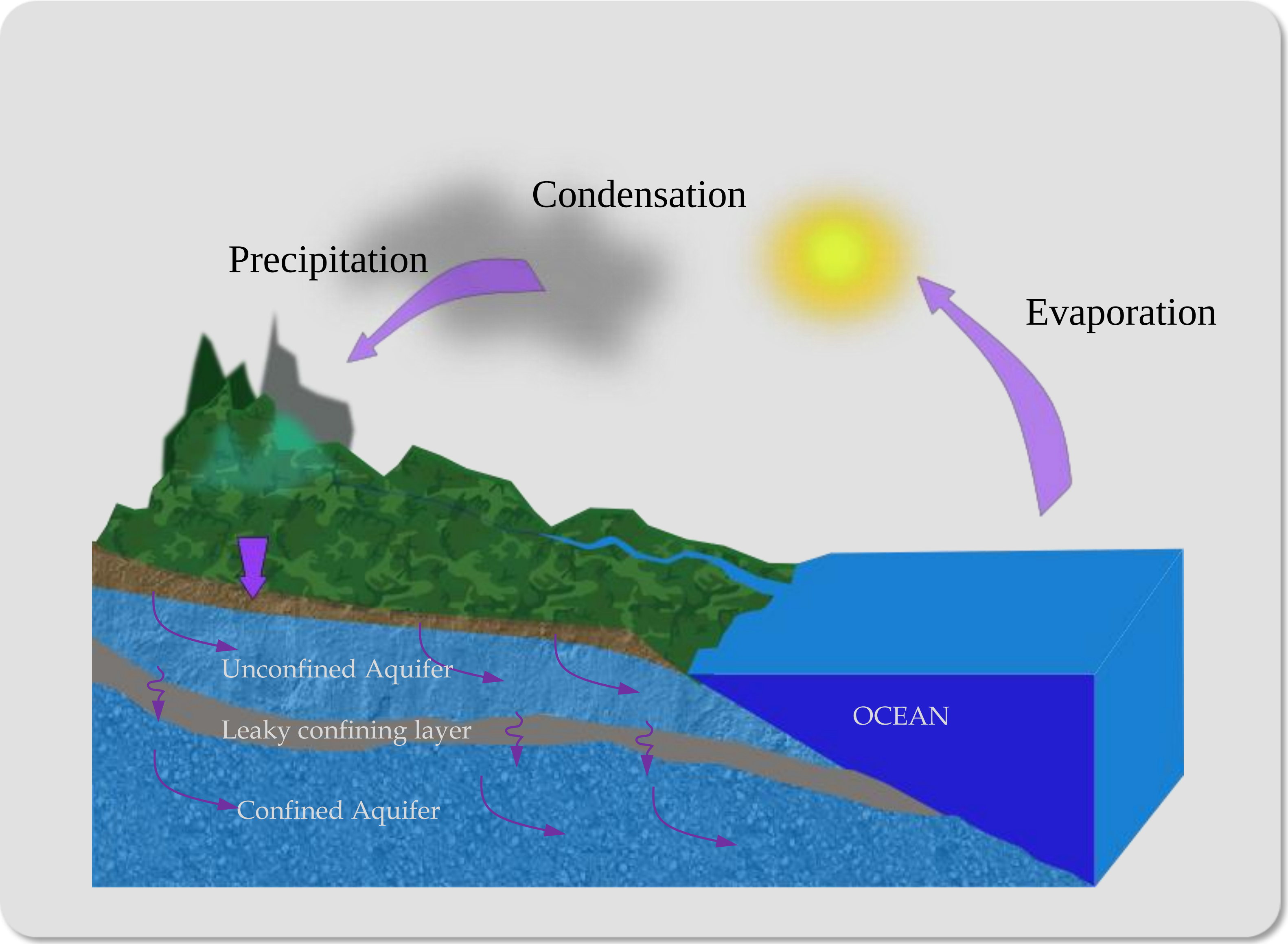
Seawater Intrusion

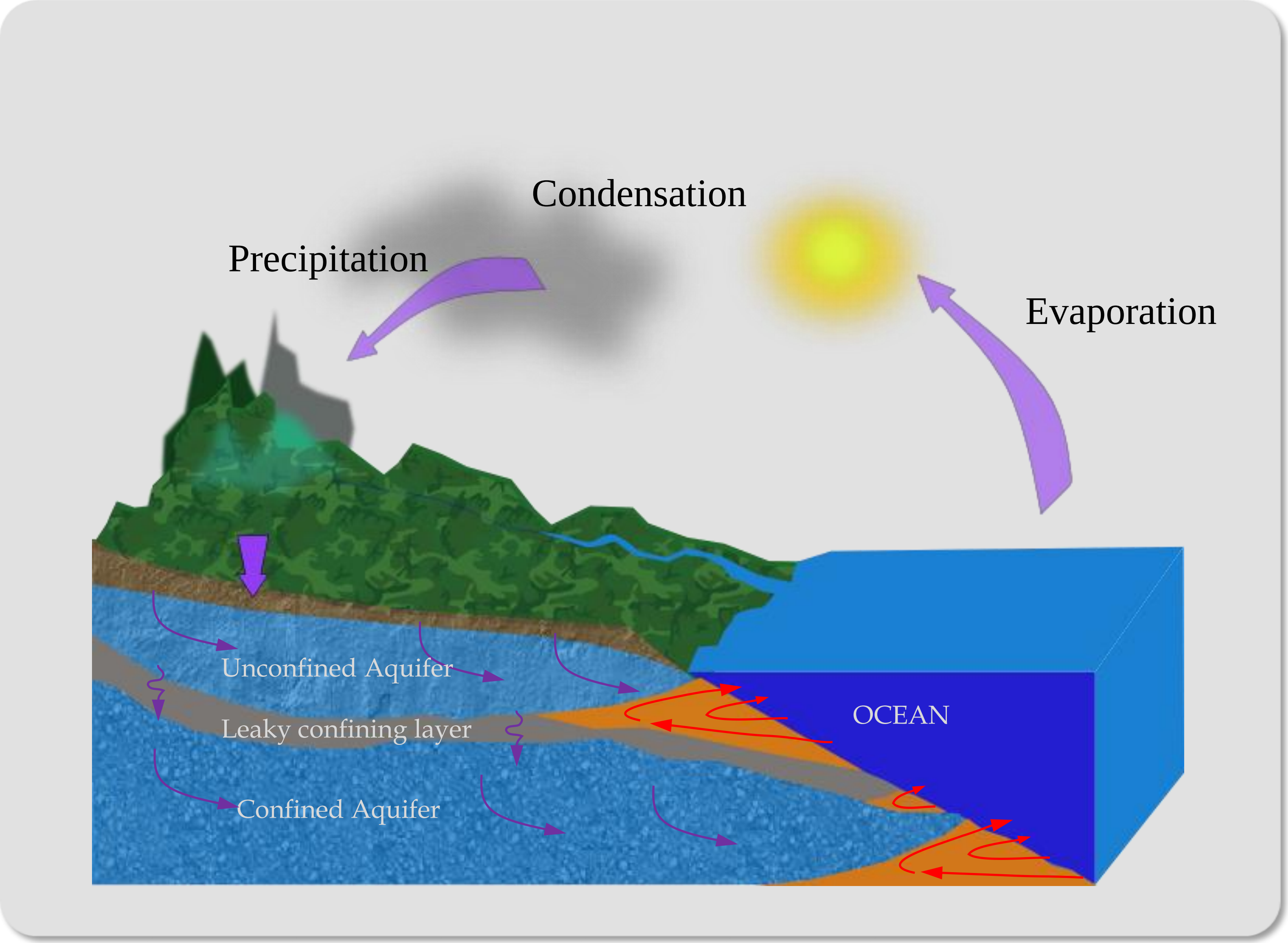
Maria Pool (1,2)

(1) Spanish National Research Council (IDAEA-CSIC), Barcelona, Spain,
(2) Associated Unit: Hydrogeology group (UPC-CSIC)

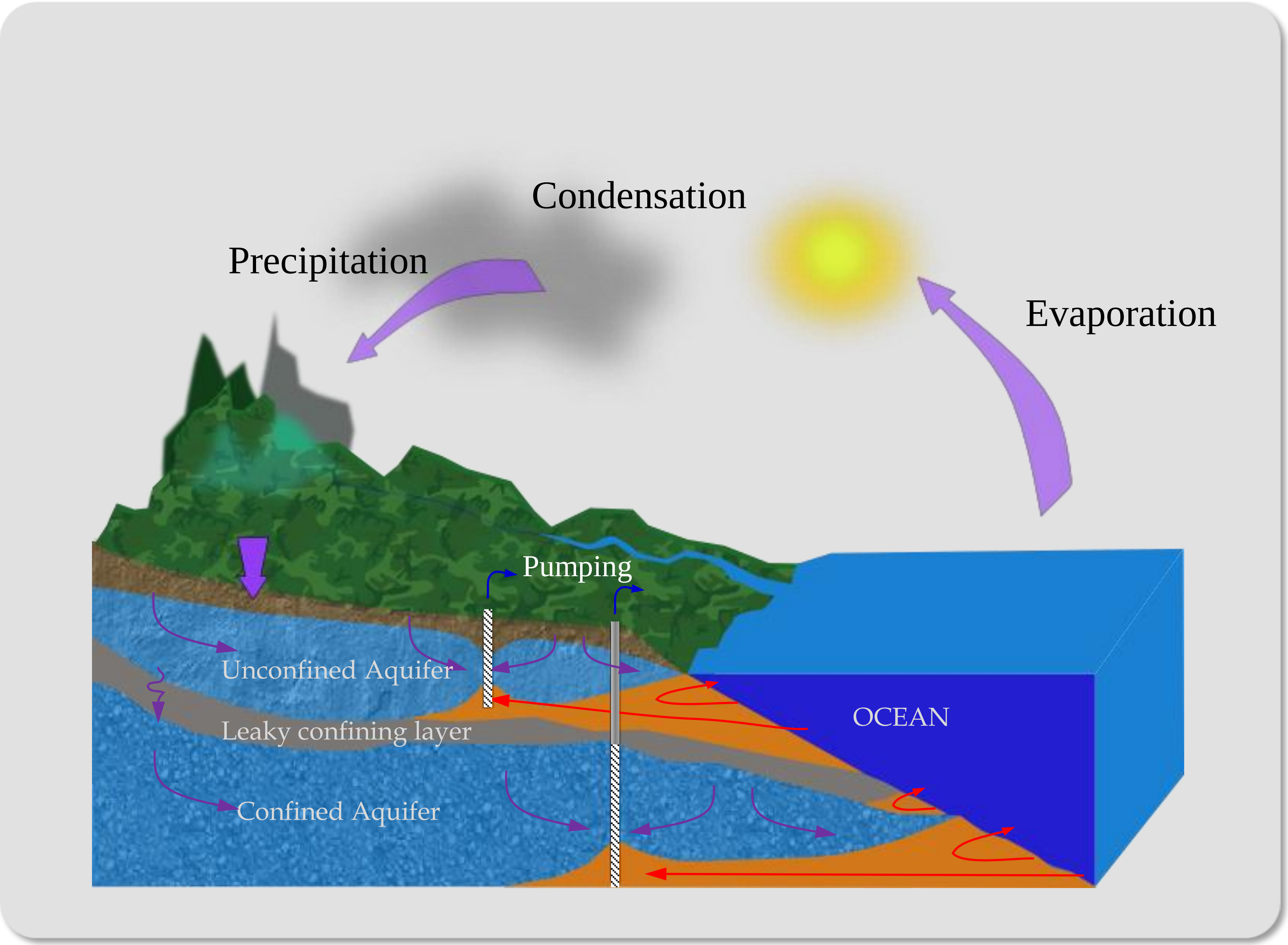
What is Seawater Intrusion?



What is Seawater Intrusion?



What is Seawater Intrusion?



Why is Seawater Intrusion a problem?

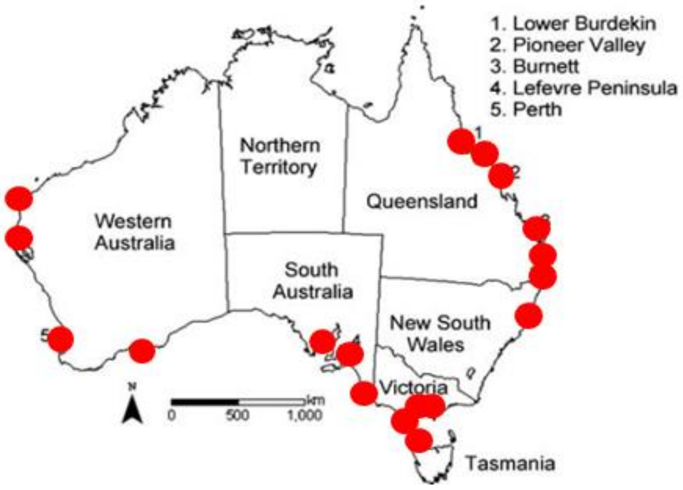
- About 70% of the world population lives in coastal areas [Bear and Cheng, 1999].

- Seawater intrusion has caused significant losses in valuable water resources and in agricultural production globally [FAO, 1997].

Global Problem

European Environmental Agency. For a detailed account of SWI in Europe, see E. Custodio [2010] *Hydrogeology Journal* 18 (1)

The Center of Advanced Materials for the Purification of Water with Systems



Werner AD (2010) , *Hydrogeology Journal* 18 (1): 281-285.

E. Bocanegra et al [2010]. State of knowledge of coastal aquifer management in South America *Hydrogeology Journal* 18 (1):

Dealing with seawater intrusion problems

- Seawater intrusion is a complex three-dimensional phenomenon governed by coupled non-linear equations that describe density dependent ground water flow and solute transport.

