Large-Scale Carbonate Slope Gravity Failures: From Stratigraphic Evolution to Numerical Failure Prediction*

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Abstract

Carbonate margin and slope systems exhibit massive scale gravity failures controlling the export of large quantities of carbonate production from the shelf and slope to deep parts of the basin. Understanding the triggering of these events, and integrating their occurrence into the stratigraphic evolution of a carbonate system is decisive for prospect evaluation at the basin scale. Gravity-driven mass transport can induce and control the location of calciclastic reservoir facies.

Gravity failures are mechanical destabilizations of sediment accumulated in a stable configuration, but influenced by pre-conditioning mechanisms (e.g. over steepening, fluid overpressure build-up by overloading, or fluid flow) that induce failure during a triggering event (e.g. seismic ground acceleration, cyclic loading, fluid escape). This contribution shows the integrated investigation of this genetic chain at each time step of system evolution using forward stratigraphic and basin numerical modeling tools.

The first step is a forward stratigraphic modeling using DionisosFlow software in order to determine the geometrical and facies evolution through time. The second step is the computation of the mechanical stratigraphy that is the time-dependent state of sediments density and associated mechanical load, fluid pressure and resulting stress state. It is determined with IFPEN basin modeling tools used for hydro-mechanical calculations. The third step is the computation with a limit analysis approach of the most probable failure geometry and associated load factor, using the OptumG2 software (U. Newcastle, Aus).

This innovative workflow is applied on 2D sections of the well-described Plio-Quaternary Western and Eastern slopes of the Great Bahama Bank. They exhibit recurrent and various types of mass failure events. The simulations are carried out using mechanical characterization of the

sedimentary material derived from dedicated oedometric and triaxial tests and from literature. Great attention is paid to the effects of early cementation on the mechanical stratigraphy.

The results shows how the internal stratigraphic and mechanical evolution of the system is a first-order control of slope failures in response to external trigger events. These results provide us with new and mechanically tested insights on the time and spatial occurrences of slope failures. These processes can be integrated into a forward basin exploration workflow.

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From Stratigraphic Evolution to Numerical Failure Prediction

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Soubeyranes Cliffs (Southern Provence Basin, France)
Turonian Carbonate Megabreccias

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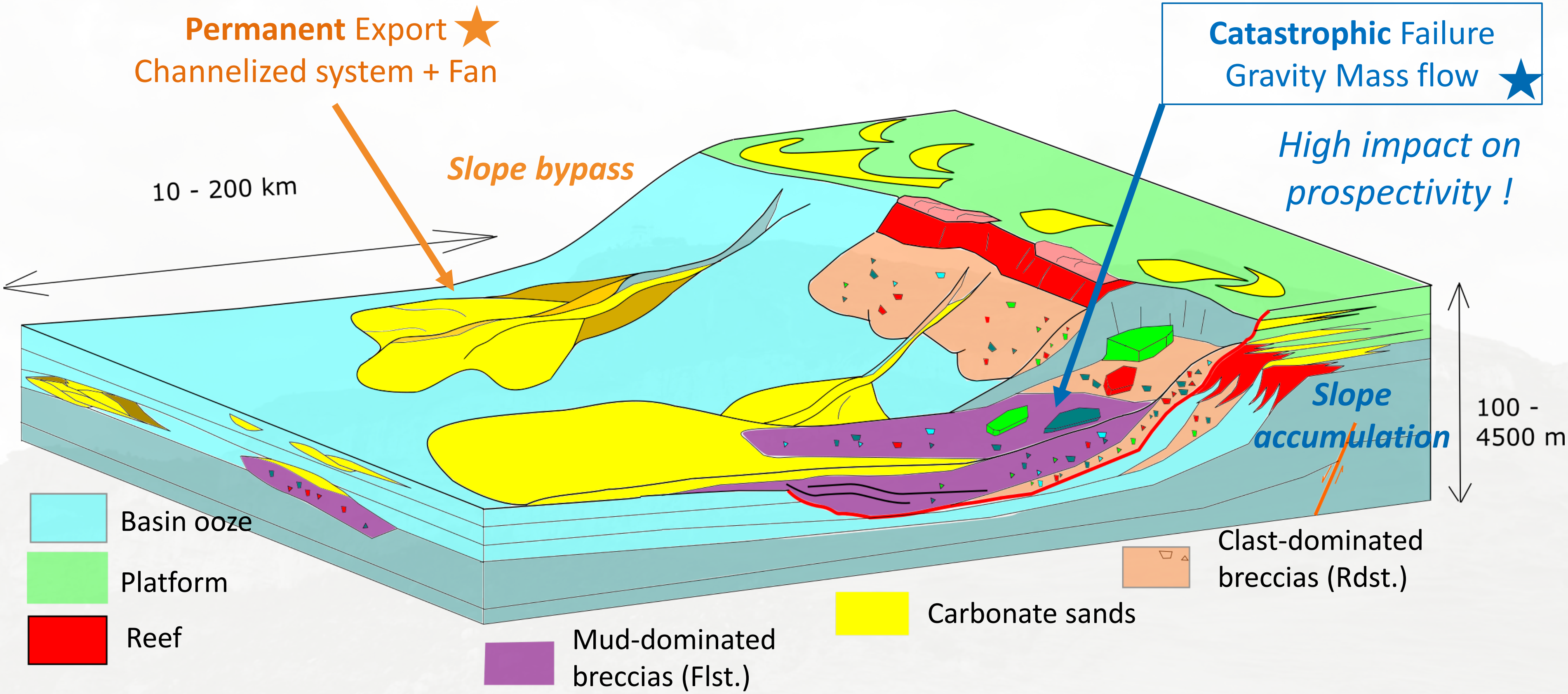
Gravity-driven transfers in Carbonate systems

Remobilisation and export by gravity flows of shallow carbonate production.



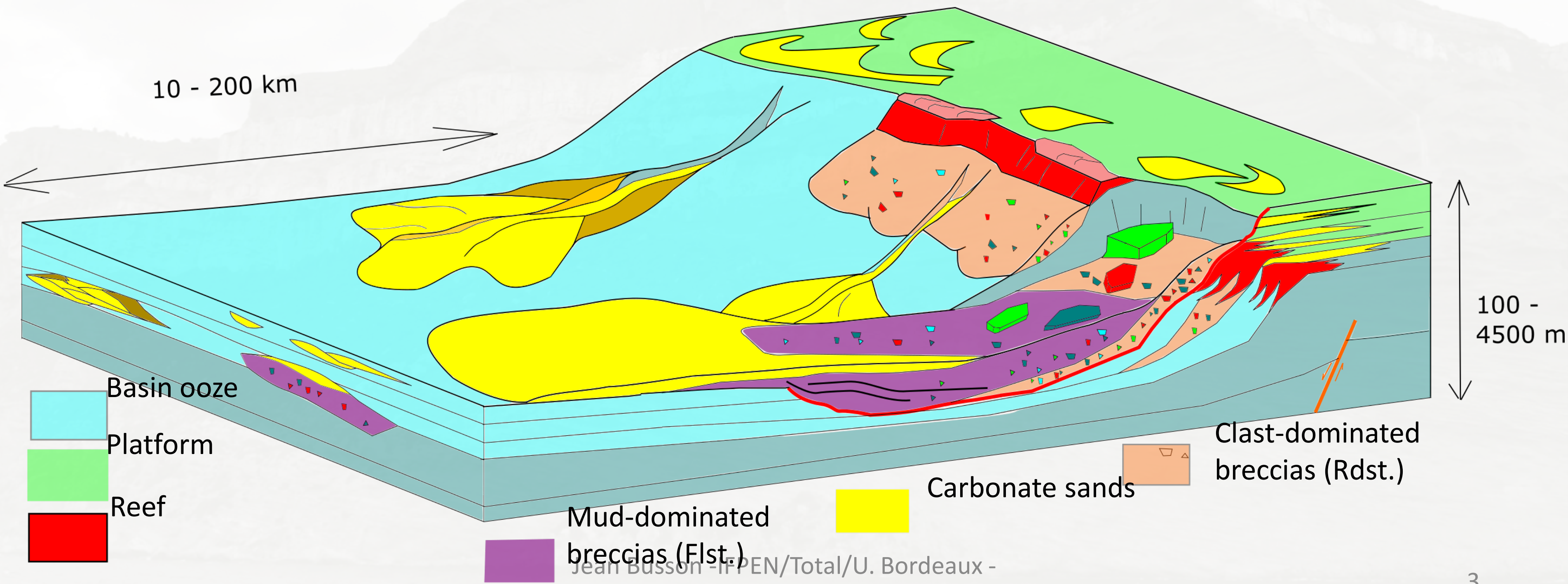
Well-identified Oil & Gas plays

- Poza Rica Field (Mexico), Albian-Cenomanian Tamabra Fm. ★ ★
- Ruby Field (Indonesia), Oligocene Berai Fm. ★
- Aquila Field (Italy), Cenomanian Mt. San Angelo Fm. ★ ★
- Mescalero Escarpe, Happy Spraberry fields (USA), Permian Basin ★ ★

Objectives

- During **Exploration** phase how can we **predict large-scale slope failures** in past carbonate systems ?
  - ➢ **Timing, location, volume …**

- Design of a **2D Forward Numerical Workflow**
- **Test** failure scenarii & **controlling factors** with mechanically valid numerical simulations.
  - ➢ Sea-level variations and associated **overpressure**
  - ➢ Heterogeneous **early cementation**



