Quantifying Climatic and Tectonic Forcing of Alluvial-Fan Stratigraphy by 3D Numerical Modeling and Comparison with Outcrop Examples*

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Abstract

We explore a new methodology to solve questions about the effects of different and varying allogenic controls on deposition patterns and morphology of alluvial fans by performing a systematic series of numerical stratigraphic simulations of fan development using the DIONISOS program (IFP, France). Model output is compared to field examples of recent and ancient alluvial-fan systems.

Model runs span different time scales, from 10 ky, for comparison with abundant studies of late Quaternary alluvial fans, to 500 ky, for comparison with ancient successions of long-lived systems preserved in the geological record. Models comprise a full spectrum of sensitivity tests. The effects of single factors; i.e., (variations in) tectonics, sediment supply, water discharge, and sediment composition, as well as combinations of these, are tested under steady to unsteady forcing conditions, and with different time resolutions.

We compare our model output with a case study of a unique Miocene alluvial fan system in the Teruel Basin (central Spain). This fan system has aggraded in an astronomically forced, cyclically alternating paleoclimate with alternating relatively humid and arid periods. Comparison of the architecture of the alluvial-fan succession with the model output corroborates the approach used in the stratigraphic modeling.

Quantifying climatic and tectonic forcing of alluvial-fan stratigraphy by 3D numerical modeling and comparison with outcrop examples

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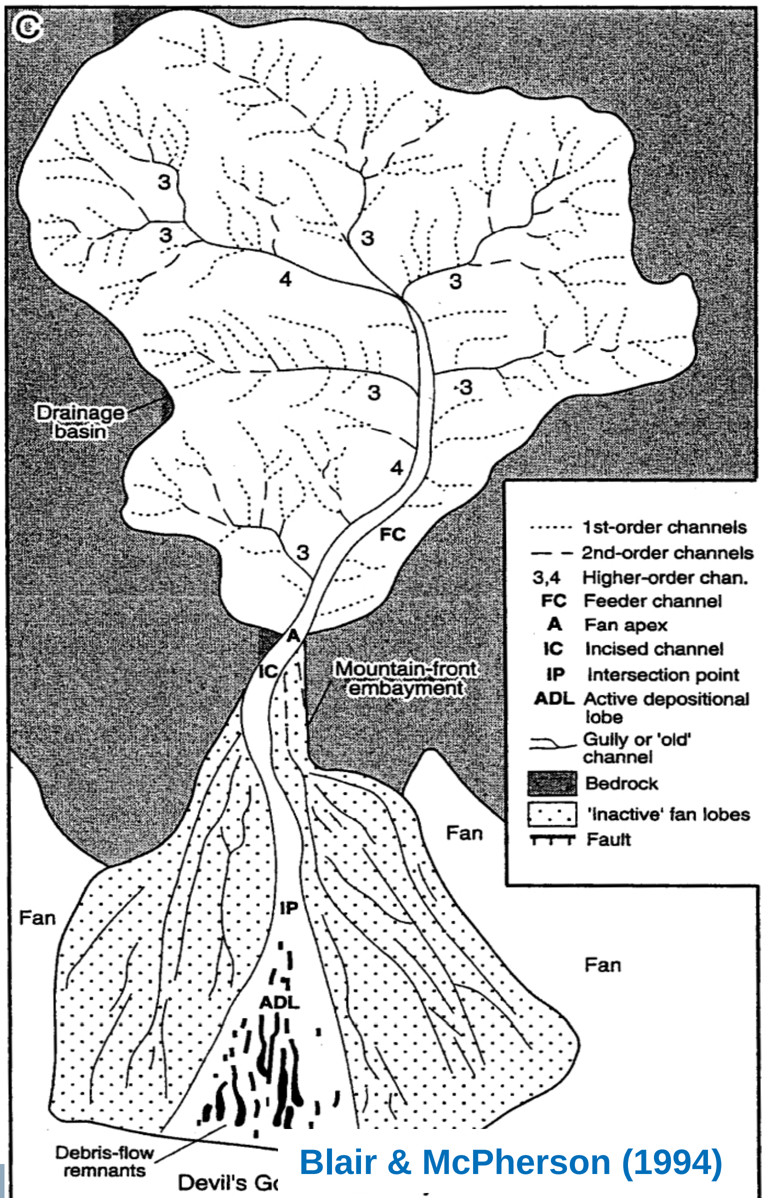
Scientific setting

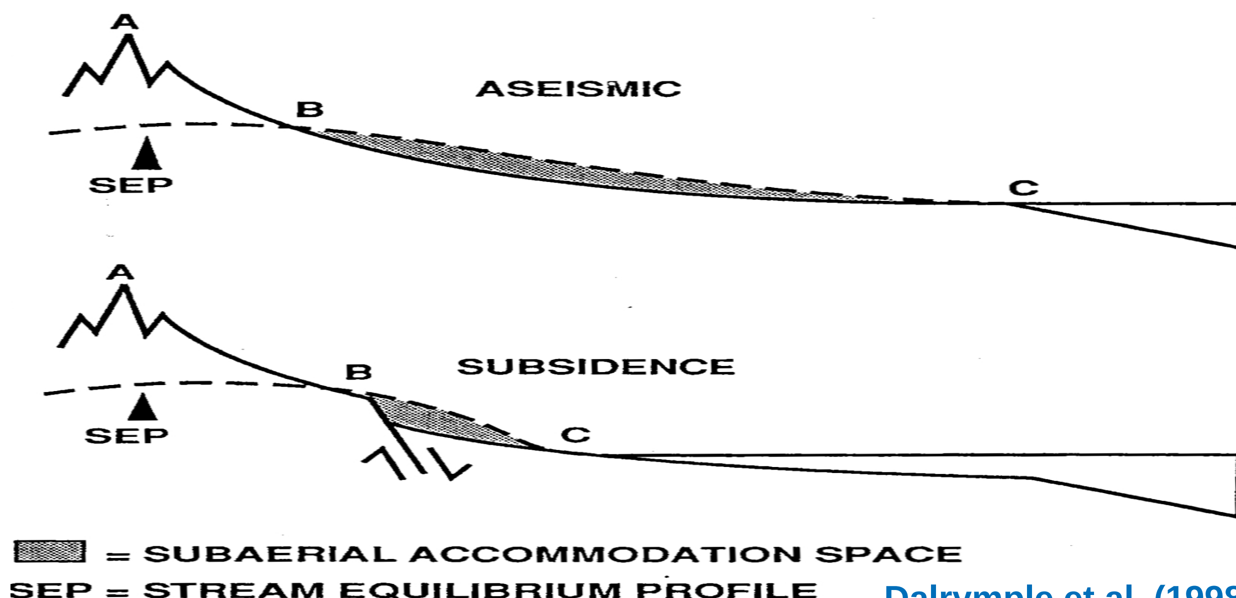
Interest on alluvial fan



Blair & McPherson (1994)

- First architectural element between the catchment and the sedimentary basin = key element for qualifying (nature) and quantifying the sediment supply dynamics (storage, by-pass…)

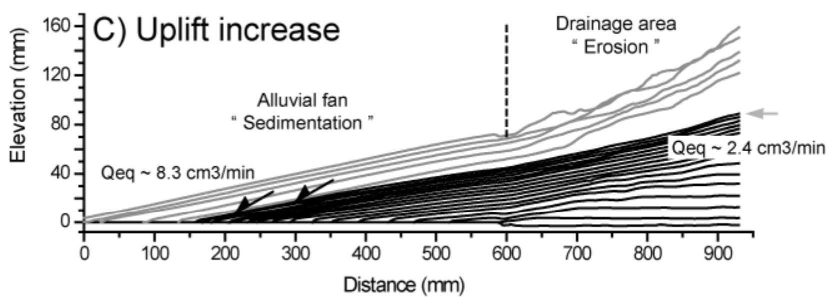
=> Direct impact on reservoir distribution (continental environments) and sequence stratigraphy concept

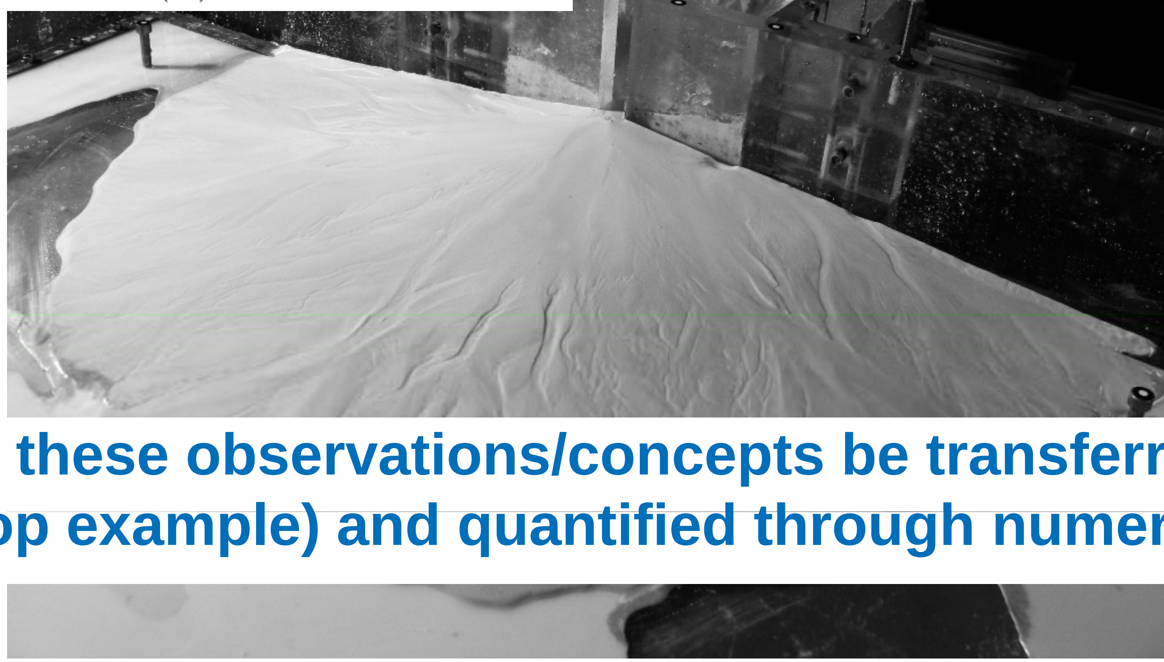


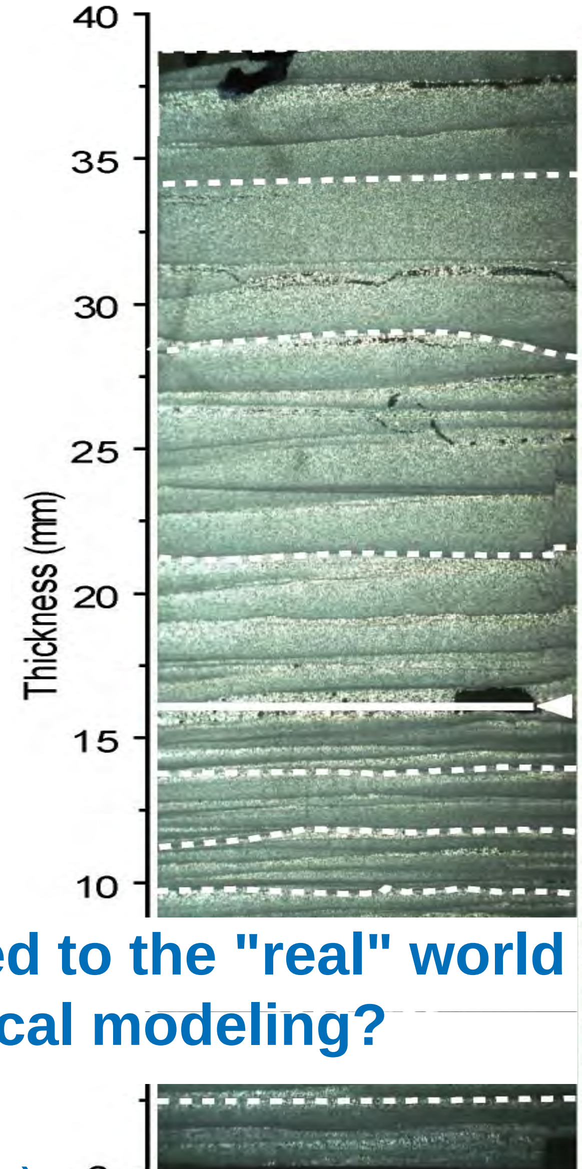
Dalrymple et al. (1998)

