[PS]Outcrop Analogue for a Mixed Siliciclastic-Carbonate Ramp Reservoir: A Multi-Scale Facies Modeling Approach*

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Abstract

The understanding of fluid flow in carbonates is key to the improvement of reservoir characterization models. Due to the relatively long distances between wells in subsurface reservoirs, outcrop analogues are used to provide insights on the geological complexity at inter-well spacings. The present work models geological heterogeneities of the same outcrop at three scales of organization, i) the depositional sequence, ii) the depositional environment and iii) the lithofacies type.

The study area, located in Amellago (Morocco), is 1 km on each side and 100 m thick. The formation consists of prograding shoals deposited on a low-angle carbonate ramp. The outcrops allowed the acquisition of 19 sections with spacings that range down to 40 m, georeferenced by using d-GPS and LiDAR methods. Based on field data and microfacies analysis, 11 lithofacies grouped into four depositional environments (EODs), were identified. A marly open ramp (EOD 1) deposited from the middle to outer ramp, changing laterally to a semi-restricted ramp (EOD 2) composed of cyanobacteria, oncoids and gastropods within the middle ramp. The inner ramp records shoals bodies in a high energy ramp (EOD 3). “Reef” buildups (EOD 4) are composed of oysters.

The multi-scale approach allows the investigation of spatial variability within shoal belts that extend tens of kilometers, specifically variabilities of morphology, dimensions, heterogeneity and connectivity of geobodies at the three scales of organization. At the kilometre scale, the depositional sequence model indicates a thickening trend of the sequences basinward. For EODs, the model shows that shoal geobodies (23.46% in vol.) average 333 m long, 192 m wide and 4.1 m thick, and their orientation is 125°N. Three types of shoal morphology have been observed, i) planar and continuous, ii) domal with thin connecting bodies and iii) isolated and domal. At the lithofacies scale, the model shows that the shoals are composed of three lithofacies with unique morphological characteristics, a peloidal oolithic packstone-grainstone (1) 330x145x4 m, an

oolithic grainstone (2) 281x163x2 m and a cyanobacteria rudstone (3) 210x191x1 m. The degree of lithofacies heterogeneity within the shoals is variable. These changes in morphology and heterogeneity are likely controlled by the position of the fair-weather wave base (FWWB) in comparison to the sea floor. Around the FWWB, the interplay of everyday waves and storm waves seems to increase heterogeneity

Part 1

Outcrop Analogue for a Mixed Siliciclastic-Carbonate Ramp Reservoir: A Multi-Scale Facies Modelling Approach

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1- Multi-Scale Geological Heterogeneity: Problematic and Objectives

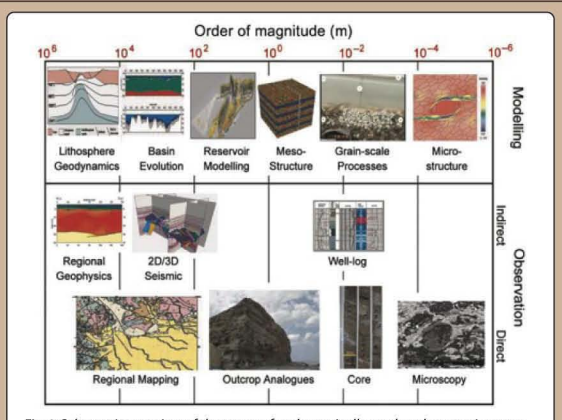

Fig. 1: Schematic overview of the range of scales typically used to characterize reservoir properties. Note that outcrop analogue covered a lack of indirect geophysical data at the hundreds of metre scale (after Jones et al., 2008).

Reservoir properties and in general geological features range in a broad scale of observation from micrometre to hundreds of kilometre (Fig. 1). Consequently, reservoir modelling needs to investigate and combine together data on the geodynamic context, basin evolution, heterogeneity of geological bodies and microstructures of a specific target in order to properly i) build a geological model (stochastic or deterministic simulation) and ii) predict fluid flow pattern. In a modelling point of view, the variability of geological association and distribution at different scale of observation (Figs 2 and 3) involves the use of different modelling methodology.