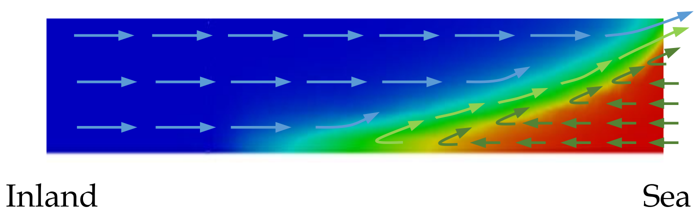
Equations

$$\mathbf{u} = -\rho K \cdot \left[\nabla h + \epsilon \frac{\omega}{\omega_s} \widehat{e_g} \right]$$

$$\frac{\partial(\rho\phi\omega)}{\partial t} = \nabla \cdot (\mathbf{u}\,\omega) - \nabla \cdot (\mathbf{D}\nabla\omega)$$

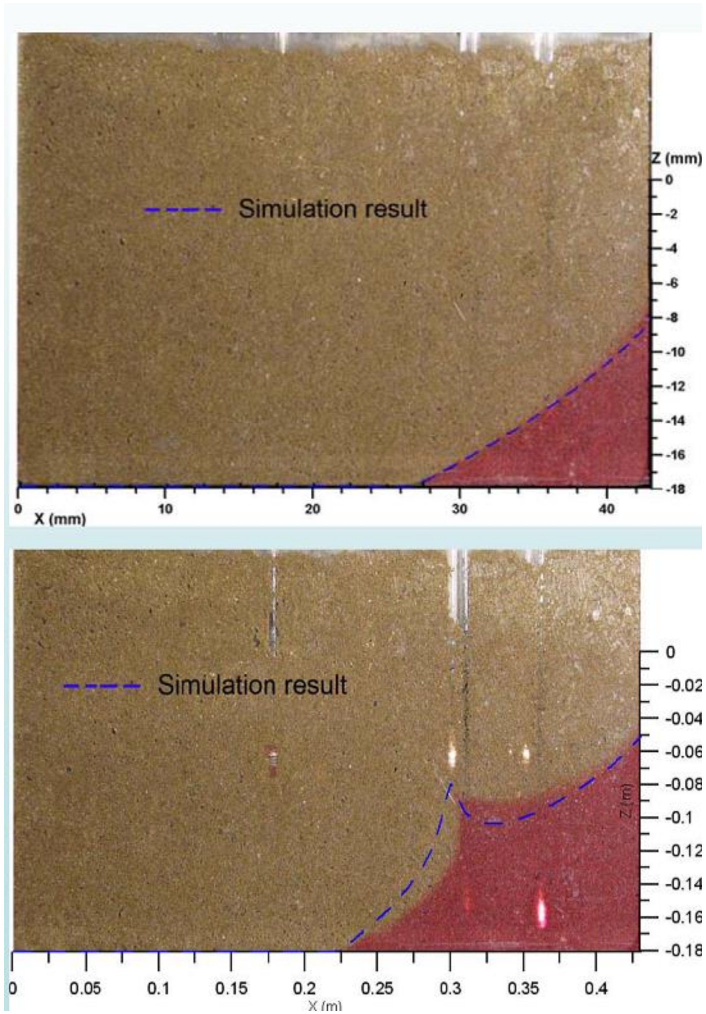
$$\rho = \rho_f \left(1 + \epsilon \frac{\omega}{\omega_s} \right)$$

density-dependent flow modeling

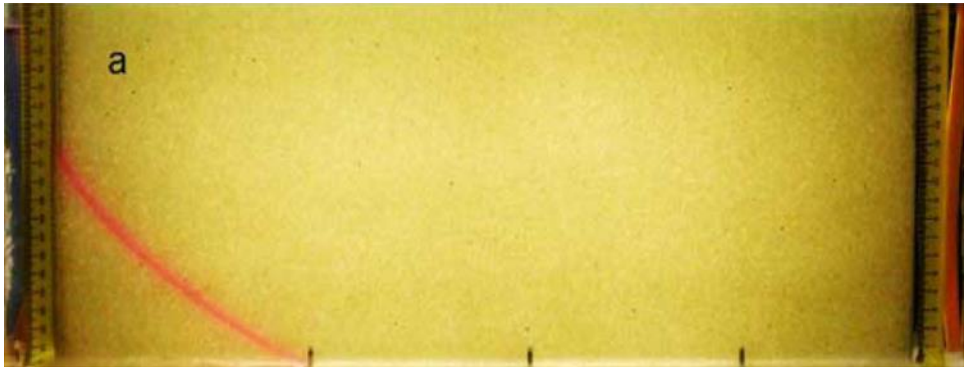


Width of the mixing zone

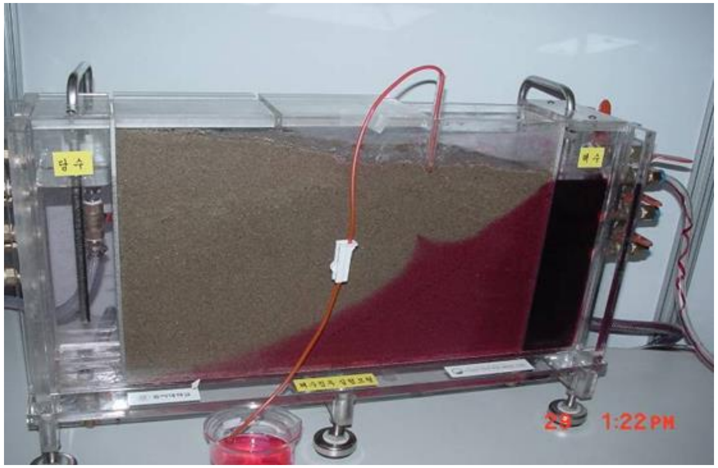
LABORATORY EXPERIMENTS suggest narrow mixing zones



Park, N.S., S.H. Hong, L. Shi, K.S. Seo, and L. Cui. 2006.



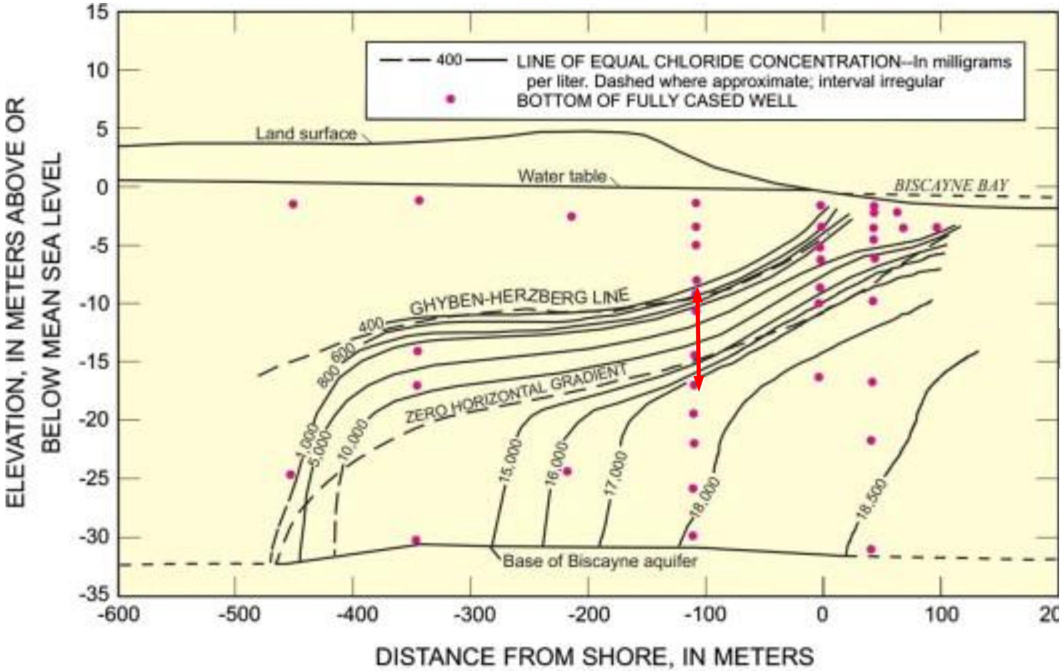
E. Abarca and T. P. Clement (2009)



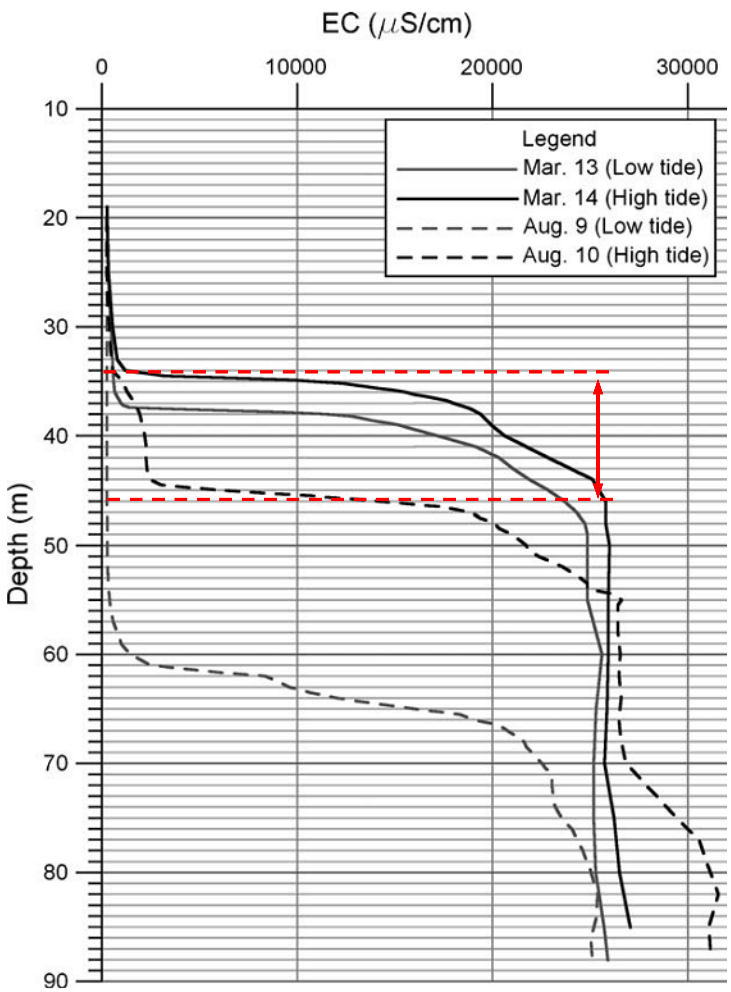
N. Park, S. Kim, and L. S. Dong (2008)

Width of the mixing zone

FIELD MEASUREMENTS suggest very wide mixing zones

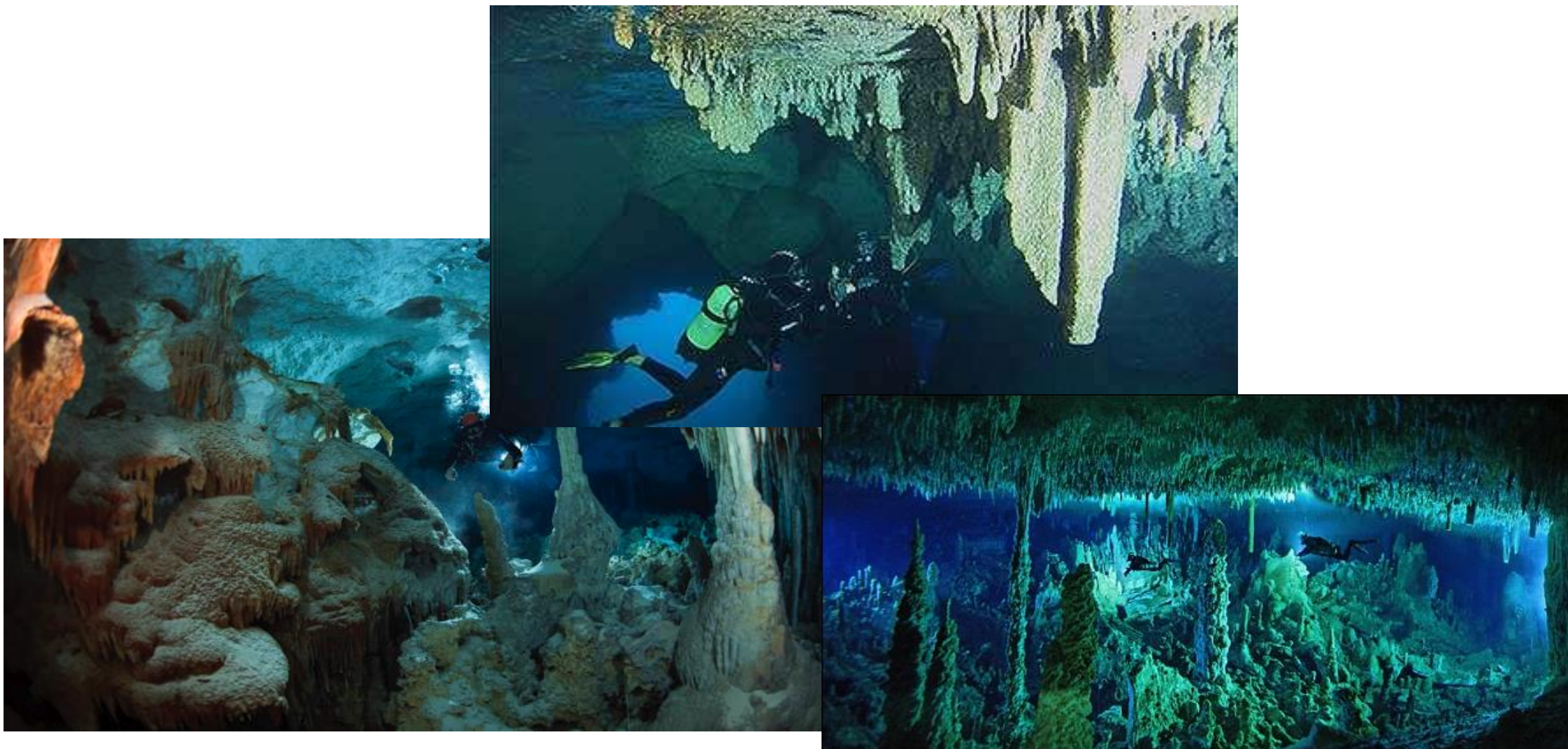


Langevin (2003)



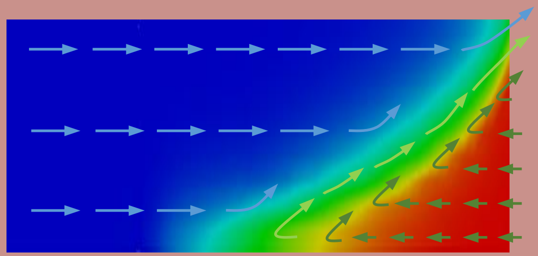
Kue-Young Kim, (2007)

Effects of periodic temporal fluctuations and fluid density effects on mixing and chemical reactions in coastal aquifers: Karst Formation