Scientific setting
Starting point and Question

- Experimental modeling – Dynamics of erosion / sedimentation and sediment supply (*Rennes University - France)*







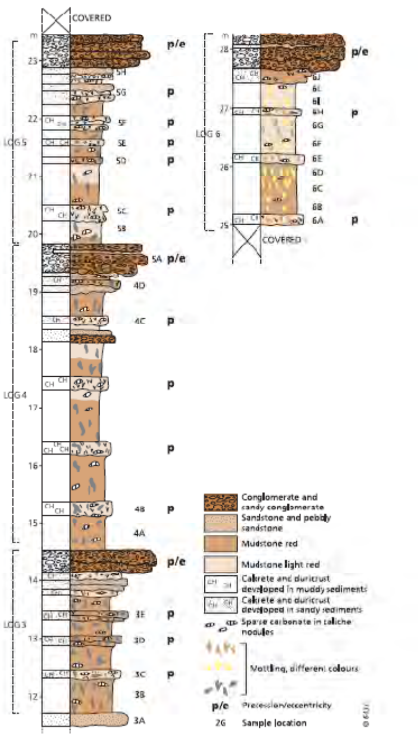
=> Could these observations/concepts be transferred to the "real" world (outcrop example) and quantified through numerical modeling?

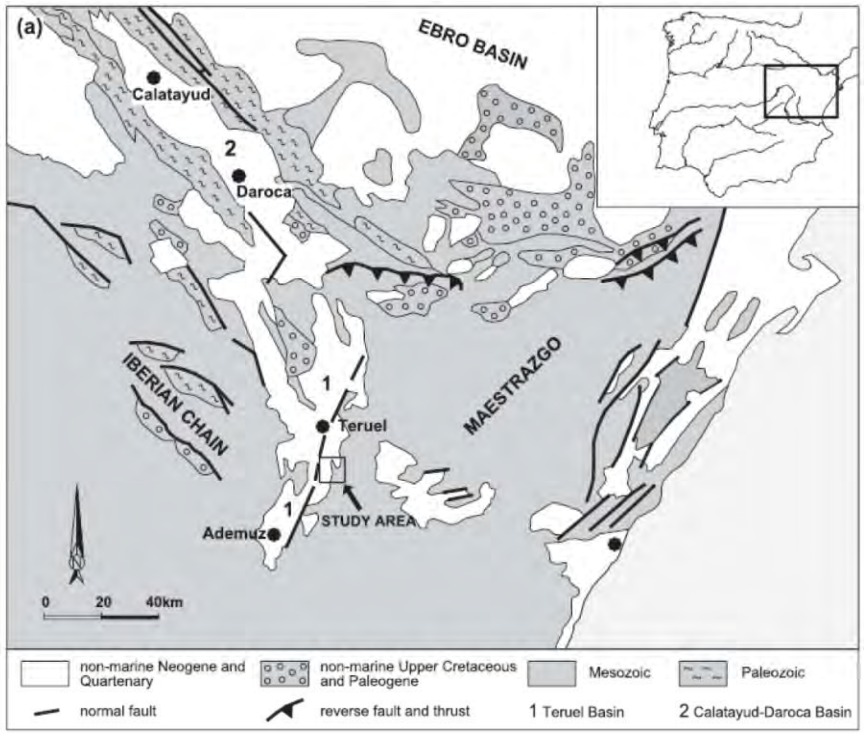
Rohais (2007), Rohais *et al*., (in prep)

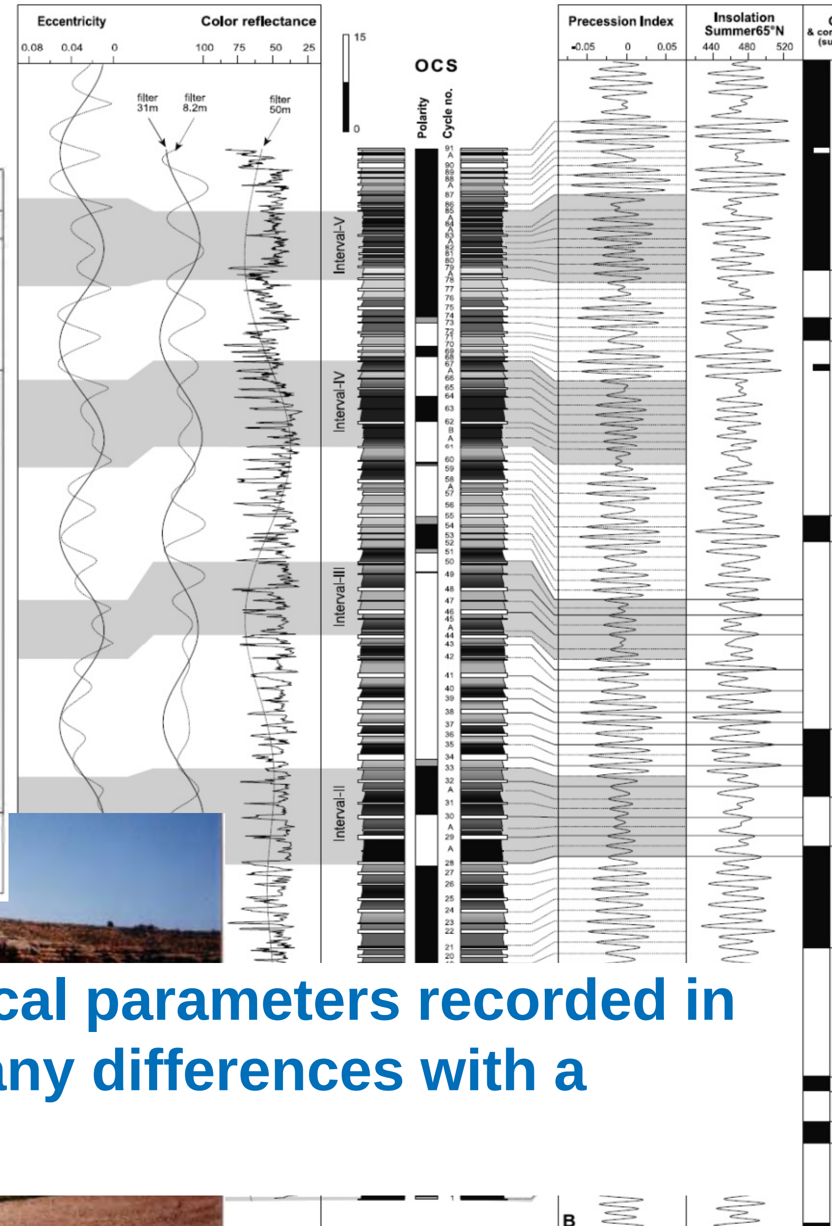
Methodology

Finding the best outcrop example to work on

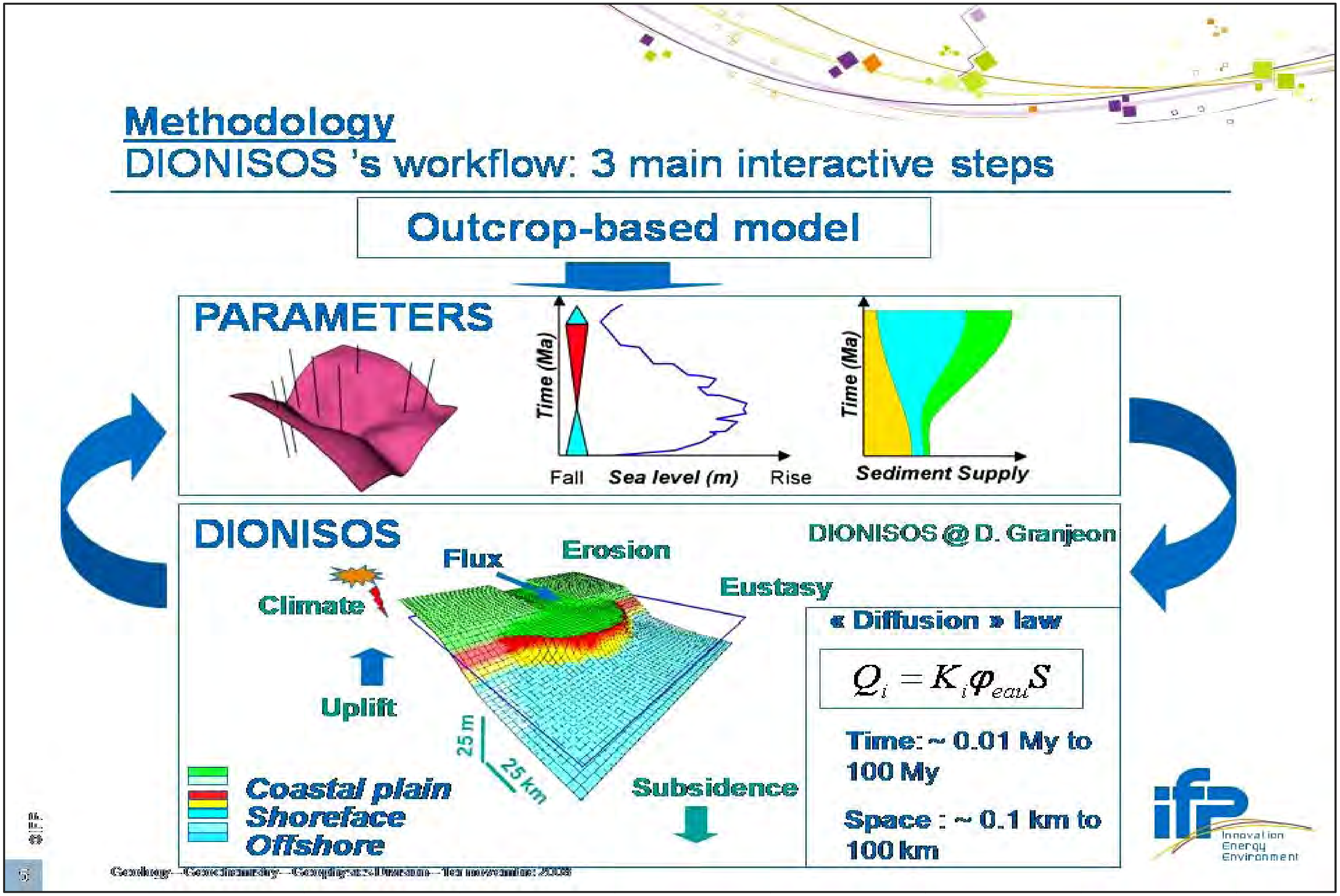
D. Ventra (PhD – Utrecht University): Orbital signatures in alluvial fan sequences