Objectives

The present study area focuses in a range of observation from 1 kilometre to micrometre corresponding to the basin evolution and to the microscopic analysis of lithofacies, respectively. The main guideline of the present study is how variable is geological heterogeneity between these different scales of observation and how can we integrate them into a geocellular model?

In this context, the main objectives of the present study are:

1- **Characterization of potential reservoir properties** (morphology, distribution and connectivity of geobodies) within an oolitic carbonate ramp (High Atlas, Morocco)

2- Development of a **Digital Outcrop Model** using GPS mapping survey of key sedimentological features and LiDAR data.

3- Establishement of **specific modelling methodology** for each scale of observation.

Basin Evolution

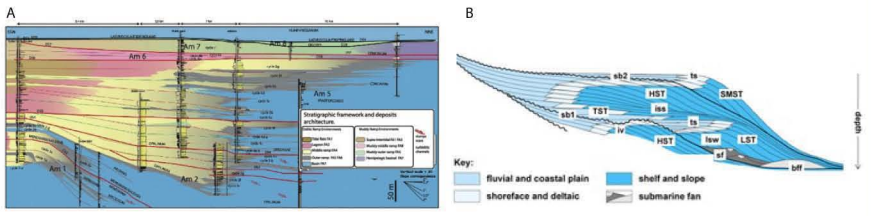

Fig. 2: Methodology to understand basin evolution using sequence stratigraphy. Example of reconstruction of basin evolution (A) using stacking pattern of system tracts (B).

At the kilometre scale, geologist uses sequence stratigraphy in order to identify progradation, retrogradation and aggradation stacking pattern in the sedimentary record and then, reconstruct the evolution of the basin (Fig. 2). In this example, the spatial distribution of depositional environements are mainly predictable from the tidal flat in brown to the lagoon in pink, the shoal complex in yellow and the offshore superior in grey and inferior in blue. This scale of observation allows to **predict where reservoirs can occur though the depositional system**. However it does not answer crucial questions required to improve prediction of reservoir properties at the inter-well spacing. To answer these questions, geologist and modeller need to investigate hundreds of metre to meter scale geological variability.

Facies Mosaic

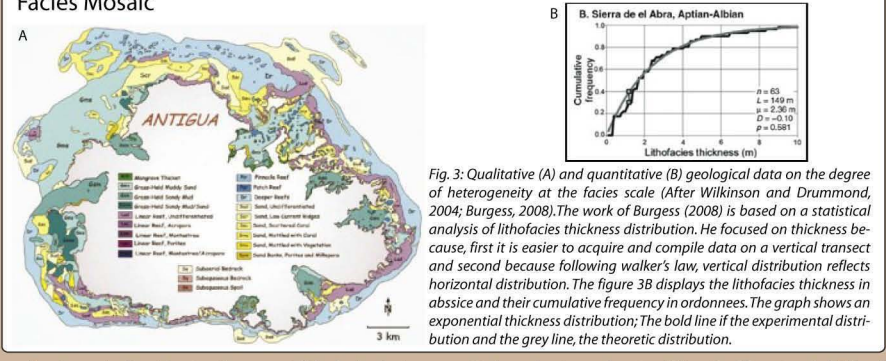

Fig. 3: Qualitative (A) and quantitative (B) geological data on the degree of heterogeneity at the facies scale (After Wilkinson and Drummond, 2004; Burgess, 2008). The work of Burgess (2008) is based on a statistical analysis of lithofacies thickness distribution. He focused on thickness because, first it is easier to acquire and compile data on a vertical transect and second because following walker's law, vertical distribution reflects horizontal distribution. The figure 3B displays the lithofacies thickness in abssice and their cumulative frequency in ordonnees. The graph shows an exponential thickness distribution; The bold line if the experimental distribution and the grey line, the theoretic distribution.

Previous studies tries to document lithofacies heterogeneity in order to understand the significant variability of carbonate deposits observed within shallow-water environment and then improve predictability.

The figure 3A provides an insight on lithofacies distribution within a Holocene carbonate atoll. As you can see, there is a siginificant spatial disorder, which is called lithofacies mosaic. The **term mosaic reflects the stochastic aspect of geological heterogeneity**. Quantitative investigation has been carried by burgess 2008 (Fig. 3B). The exponential distribution displays by shallow-water carbonate rocks (Fig. 3B), indicates a deposition mode or record process involving stochastic Poisson process. The latter study compiles numerous outcrop investigations all around the world.