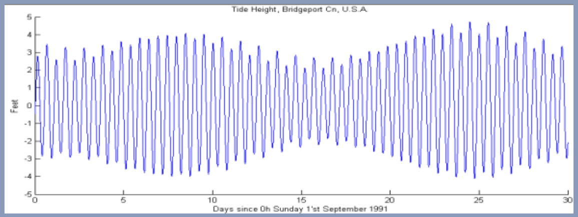


COASTAL AQUIFERS: Processes

Density variations



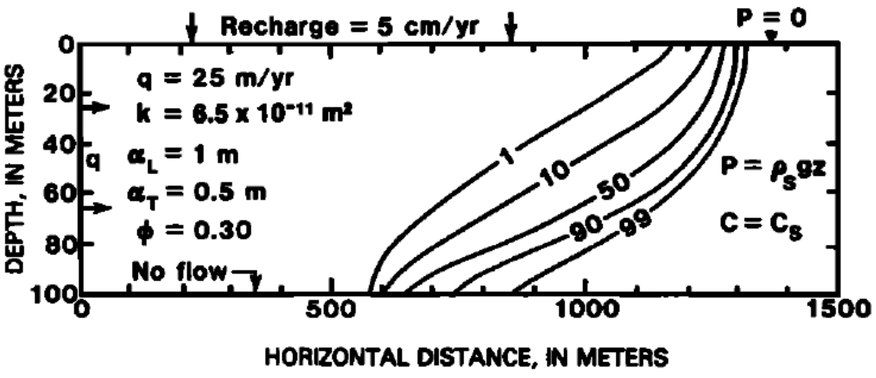
Temporal Fluctuations Transient effects



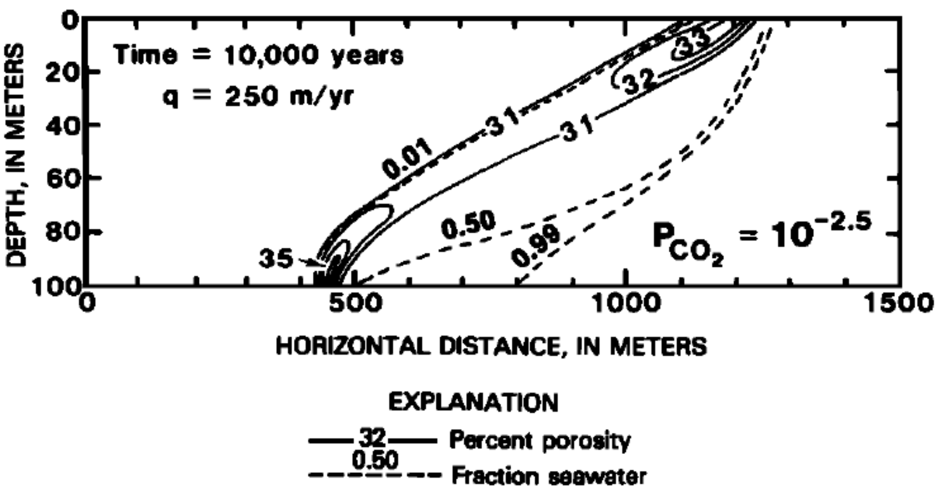
DISPERSION AND MIXING

Chemical Reactions: karst

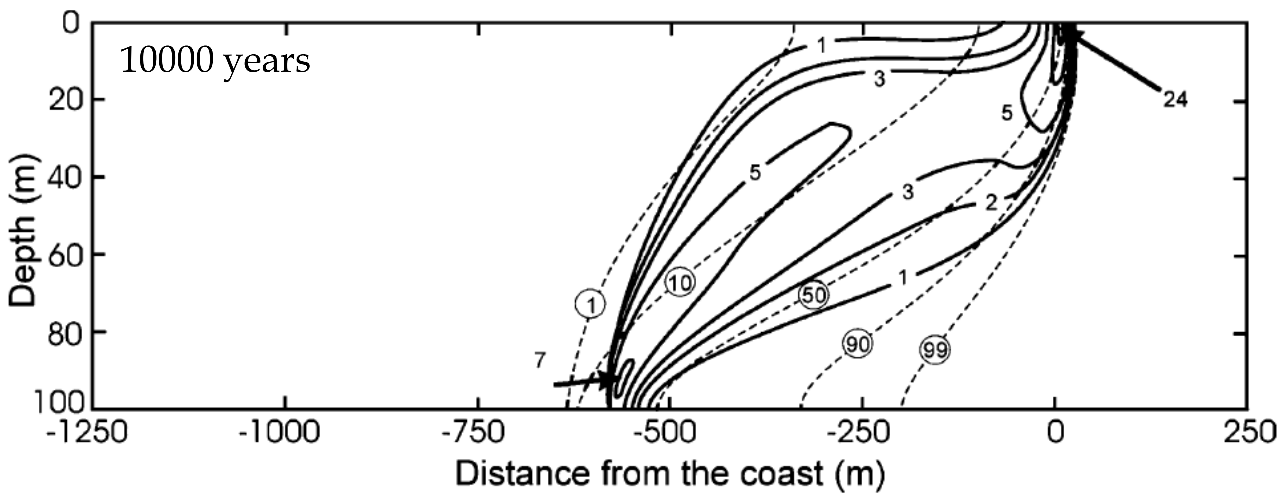
Calcite Dissolution – Coastal Aquifers



Sanford and Konikow, Water Resour. Res. (1989)



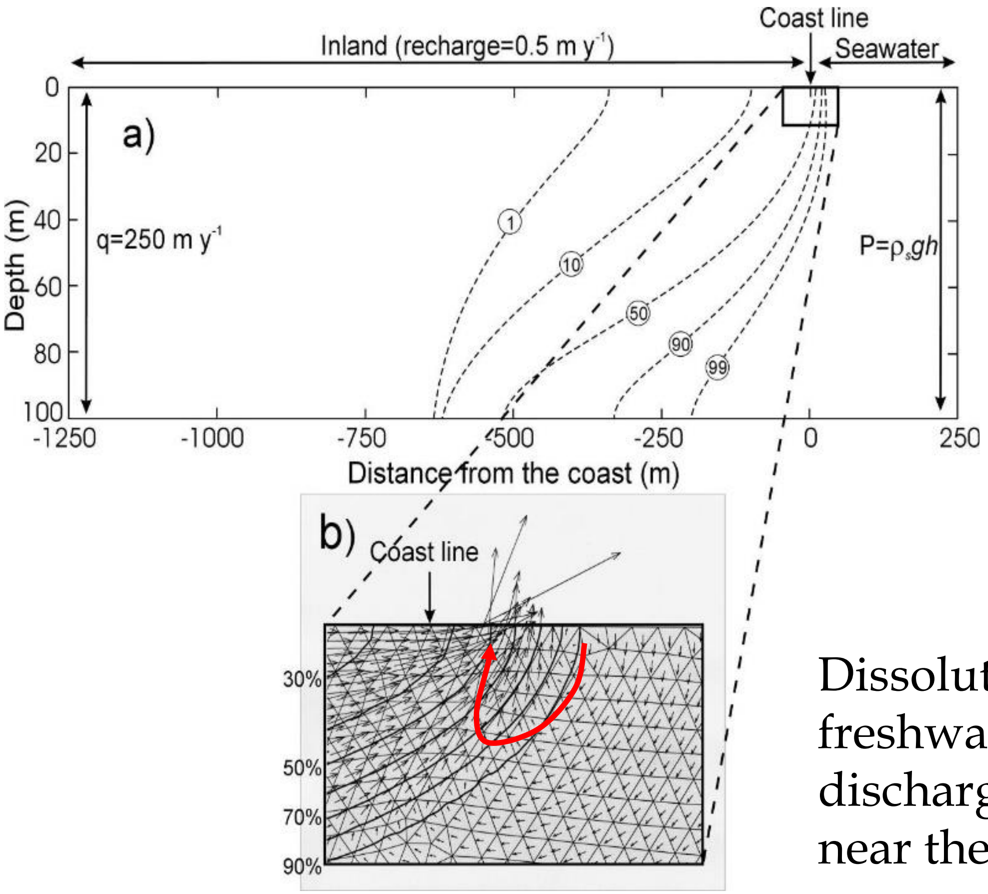
Fully Coupled Reactive transport

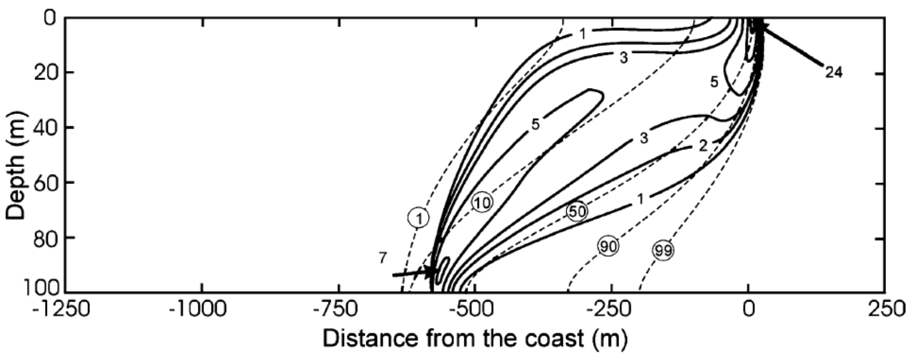


Rezaei et al, J. Hydrology, 2005

Transport processes (mixing) control how much, when, and where dissolution occurs.

Calcite Dissolution – Coastal Aquifers





Rezaei et al, Water Resour. Reseach 2005

Dissolution tends to concentrate at the freshwater side of the mixing zone, except at the discharge area, where dissolution is maximum near the saline side.

The PCO2 of both end-members control the rate of dissolution

Calcite Dissolution – Approach

Calcite Dissolution

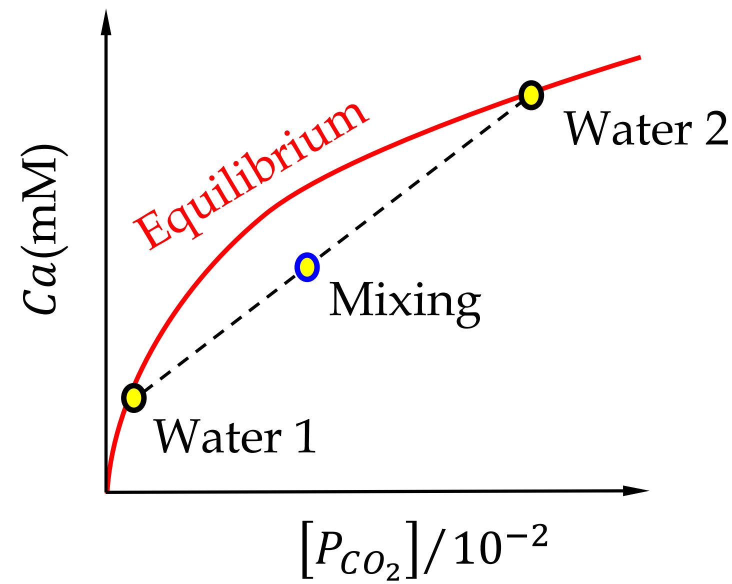
We consider:
An instantaneous dissolution reaction
(pure dissolution at equilibrium)

$$CO_{2(g)} + CaCO_3 + H_2O \rightarrow Ca^{2+} + 2HCO_3^-$$

$$\frac{\partial C_1}{\partial t} - L_t(C_1) = -r \qquad (1)$$

$$\frac{\partial C_2}{\partial t} - L_t(C_2) = -r \qquad (2)$$

$$L_t(C) = -\boldsymbol{q}\nabla C + \nabla \cdot (\mathbf{D}\nabla C)$$



Appelo & Postma, Geochemistry, groundwater and pollution

(1)-(2): $$\frac{\partial \alpha}{\partial t} = L_t(\alpha)$$

Conservative Component
$\alpha = C_1 - C_2$

De Simoni et al., *Water Resour. Res.* (2005, 2007)

Calcite Dissolution – Approach

Calcite Dissolution

$$\frac{\partial \alpha}{\partial t} = L_t(\alpha) \qquad L_t(C) = -\boldsymbol{q}\nabla C + \nabla \cdot (\mathbf{D}\nabla C)$$

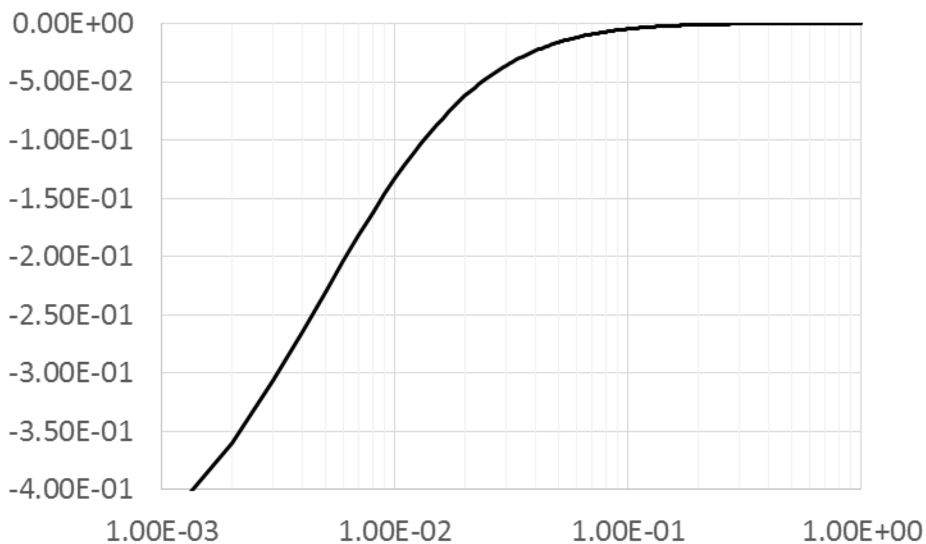
Reaction Rate

$$r = \frac{\partial^2 C_2}{\partial \alpha^2} \left(\nabla^T \alpha \, \boldsymbol{D} \, \nabla \alpha \right)$$

Numerical Model (conservative)

PhreeqC

$$\frac{\partial^2 C_{Ca^{2+}}}{\partial \alpha^2}$$



Freshwater α Saltwater

Calcite Dissolution – Approach

Calcite Dissolution

Reaction Rate

$$r = \frac{\partial^2 C_2}{\partial \alpha^2} (\nabla^T \alpha \, \boldsymbol{D} \, \nabla \alpha)$$

Porosity

$$\phi(t + \Delta t) = \phi(t) + r \, V_m \Delta t$$

V_m → Molar Volume

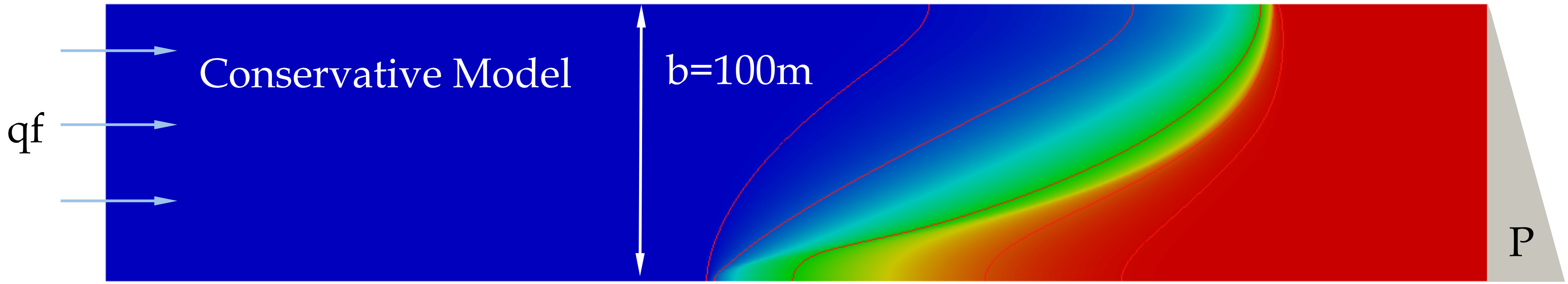
De Simoni et al., *Water Resour. Res.* (2005)

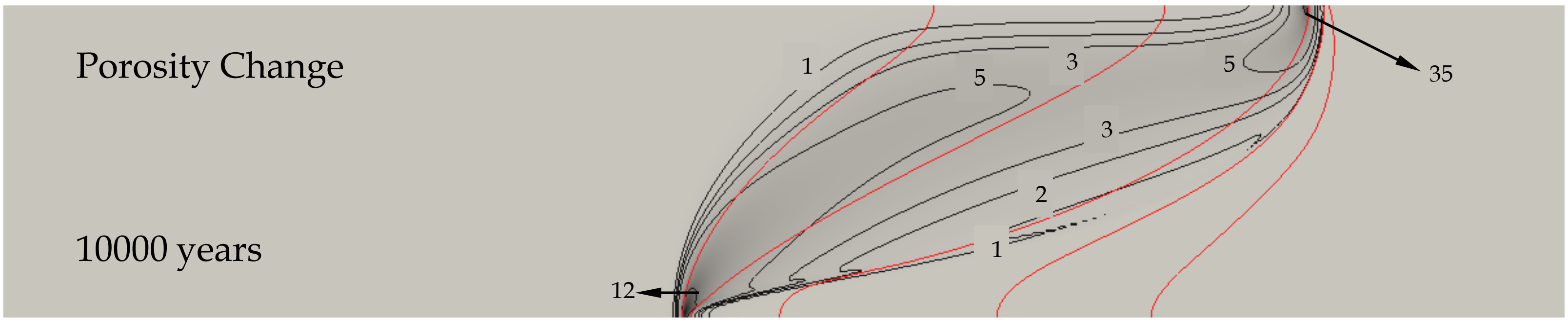
Calcite Dissolution – Coastal Aquifers

Application
De Simoni (2005) formulation

Reaction Rate $r = \frac{\partial^2 C_2}{\partial \alpha^2} (\nabla^T \alpha \, \boldsymbol{D} \, \nabla \alpha)$

