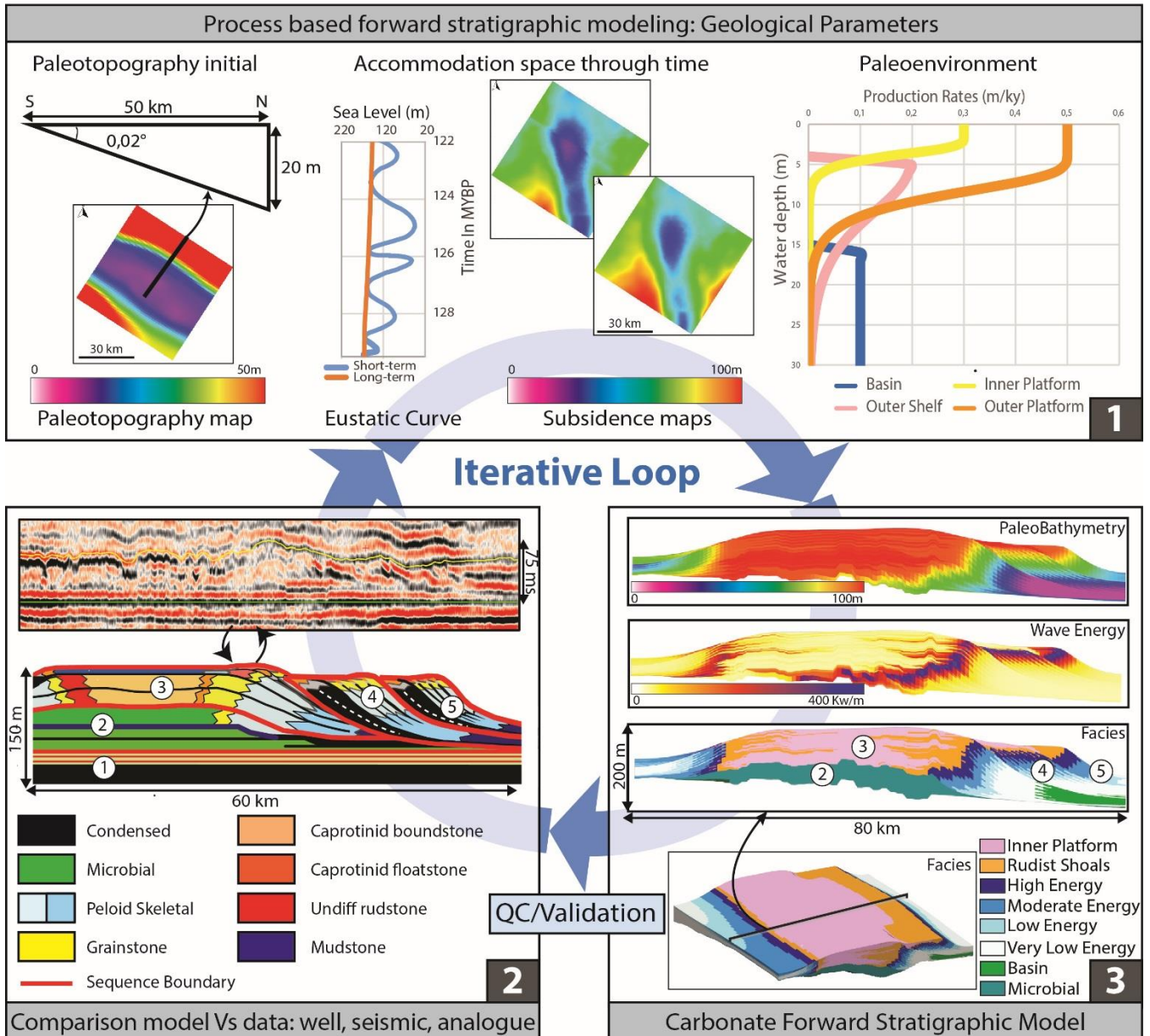


Figure 3

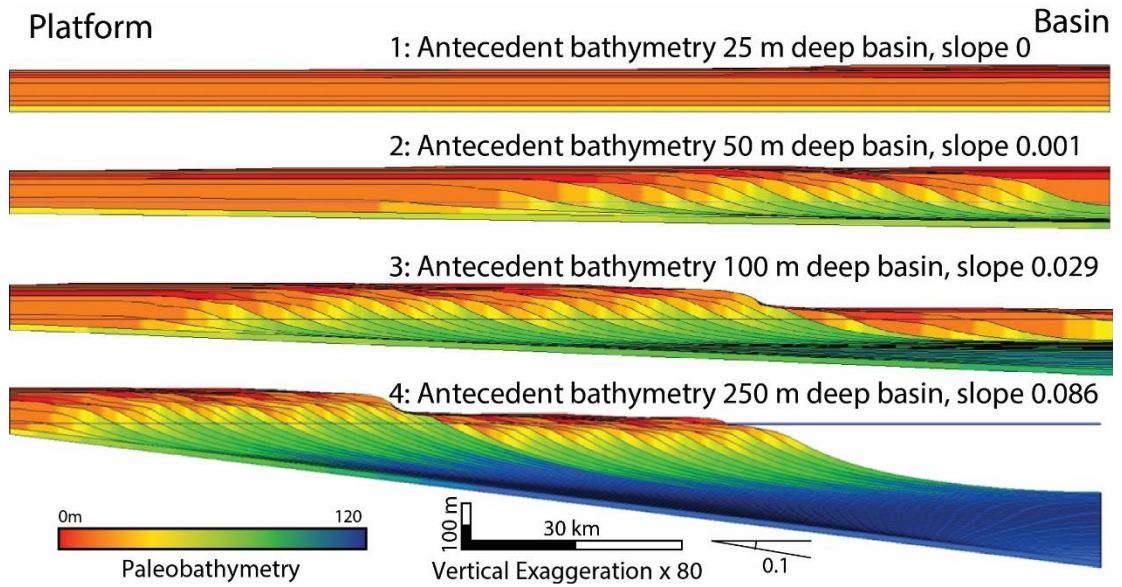


Figure 4

$$P_{L(m/My)} = P_{ref(t)} \cdot