3- Methodology

Sedimentological data collection

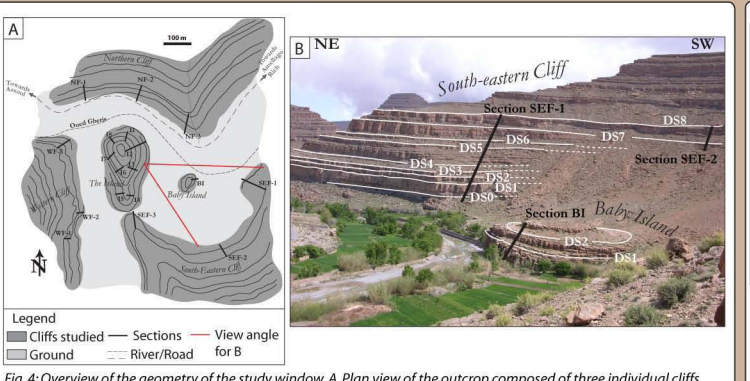

Fig. 4: Overview of the geometry of the study window. A. Plan view of the outcrop composed of three individual cliffs and two isolated reliefs in the central part of the figure. Note the amount of sections carried out in the field due to the well outcrop exposures. B. Pictures of the "South-Eastern Cliff" and "Baby Island" outcrop. The view angle of the picture is shown in A. Nine discontinuity surfaces (DS; white line), which has been mapped in the field thank to their outcrop conditions and three sections (Black line) are located in the figure.

Logging

In order to characterize lithofacies types and their spatial variabilities:

- **19 densely-spaced stratigraphic sections** have been carried out bed by bed (Fig. 4). The inter-section spacing ranges from 40 to 250 m.
- **Lateral bedding and facies transitions** have been traced.
- In the laboratory, **150 thin-sections** were analyzed.
- **X-ray Diffraction** was used to determine the type and proportion of clay minerals in marls.

Multi-scale modelling strategy

A multi-scale approach is used to build the digital outcrop model and consists on three steps:

- **First**, the model framework consists on the extrapolation of sequence boundaries between data points.
- **Second**, a geological model at the depositional environment scale is built using **TGSim algorithm**.
- **Third**, the building of a lithofacies model is carried out using **SISim algorithm** in order to understand the degrees of heterogeneity within each depositional environment.

Georeferencing of key geological features

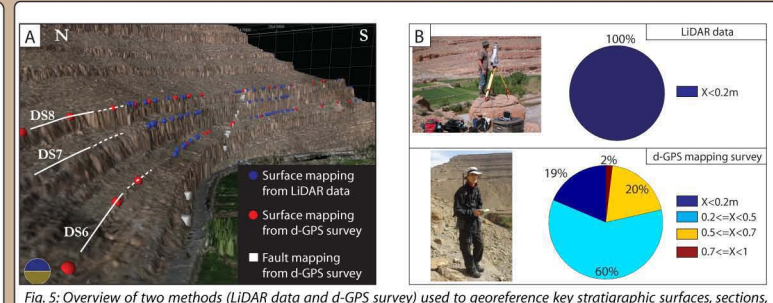

Fig. 5: Overview of two methods (LiDAR data and d-GPS survey) used to georeference key stratigraphic surfaces, sections, faults and DEM associated with their corresponding quality factors. A. Picture from Petrel showing a significant fit between DEM and GPS points of key surfaces (DS6, DS7 and DS8) mapped directly in the field (red point) and from the photo-textured topographic model built using LiDAR data (blue point) (Fig. 6). B. Pie chart pointing out the similarity of quality factors of GPS points between both methods, LiDAR and d-GPS survey. On the left side, pictures of the device during the data acquisition are shown.

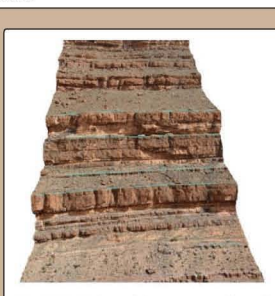

Fig. 6: LiDAR data of the outcrop collected by terrestrial LiDAR during the field season.