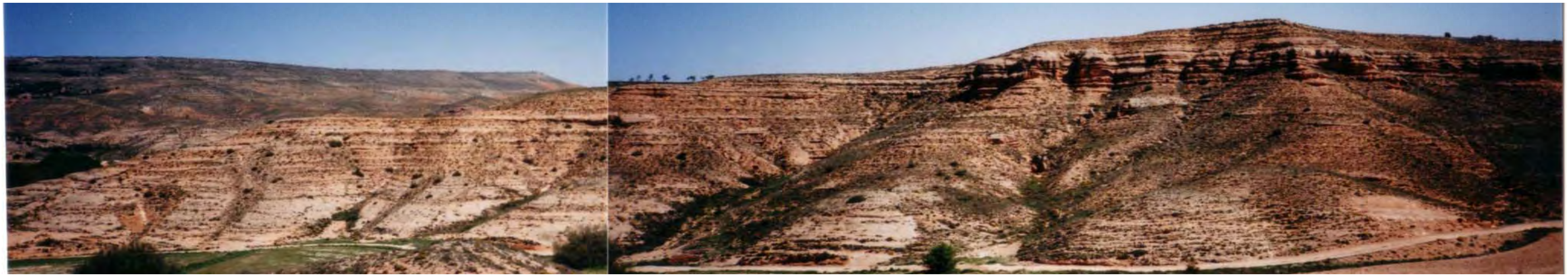
=> How is a cyclic climate due to astronomical parameters recorded in the stratigraphic architecture? Are there any differences with a tectonic forcing?

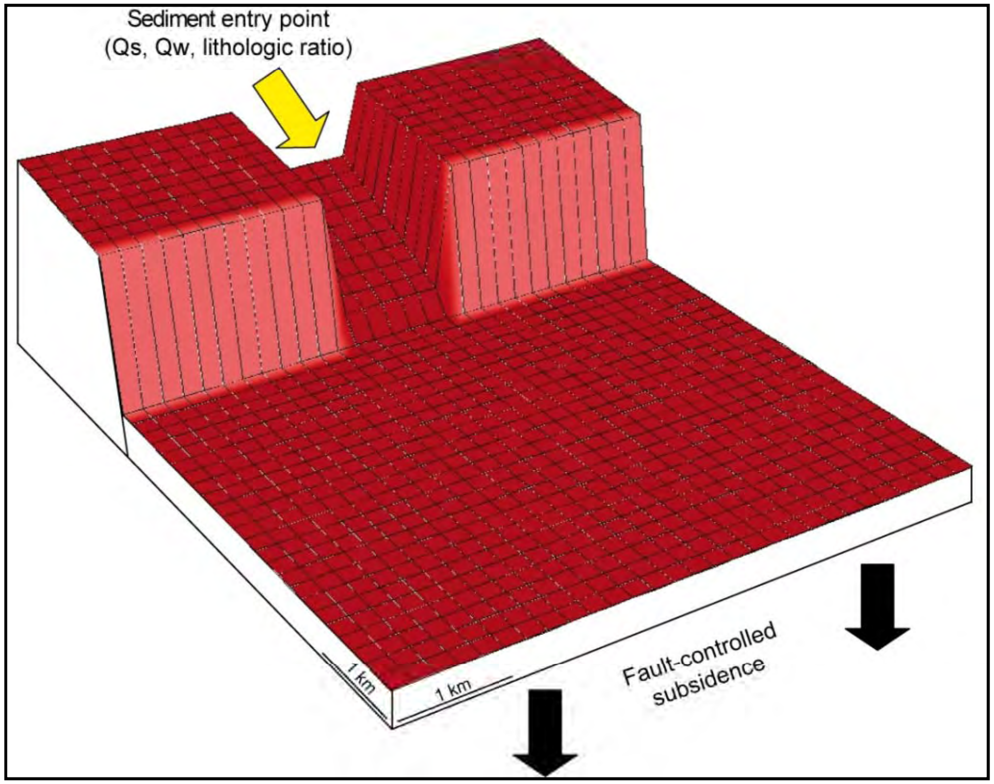


1. **Model calibration (sensitivity analysis) based on field data and bibliographic review** ***(Teruel Basin, Spain – D. Ventra's PhD)***
2. **Numerical modeling - Stratigraphic simulations** ***(IFP, Dionisos)***
3. **Feed-back for improving the field study, and consequently increasing the robustness of the modeling approach**

1. Model calibration: alluvial fan of the Teruel Basin (Spain)

1. Model calibration
Initial setup: outcrop-based dataset

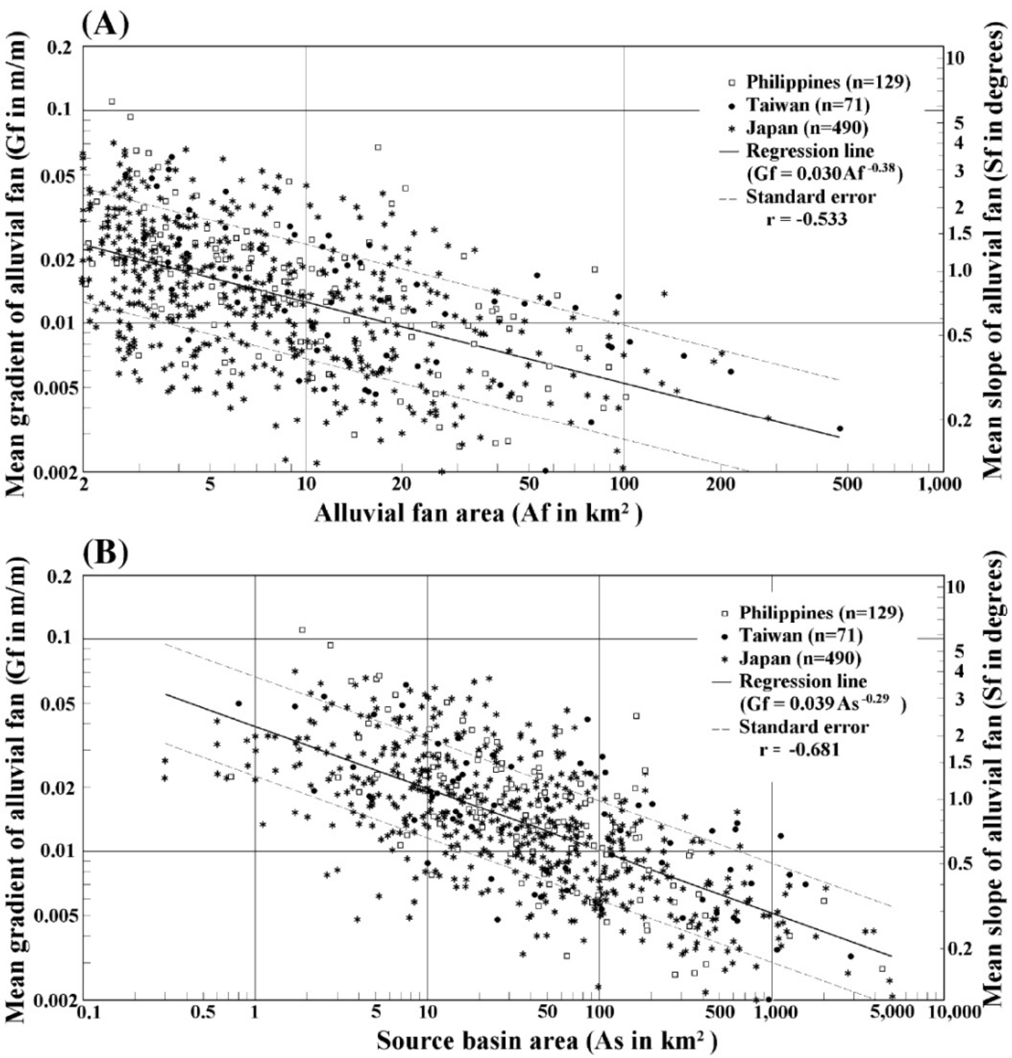




- Endorheic basin 5x6 km (dx: 0.2 km)
- Fan radius ~2 km, 70 m thick
- Slope (20° to 1°)
- Duration ~500 kyr (dt: 5 kyr, Upper Miocene)
- Lithology
  - 2% cobble (1-4%)
  - 20% pebble (4-40%)
  - 10% granule (4-20%)
  - 8% sand (2-16%)
  - 60% mud (20-90%)

1. Model calibration

Dataset constraints



Saito & Oguchi (2005)

- Water discharge (Qw)
  - 0.03-2 m^3/s, mean 0.3 m^3/s
- Sediment supply (Qs)
  - 0.05-12 km^3/Ma, mean 3 km^3/Ma
- Subsidence rate
  - mean 150 m/Ma
- Diffusion coefficients are derived from all these parameters
  - $K_{water-driven}$: 35-0.8 km^2/ky
  - $K_{gravity-driven}$: 0.15-0.004 km^2/ky