Numerical Modeling Workflow

INPUTS

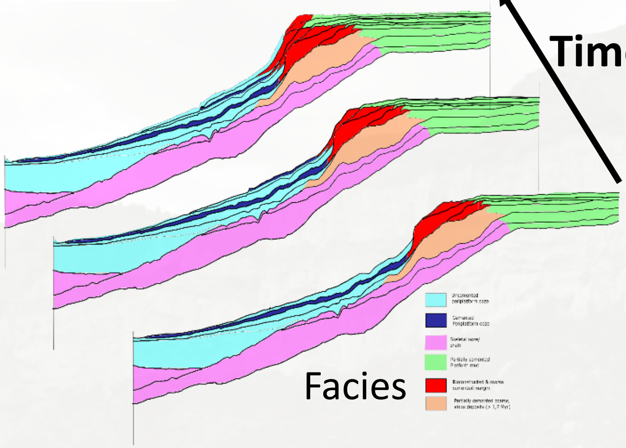
Reference section
Depositional model

Hydro-mechanical characterization:
$\Phi(z)$, $K(\Phi)$

Mechanical characterization:
E, ν, Failure Law

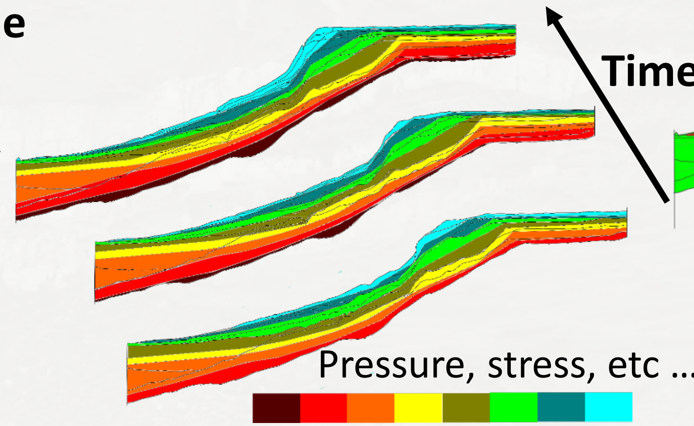
1. Forward Stratigraphic Model

DionisosFlow™ Stratigraphic Modeling



2. Mechanical Statigraphy Model

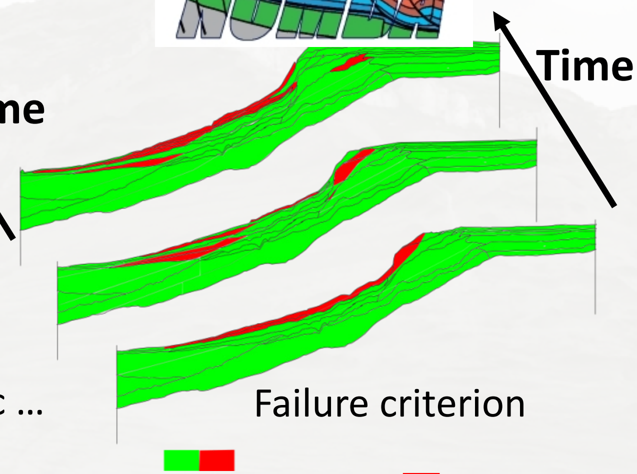
TemisFlow™ Petroleum System Modeling



3. Stability Evaluation

Code A²

\+ NOMBA



OUTPUTS

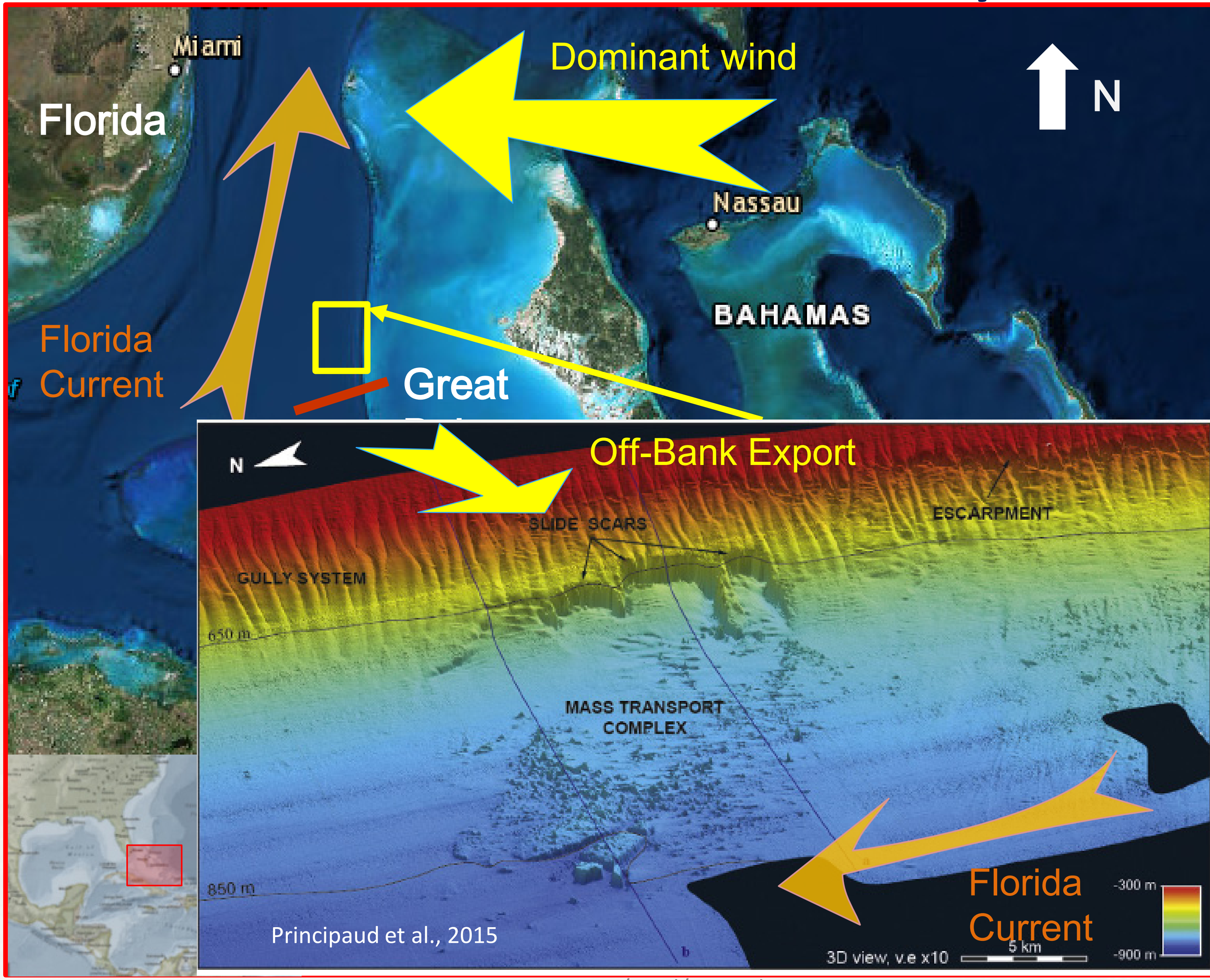
Stratigraphic Architecture :
Facies (x,z,t)

Mechanical Stratigraphy

Pressure (x,z,t), Stress (x,z,t)

Overpressure
Failure criterion

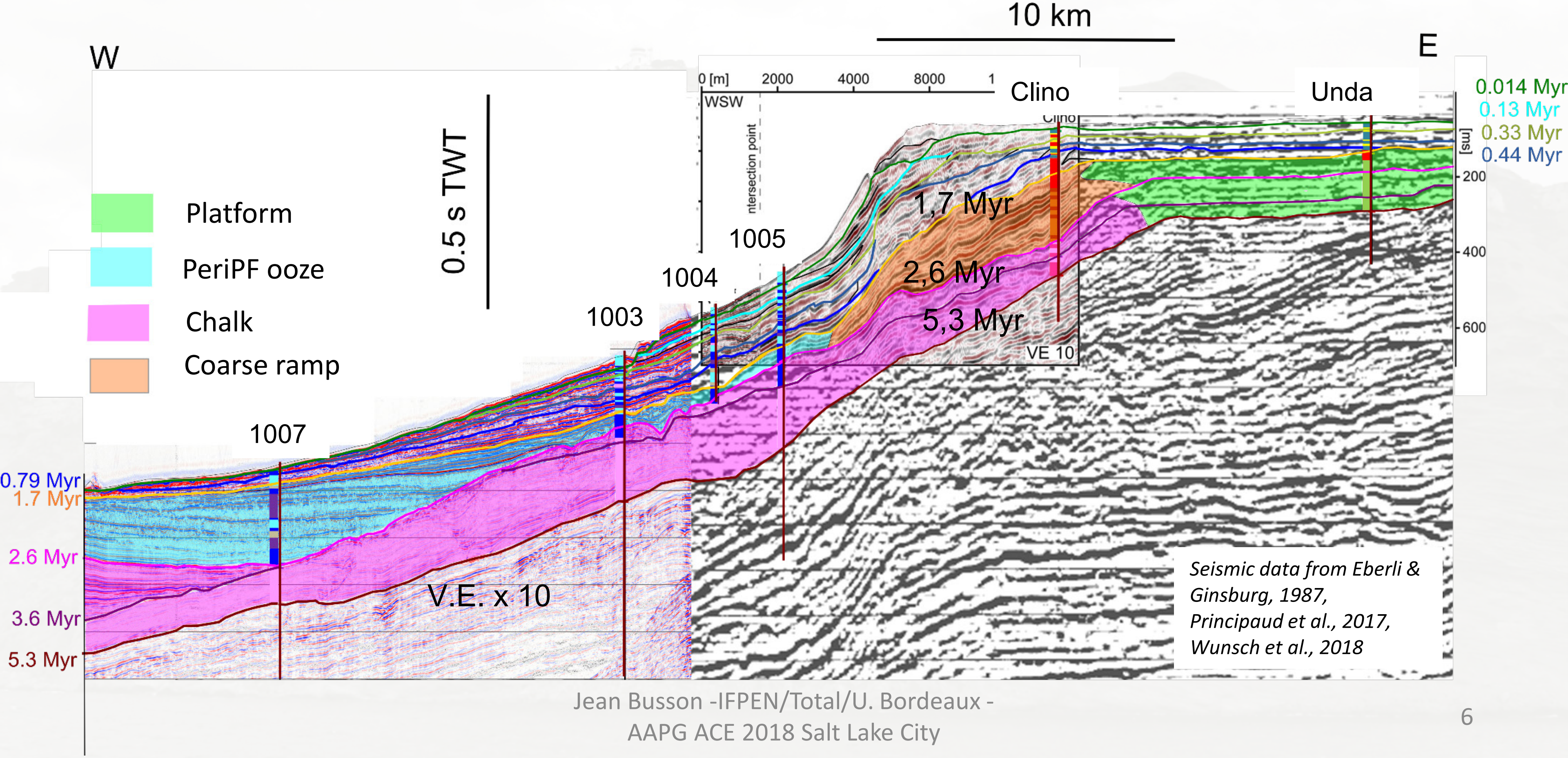
Bahamas Case Study



Bahamas Case Study (5.3 – 0 Myr)

- « Western Line » Seismic Section (Eberli and Ginsburg, 1987), 4 ODP 166 Wells and 2 platform wells.
- Sedimentary processes documented by recent scientific cruises (Wunsch et al., 2016 & 2018; Principaud et al., 2017 & 2018).