A GPS mapping survey was carried out using two methods, d-GPS mapping and LiDAR data (Fig. 5). The d-GPS mapping consisted of two single-frequency receivers, which worked simultaneously. The first one, called "rover" was used in two different modes to collect points. The "moving point" acquisition mode allowed a quick mapping of a large area with a resolution of about 0.7 m. The second one called "static point" acquisition mode, for which the unit must remain stationary at a location for a period of time, was used to measure specific high-resolution (< 0.5 m) points, such as the top and base of sections. The second d-GPS receiver, called "static base station", was mounted on a tripod at a distance of 8 km from the study window. The base collects second-by-second satellite data correction relative to a reference point location, which was used for the post-processing of data points acquired with the rover.

LiDAR data (Fig. 6) was used to i) to obtain an accurate DEM (20 cm accuracy) and ii) map geological data for inaccessible outcrop areas by picking surfaces and faults on the photo-textured topographic model like for seismic interpretation. Outlier between two datasets are not observed thank to the similar GPS point accuracy below 0.5 m between both mapping techniques.

4- Geological Setting: Shallow-Water Carbonates from Assoul Formation

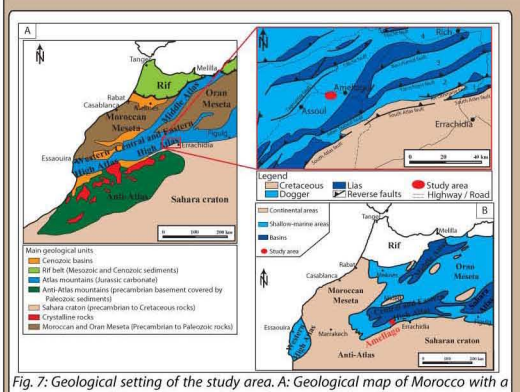

Fig. 7: Geological setting of the study area. A: Geological map of Morocco with a close-up view of the study area. The south margin of the High Atlas mountain is composed of 5 tilted blocks, 1: Boutazart block, 2: Ait Othmane block, 3: Seddour block, 4: Rich block and 5: Tillicht block. B: Palaeogeographic reconstruction of northwest Africa during the Middle Lias (modified after Bloemeier & Reijmer, 1999).

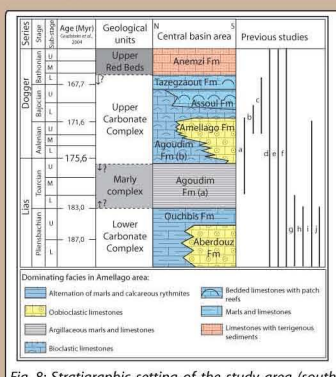

Fig. 8: Stratigraphic setting of the study area (south margin of the High Atlas mountains) during the Lias and Dogger (Milhi et al., 2006; Pierre, 2006) associated with a compilation of previous studies in the region.

Situated 50 km toward the west of the city of Rich, the study window is located in Assoul Formation (Fig. 7). The 220 m thick Assoul Formation represents the progradation of shallow-water carbonate deposits of a ramp system toward the basin that is recorded by marl deposits of Agoudim Formation (Figs 8 and 9).

During the **Bajocian**, the ramp system is composed of:

- An **inner ramp** with numerous kilometre long **oolithic- and peloidal-dominated shoals** and marly deposits within the back-shoal. The fore-shoal deposits are characterized by intraclastic rudstone dominated by centimetre-sized cyanobacteria nodules.
- A **middle ramp** with **mud-dominated lithofacies** showing bioclasts of gastropods, corals debris, bivalves, cyanobacteria and brachiopods. Toward the distal middle ramp setting, alternating mud-marls are deposited and composed of brachiopods and echinoid spines debris. The latter lithofacies are associated with hundreds metre long and few metres thick oyster-dominated bioconstructions (Amour et al., in press).
- An **outer ramp** with thick and laminated marl deposits.

