PS Geometric Quantification of Dolomitized Clinoforms Using Digital Outcrop Models and Surface-Based Modeling: Insights for Geobody Connectivity From Outcrop Analogues*

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Abstract

Carbonate clinoforms have a proven track record as successful hydrocarbon targets, such as those in the Wasson and Means fields of the Permian Basin. However, reservoir characterization of these lucrative plays is often difficult due to their complex geometries and additional heterogeneity arising from diagenetic processes such as dolomitization. This leads to difficulties in predicting and quantifying static and dynamic behavior within these reservoirs. Our study aims to answer these questions by quantifying and characterizing an outcrop analogue of dolomitized carbonate clinoforms using digital outcrop model studies; and subsequently testing the impact of different interpretations (degree of dolomitization, facies boundary positioning, porosity and permeability distributions) on flow behavior within these clinoforms. Our flow simulations use a novel surface-based modelling (SBM) approach coupled with an unstructured mesh flow simulator (IC-FERST). In contrast with conventional geomodelling techniques, SBM can more accurately preserve complex geometries realistically, such as those found in clinoforms and dolomite geobodies without the resolution and geometry limitations related to traditional cornerpoint grids. Our outcrop analogue in Seru Grandi in Bonaire consists of a series of heterogeneous shallow marine red algae rich clinoforms partially replaced by tongues of Late-Miocene dolomite that extend down from an erosional unconformity marking the transition to overlying undolomitized limestone.

Detailed geometrical measurements taken on the digital outcrop model form the input for subsequent modelling. Clinoforms are on average 33 m long and 9 m high, with dolomite bodies ranging from 10 - 30 m long and porosity values ranging from 3 % to 28 %. This database of outcrop geometry quantifications (and variations thereof) is sampled to produce multiple stochastic realizations of surface-based reservoir models at a similar scale to the outcrops (interwell scale). Flow simulation results combined with these geological scenarios can provide a better understanding of the spatial distribution of reservoir properties and provide insights for development planning. This study has direct applications on improving quantification and characterization of complex carbonate subsurface geometries. These improvements allow for

better capturing of carbonate geometries and better predictions of flow behavior and connectivity in these systems and will thus be valuable for exploration, production, and development of analogous existing and future carbonate prospects.

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INTRODUCTION

- Carbonate clinoforms have a proven track record as successful hydrocarbon targets, such as those in the Wasson and Means fields of the Permian Basin.
- Reservoir characterization is difficult and uncertain.
    - Complex geometries.
    - Heterogeneity from diagenetic processes such as dolomitization.
    - Few tools exists to reliably test impact on flow.
- Digital Outcrop Models can provide essential information for characterization.
- Surface-based reservoir modelling allows flow simulations on complex geometries.

AIMS

- **Quantification and characterization of an outcrop analogue of dolomitized carbonate clinoforms.**
- **Testing the impact on flow behavior of different interpretations of:**
    - **degree of dolomitization**
    - **facies boundary positioning.**

METHODS

- **Quantification and Characterization**
    - 3D DOM of the Seru Grandi outcrop is created by drone-based photogrammetry.
    - Geological interpretation is performed on the DOM and ground-truthed in the field.
    - Bounding surfaces are traced on the DOM and geometrical parameters derived for modelling (**Fig 1, Table 2**).
- **Flow behavior**
    - Surface-Based Modelling models heterogeneity explicitly by its bounding surfaces without reference to a predefined grid (Jacquemyn et al., 2019).
    - Flow simulations are performed on surface-based models using a tetrahedral dynamically-adapting mesh flow simulator (IC-FERST; Salinas et al., 2017).
- **Multiple realizations of flow models based on outcrop clinoform measurements (Fig 1, Fig 2) were simulated to test impact on flow**