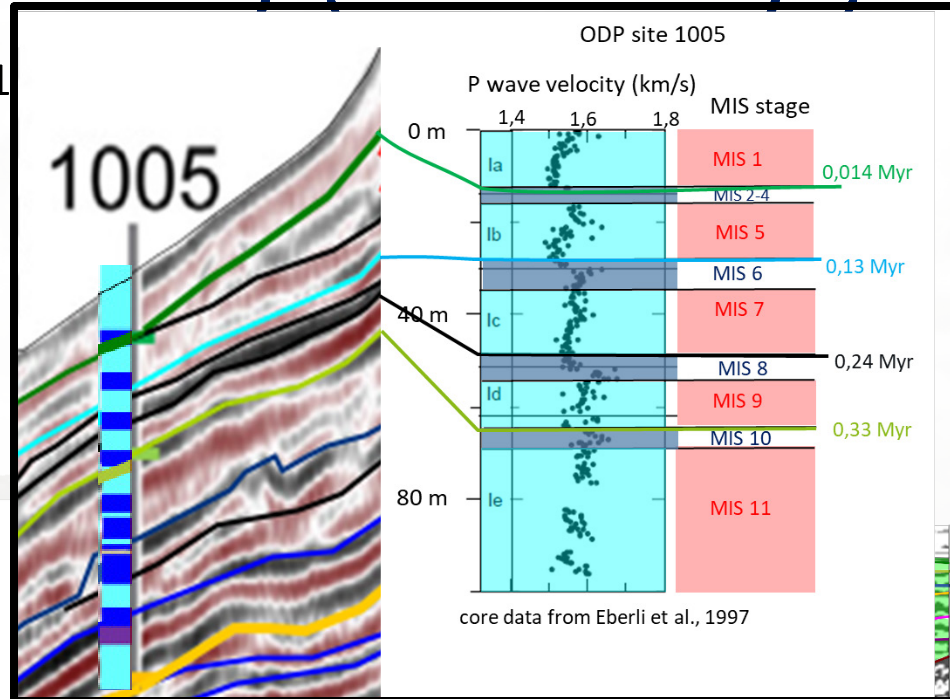
- Detailed sequence stratigraphy and lithofacies interpretation.

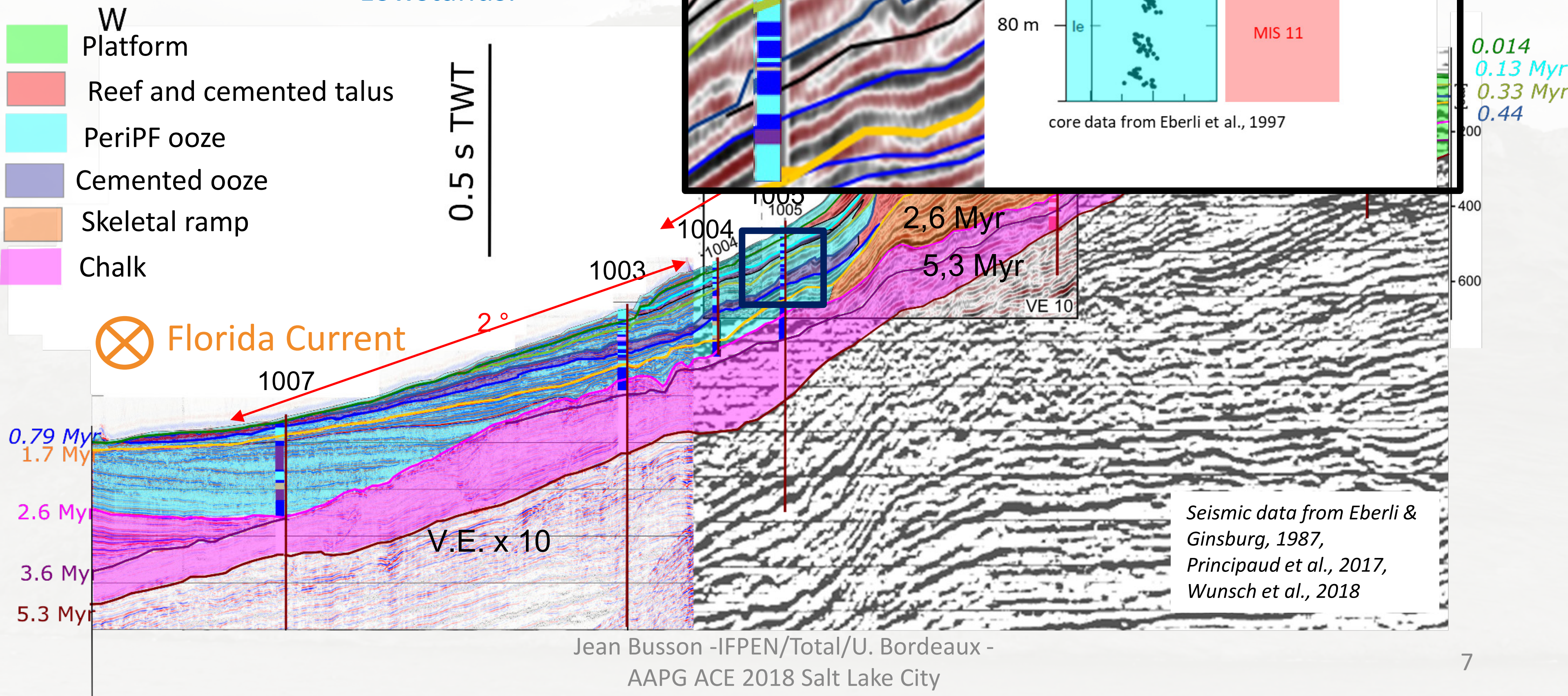


Bahamas Case Study (5.3 – 0 Myr)

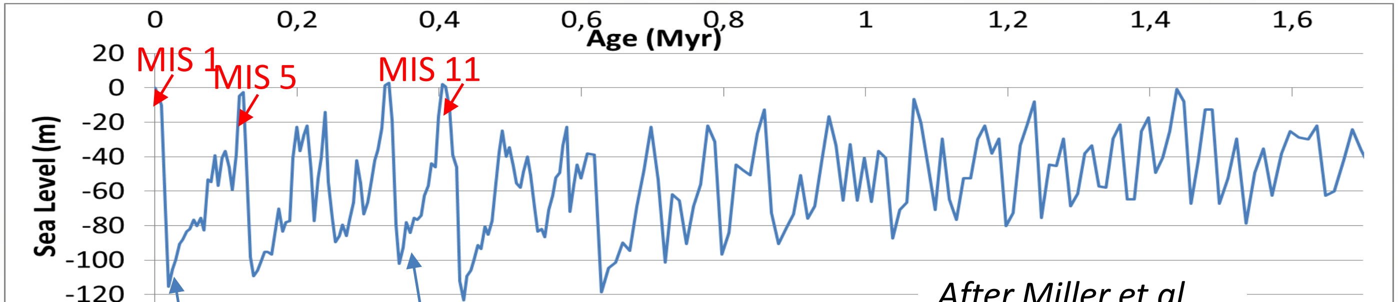
- Forward Stratigraphic model for the 1
- Slope profile controlled by carbonate

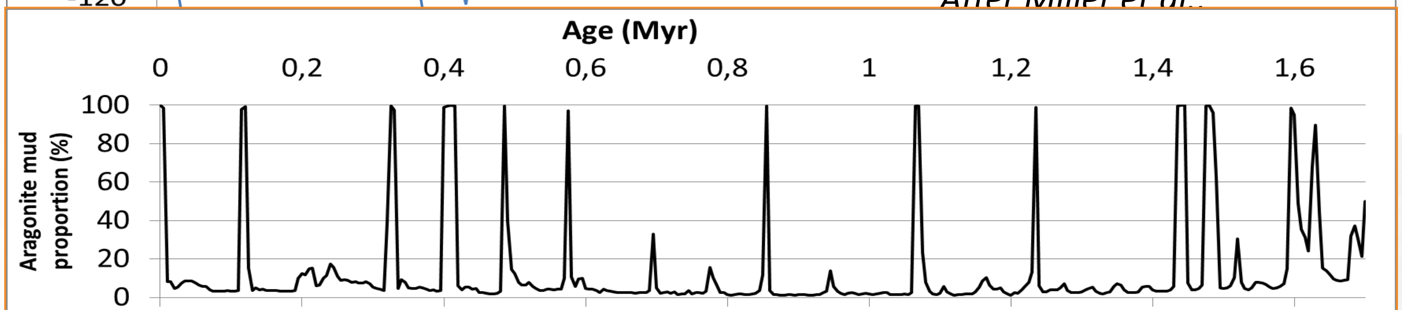
Early cemented layers (Aragonite → HMC) associated with glacial Lowstands.