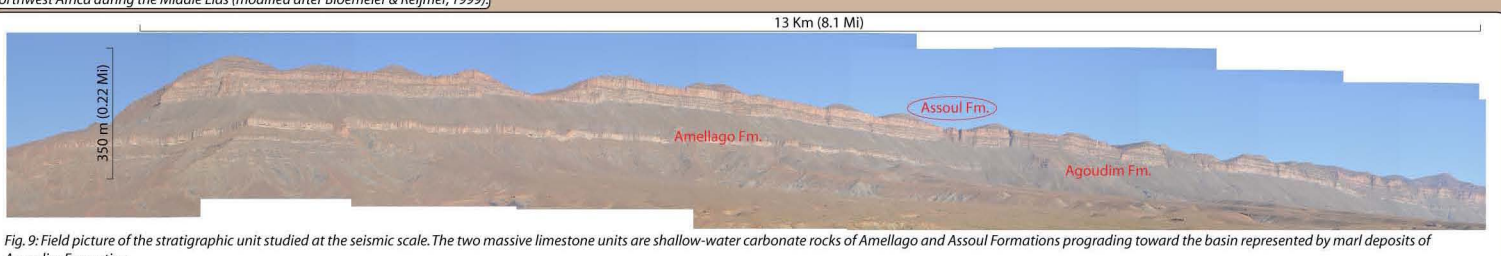

Fig. 9: Field picture of the stratigraphic unit studied at the seismic scale. The two massive limestone units are shallow-water carbonate rocks of Amellago and Assoul Formations prograding toward the basin represented by marl deposits of Agoudim Formation.

Part 2

Outcrop Analogue for a Mixed Siliciclastic-Carbonate Ramp Reservoir: A Multi-Scale Facies Modelling Approach

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5- Lithofacies Types and Depositional Environments

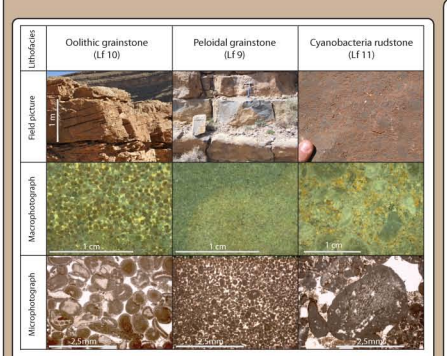

Fig. 10: Micro- and macroscopic characterization of grain-supported lithofacies ranges from proximal (Lf 10) to distal (Lf 11) part of the shoal complex.

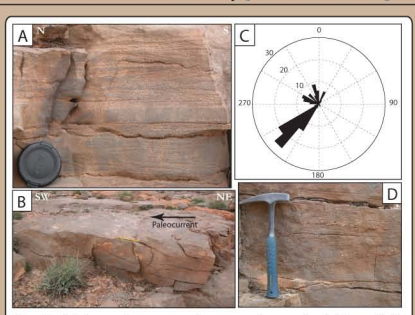

Fig. 11: Major paleocurrent features observed within oolithic grainstone lithofacies and measured in the field. A. Bidirectional ripples showing quiet periods with the occurrence of homogeneous centimeters thick oolithic grainstone layers. B. Asymmetric ripples showing unidirectional current toward the land. C. Major paleocurrent direction of 225°N thank to around one hundred measurements in the field. D. Brachiopod shells layers within the oolithic shoals showing the influence of storm event or high tide.

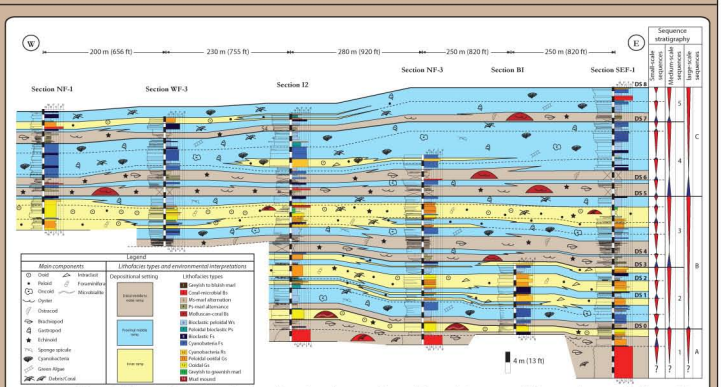

Fig. 12: West to East correlation showing the stratigraphic architecture of the study area (Refer to Fig. 4 for location of sections).