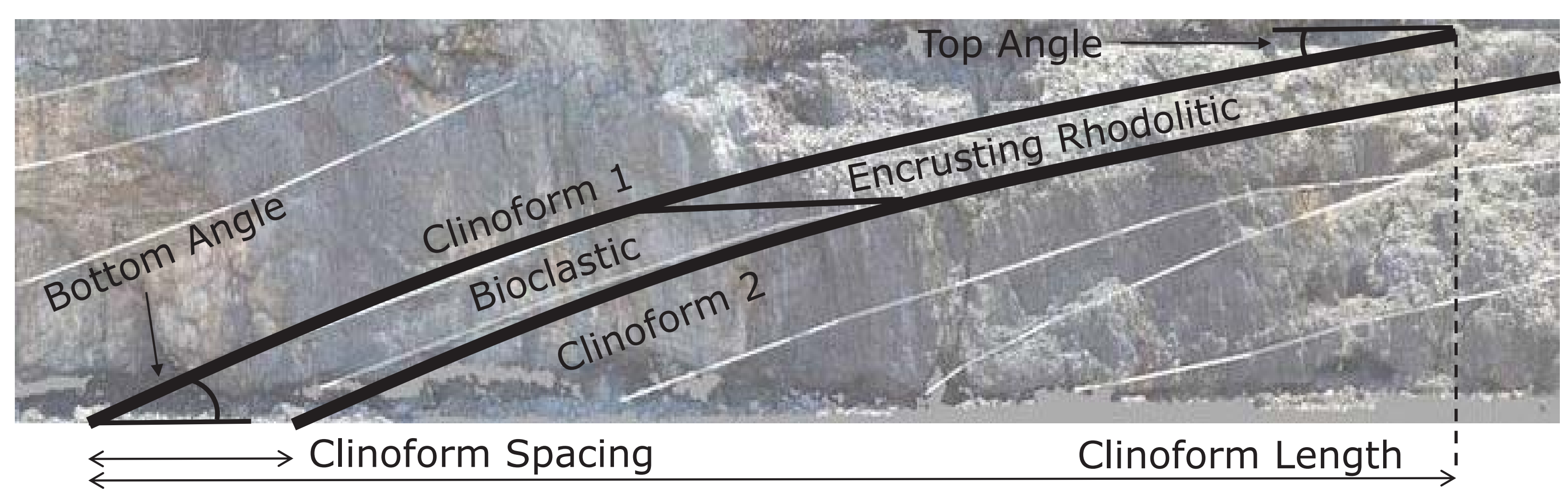
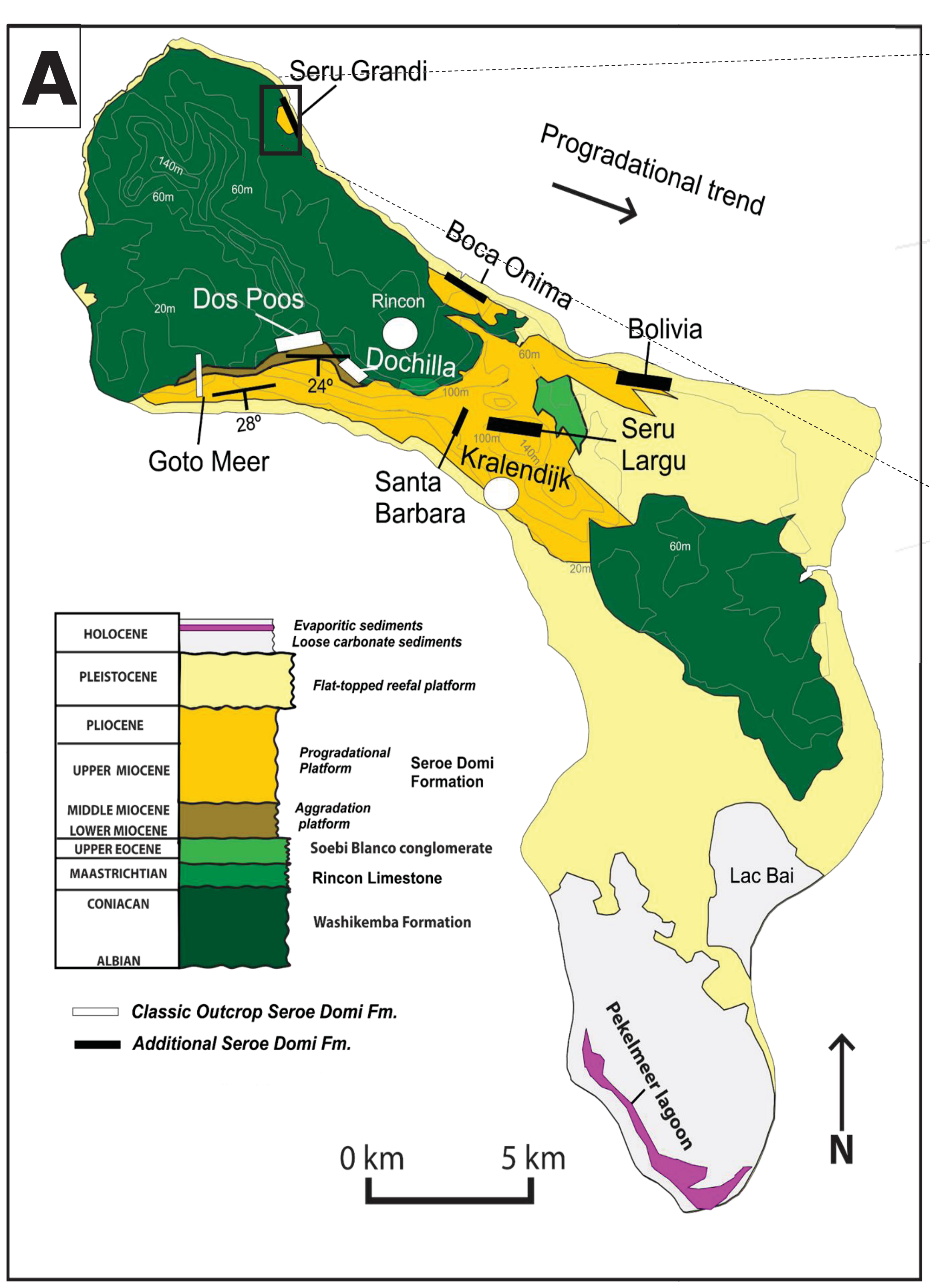