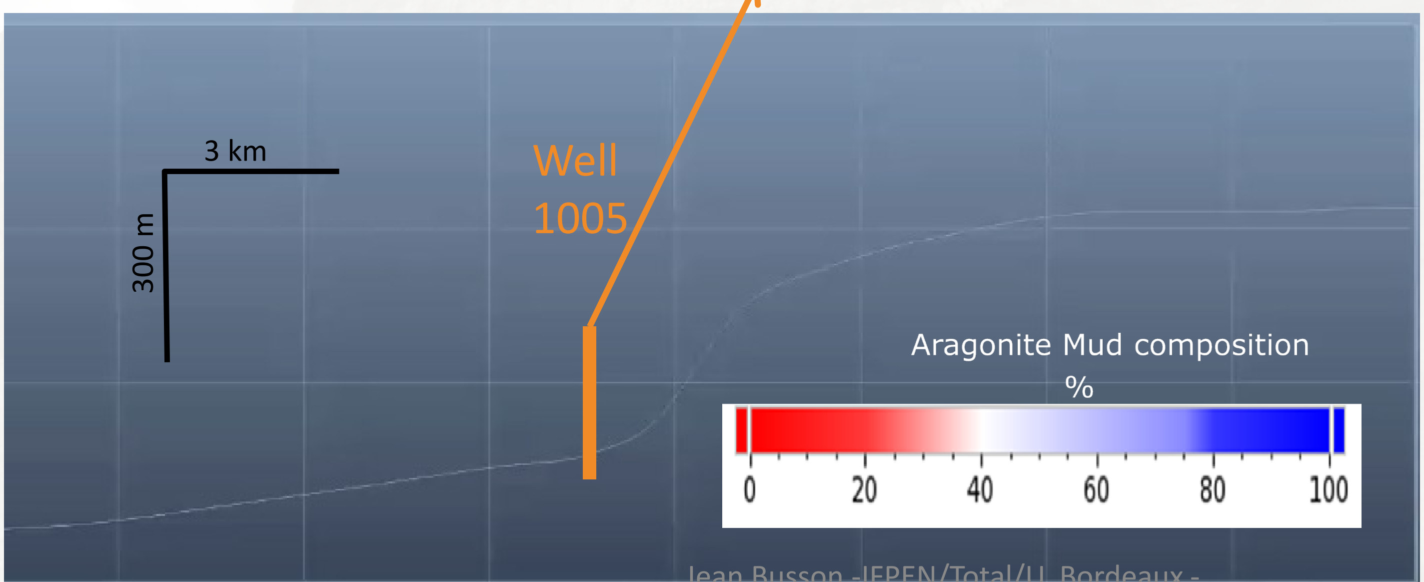


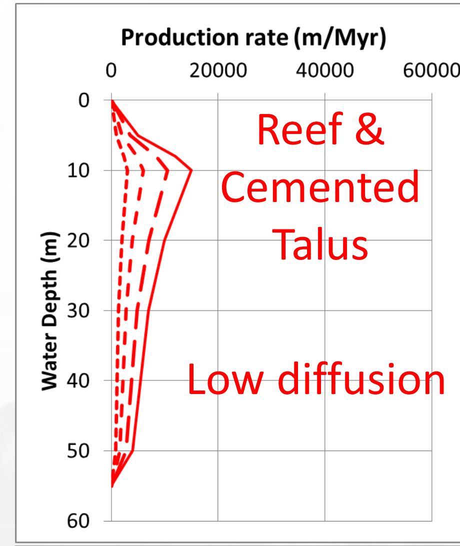


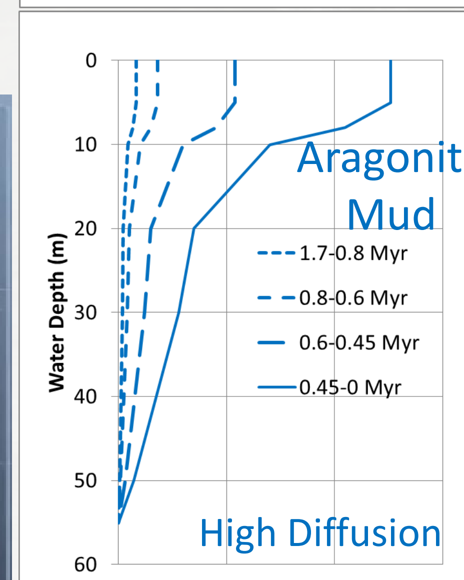
DionisosFlow Stratigraphic Model



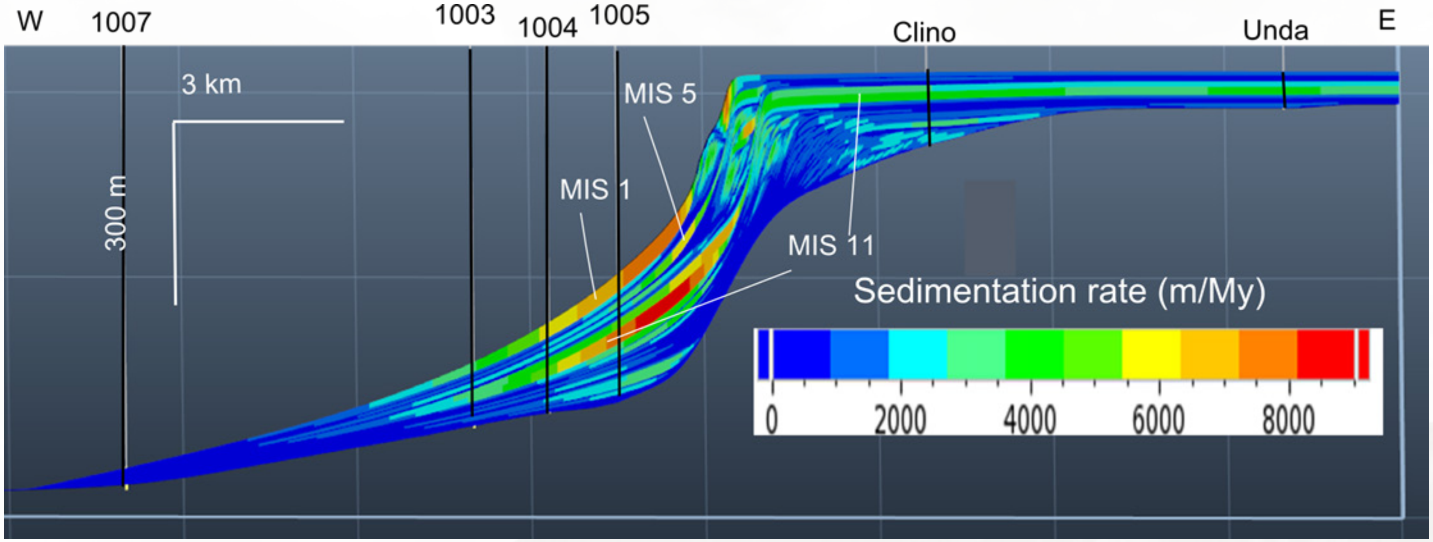


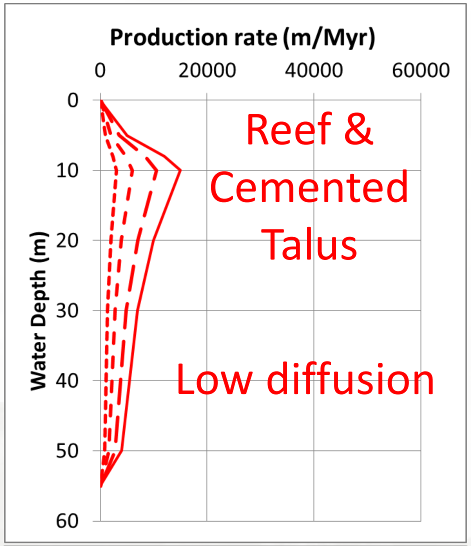


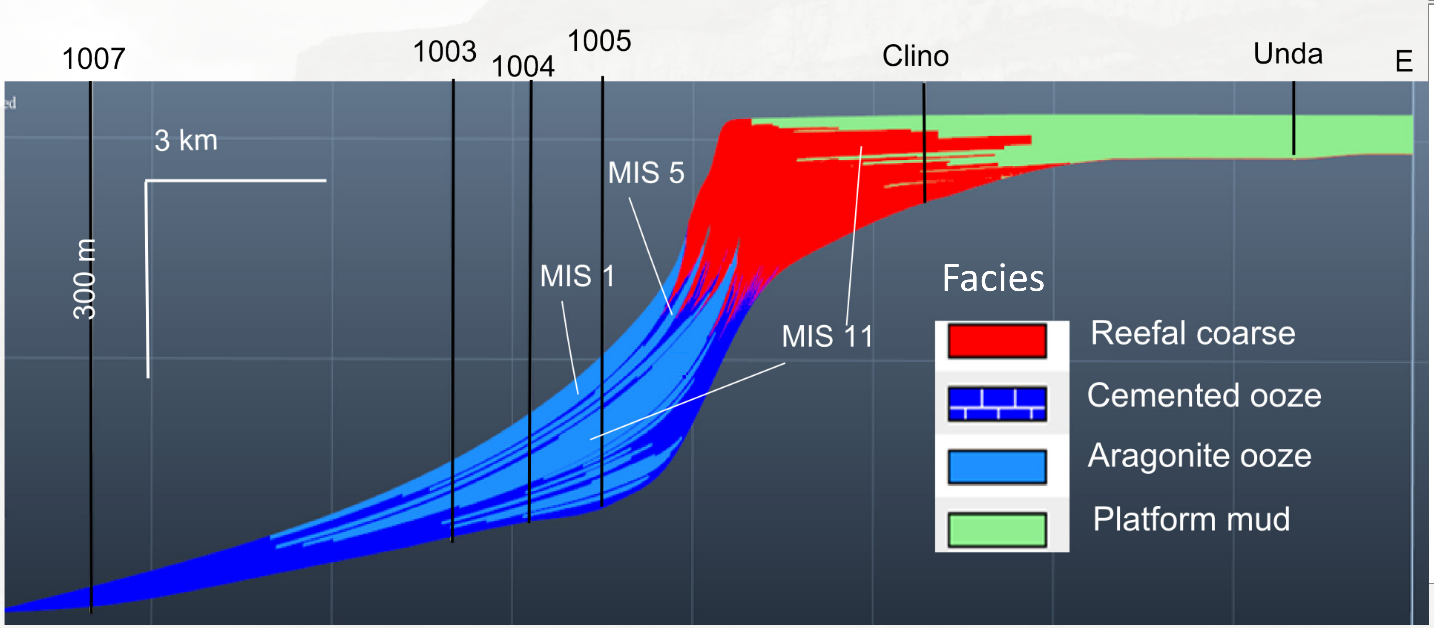


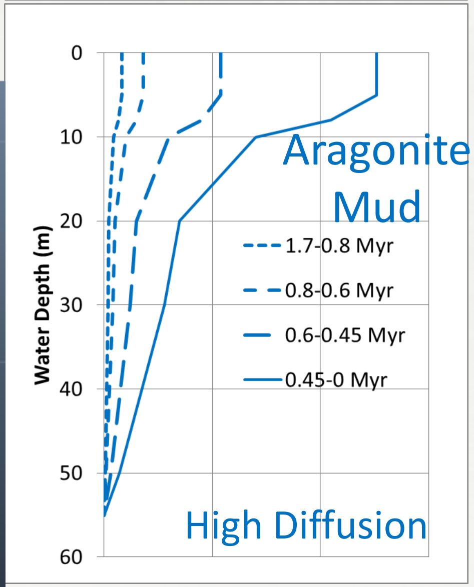


DionisosFlow Stratigraphic Model



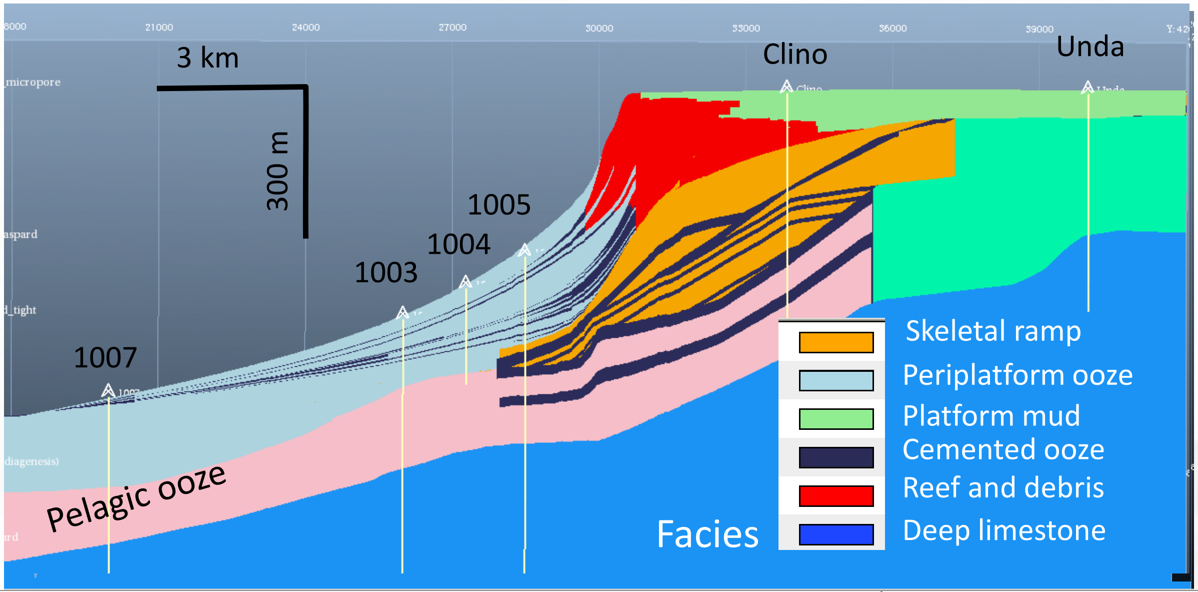