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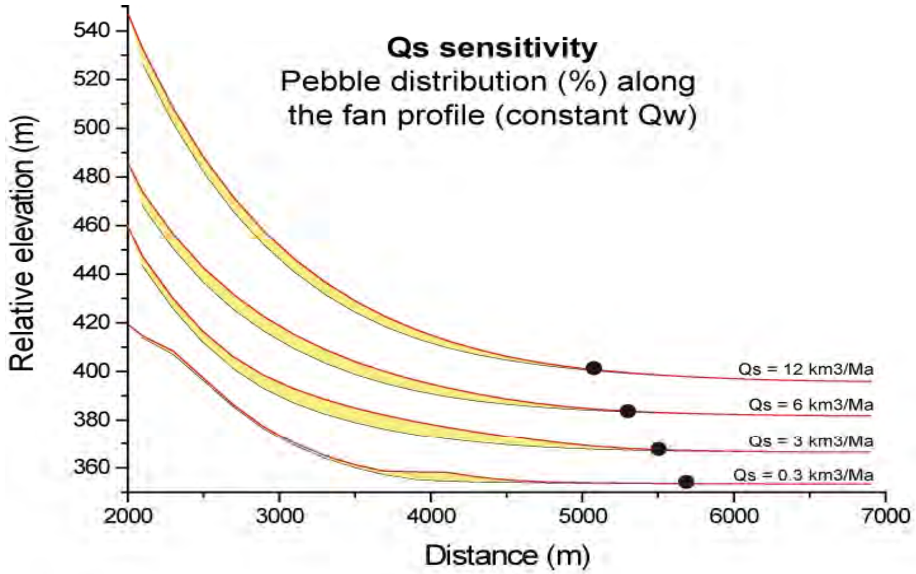
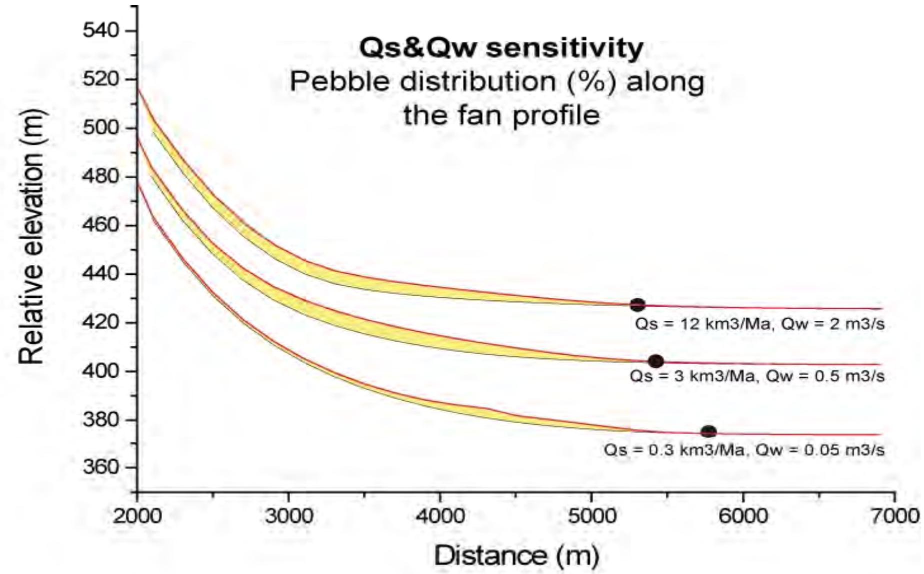
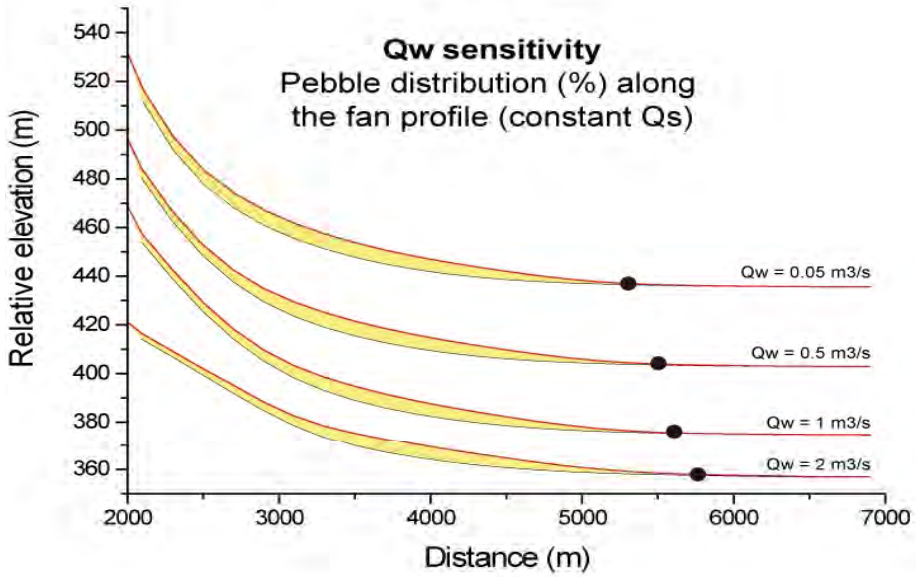
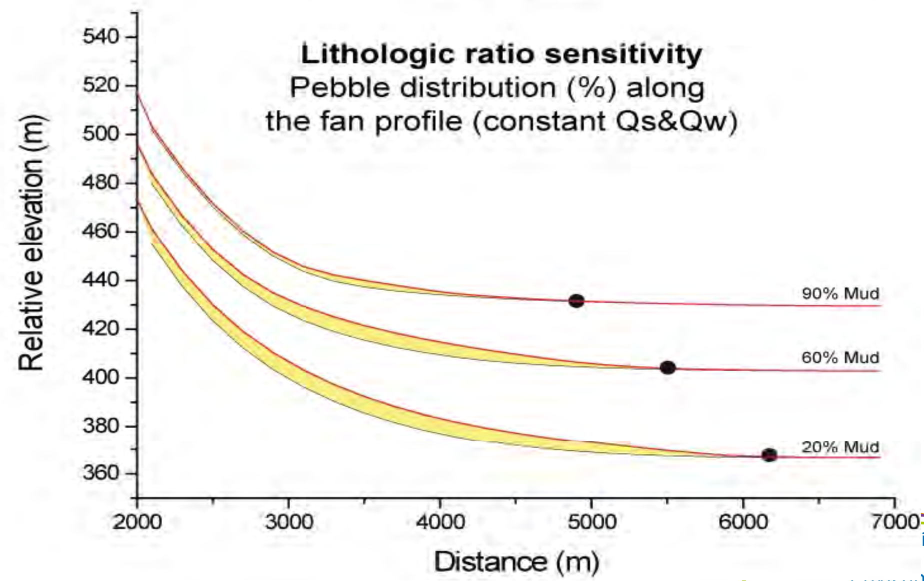
1. Model calibration

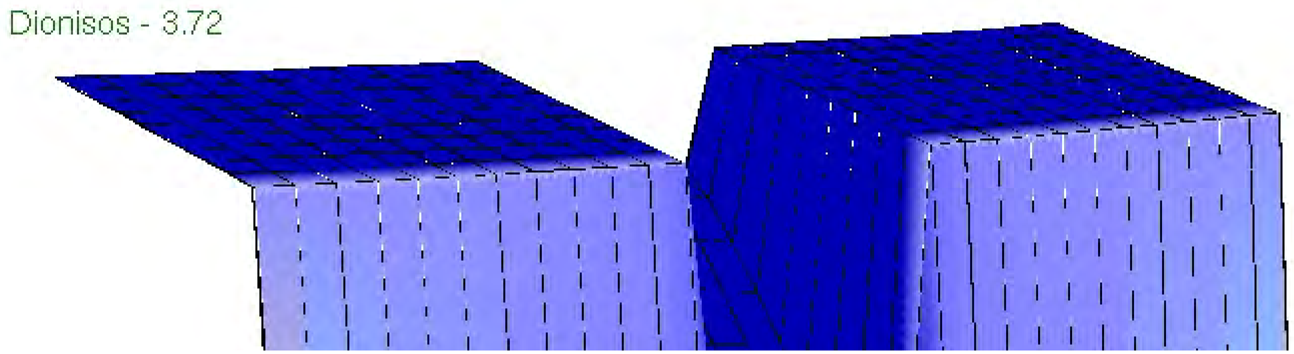
Sensitivity analysis – Fan profile



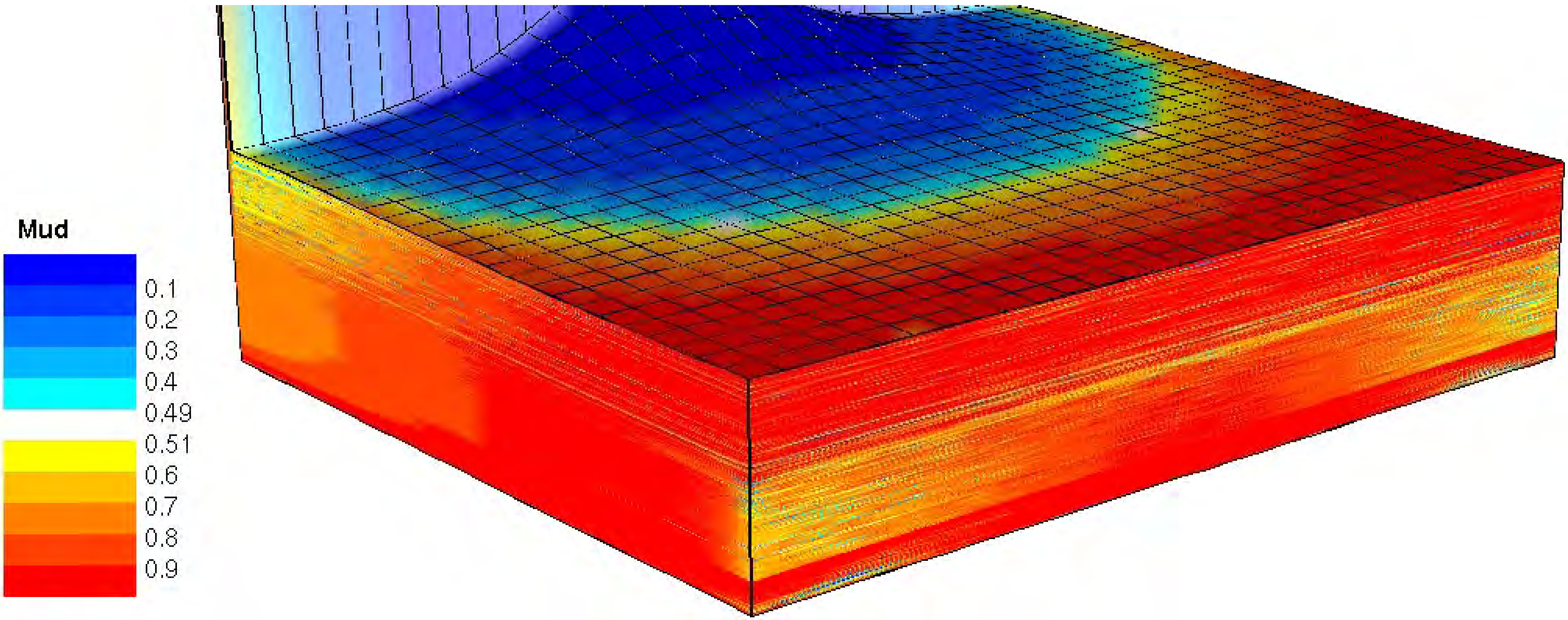








2. Numerical modeling of cyclic changes



2. Cyclic changes
3D modeling objectives

- To restore the overall architecture of the fan (slope distribution, grain-size distribution, distance of progradation, thickness);
- To restore the cyclicity in the distal part of the fan;
- To restore the onlap geometry of the fan onto the feeding valley;
- To restore the overall backstepping of the fan.