Porosity $\phi(t + \Delta t) = \phi(t) + r \, V_m \Delta t$





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Calcite Dissolution – Coastal Aquifers

Application
De Simoni (2005) formulation

Reaction Rate $r = \frac{\partial^2 C_2}{\partial \alpha^2} (\nabla^T \alpha \, \boldsymbol{D} \, \nabla \alpha)$

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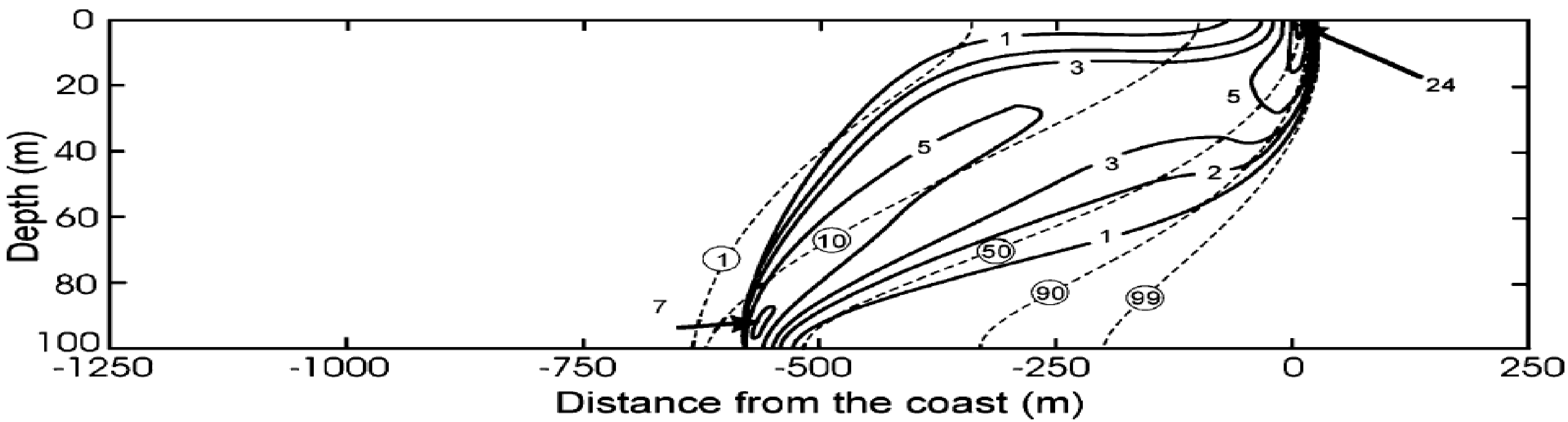
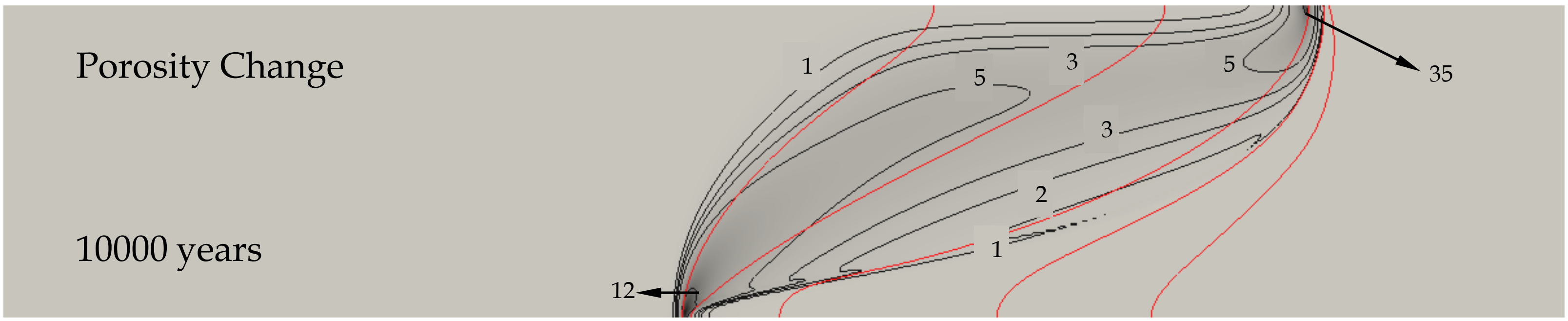




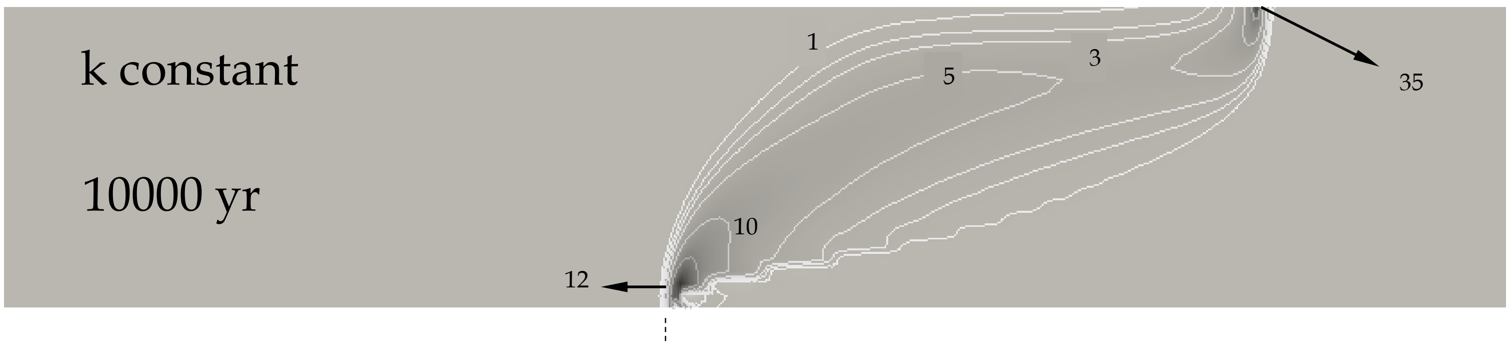
It works!!!

Calcite Dissolution – Coastal Aquifers

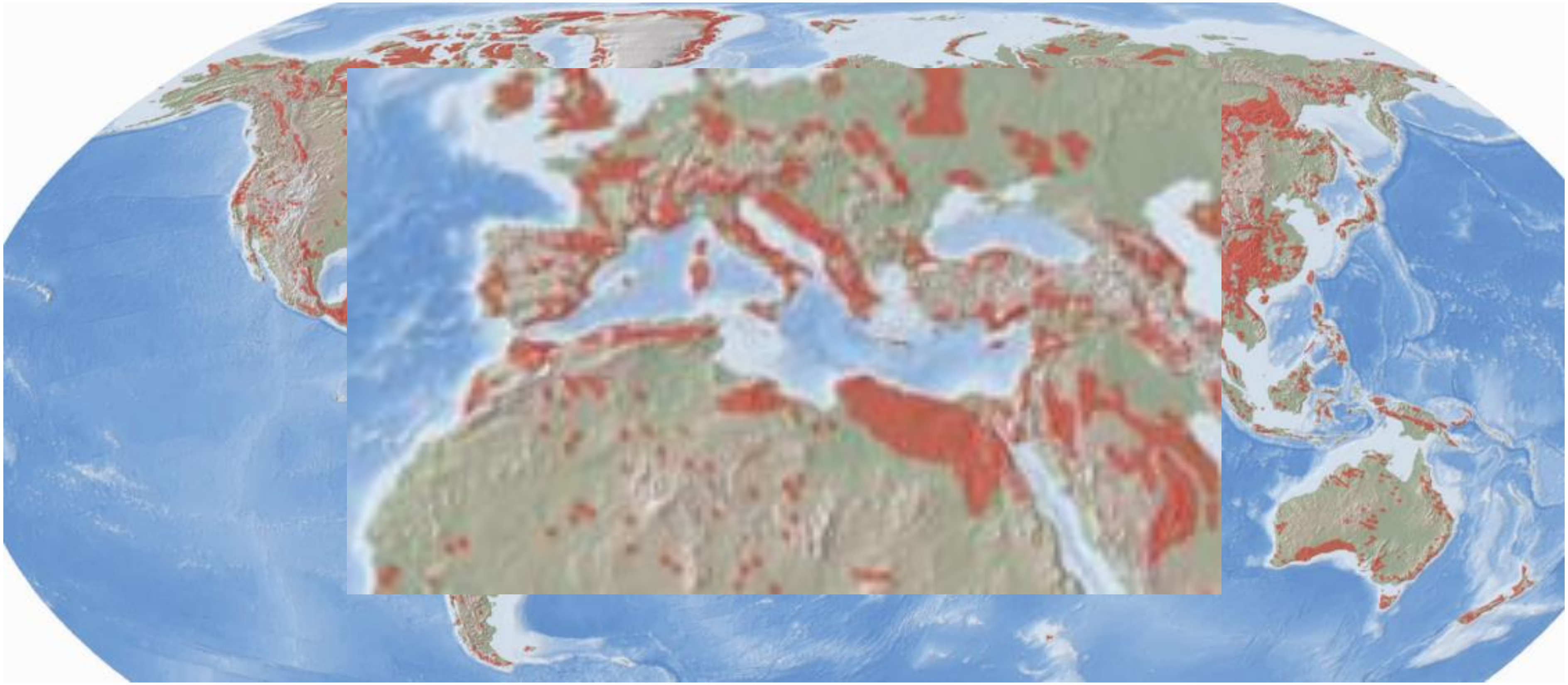
Change in Permeability

$$k(t) = k_0[\emptyset(t)/\emptyset_0]^3$$

Civan (2001), Carroll et al. (2013)

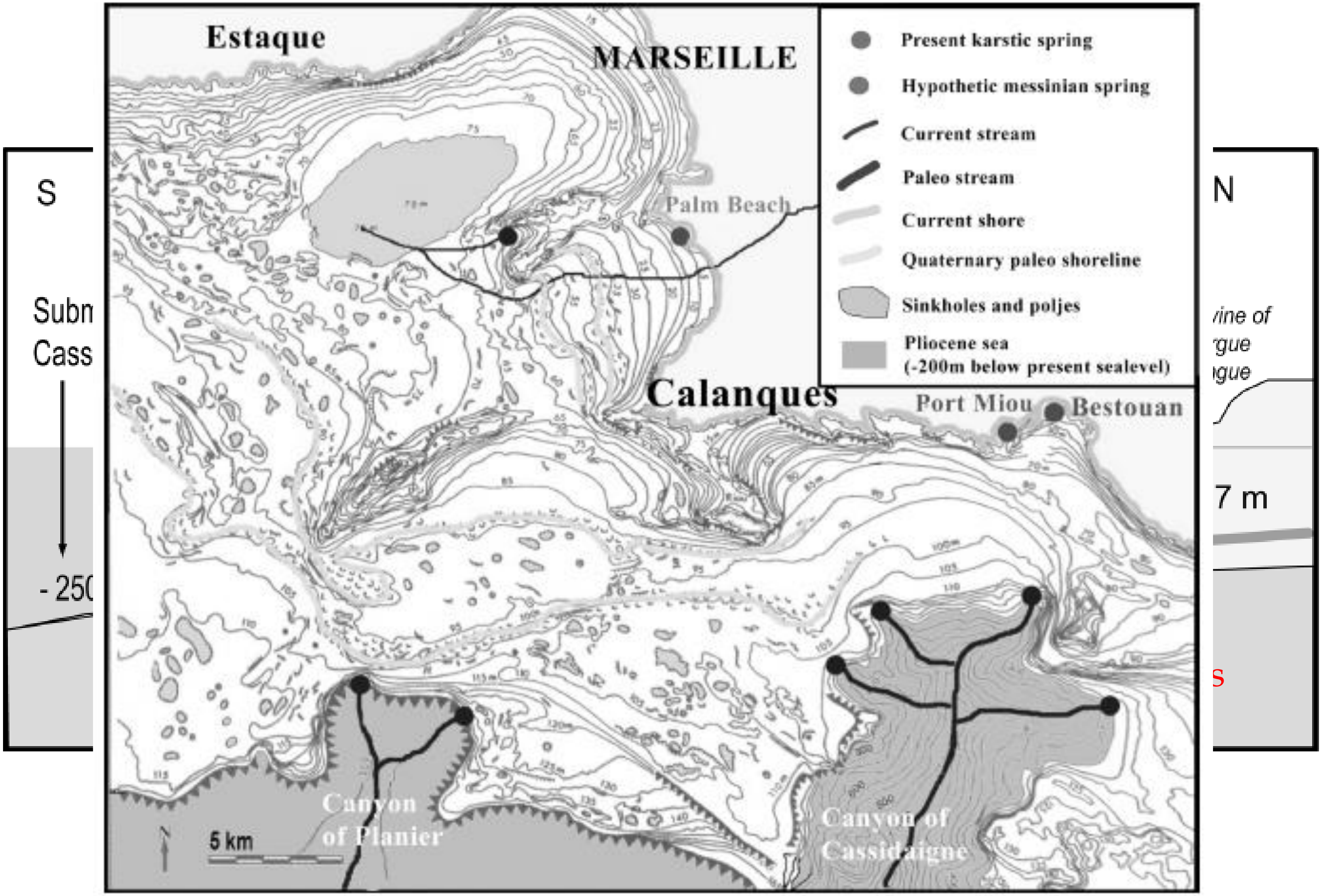


Karst Distribution



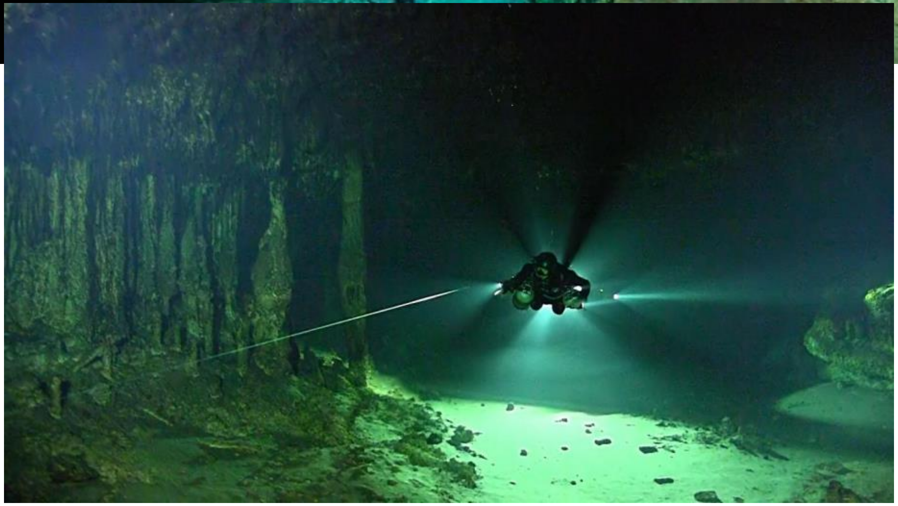
Ford, D.C., and Williams, P.W., Karst Geomorphology and Hydrology, (1989)