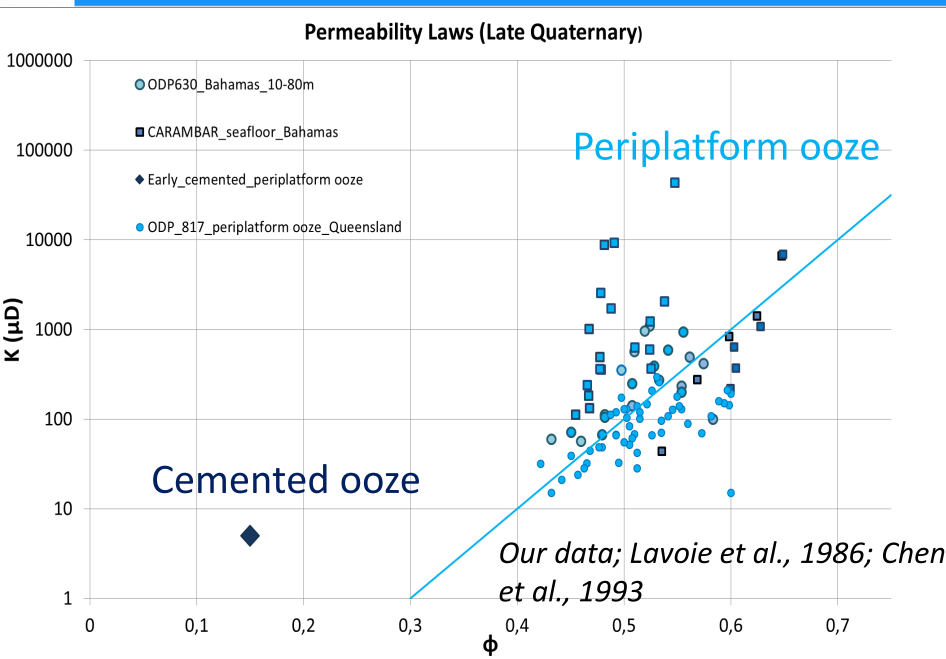
Forward stratigraphic model | Mechanical stratigraphy model | Stability evaluation

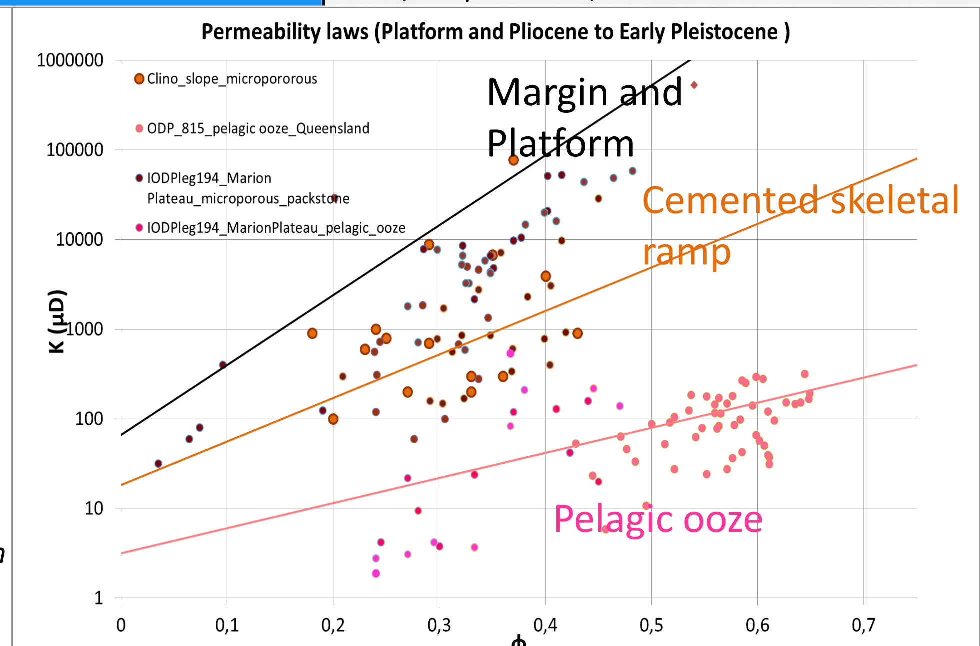
Hydro-Mechanical Characterization



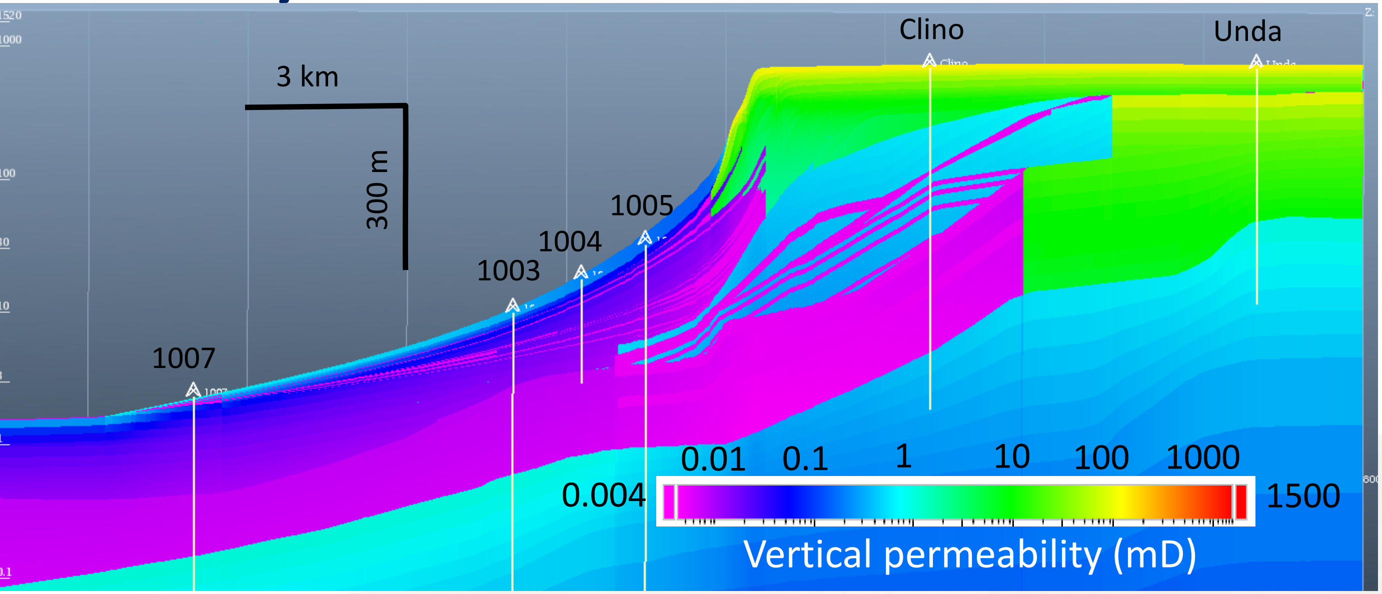
- Compaction and Permeability Laws for each facies.
- Based on our mechanical experiments on periplatform ooze, and published measurements.