P_{bathy.L} \cdot P_{wave.L}$$

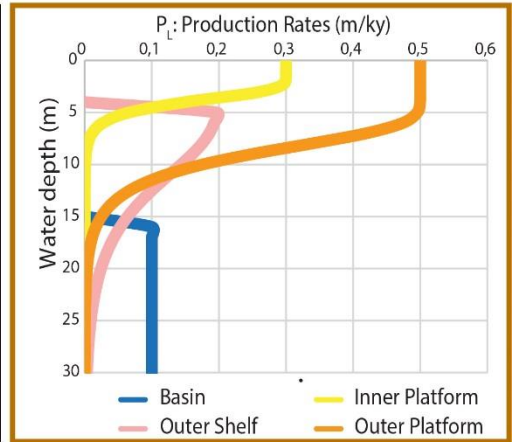
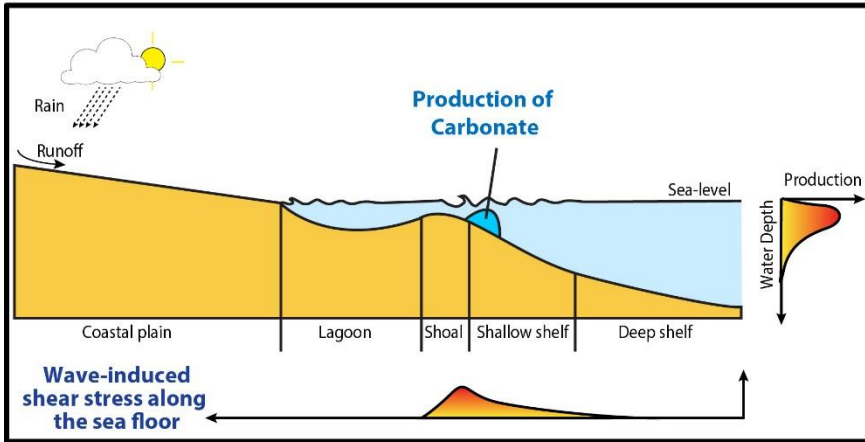