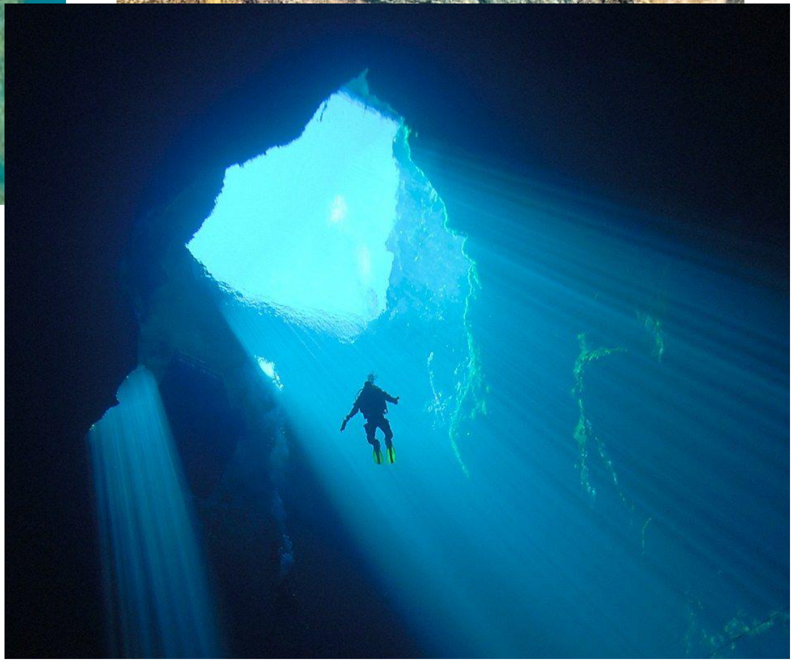
Karst Distribution



Audra, Geod. Acta (2004)

Karst Distribution





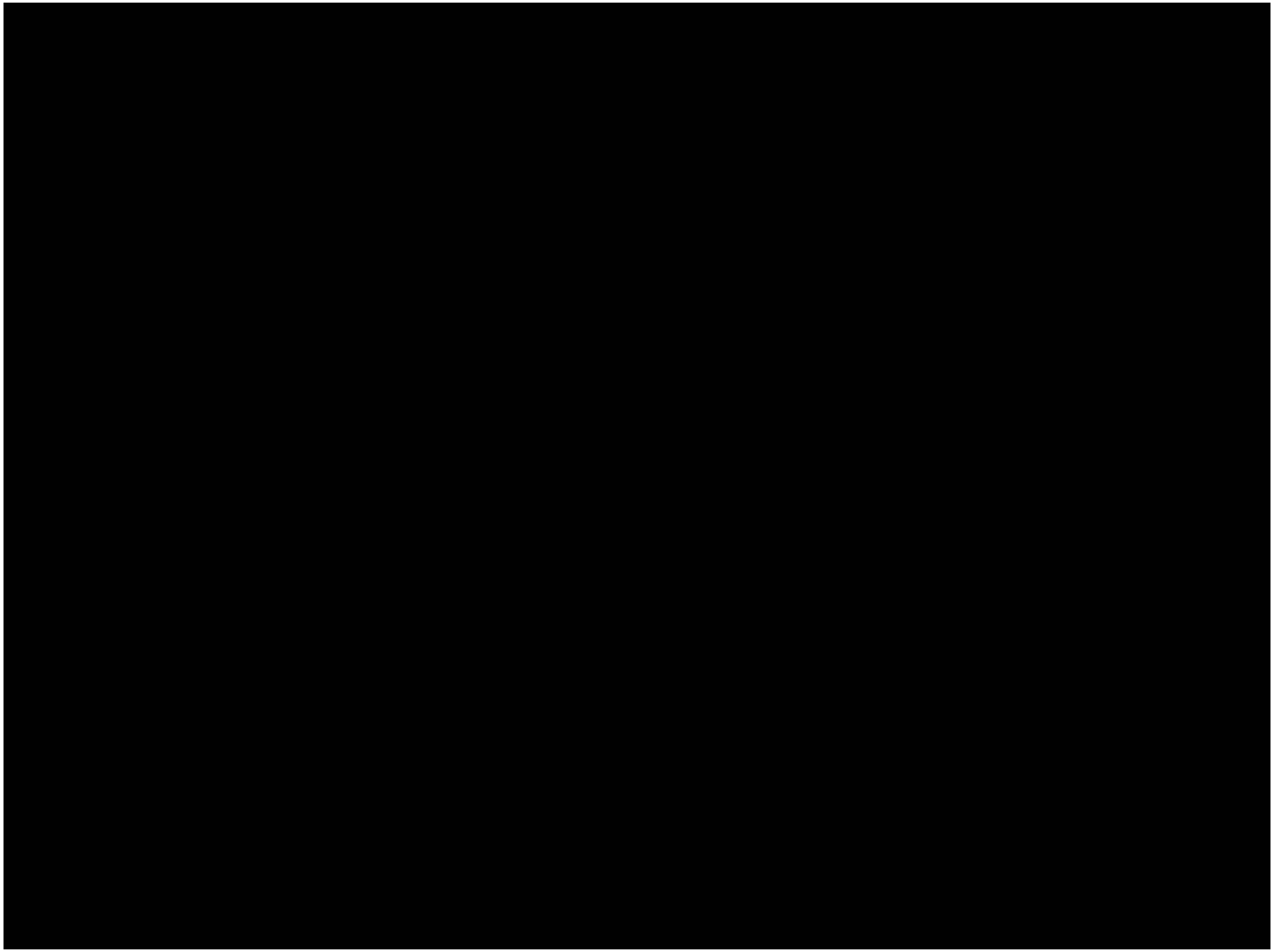
Hypothesis

Karst development in response to mixing and sea level fluctuations.

Messinian Crisis (5.96 to 5.33 million years ago)

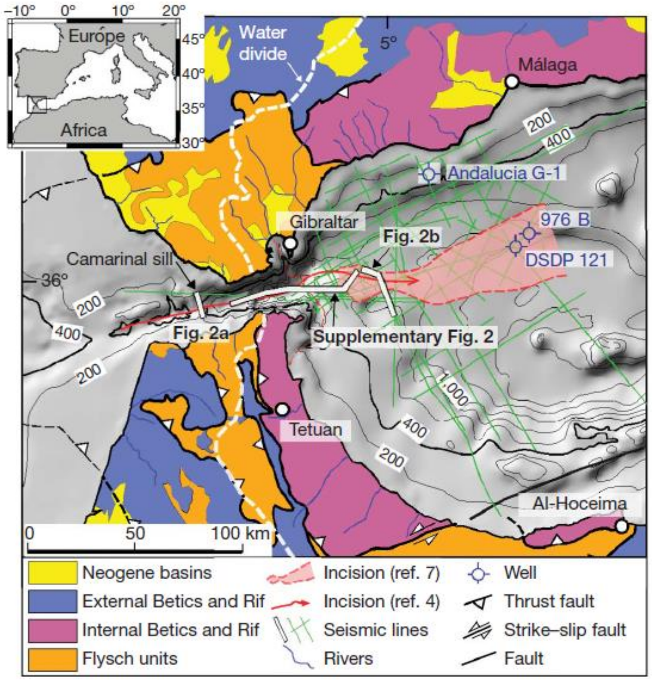
Story….Once upon a time

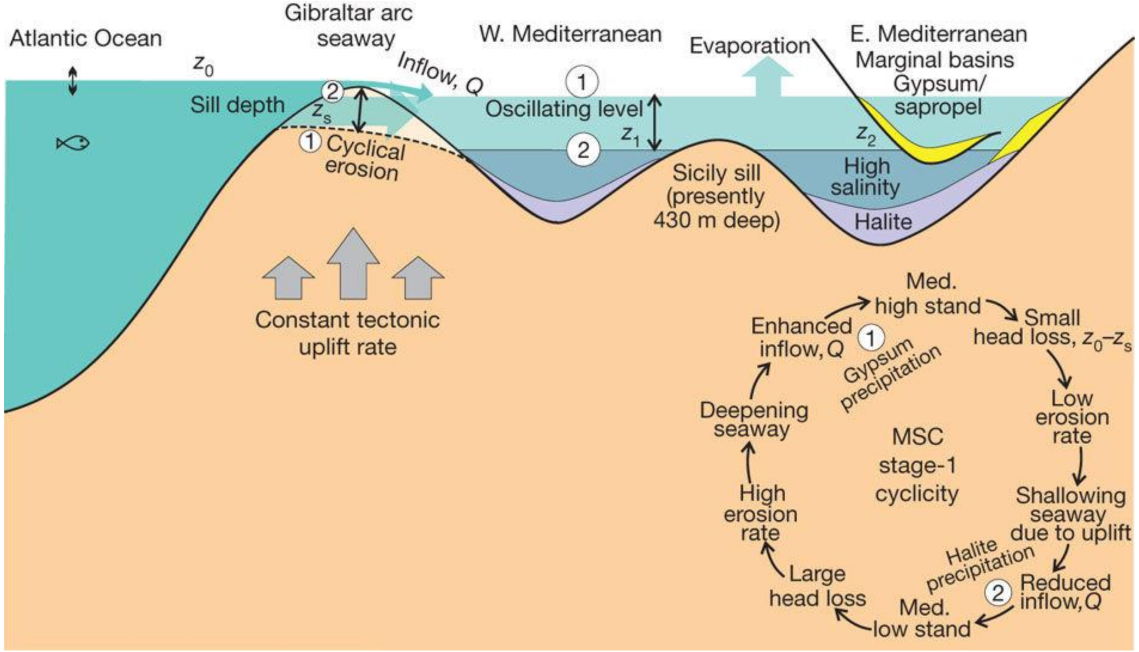
Messinian Crisis (5.96 to 5.33 million years ago)



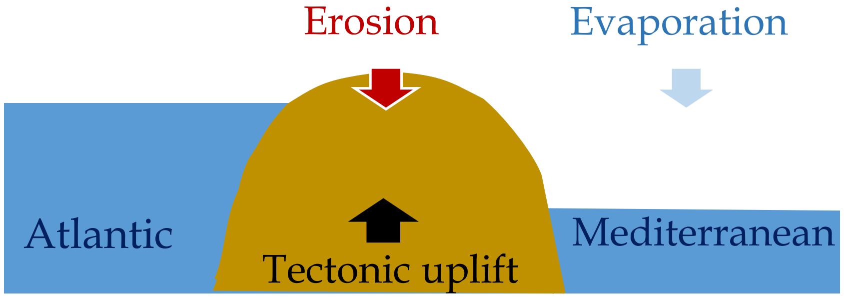
Daniel García-Castellanos (Project WikiArS
https://outreach.wikimedia.org/wiki/W...)

Messinian Crisis (5.96 to 5.33 million years ago)



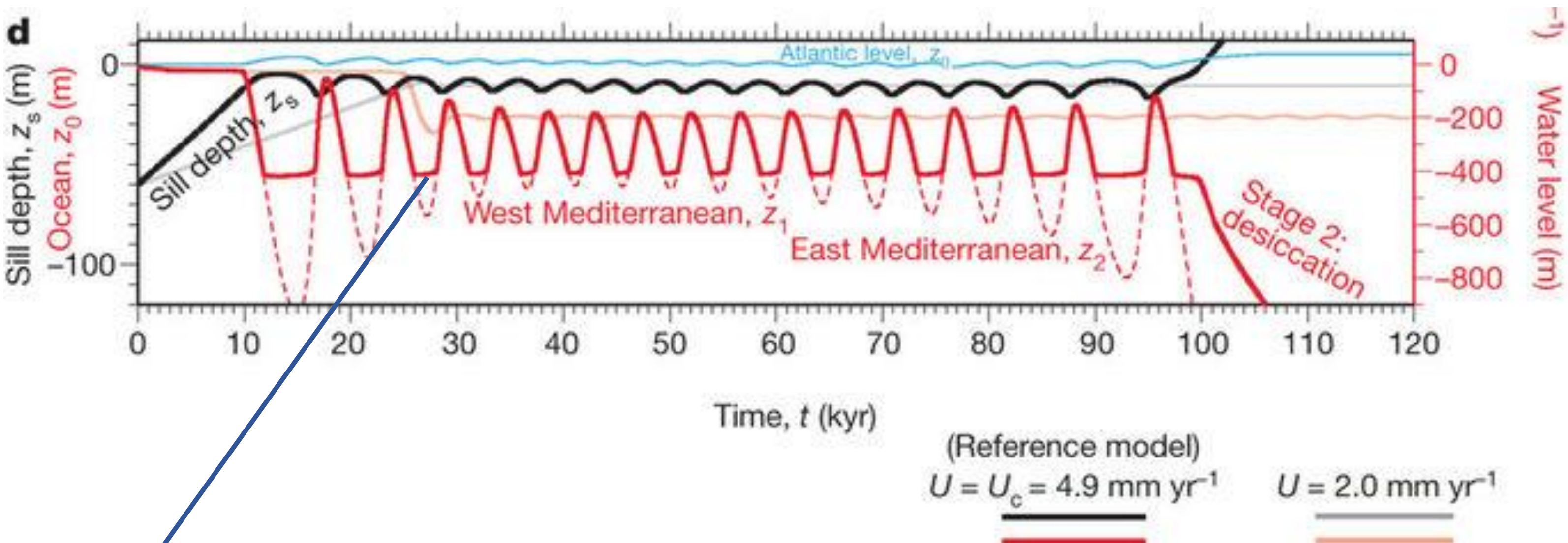


García-Castellanos et al, *Nature* (2009,2011)



Messinian Crisis (5.96 to 5.33 million years ago)

Oscillations in sea level as the result of dynamic harmonic coupling between the drawdown and the refill triggered when erosion deepens the seaway.