Ehrenberg et al., 2004; Melim et al., 2001; Chen et al., 1993; Dugan et al., 2004; Caspart et al., 2004





Hydro-Mechanical Characterization



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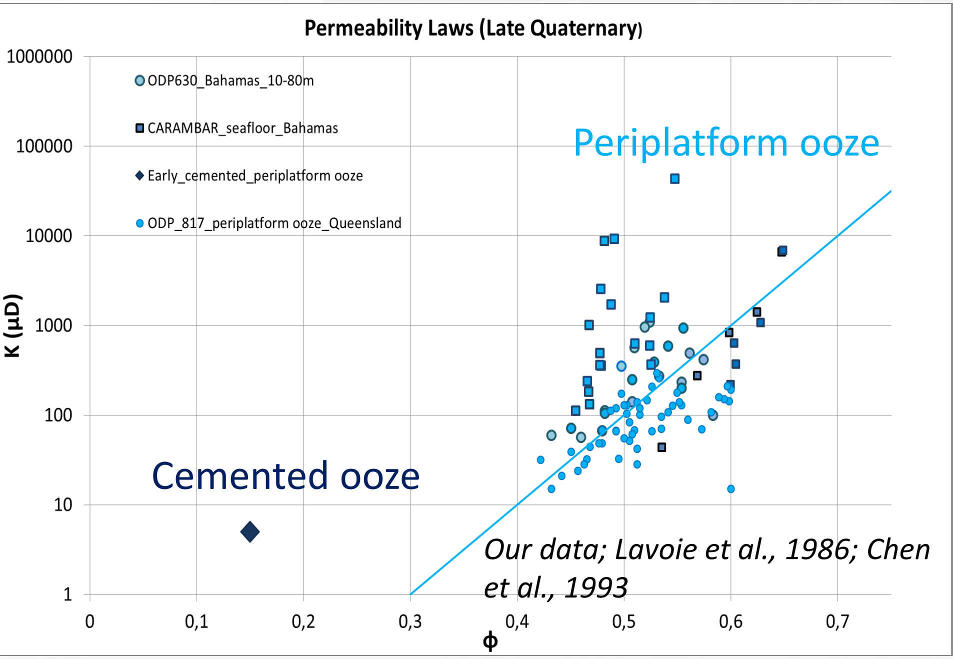
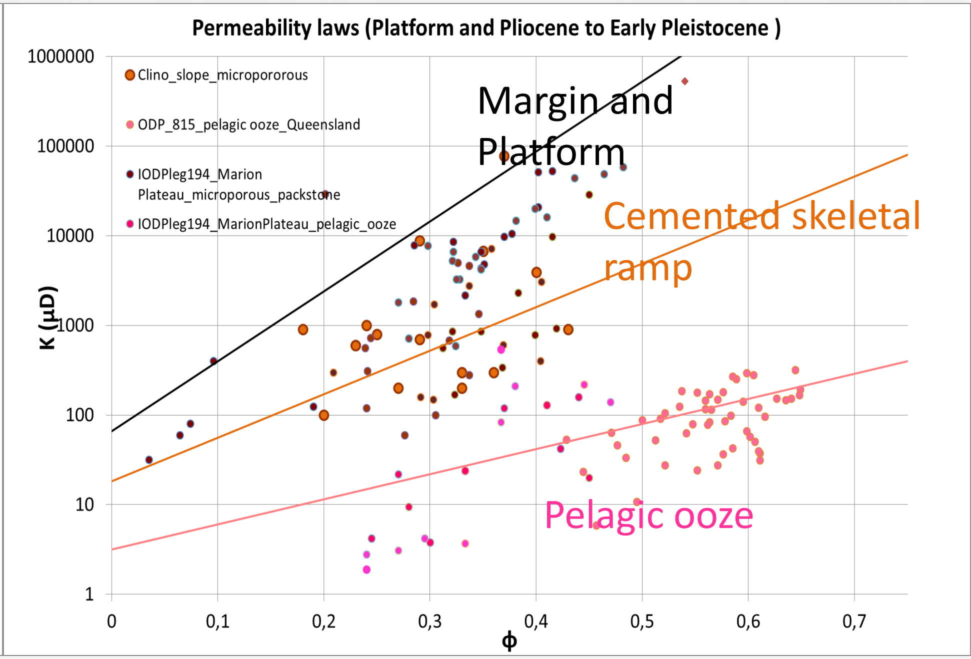
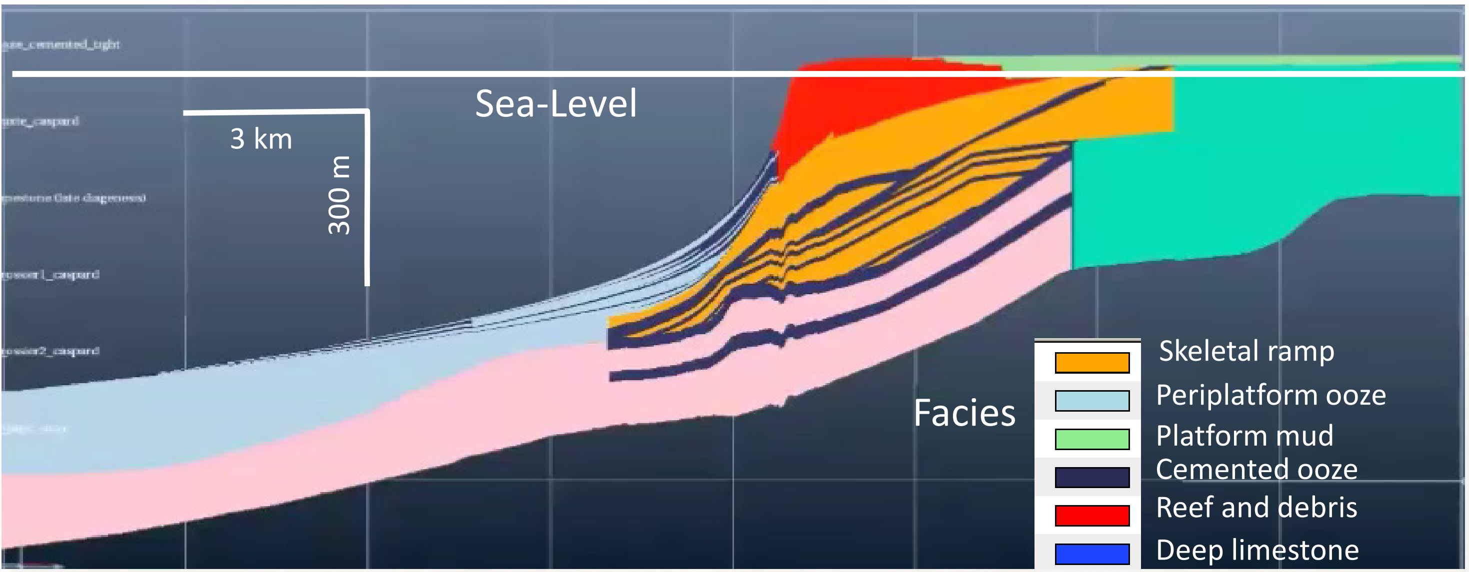


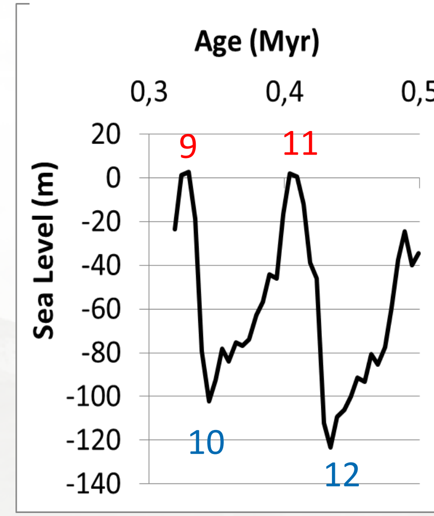


Overpressure simulation

Large overpressures ($\lambda^* > 0.3$) can develop during **sea-level lowstands**



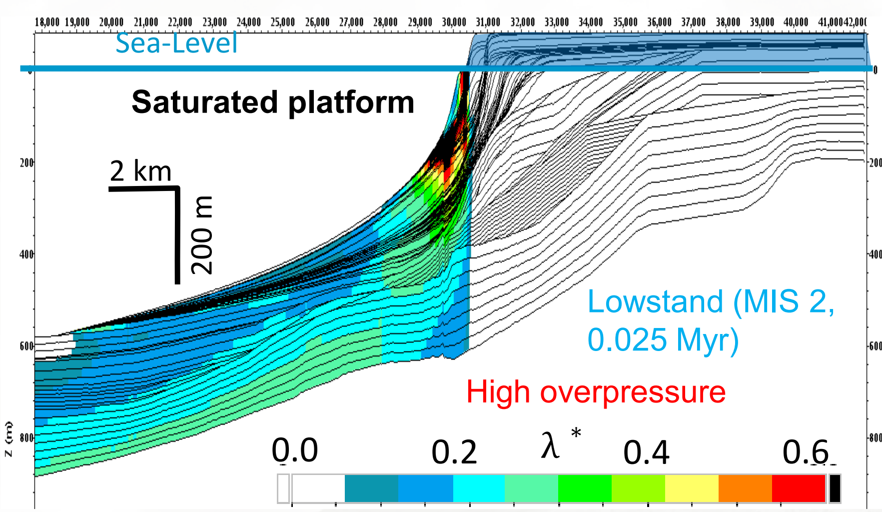
After Miller et al., 2011

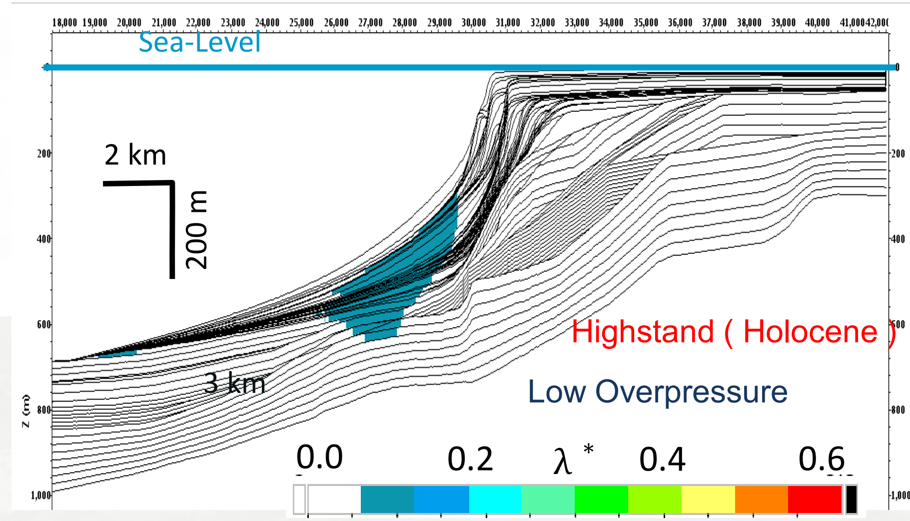


- $\lambda^* = {(P-P_H)}/{(\sigma_v-P_H)}$
- Ratio of overpressure to vertical effective stress in hydrostatic conditions.