Figure 5

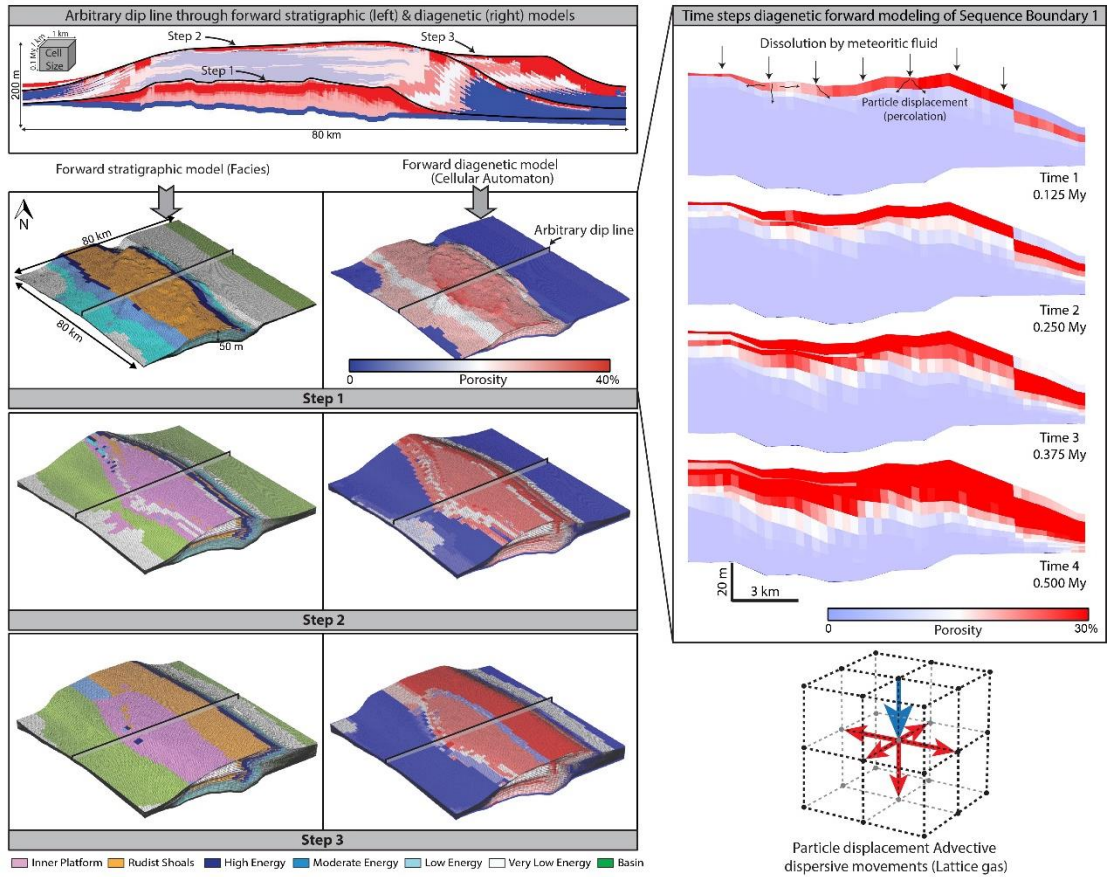