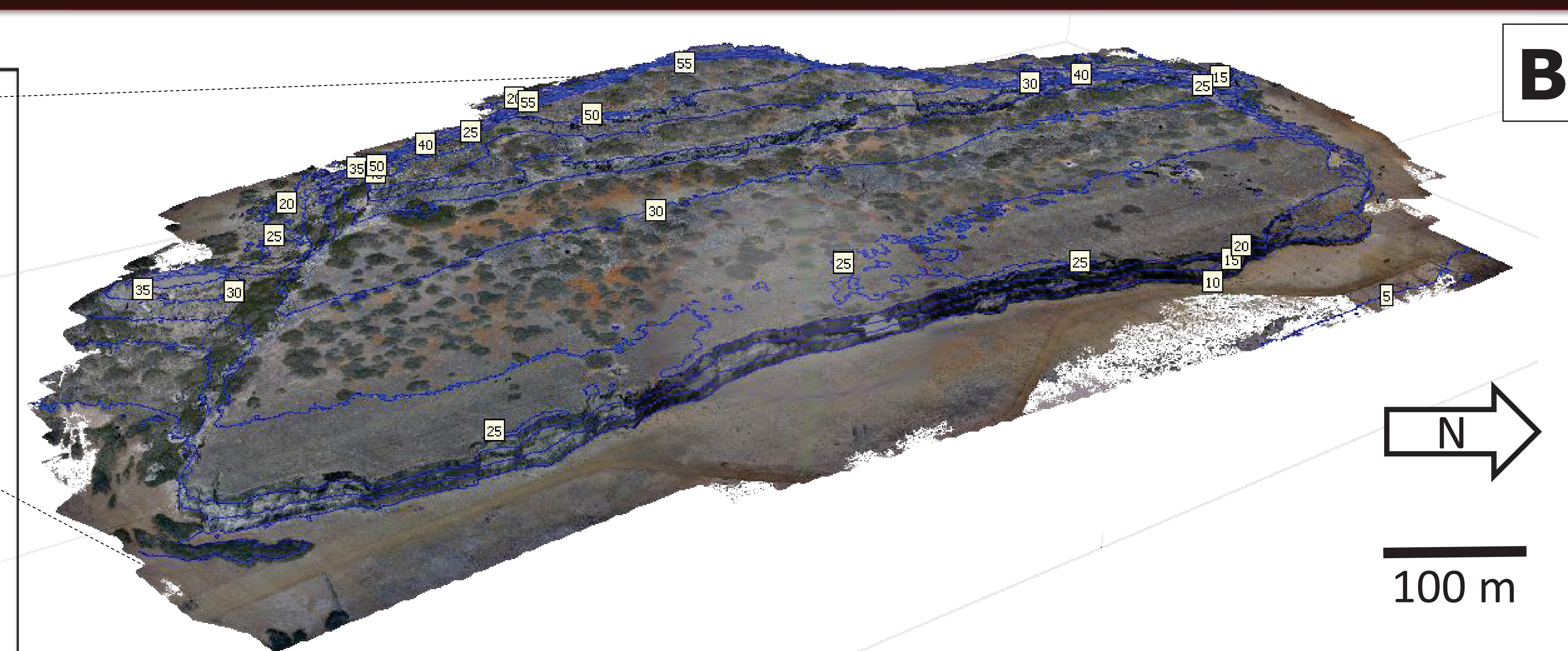