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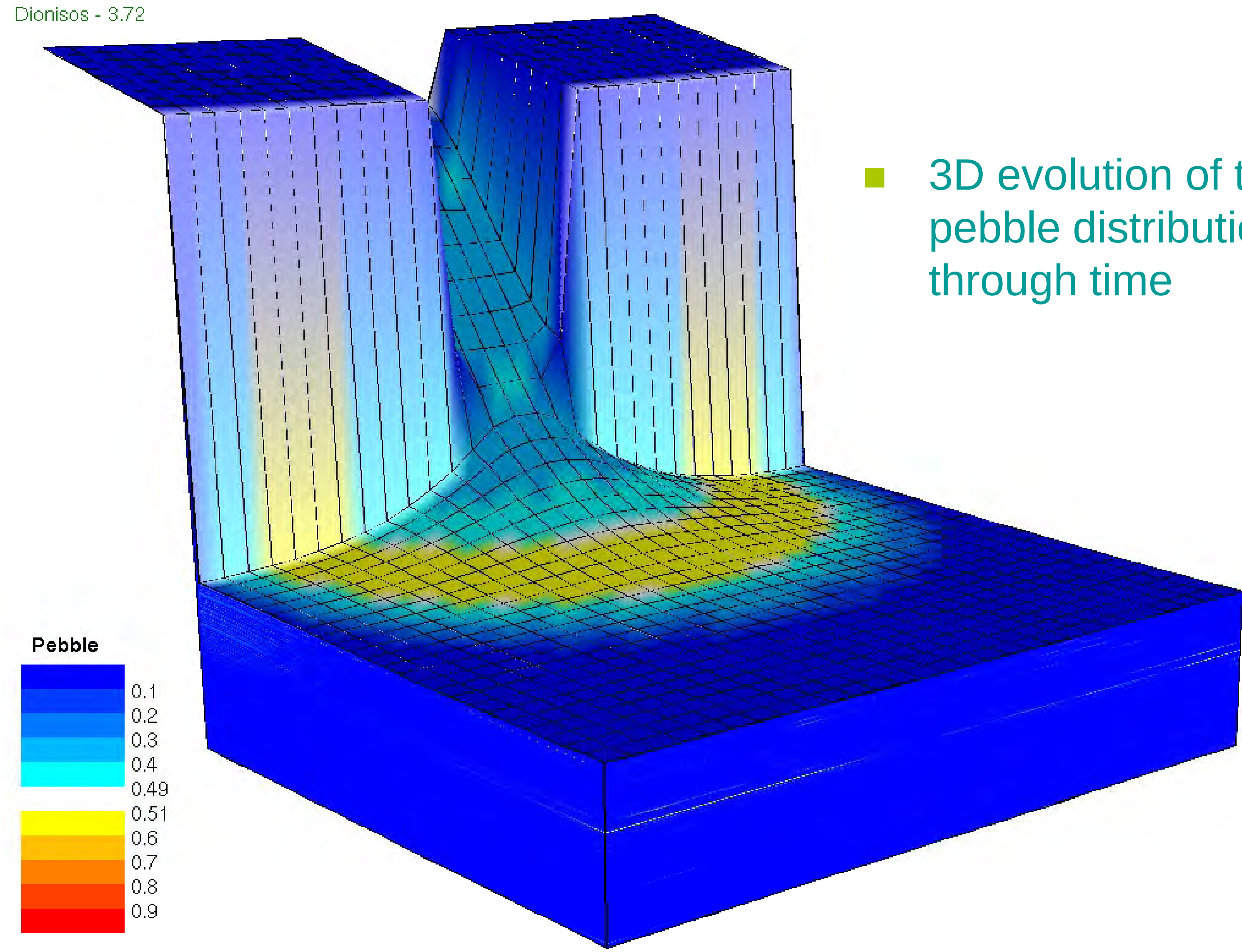
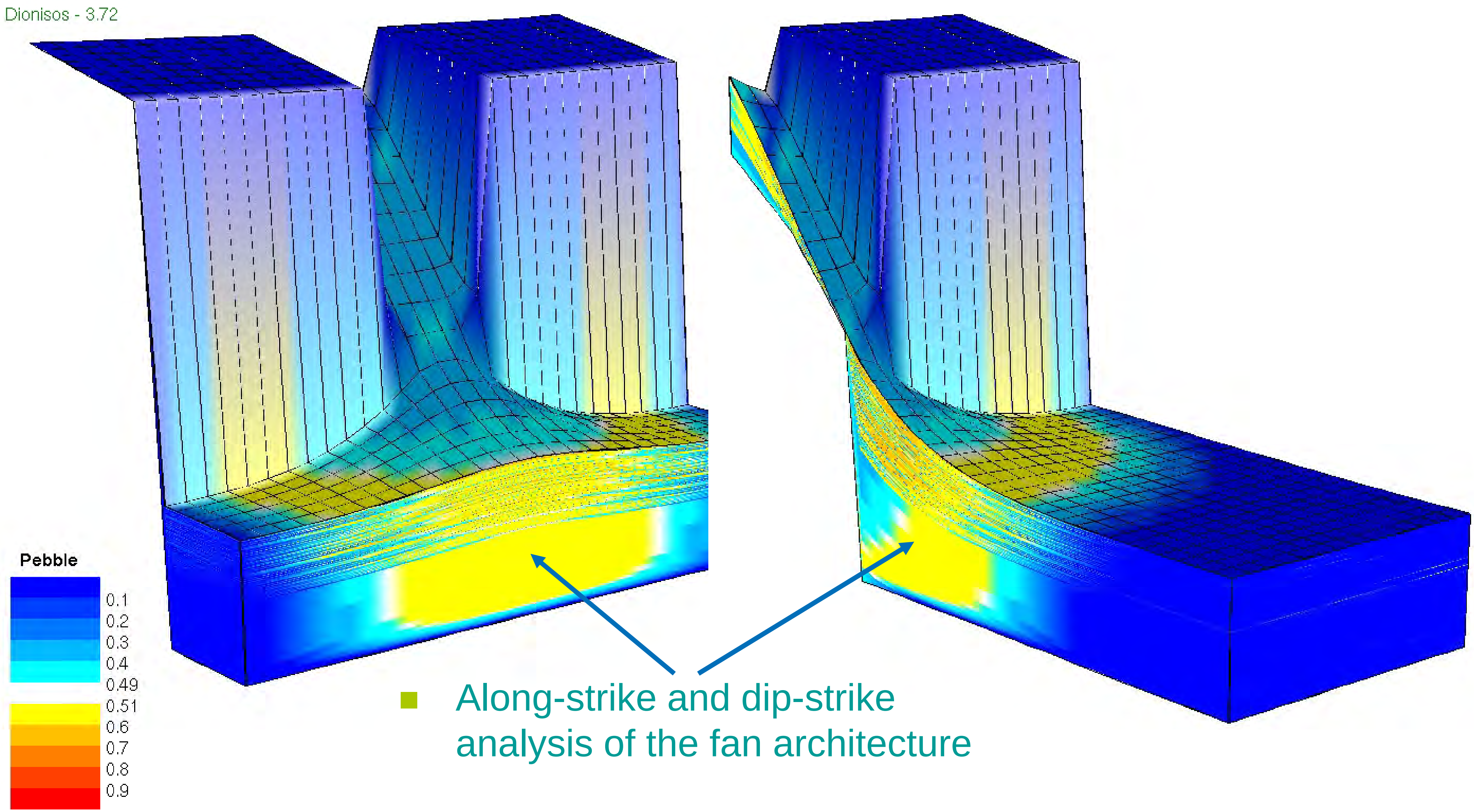
2. Cyclic changes
3D modeling - Reference model