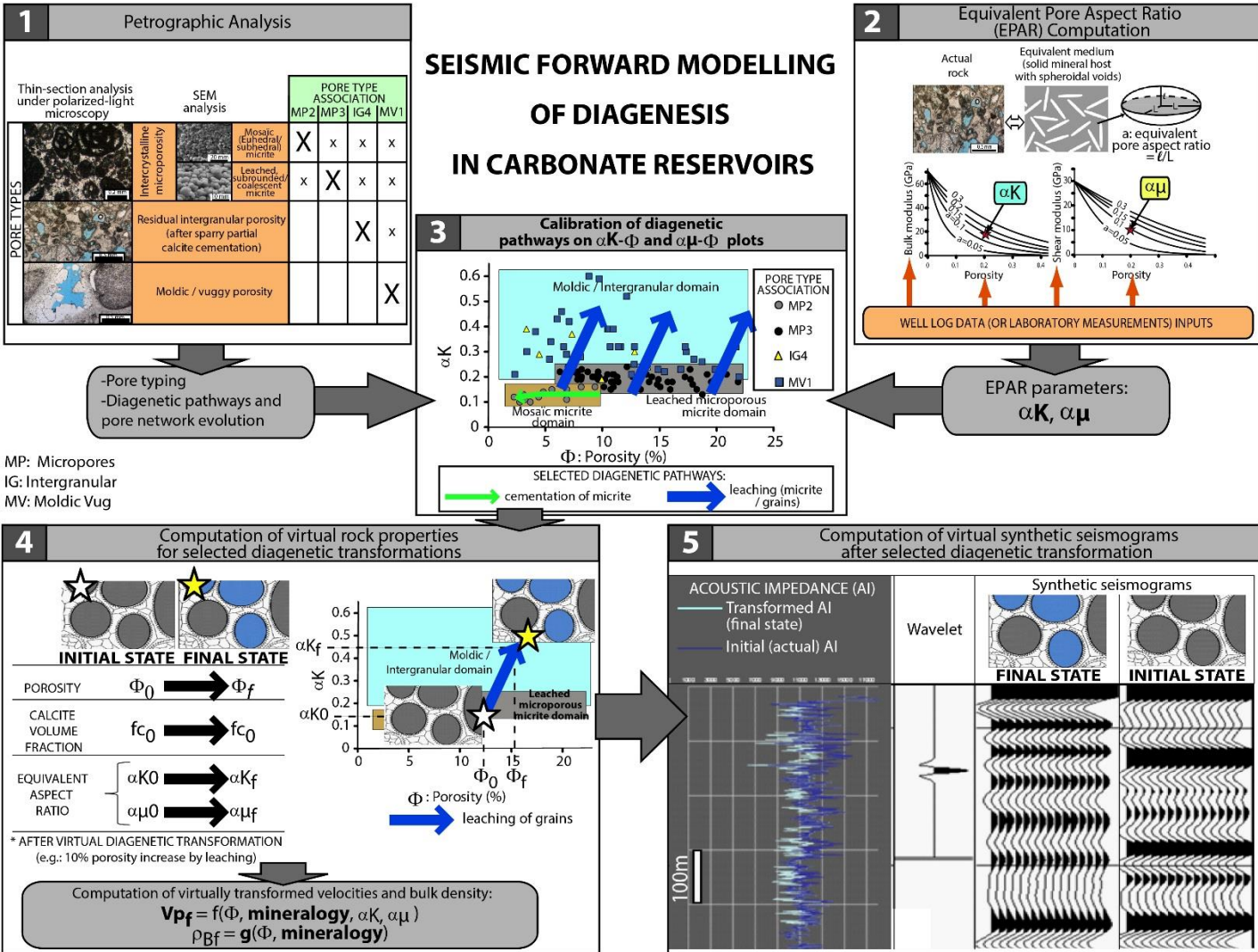
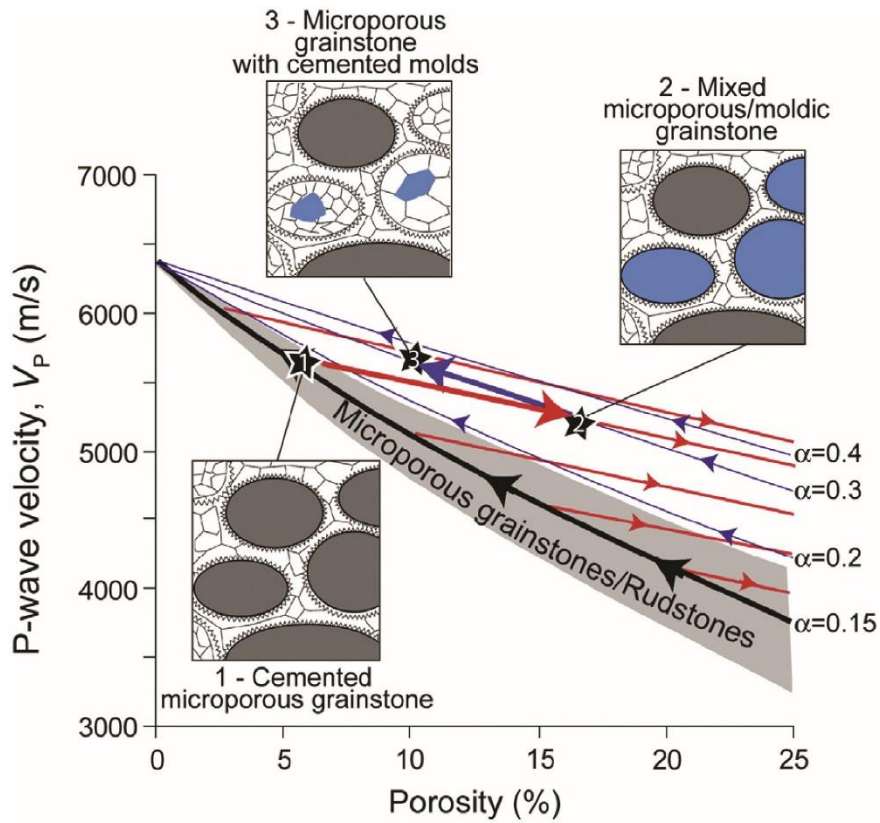