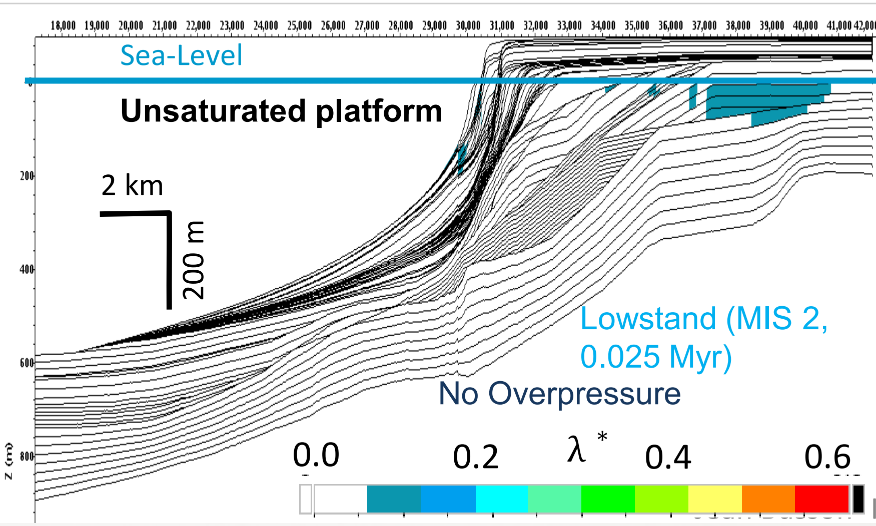
Slope overpressure & Piezometry

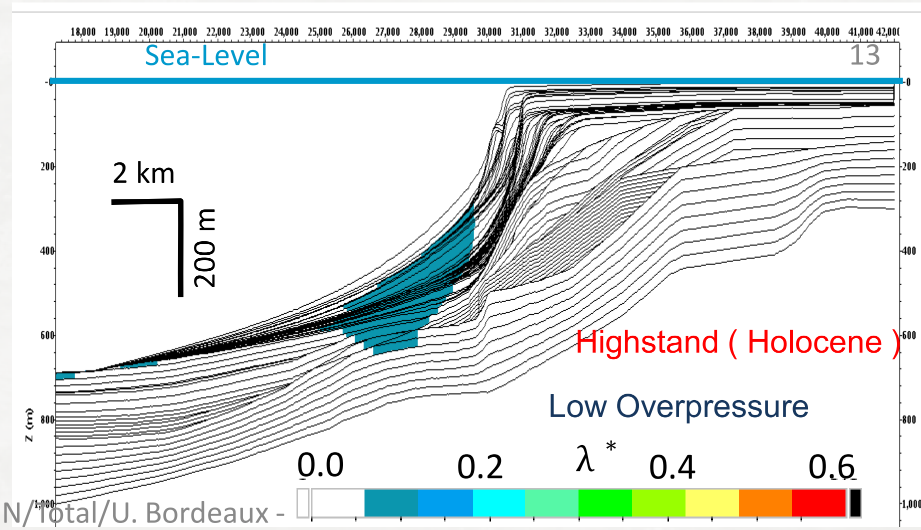
- **Saturated Platform** : Slope overpressure controlled by piezometric head during lowstands





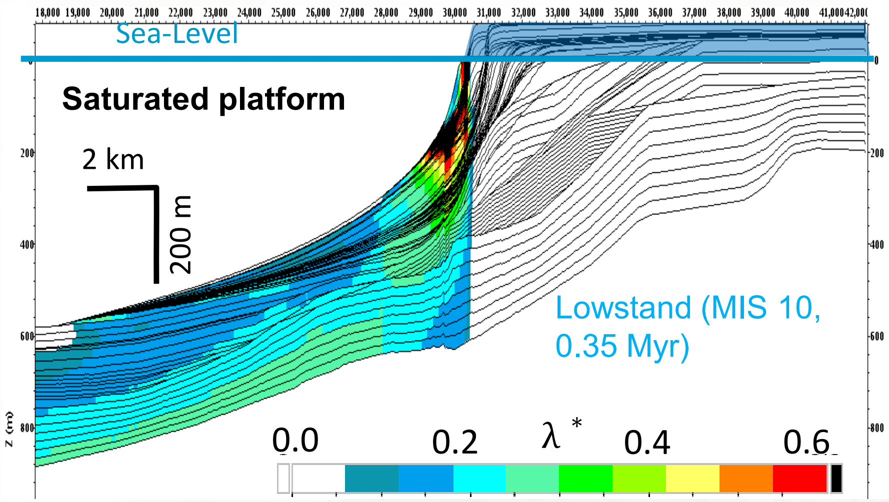
- **Unsatured Platform** : No slope overpressure during lowstands

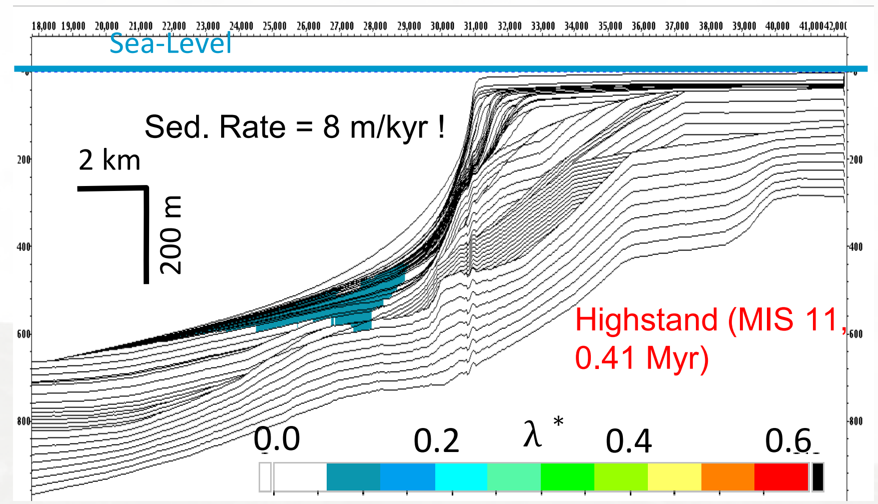




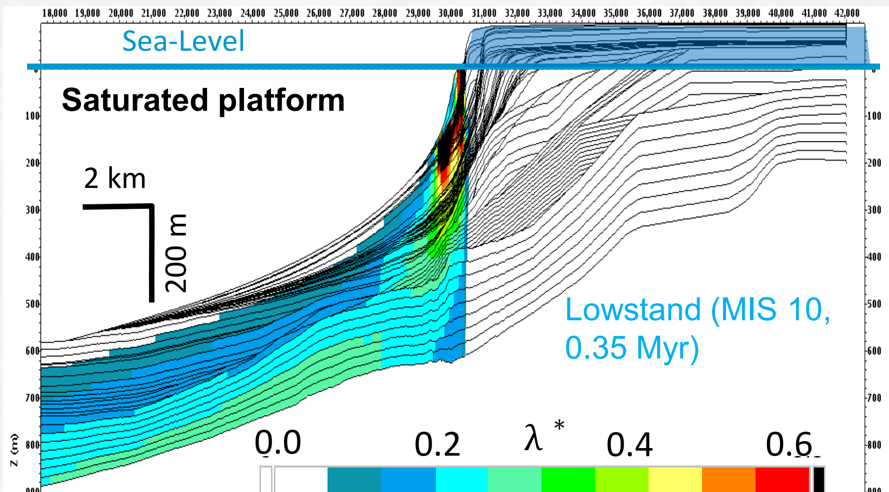
Slope overpressure & Cemented layers

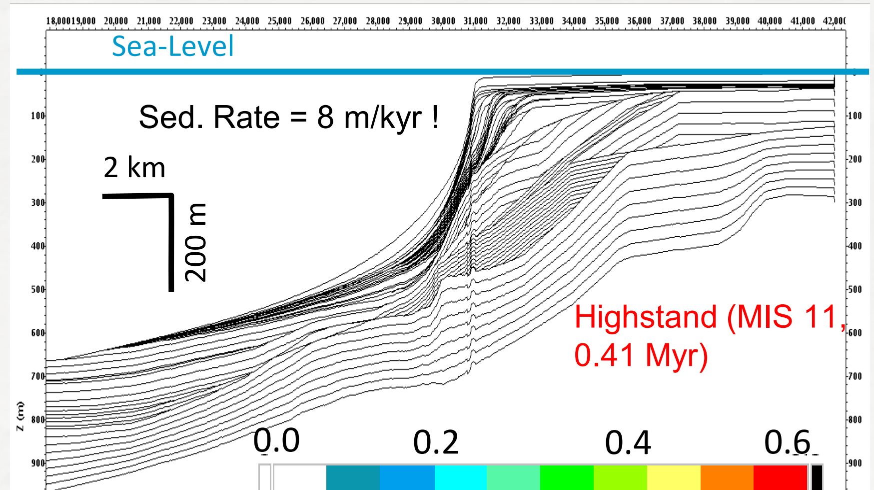
- **With cemented levels** : shallow overpressure during Highstand





- **No cemented levels** : minor overpressure losses



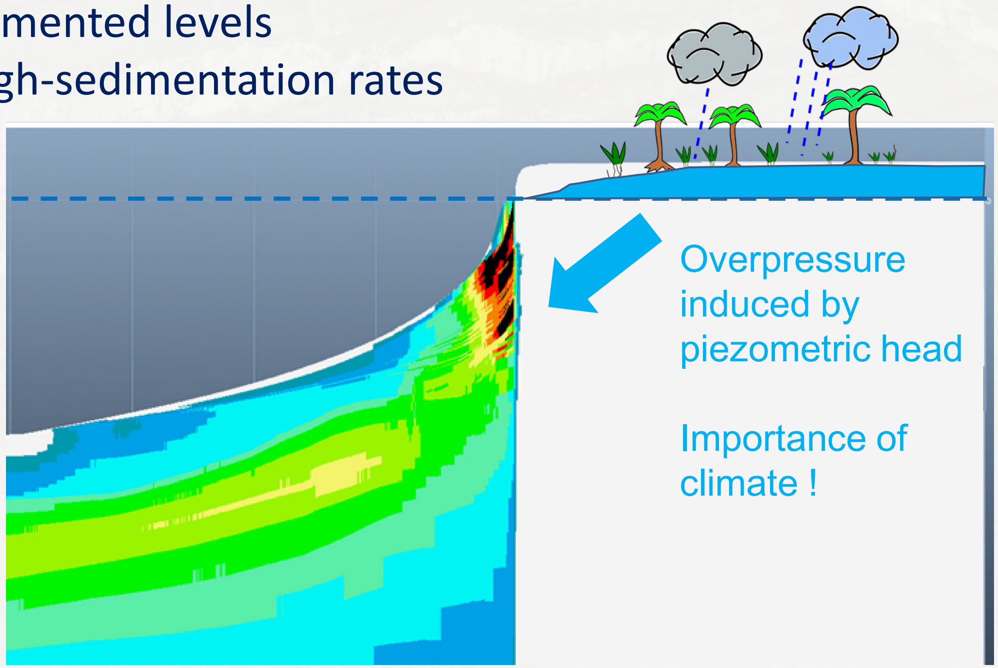


Conclusions on overpressure

- Large shallow overpressures ($\lambda^* > 0.3$) can develop under sea-level lowstands … when the emerged platform is still saturated.