- 3D evolution of the pebble distribution through time

2. Cyclic changes

3D exploration of the simulation

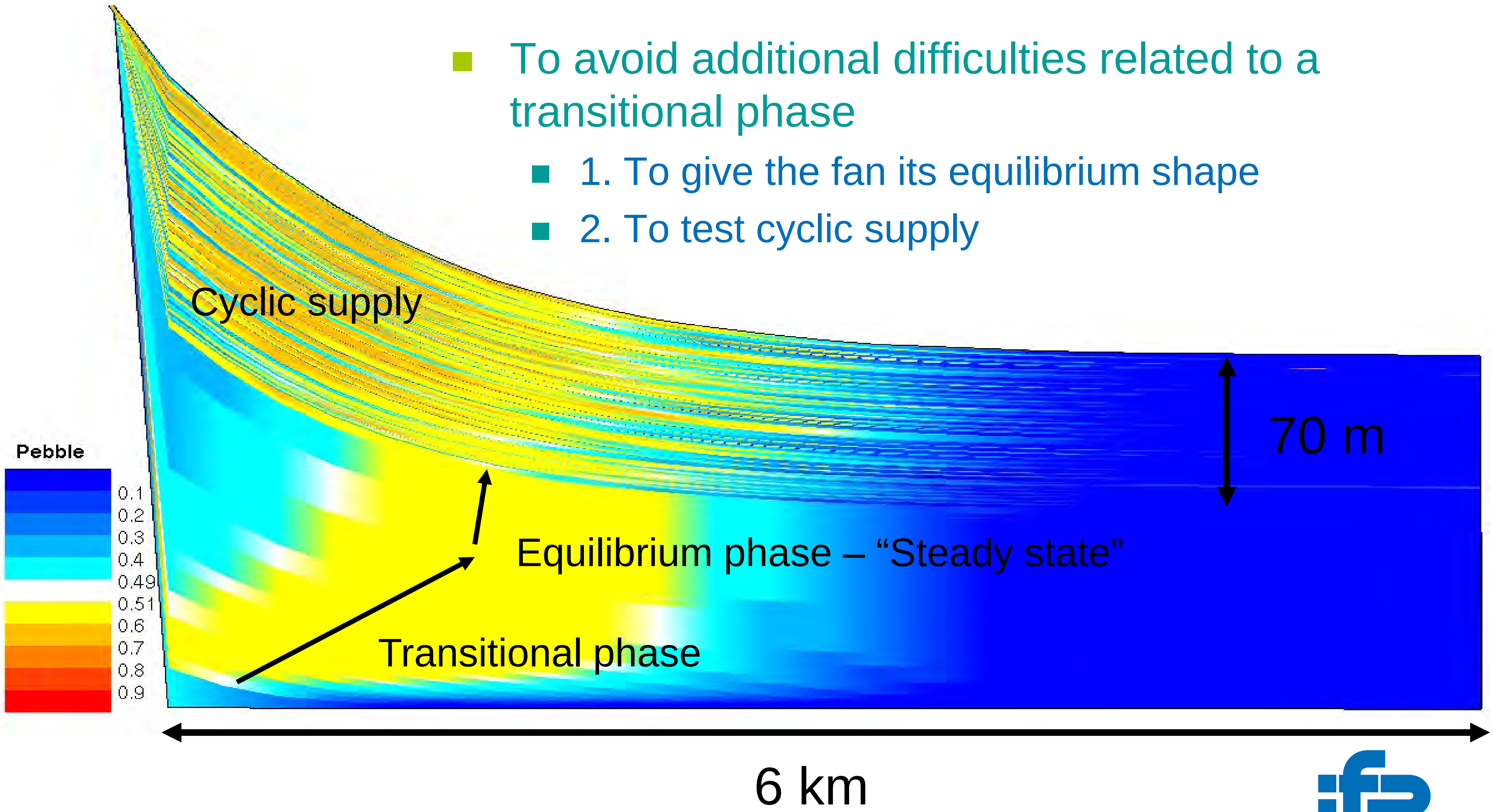


- Along-strike and dip-strike analysis of the fan architecture

2. Cyclic changes

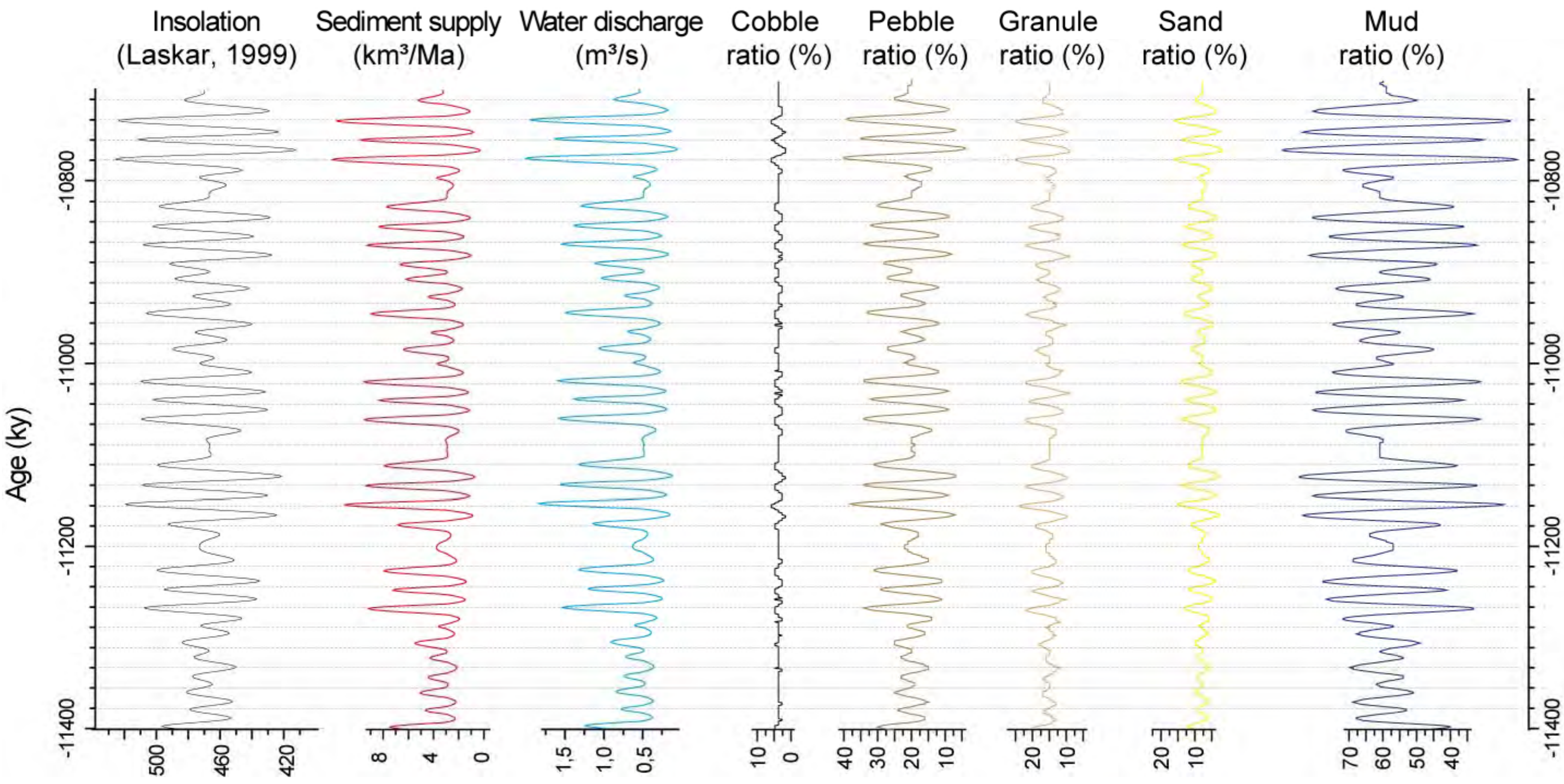
Reference model – Longitudinal cross-section

- To avoid additional difficulties related to a transitional phase
  - 1. To give the fan its equilibrium shape
  - 2. To test cyclic supply



2. Cyclic changes

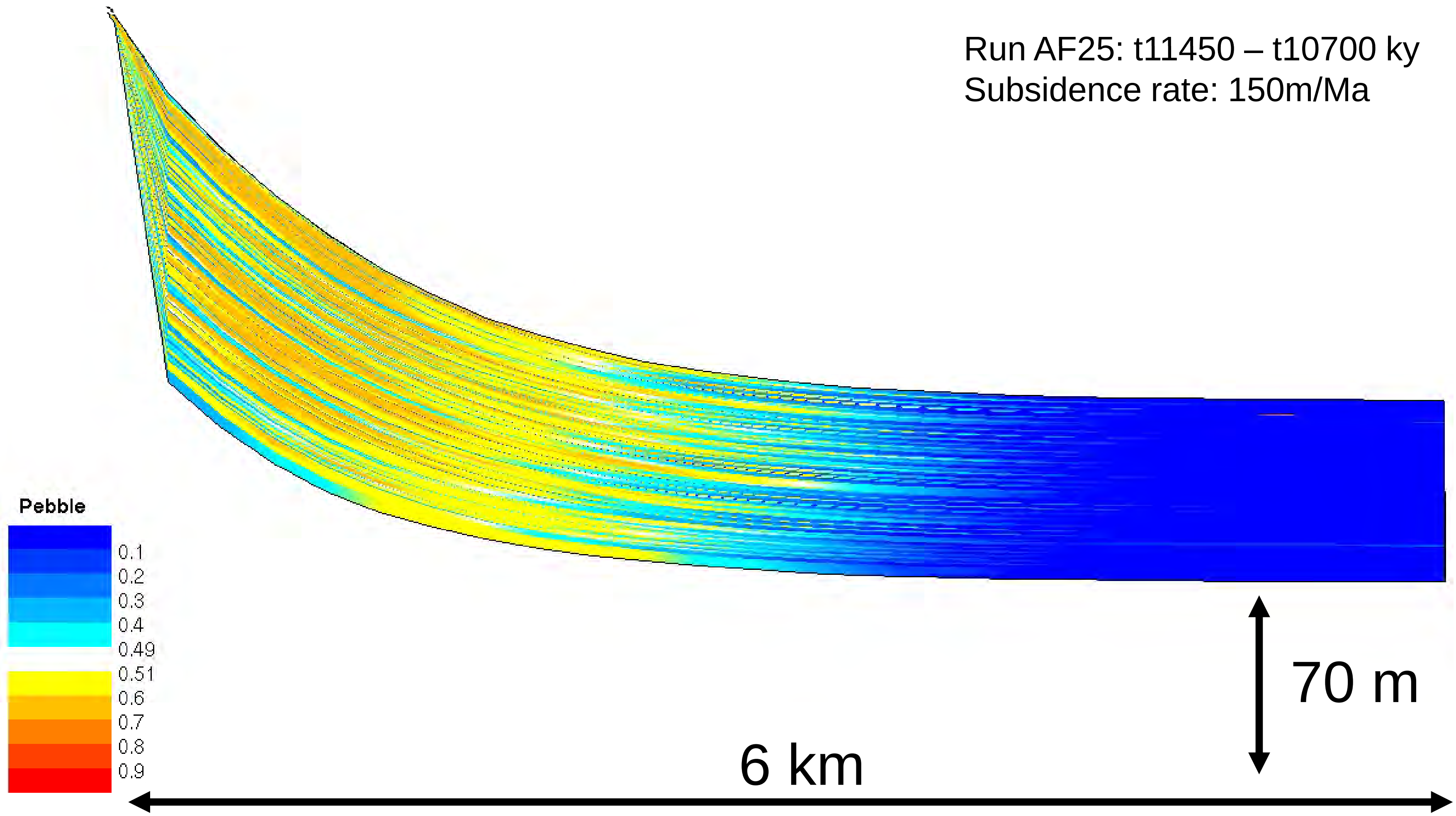
Reference model (AF25)- Parameters



- Simple hypothesis: linear relationship between supply (Qs, Qw, ratio) and insolation

2. Cyclic changes

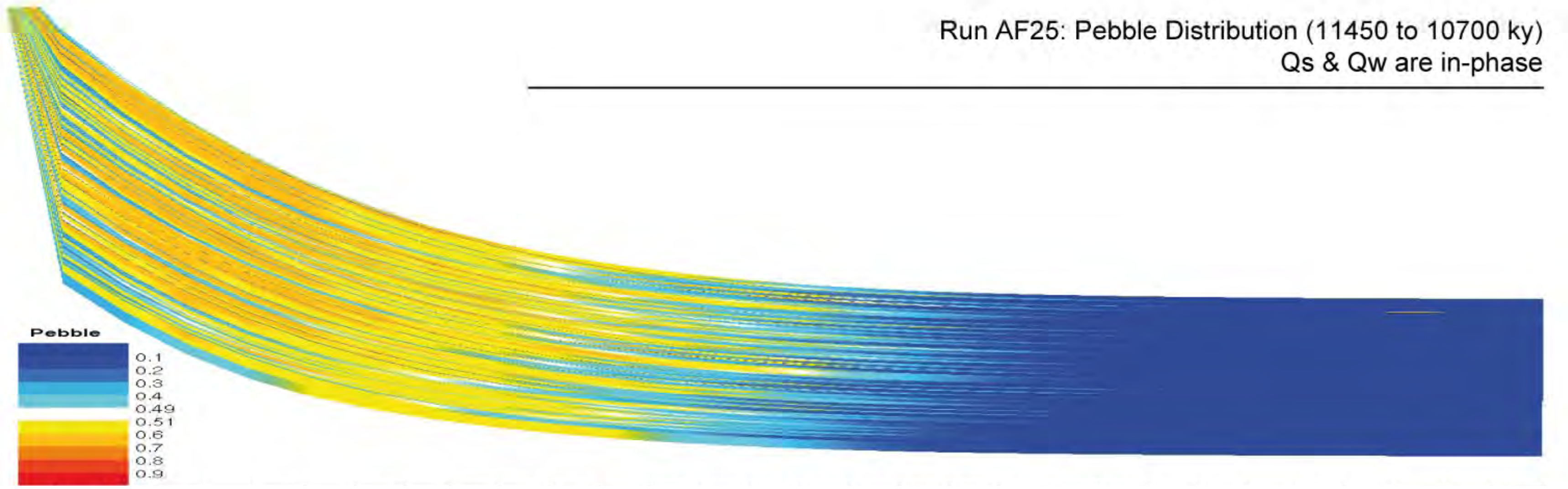
Reference model – Longitudinal cross-section



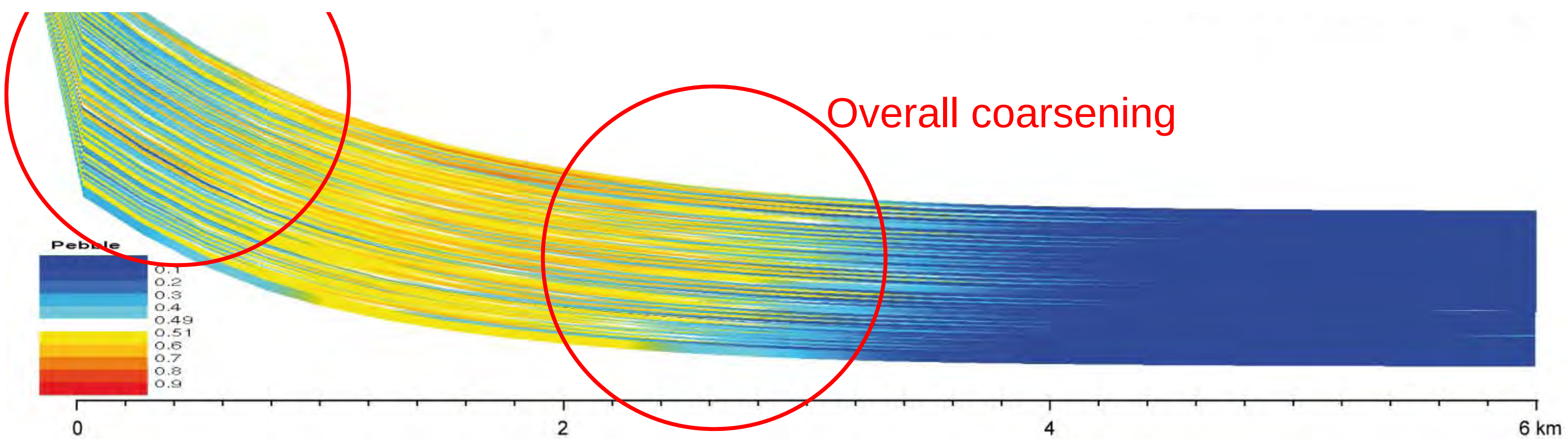
- Consistent grain-size & slope distribution
- Interfingering of coarse-grained deposits with distal fine-grained deposits