Figure 6



MP: Micropores
 IG: Intergranular
 MV: Moldic Vug

Figure 7



— DEM velocity models of spheroidal inclusions within a calcitic host (α : aspect ratio of spheroidal inclusions)

PORE SPACE TRANSFORMATIONS




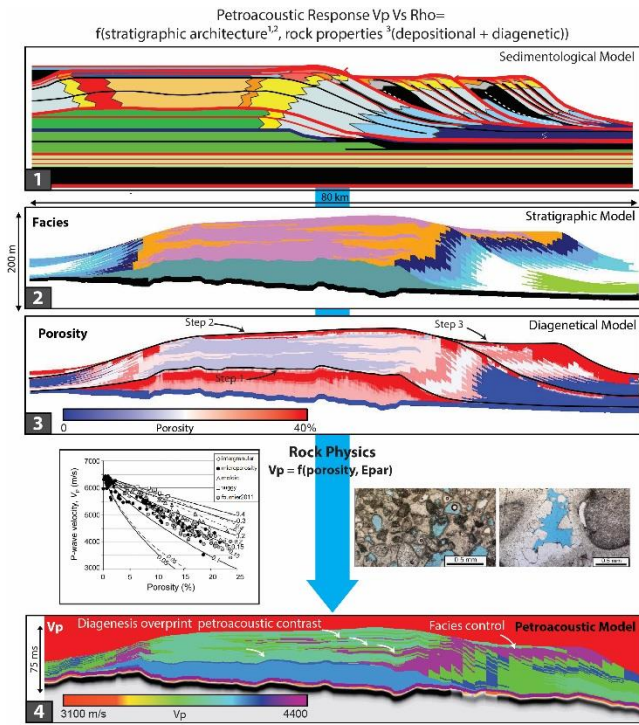
-  Cementation of intercrystalline micropores within micritic grains
-  Leaching : moldic macropore development
-  Occlusion of moldic macropores by sparry calcite cements