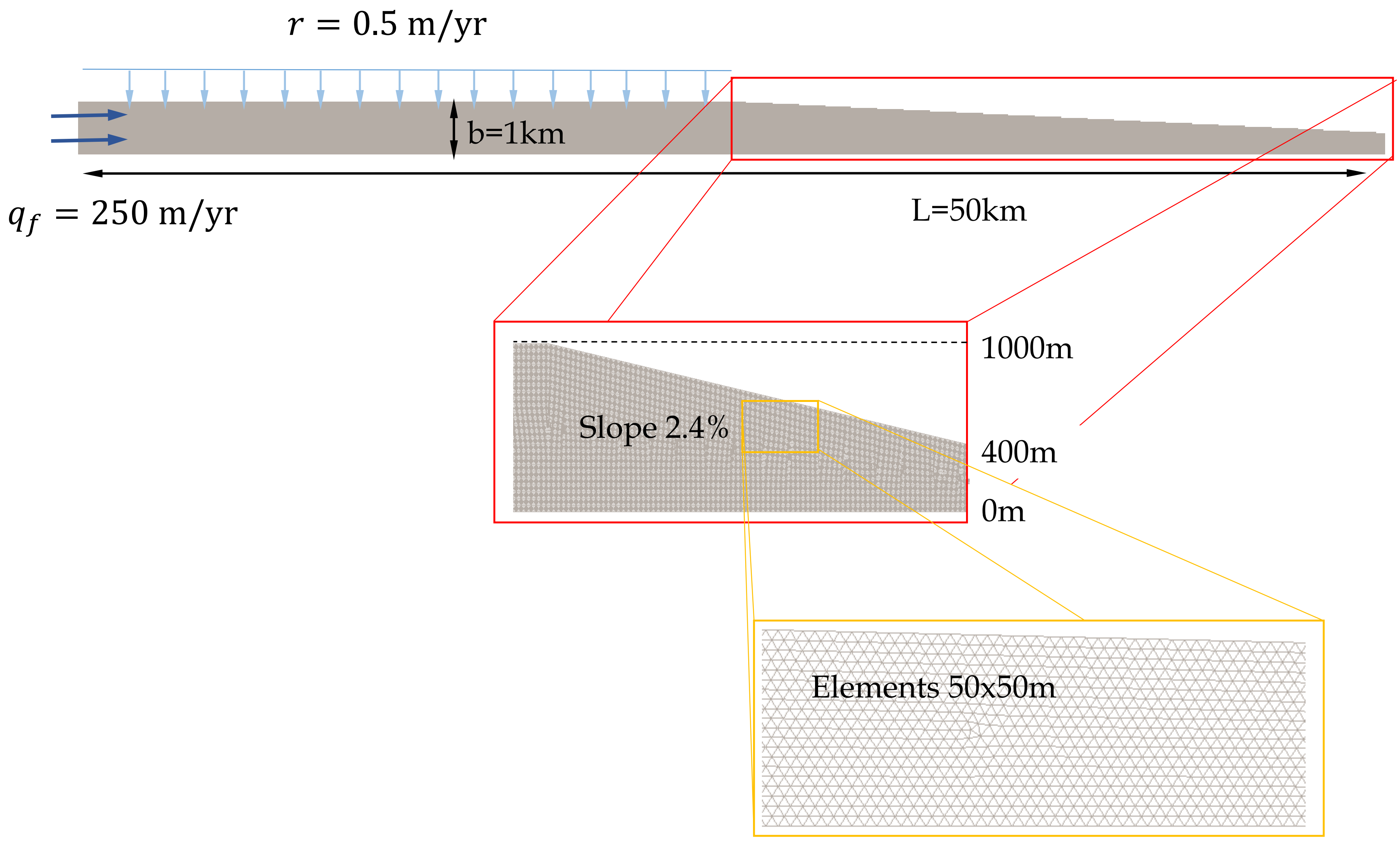


García-Castellanos et al, *Nature*, 2011

- Fluctuations of Amplitude 200m and period 6000yr

Messinian: Conceptual Model

Boundary Conditions I



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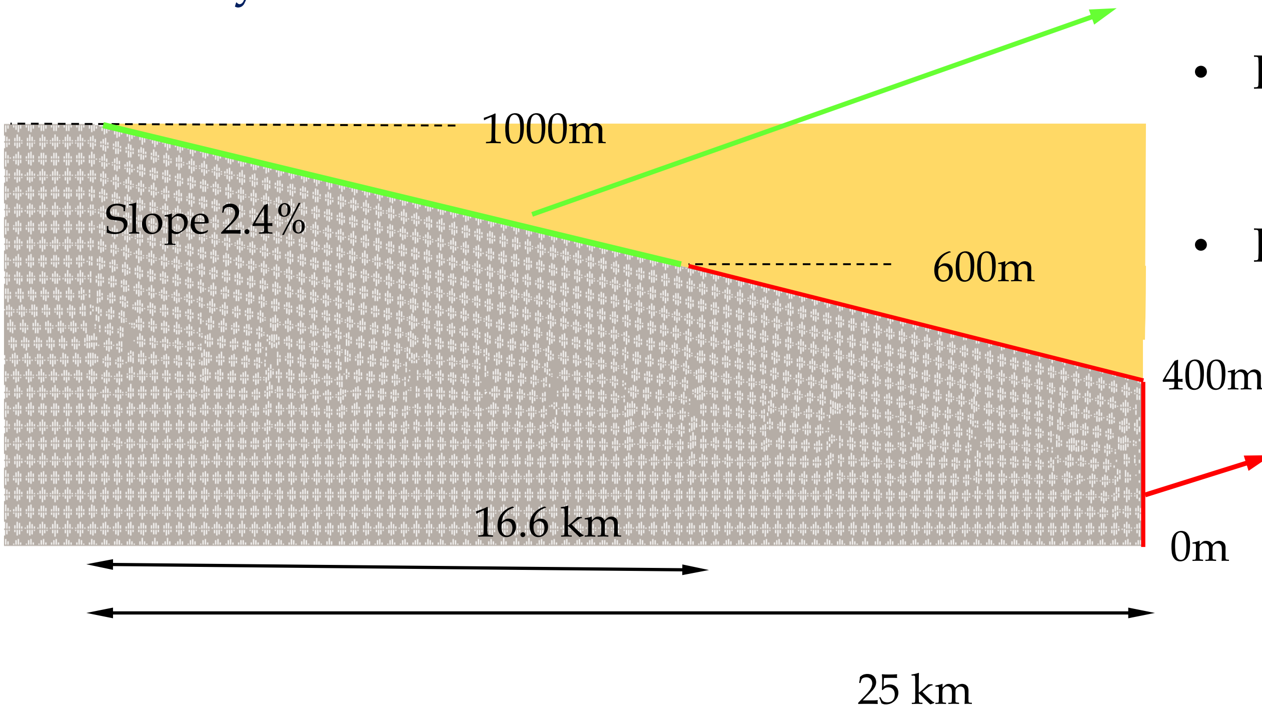
Messinian: Conceptual Model

Boundary Conditions II



Conditional Boundary Condition

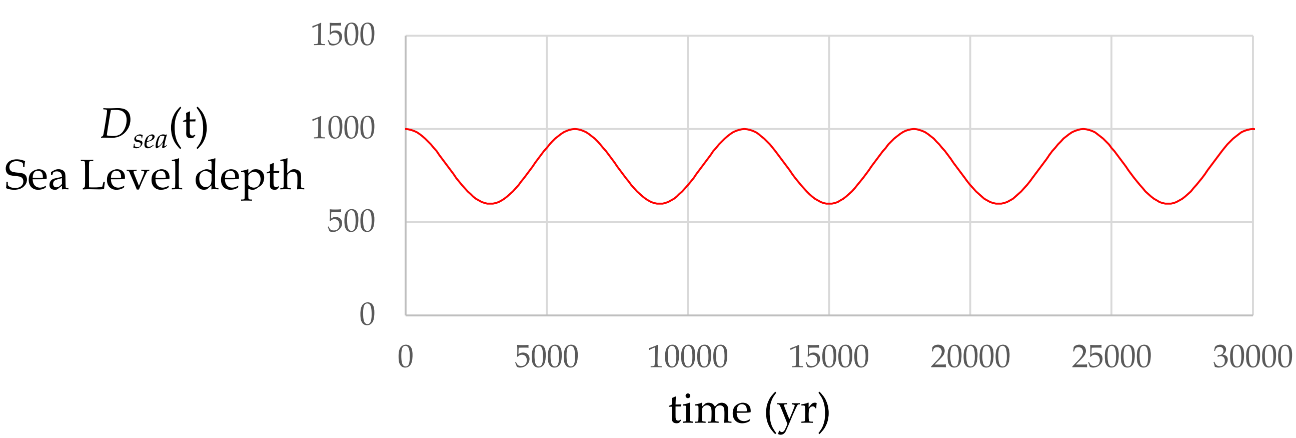
- If $z_i < D_{sea}(t)$

  $P(t) = \rho_s\, g[D_{sea}(t) - z_i]$

- If $z_i > D_{sea}(t)$

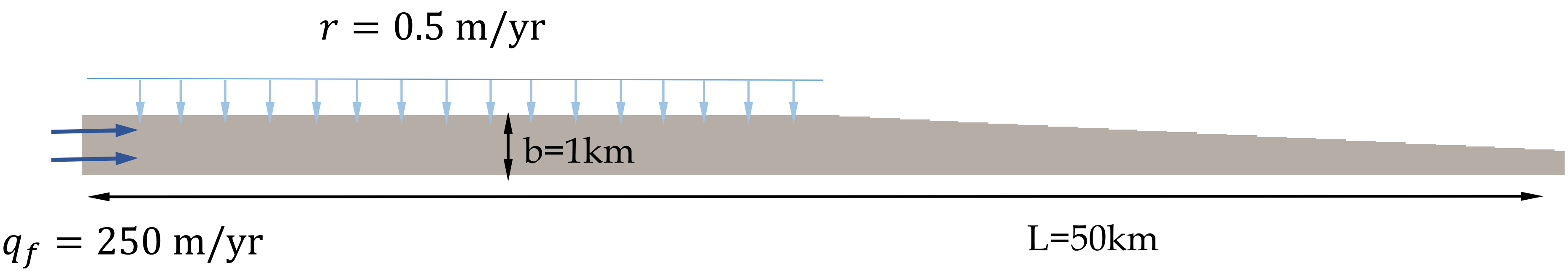
  $P(t) = p$

$P(t) = \rho_s\, g[D_{sea}(t) - z_i]$



COMSOL

Messinian: Conceptual Model



De Simoni (2005) formulation

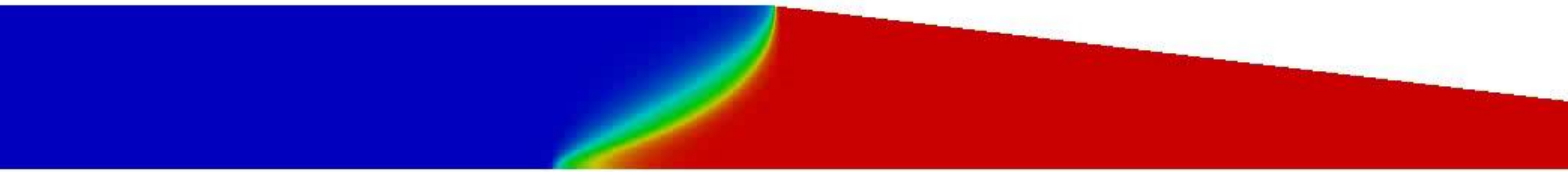
Reaction Rate $$r = \frac{\partial^2 C_2}{\partial \alpha^2} (\nabla^T \alpha \, \boldsymbol{D} \, \nabla \alpha)$$

Change in Porosity $$\phi(t + \Delta t) = \phi(t) + r \, V_m \Delta t$$

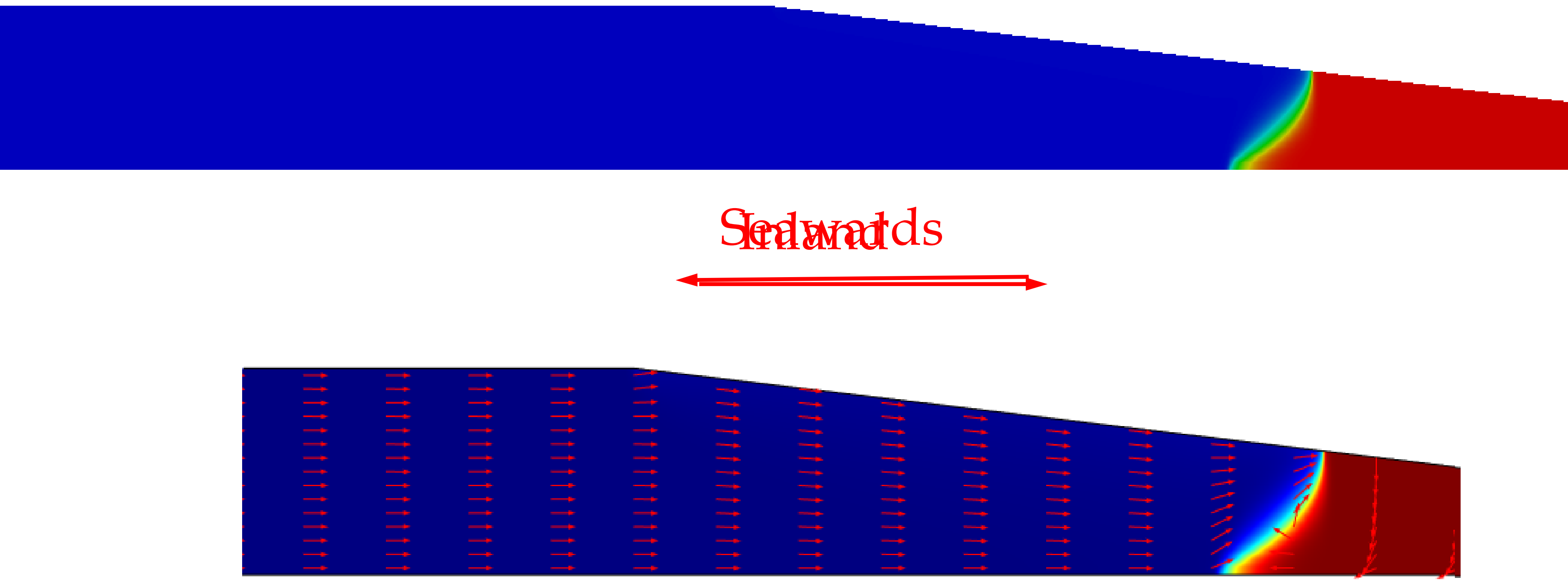
Change in Permeability $$k(t) = k_0 [\emptyset(t)/\emptyset_0]^3$$

Messinian: Results

Concentration distribution (6000 yr, 1 cycle)