2. Model calibration

Qs & Qw are out-of-phase (10 kyr)

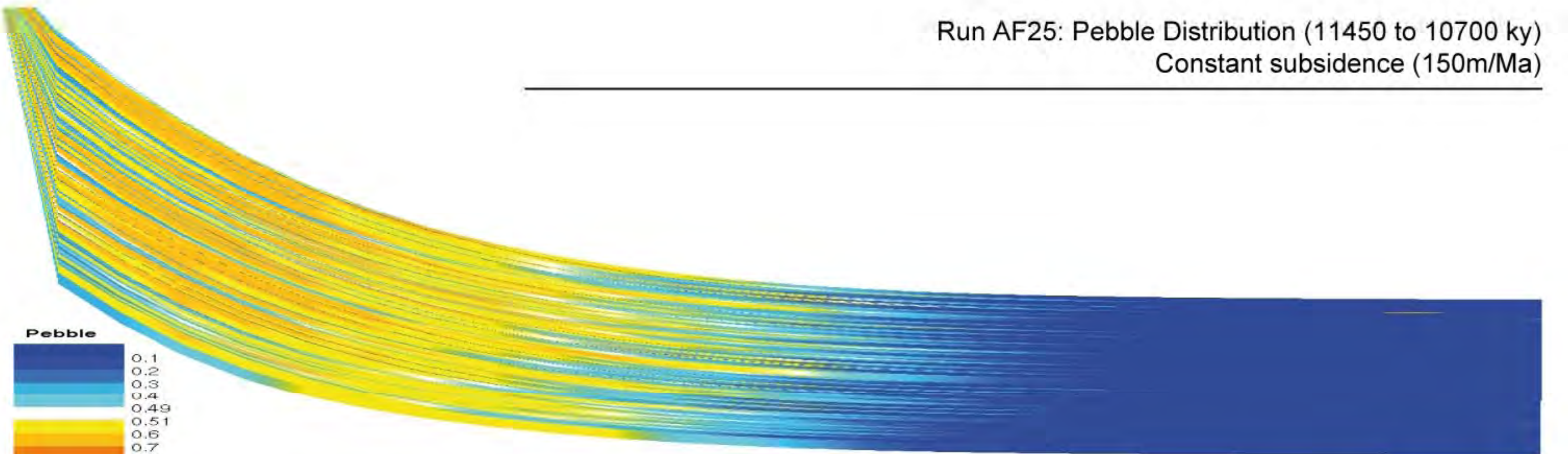


=> « In-phase » model (reference model AF25) is more consistent with the architecture of the Teruel fan than the « out-of-phase » model

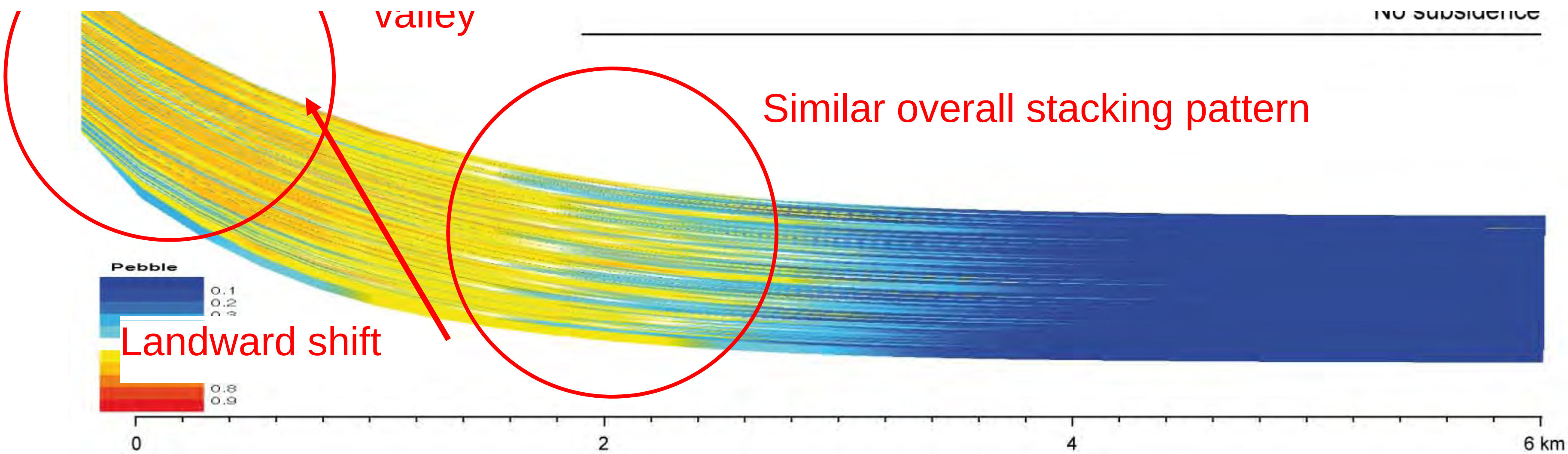


2. Cyclic changes

Tectonic influences – No Subsidence

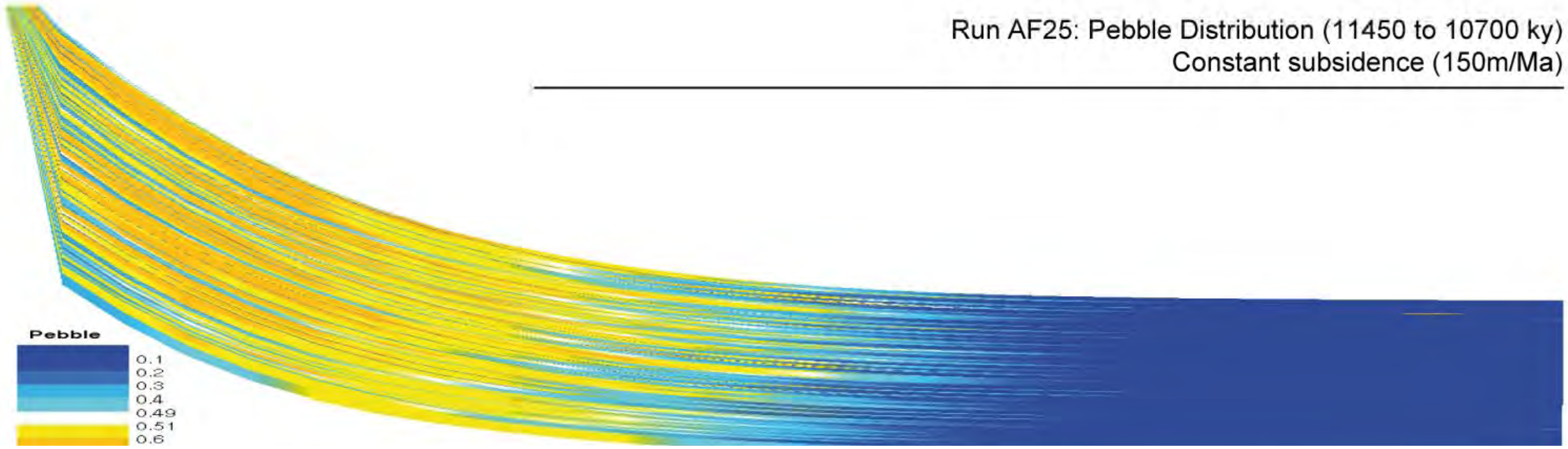


=> « No subsidence » model is more consistent with the overall architecture of the Teruel fan than the reference model

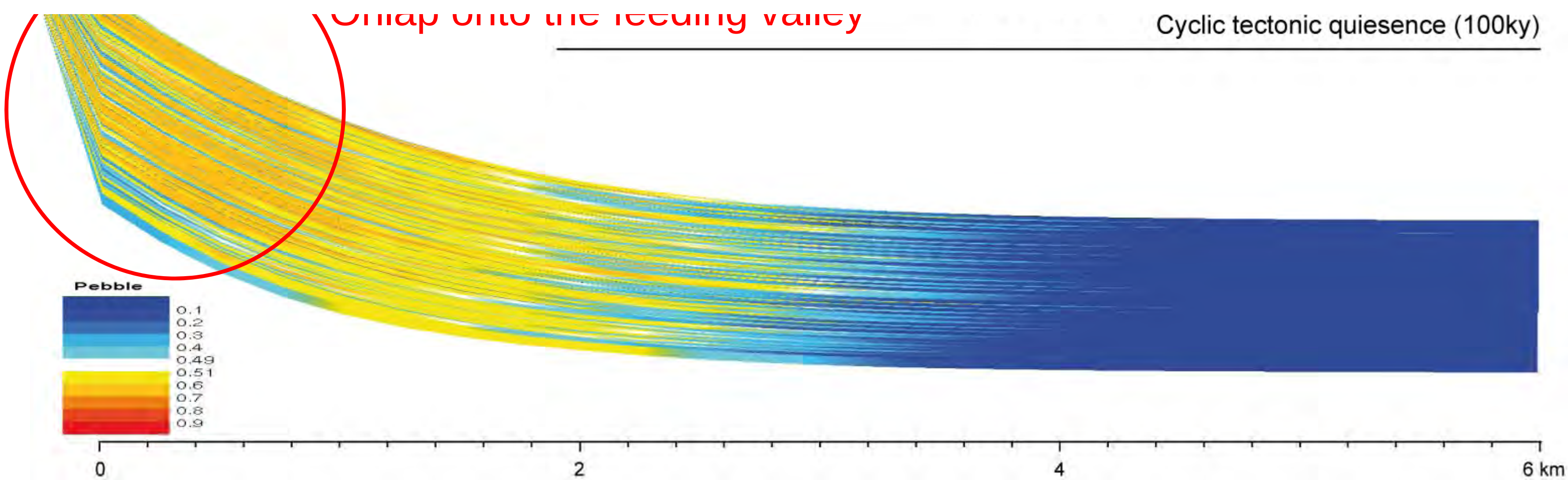


2. Cyclic changes

Tectonic – Non-linear Subsidence



=> Major difficulty to distinguish the overprint of cyclic tectonics into the stratigraphic record