Figure 8



Multi 1D Convolutional modeling

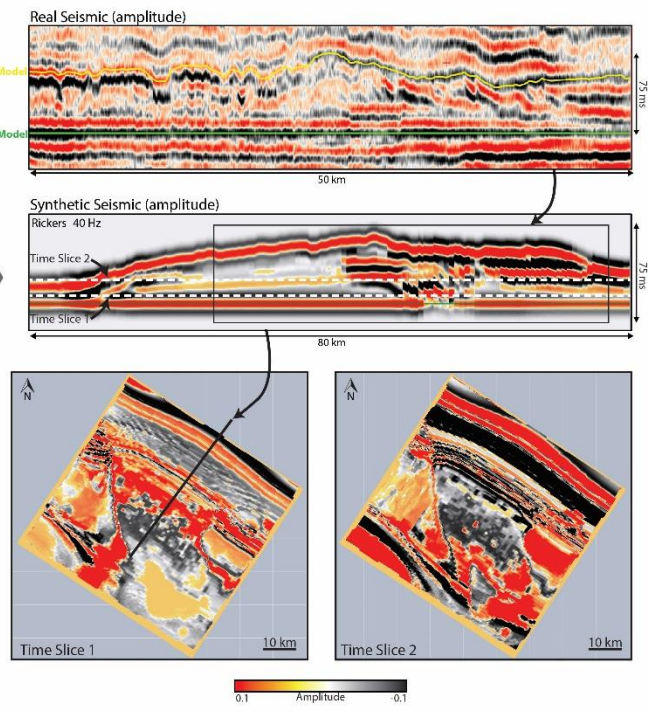


Figure 9

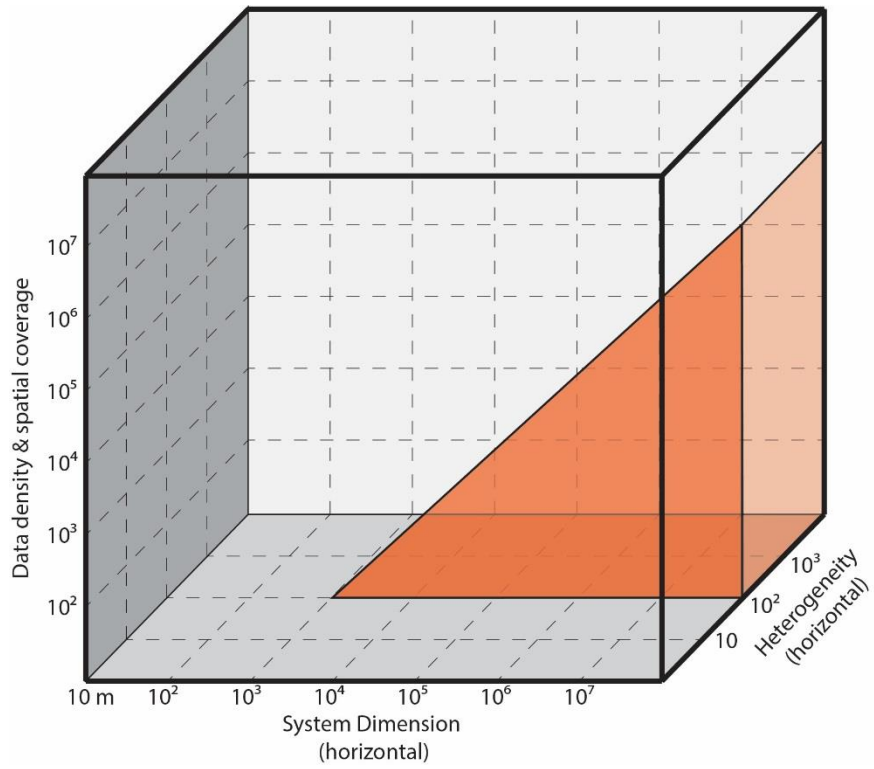


Figure 10