Three depositional settings are identified an outer to distal middle ramp composed of alternating mud/marls, a proximal middle ramp with mud-dominated lithofacies and an inner ramp dominated by grain-supported lithofacies and composed of (Fig. 13):

- A **fore-shoal**, which consists of **rudstone bodies** with sub-rounded oncoliths preserving filaments of cyanobacteria (Fig. 10)
- A **Lower shoal** composed of very-well-sorted **peloidal grainstone bodies**. Superficail ooids are present to frequent and radial ooids are rare.
- An **Upper shoal** with **oolithic grainstone bodies**. Ooids are mainly superficial with in less amount laminated fine radial cortical fabric. Numerous directions of paleocurrent have been measured and the major direction is 45°N showing a paleoflow toward the southwest (landward).
- An **Inter- to back-shoal** composed of thick, greyish to greenish **marls interbedded with medium- to poorly-sorted oolithic grainstone** showing numerous millimetre-sized micritic and oolitic intraclasts.

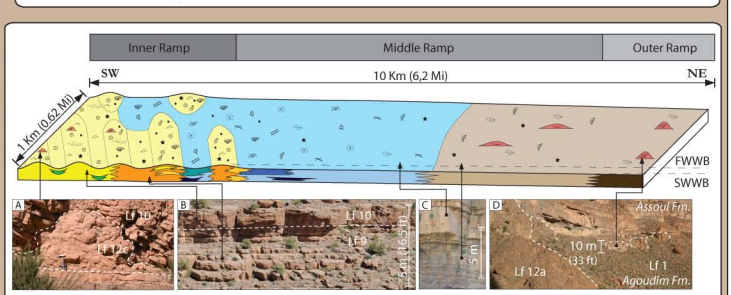

Fig. 13: Palaeodepositional profile reconstruction of the Bajocian carbonate ramp of Assoul Fm. within the southern margin of the Atlas rifting basin with field pictures showing the major contrasts of bedding stacking between geological bodies (Refer to Fig. 12 for color legend).

6- High-Frequency Depositional Sequences

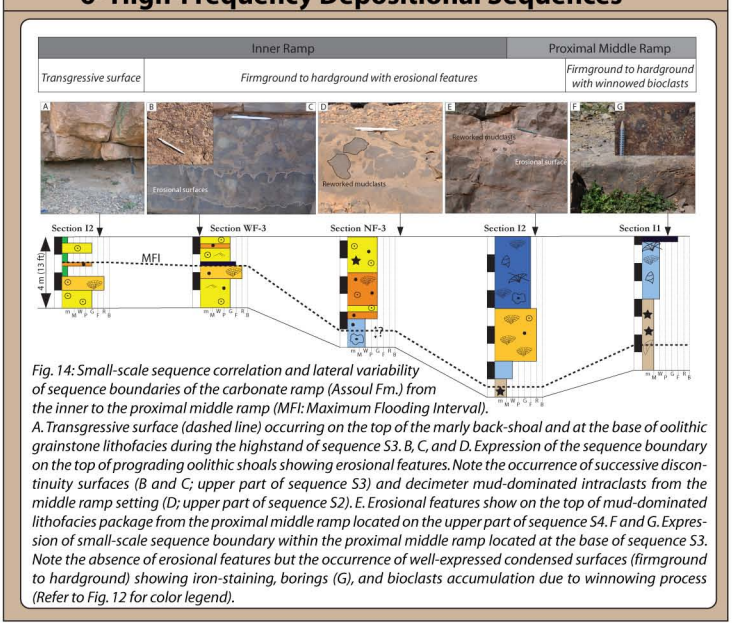

Fig. 14: Small-scale sequence correlation and lateral variability of sequence boundaries of the carbonate ramp (Assoul Fm.) from the inner to the proximal middle ramp (MFI: Maximum Flooding Interval). A. Transgressive surface (dashed line) occurring on the top of the marly back-shoal and at the base of oolithic grainstone lithofacies during the highstand of sequence S3. B, C, and D. Expression of the sequence boundary on the top of prograding oolithic shoals showing erosional features. Note the occurrence of successive discontinuity surfaces (B and C; upper part of sequence S3) and decimeter mud-dominated intraclasts from the middle ramp setting (D; upper part of sequence S2). E. Erosional features show on the top of mud-dominated lithofacies package from the proximal middle ramp located on the upper part of sequence S4. F and G. Expression of small-scale sequence boundary within the proximal middle ramp located at the base of sequence S3. Note the absence of erosional features but the occurrence of well-expressed condensed surfaces (firmground to hardground) showing iron-staining, borings (G), and bioclasts accumulation due to winnowing process (Refer to Fig. 12 for color legend).