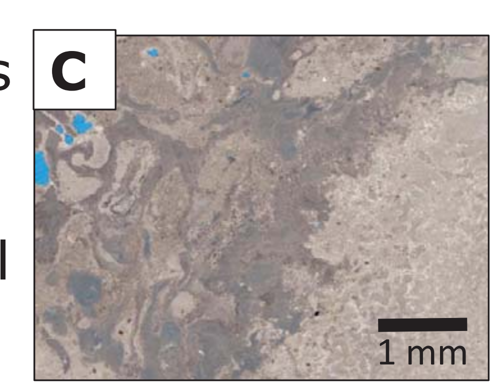
Fig. 1: Simplified diagram showing different clinoform geometry parameters measured on outcrop (Fig 4)

GEOLOGICAL SETTING





- The Seru Grandi outcrop analogue consists of a series of heterogeneous Miocene shallow marine red algae rich clinoforms partially replaced by tongues of Late-Miocene dolomite that extend down from an erosional unconformity marking the transition to overlying undolomitized limestone.
- The clinoforms can laterally be broadly separated into 2 facies, encrusting rhodolitic made up mostly of in situ coralline algae, and bioclastic coralline algae, made up primarily of coralline algae fragments.



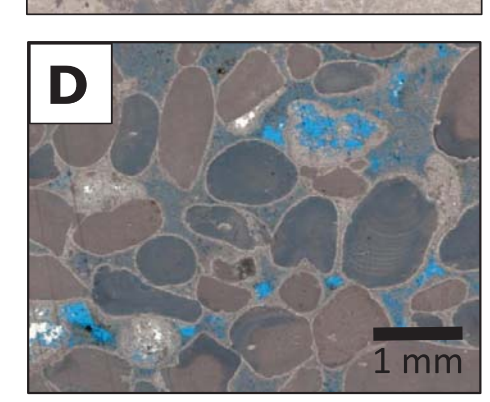


Fig 2: A) Simplified Geological Map of Bonaire, with location of Seru Grandi and direction of progradation for clinoforms. Bonaire is located in the southern Caribbean, 90 km north of the Venezuelan coast. It consists of a Cretaceous volcanic core with Eocene to Holocene carbonate sediments (modified from Laya et al., 2018).

B) Digital outcrop model (DOM) of Seru Grandi terraces with associated elevation contour lines.

C) PPL thin section of encrusting rhodolitic facies.

D) PPL thin section of bioclastic facies.