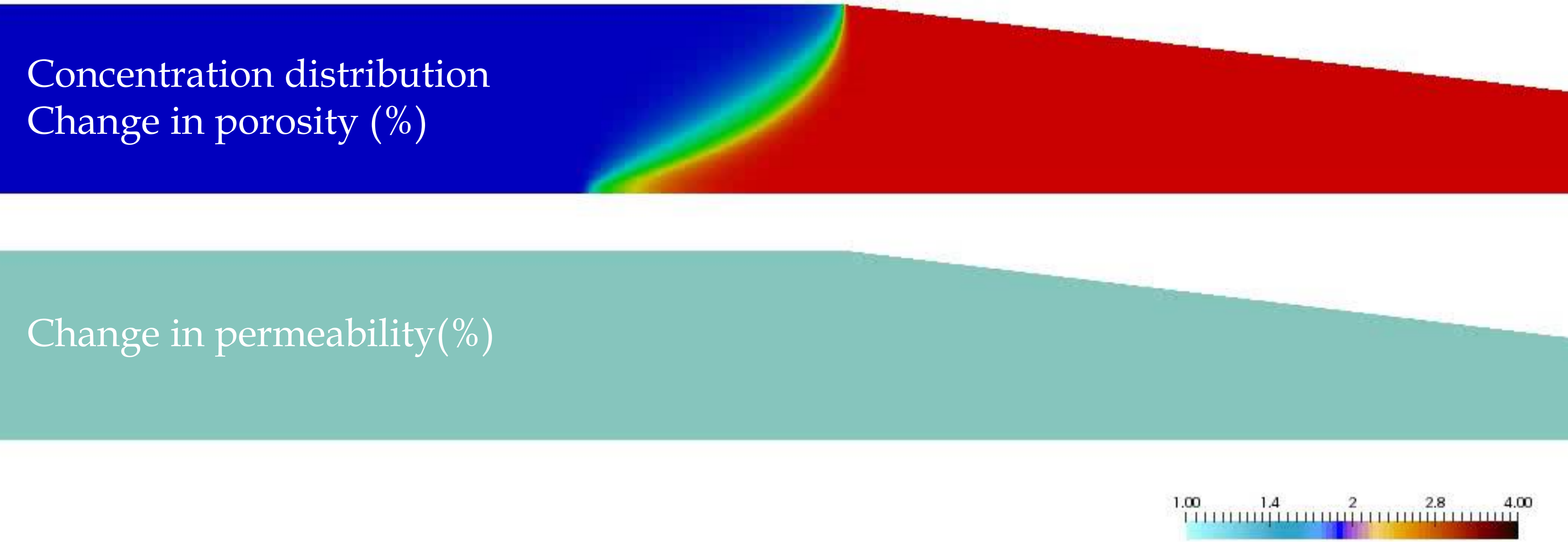


Messinian: Results



Messinian: Results

24000 yr, 4 cycles



Messinian: Results

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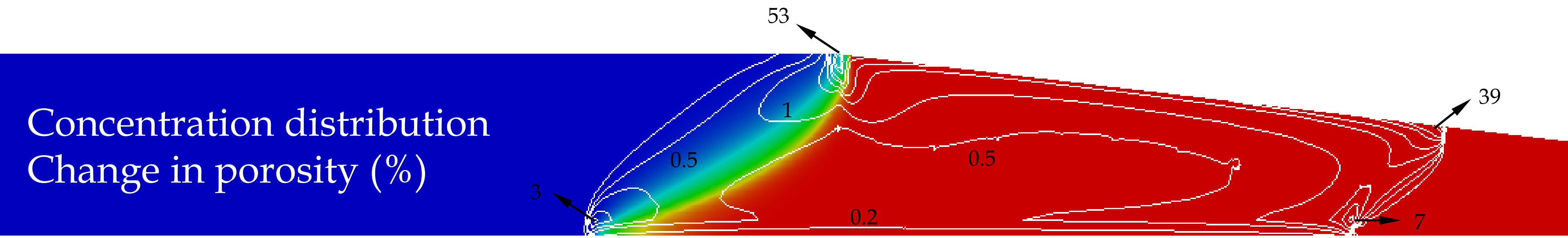
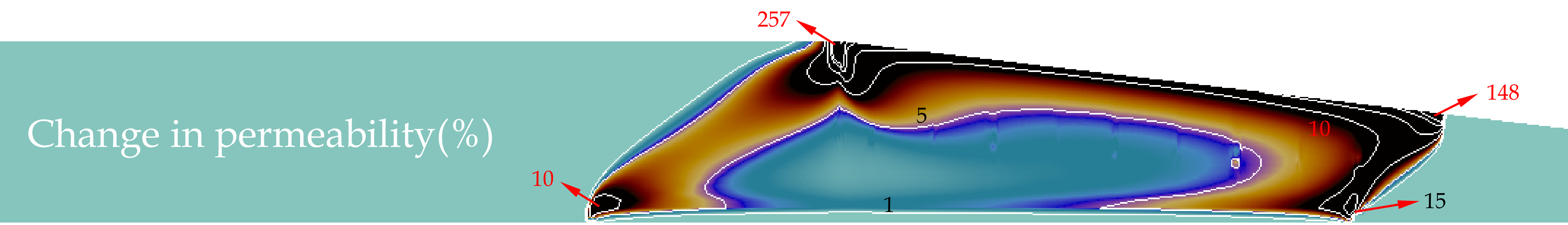
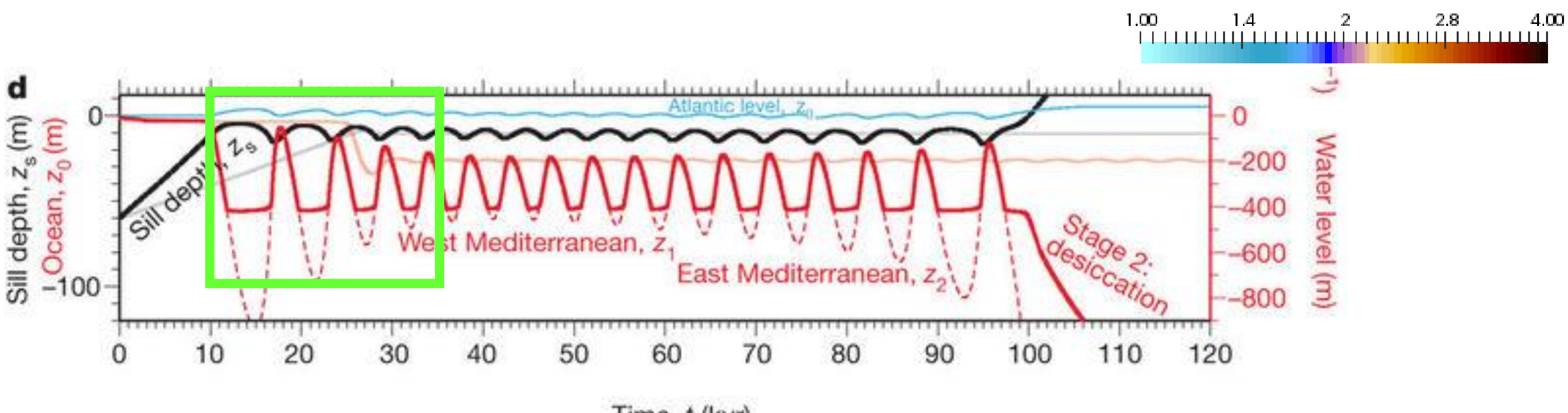


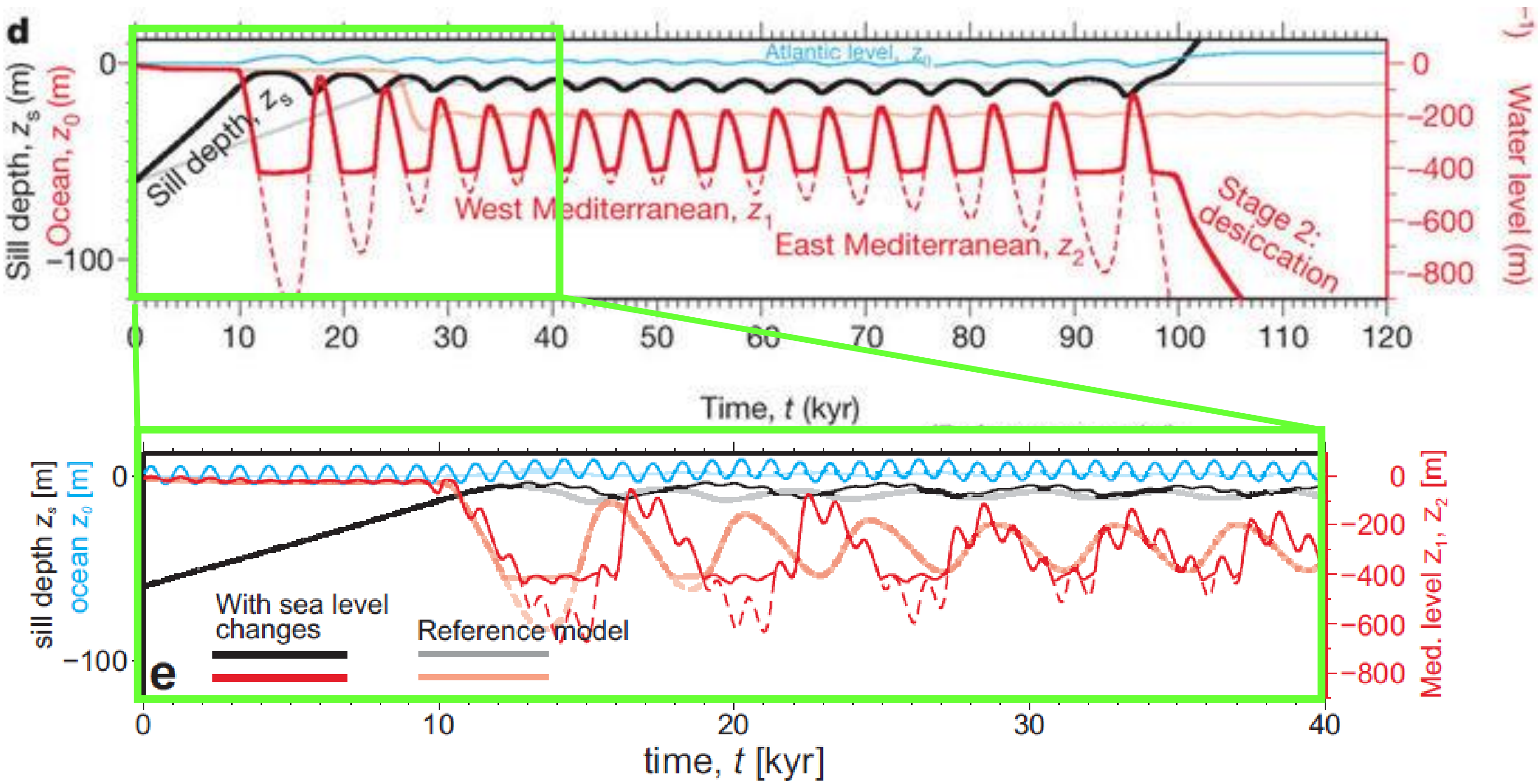




Messinian Crisis (5.96 to 5.33 million years ago)

More complex temporal fluctuations

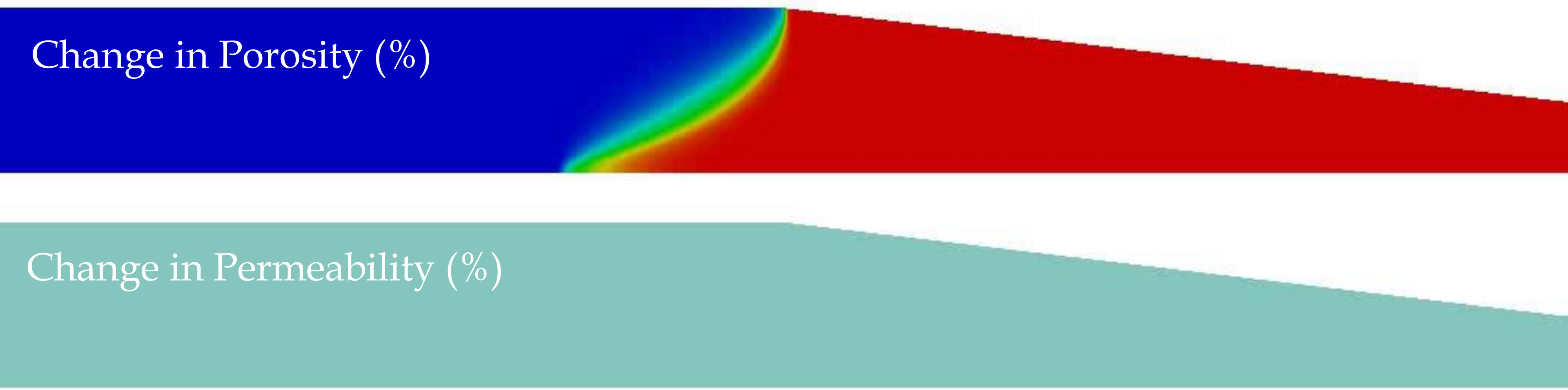
Including changes in the Atlantic Level

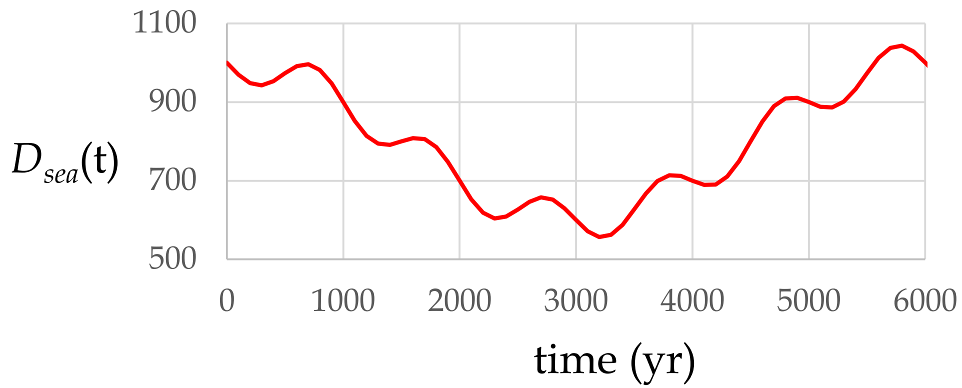


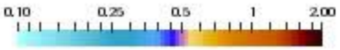
García-Castellanos et al, *Nature*, 2011

Messinian: Results

6000 yr (1 cycle)

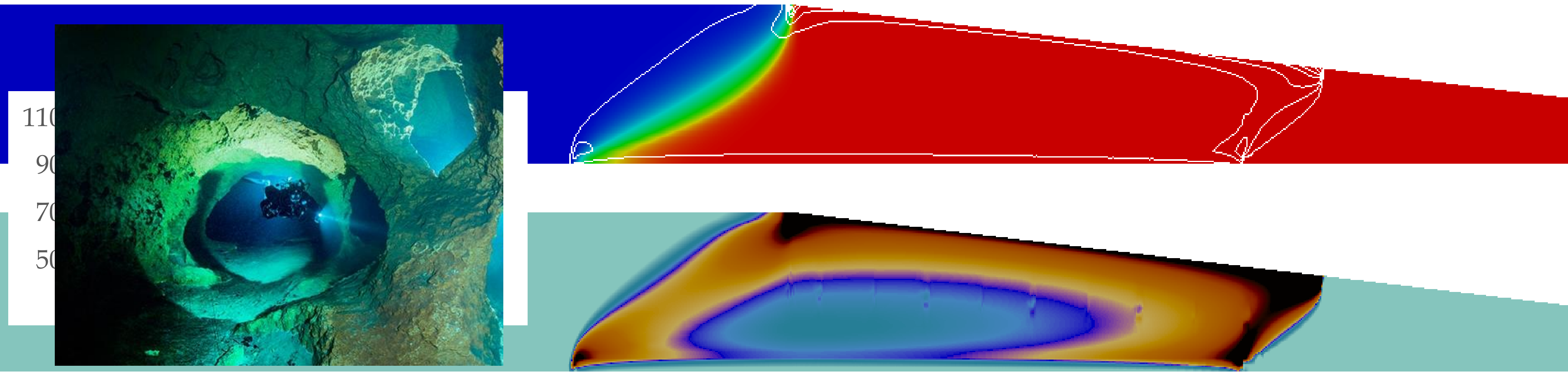


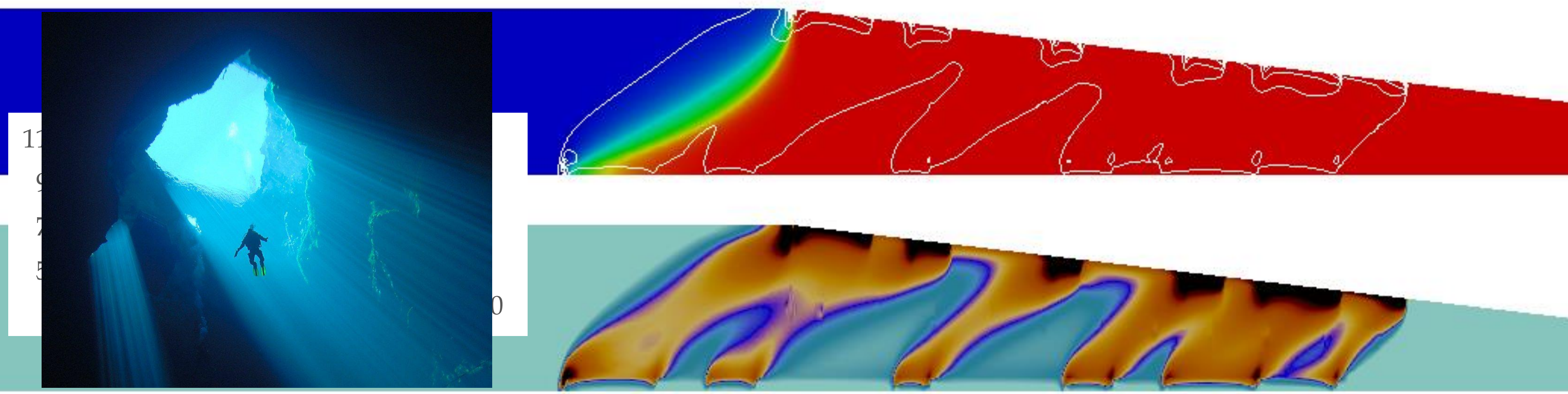


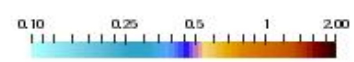


Messinian: Results

6000 yr (1 cycle)