7- Facies Heterogeneity

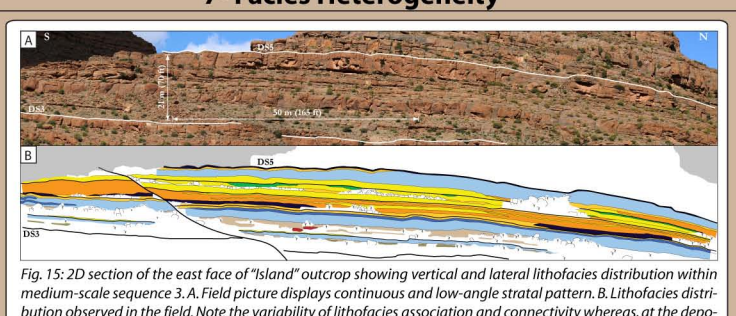

Fig. 15: 2D section of the east face of "Island" outcrop showing vertical and lateral lithofacies distribution within medium-scale sequence 3. A. Field picture displays continuous and low-angle stratal pattern. B. Lithofacies distribution observed in the field. Note the variability of lithofacies association and connectivity whereas, at the depositional setting scale, a layer-cake stratal pattern is observed (Refer to Fig. 12 for color legend).

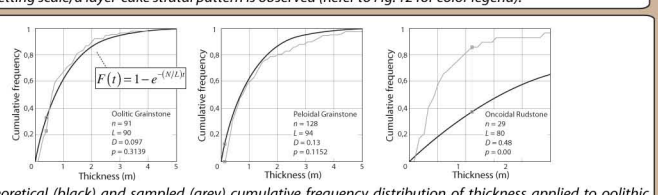

Fig. 16: Theoretical (black) and sampled (grey) cumulative frequency distribution of thickness applied to oolithic grainstone, peloidal grainstone and oncoidal rudstone. The formula of the theoretical distribution (black square) reflects an exponential distribution, where T is the thickness, n is the number of lithofacies units and L the stratigraphic thickness studied. The maximum difference between both curves is called D (grey square). The significant probability p above 0.1 shows that lithofacies can be characterized by an exponential distribution of their thickness.

8- Modelling Phase 1: Data Input and Analysis

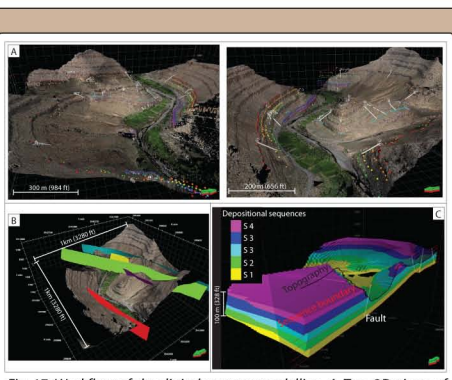

Fig. 17: Workflow of the digital outcrop modelling. A. Two 3D views of the data input including GPS points from the mapping of i) key stratigraphic surfaces (pink to red points) and ii) faults (grey squares). Moreover the georeferencement of sections allows their integration into the model (white lines). The DEM has been build using the LiDAR data. B. Dimensions of the digital outcrop model and location of the five majors post-depositional faults observed in the field. C. Building of the depositional sequence model using geological data described above.