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DIGITAL OUTCROP MODEL, SURFACE-BASED RESERVOIR MODEL REALIZATION & FLOW SIMULATION

Fig 3: A) Panorama of the Seru Grandi clinoforms, with interpreted clinoforms. **B)** 1 Stochastic realization of surface-based reservoir model. **C)** Flow simulation after 1.5 years of production.

OUTCROP QUANTIFICATION

- **Greatest permeability and porosity found in reworked bioclasts, lowest in encrusting rhodolites.**
- **Clinoform dimensions:**
  - **Average spacing: 16 m**
  - **Average length: 33 m**
  - **Average angles (toe and top): 15 degrees**

TABLE 1: Permeability and porosity values for assigned facies in flow model. Porosity measurements from outcrop core samples, permeability values based on poro-perm relationship in Budd and Mathias (2015).

	Permeability (mD)			Porosity		
Facies	Max	Mean	Min	Max	Mean	Min
Encrusting Rhodolites	10	1	0.1	0.09	0.046	0.015
Reworked Bioclasts	1000	5	0.1	0.4	0.087	0.029
Dolostone	100	10	0.1	0.15	0.066	0.009

TABLE 2: Distribution of best fit for clinoform measurements.

	Spacing (m)	Length (m)	Height (m)	Angle bottom	Angle top
distribution	Gamma	Lognormal	Normal	Chi	Chi
mu/A	1.1	3.4	8.8		
sigma/B	14.0	0.4	1.7	13.5	10.5

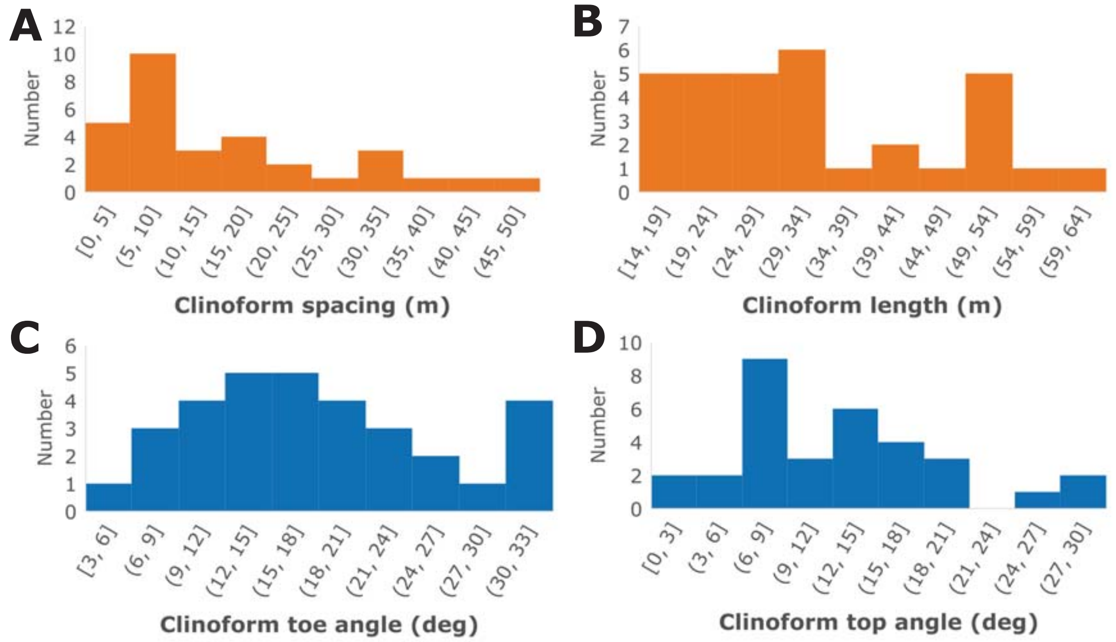


Fig. 4: Histograms of outcrop measurements. **A)** Clinoform Spacing **B)** Clinoform Length **C)** Clinoform Toe Angle **D)** Clinoform Top Angle