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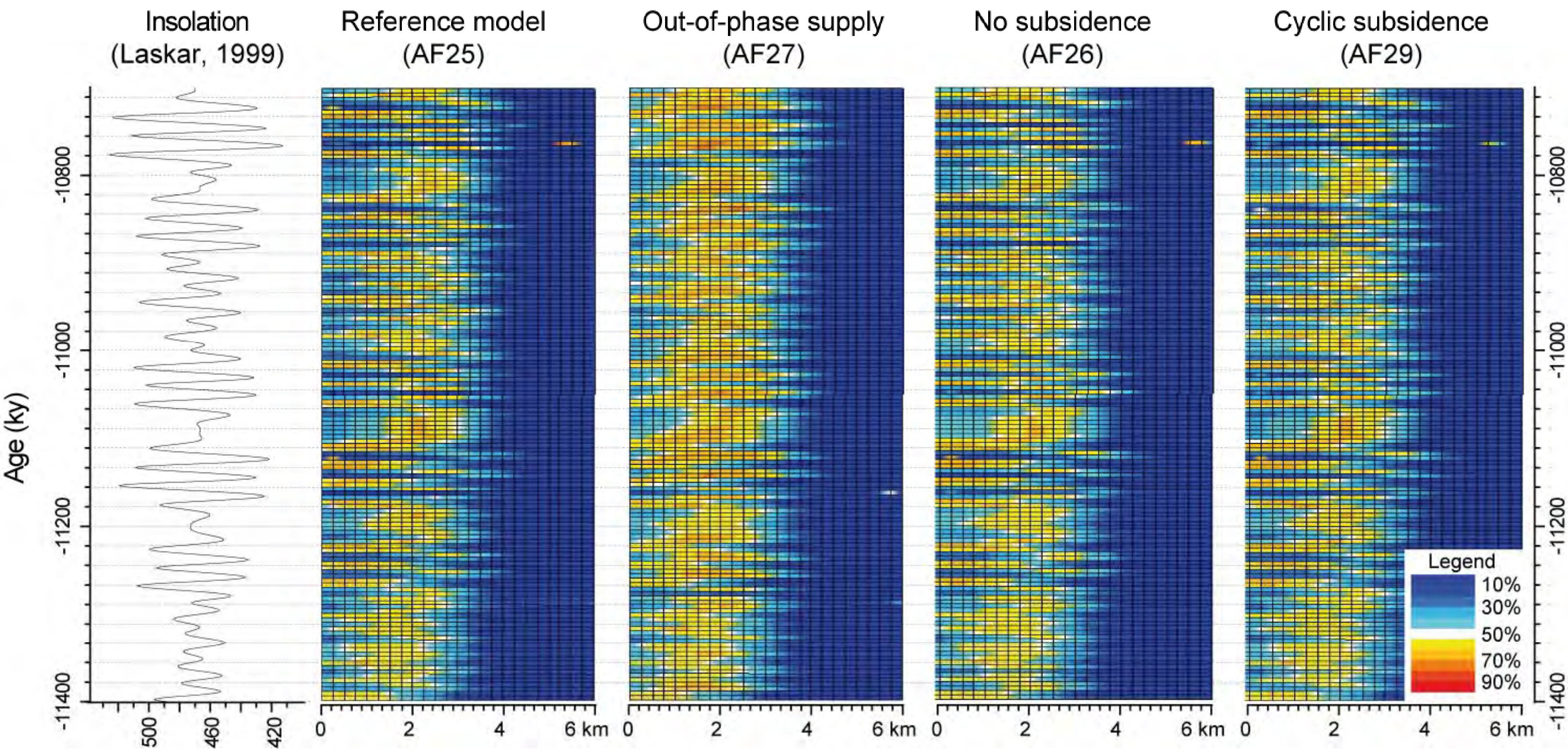
Conclusion

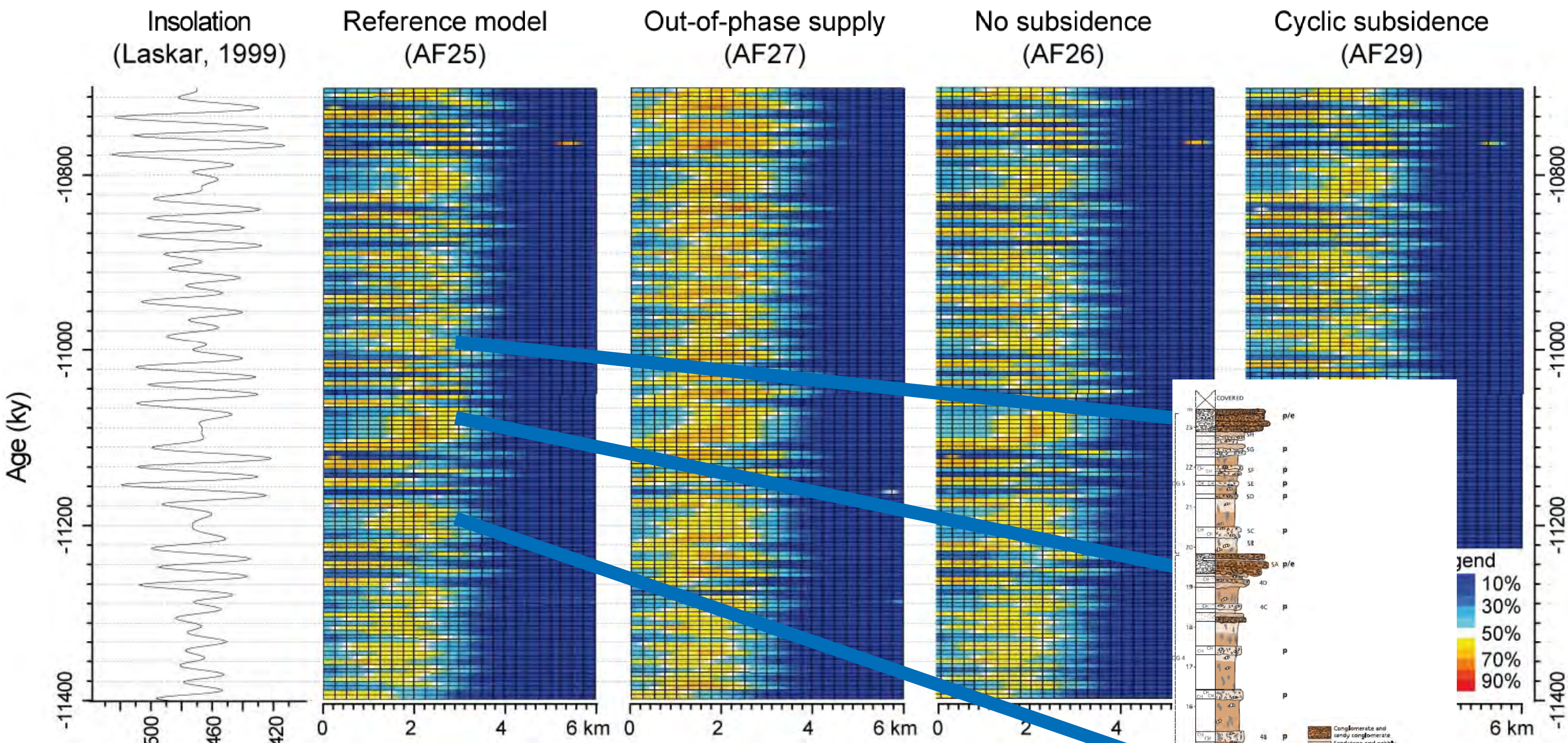
Feed-back to the "real" world



- Several tectonic scenarios produce very similar stratigraphic architecture
- Coarse-grained deposits during eccentricity minima

Conclusion

Feed-back to the "real" world



- Several tectonic scenarios produce very similar stratig cture
- Coarse-grained deposits during eccentricity minima

Conclusion
What to keep a lookout?

- **The vertical stacking and the overall architecture of the models are consistent with the outcrop suggesting that the hypothesis of a linear relationship between insolation and supply is reasonable;**

- **Several tectonic scenarios produce very similar stratigraphic architecture for the Teruel study case. The only clue to identify changes in tectonics is the overall stratigraphic architecture (onlap in the feeding valley, overall migration of the depocenter);**

- **This modeling approach suggests that the maximum progradation of the coarsest facies occurred during eccentricity minima.**

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Perspectives
What's next?

- **To test several scenarios with varying amplitude and timing of supply (Qs, Qw, lithologic ratio);**

- **To validate the methods (final validation of the chronostratigraphic scheme this summer) <u>or</u> to improve the code for catastrophic events (critical water discharge Qw);**

- **To take into account the catchment dynamics (response time, storage, weathering, sediment supply evolution).**

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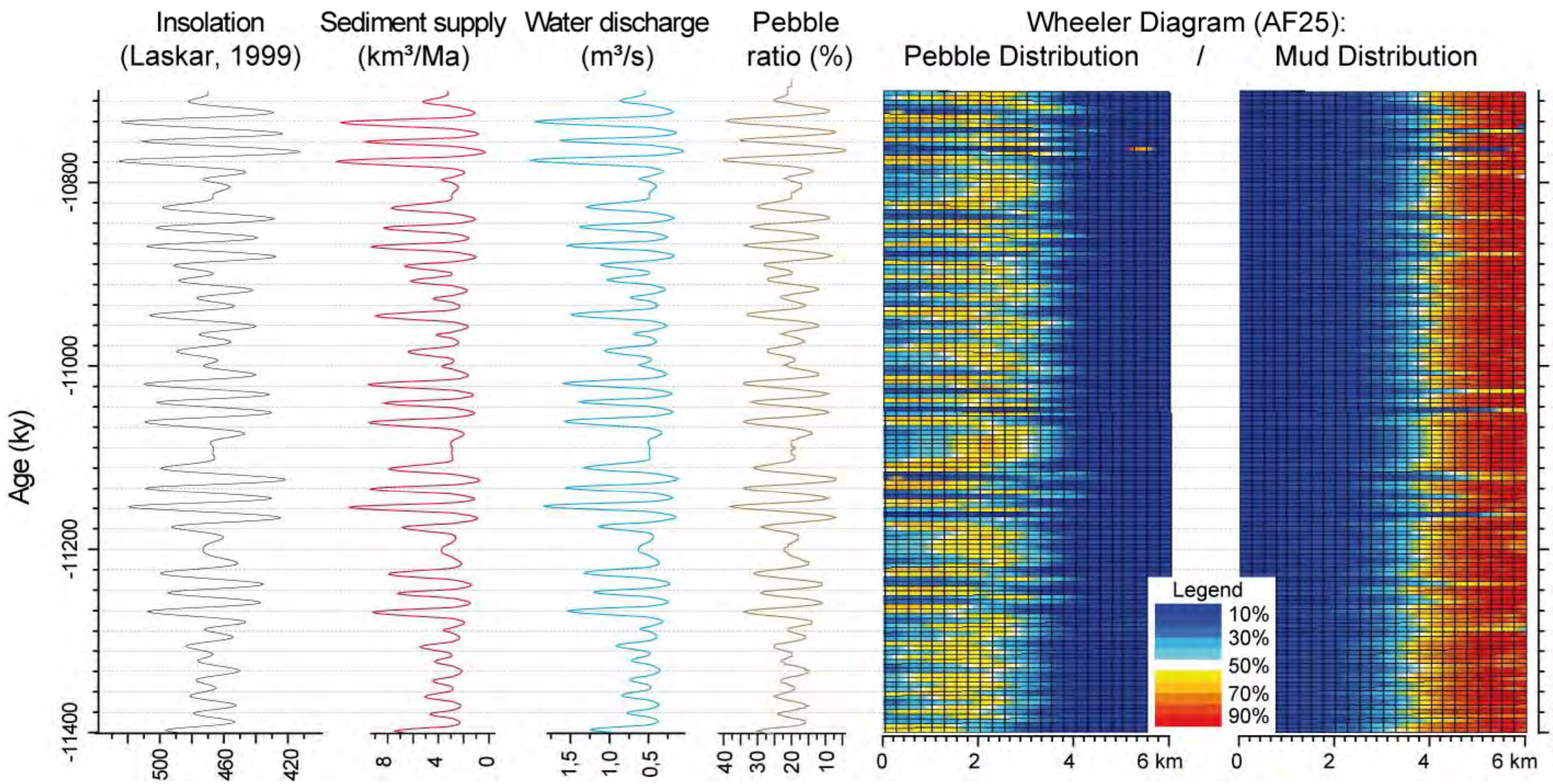
2. Cyclic changes
Wheeler diagram



- Distance of progradation, lithology distribution are consistent with observation in the outcrop

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