- **Sea-level fall slope overpressures** (Spence and Tucker, 1997) **appear controlled by the onshore Piezometry.**

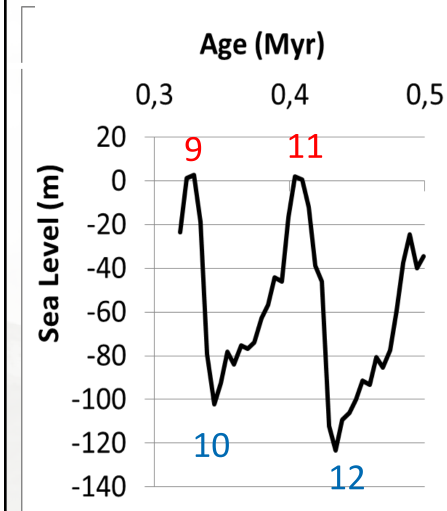
- Plio-Quaternary Bahamas case :
  - ➢ Transient slope overpressure possible (rainfall event)
  - ➢ 2nd order effect of cemented levels
  - ➢ 2nd order effect of high-sedimentation rates



Failure simulation

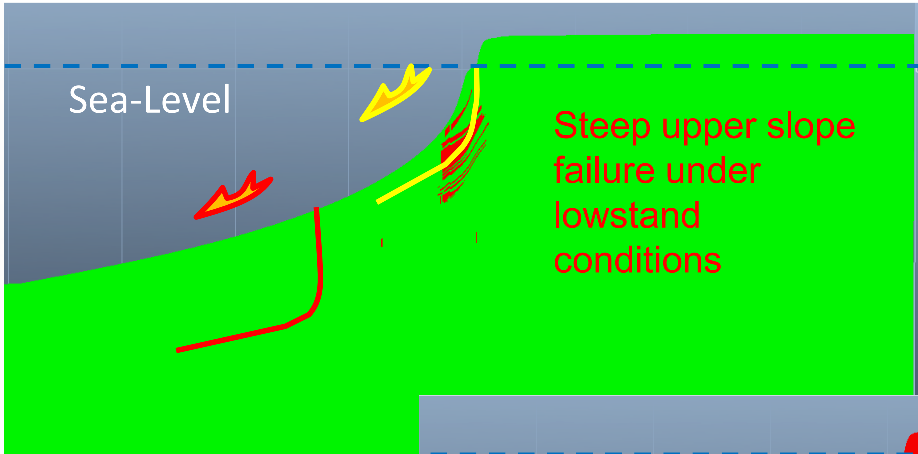
Upper slope failures can develop during **sea-level lowstands**

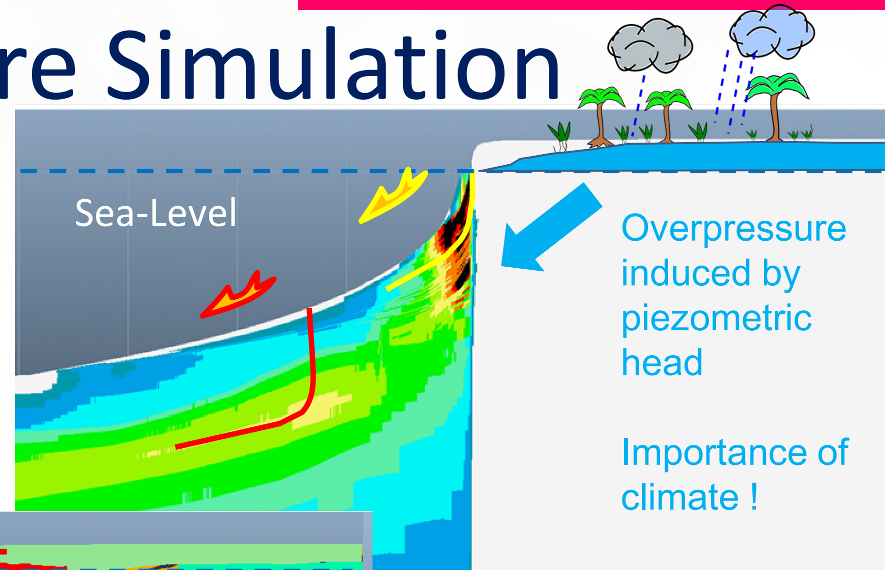
After Miller et al., 2011



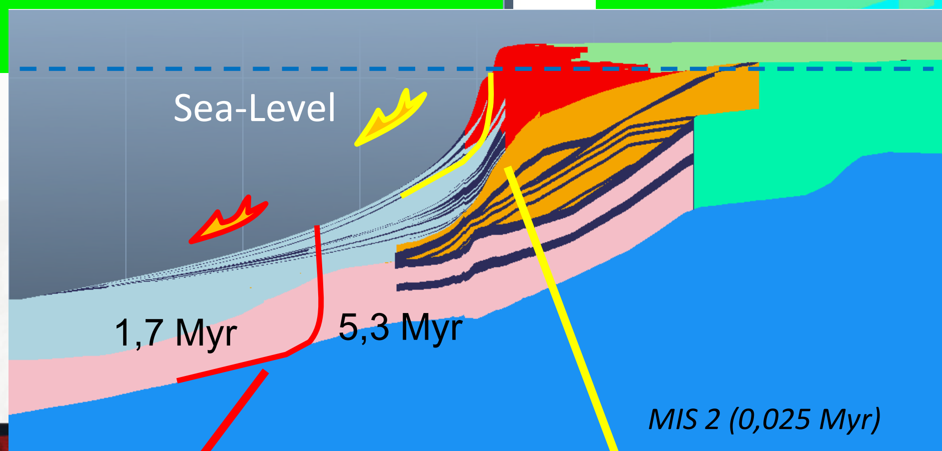
- Drucker-Prager failure criterion
- Identification of shear failure zones
- Control by rigid cemented levels

Lowstand failure Simulation

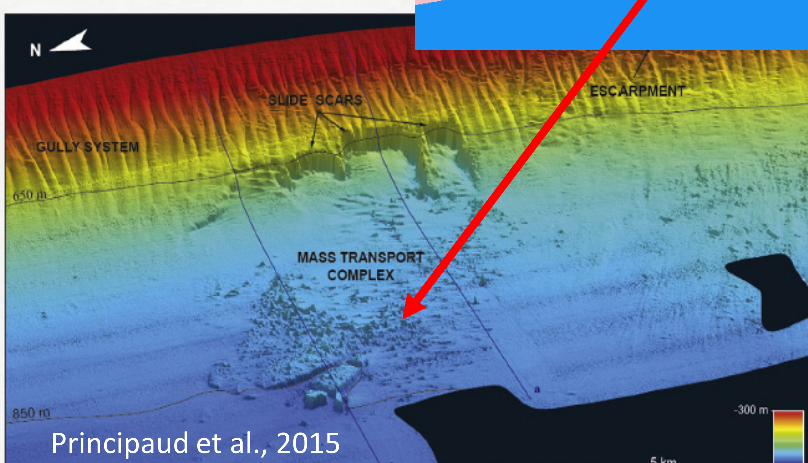


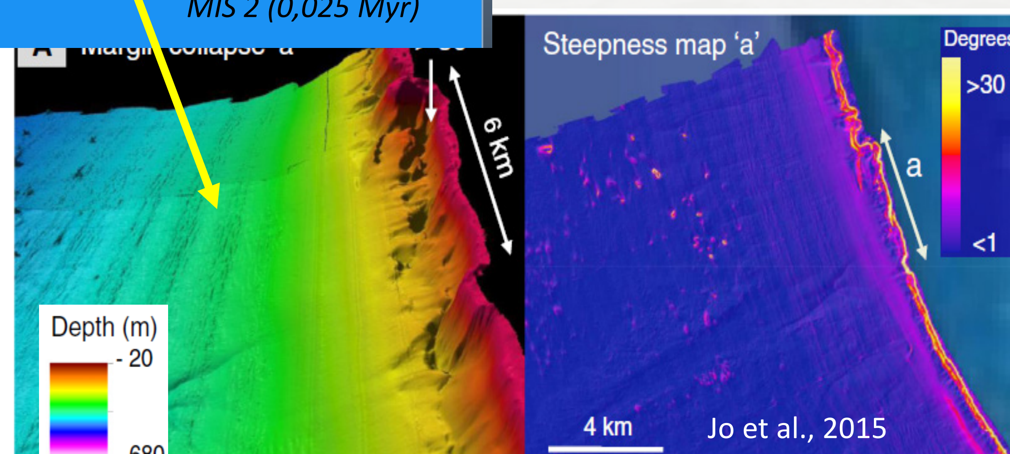


Lower slope : Favorable overpressure, but stable configuration.



Upper slope : Favorable overpressure and effective failure at high slope angle.





Conclusions and Perspectives

- Successful proof of concept for a **forward numerical assessment of potential failures**:
  - Industrial Forward Stratigraphic modeling + Advanced Basin Modeling

- Western Bahamas slope high-resolution case study
  - Mechanically valid evaluation of overpressure and failure
  - **1st control : Lowstand piezometry**, controlling the slope **overpressure**.
  - **2** favorable **failure mechanisms** correctly identified.

- Short-term perspectives
  - **Sensitivity** to the **characterization of sediments** (Permeability & Failure laws)
  - Develop mechanical post-treatment to **test seismic acceleration**

- Long-term perspectives
  - Test older cases with less constraining data
  - Test **different carbonate geometries** with different control factors.

Thank you for your attention !

We can discuss at IFPEN booth #607

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Soubeyranes Cliffs (Southern Provence Basin, France)
Turonian Carbonate Megabreccias

Learn more about DionisosFlow ?
High-performance stratigraphic modeling of shelf to deep-water plays, by B. Chauveau (IFPEN)
Ballroom E 2:20 PM