SURFACE-BASED RESERVOIR MODEL REALIZATIONS

- **Clinoform dimensions and spacing are stochastically sampled from Table 3**
- **Position of facies boundary location is varied from 40% to 60% of clinoform height**
- **Dolomite bodies are represented by ellipsoidal geobodies (40x50x8m) warped onto clinoforms**
  - **1 dolomite body per clinoform uniformly distributed laterally**
  - **Selective dolomitization of rhodolitic vs bioclastics facies**

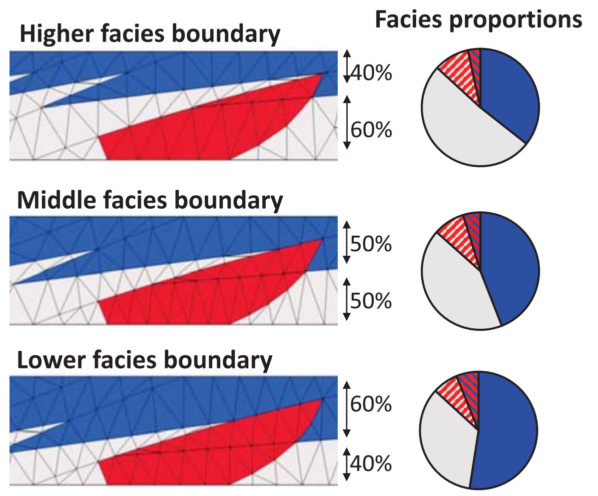


Fig. 5: Comparison of the difference in position of the facies boundary and the related changes in facies proportions

Encrusting rhodolitic facies | Reworked bioclastic facies | Dolostone

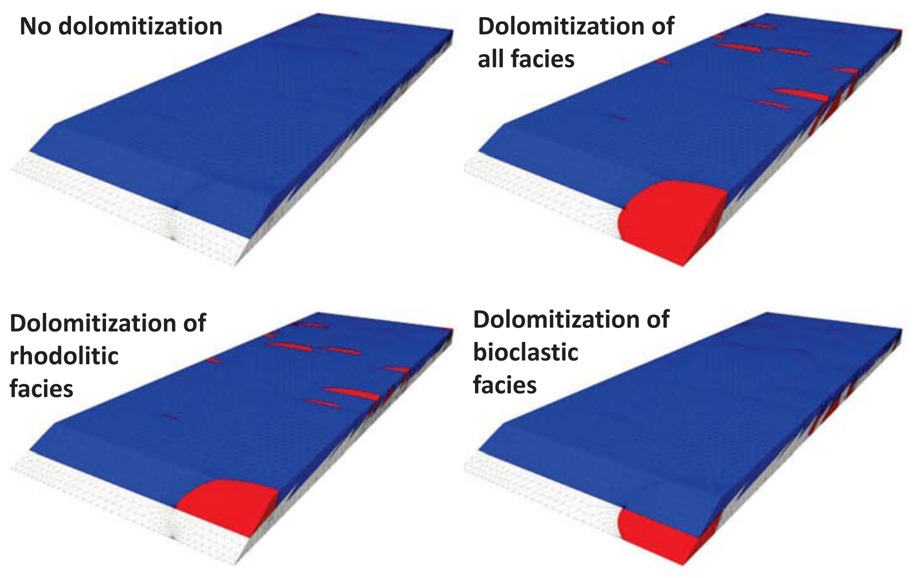


Fig. 6: Comparison of different scenarios of no dolomitization, unselective dolomitization and selective dolomitization

FLOW SIMULATIONS (IC-FERST)

- **Mesh adapts over time to ensure the most accurate solution of flow equations.**