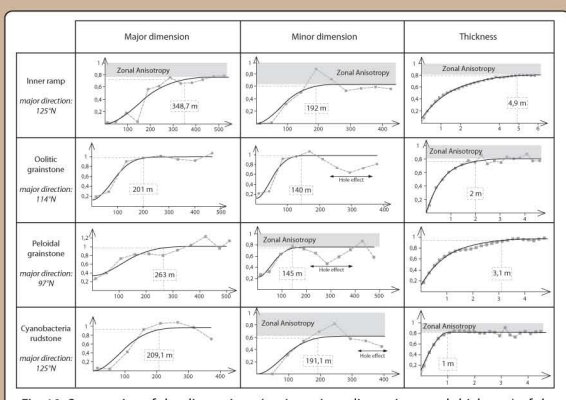

Fig. 18: Summarize of the dimensions (major, minor dimensions and thickness) of the inner ramp and grain-supported lithofacies using semi-variogramms. Note the fitting between experimental variogramms (dashed grey curve) and modelled variogamms (black cuve).

After importing data and building the framework of the model (Fig. 17), semi-variogramm needs to be determined in order to better constraint stochastic simulation (Fig. 18):

- **Inner ramp geobodies** (25% in volume) are 350 m long, 190 m width and 5 m thick. Their preferential orientation is 125°N, which is perpendicular to paleocurrent measurements carried out in the field (Fig. 11). A high degrees of spatial anisotropy is also observed. Called zonal anisotropy, this variogramm behavior suggests that **at the scale of the depositional environment (>1 km), geobodies morphology is difficult to determine**.

- At the **lithofacies scale**, shoal bodies are around 200 m long, 150 m width and few metre thick. **The investigation of geobody dimensions is more accessible** because of the decrease of zonal anisotropy. The hole effect (Fig. 17) points out the occurrence of two successive geobodies correlated over a large distance and separated by another type of geobody.

9- Modelling Phase 2: Multi-scale Approach

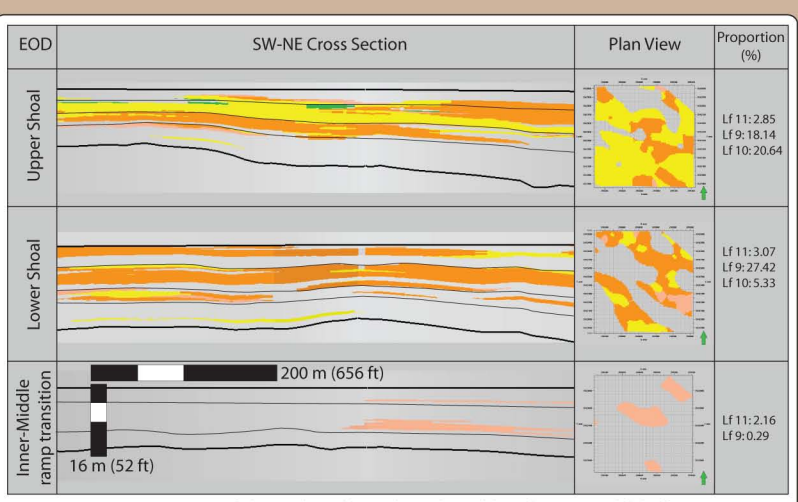

Fig. 19: SW-NE cross-section of the multi-scale geological model and associated lithofacies proportion within the upper to back-shoal, lower shoal and fore-shoal (Refer to Fig. 12 for color legend).

The final model shows that the distribution and connectivity of individual and hundreds metre long geological bodies described above, evolve through time. **Connectivity and distribution depend of the stacking pattern of small-scale deposition sequences**, which leads to the occurrence of three different types of shoal morphology (Fig. 19):

- Within the **proximal part of the middle ramp**, grain-supported geobodies form **individual and hundreds metre long geobodies** surrounding by mud-dominated lithofacies. The degrees of horizontal and vertical connectivity between bodies is increasing landward leading to more complex morphology.

- Within the **lower shoal**, peloidal grainstone lithofacies are characterized by **planar and kilometre long bodies** as shown in medium-scale sequence 2 (Fig. 12). The high degree of horizontal bodies connectivity contrasts with their individualization in vertical direction. The stacking pattern of small-scale cyclicity involves a significant **vertical compartimentalization** of the potential reservoir.

- Within the **upper shoal**, grain-supported geobodies show **high horizontal as well as vertical connectivity** between small-scale sequences, which form up to **5 metres thick domal geobodies**.

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