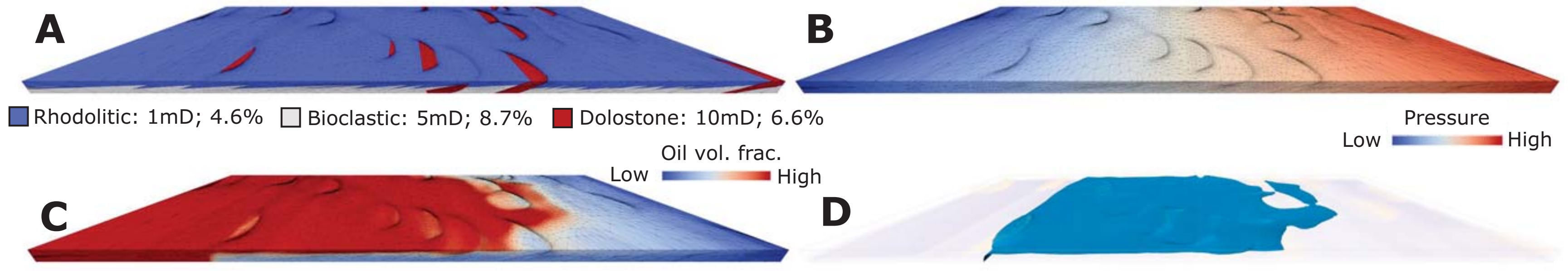
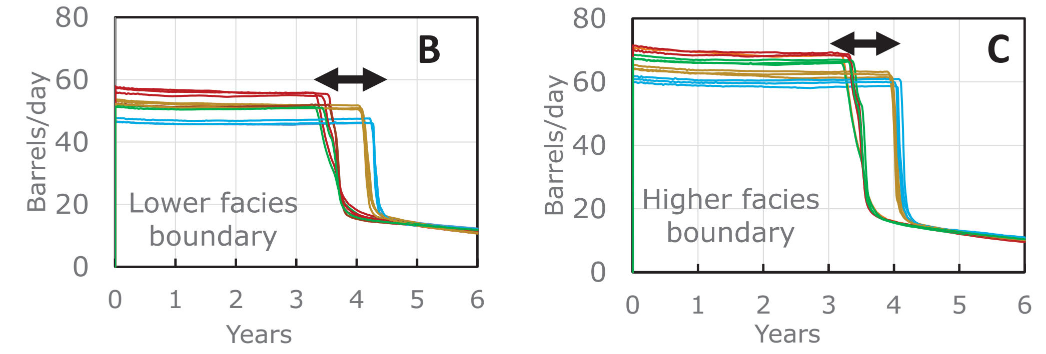


Fig. 7: Flow simulation model after 2.5years of production. Water is injected right to left at fixed pressure. **A)** Input facies model; **B)** Pressure distribution across model; **C)** Oil volume fraction discrtibution; **D)** Waterfront geometry

FLOW RESULTS

Effects of dolomitization:

- **Dolomite bodies cause increase in flow rates.**
- **Selective dolomitization of rhodolitic facies does not affect water breakthrough.**
- **Dolomitization of bioclastic facies always results in earlier water breakthrough.**



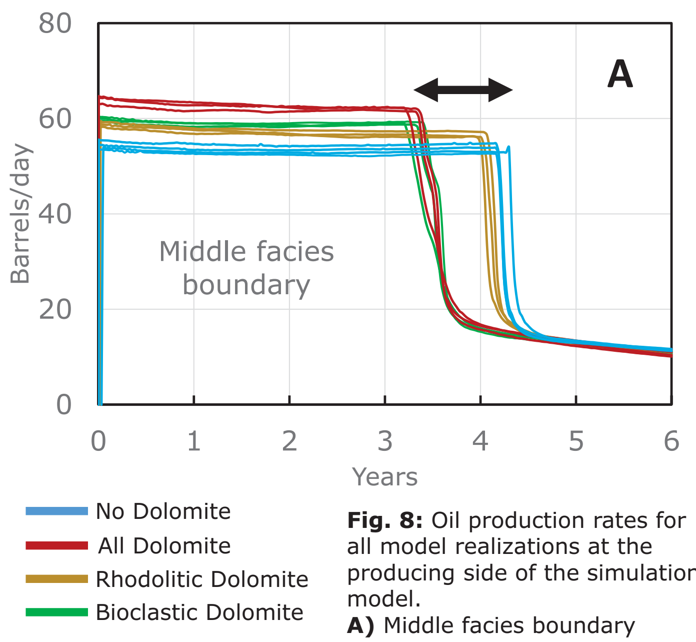


Fig. 8: Oil production rates for all model realizations at the producing side of the simulation model.
A) Middle facies boundary
B) Lower facies boundary
C) Higher facies boundary

Effect of facies boundary position:

- **Impact on flow rates by changing facies proportions.**
- **No effect on water breakthrough times.**

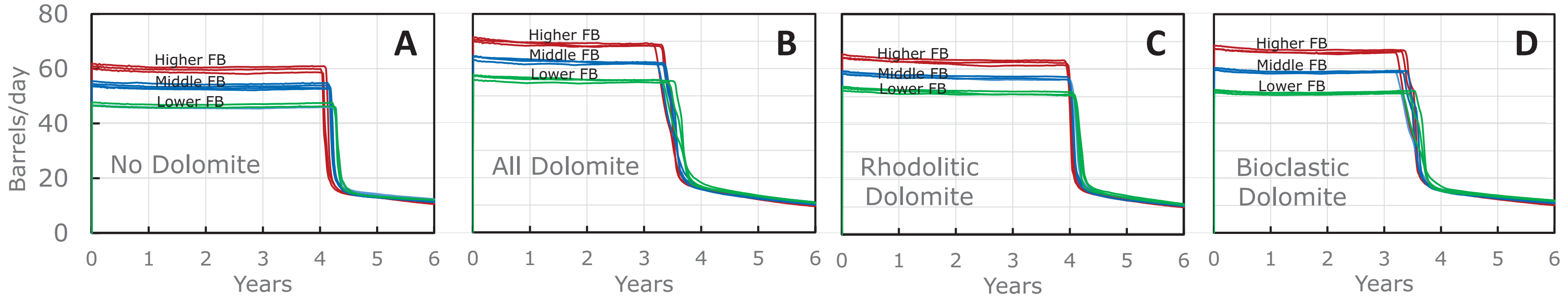


Fig. 9: Oil production rates for all model realizations at the producing side of the simulation model. **A)** No dolomitization; **B)** All facies are dolomitized; **C)** Selective dolomitization of rhodolitic facies; **D)** Selective dolomitization of bioclastic facies.

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DISCUSSION

- Dolomitization of the bioclastic facies (**Fig. 9 B & D**) results in faster water breakthrough as the floodfront preferentially moves throught the slightly higher permeability basal facies.
- Dolomitization of the rhodolitic facies (**Fig. 9 C & D**) causes the floodfront to be pulled up, rather than move laterally. This causes a delay in water breakthrough even though flow rates are increased.
- Flow rates are only slightly increased in case of selective dolomitization of rhodolitic facies.

Fig. 10: Flow simulation steps and floodfront when the same dolomite body location is reached. Timestep between successive fronts is 10 days. **A)** No dolomitization; **B)** Bioclastic facies dolomitized; **C)** Rhodolitic facies dolomitized; **D)** both facies dolomitized.

- Surface-based modelling and simulation is able to preserve the detail in heterogeneity that would be lost using conventional modelling approaches.
- This is despite the wide distribution of clinoforms length and spacing, with large ranges in angles.
  - 5 → 50 m
  - 6 → 30 deg

CONCLUSIONS

- **Outcrops are essential for providing the quantitative information necessary for assessing facies proportions and understanding flow.**
- **Surface-based reservoir modelling and simulation allows realistic representation of heterogeneity**
- **Dolomitization does not always affect water breakthrough**
  - **Selective dolomitization can cause increase in flow rates while not changing water breakthrough times.**
- **The Seru Grandi Clinoforms range in porosity from 2% to 28%, and are on average 33 m long and 9 m high, with dolomite bodies ranging from 10 - 30 m long.**

FUTURE WORK

- Additional realizations incorporating more complex facies variations (e.g. erosional top surface) and petrophysical uncertainty.
- Applying SBM to other similar outcrops with clinoform geometries at larger scales.

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