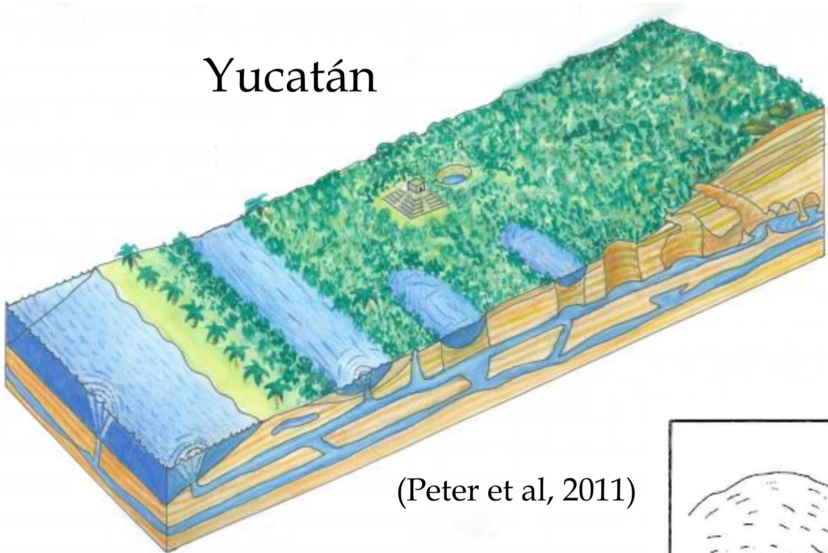


Conclusions

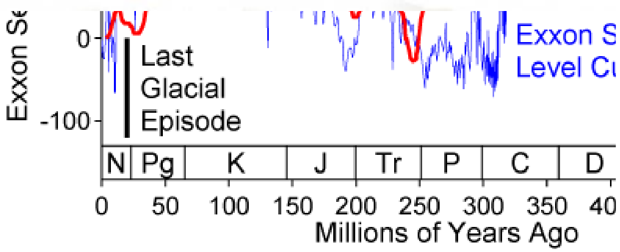
- The coupling of temporal fluctuations and density-driven flow can be a very likely mechanism for the formation of geochemical reaction patterns observed in coastal karst aquifers.

Not only in the Mediterranean

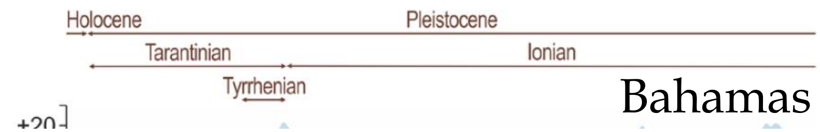
Yucatán



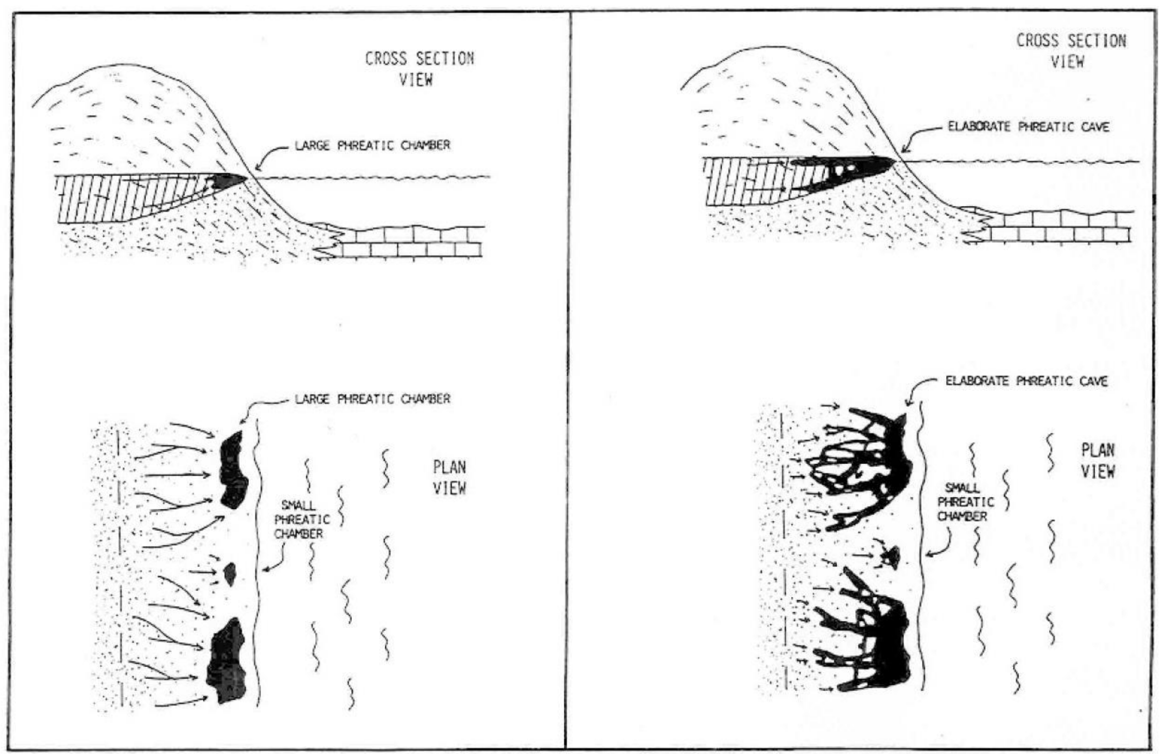
(Peter et al, 2011)



Hallan



Bahamas



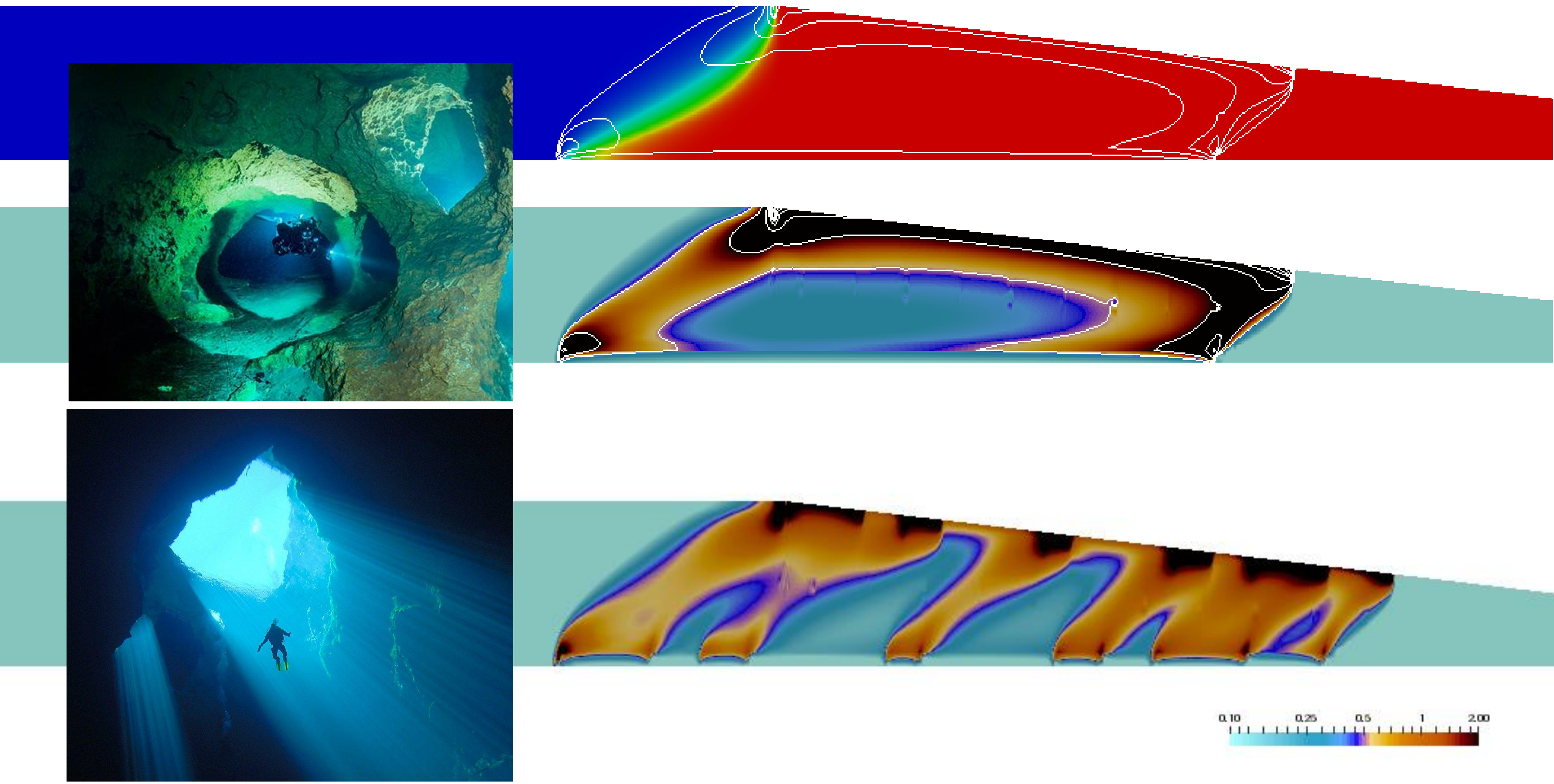
Mylroie et al. 1990

Conclusions

- The coupling of temporal fluctuations and density-driven flow can be a very likely mechanism for the formation of geochemical reaction patterns observed in coastal karst aquifers.

- Long period fluctuations promote horizontal conduit networks and irregular and short period fluctuations promote sinkholes and vertical karst conduits.

Thanks

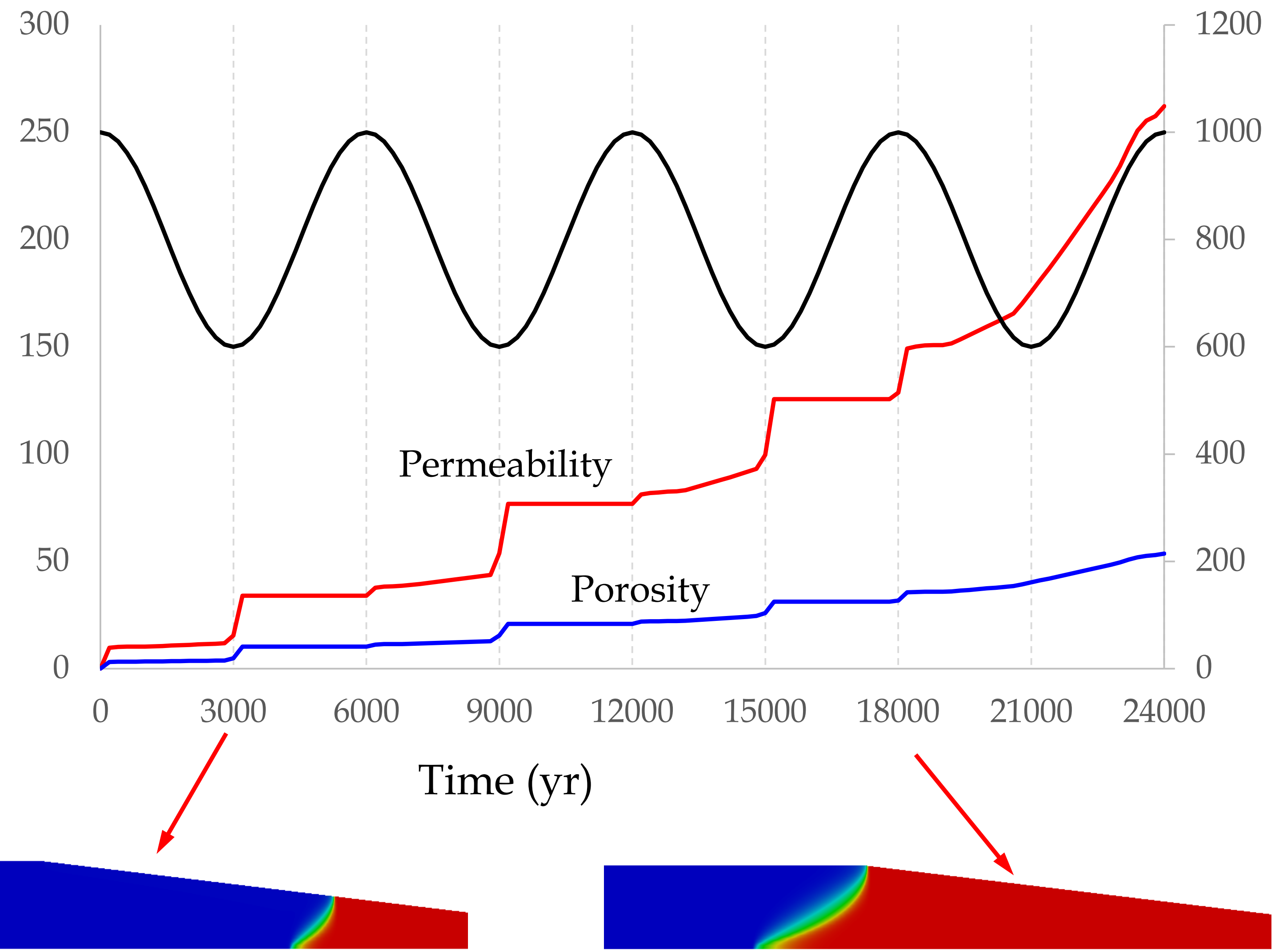


Messinian: Results

Maximum Increase (%)

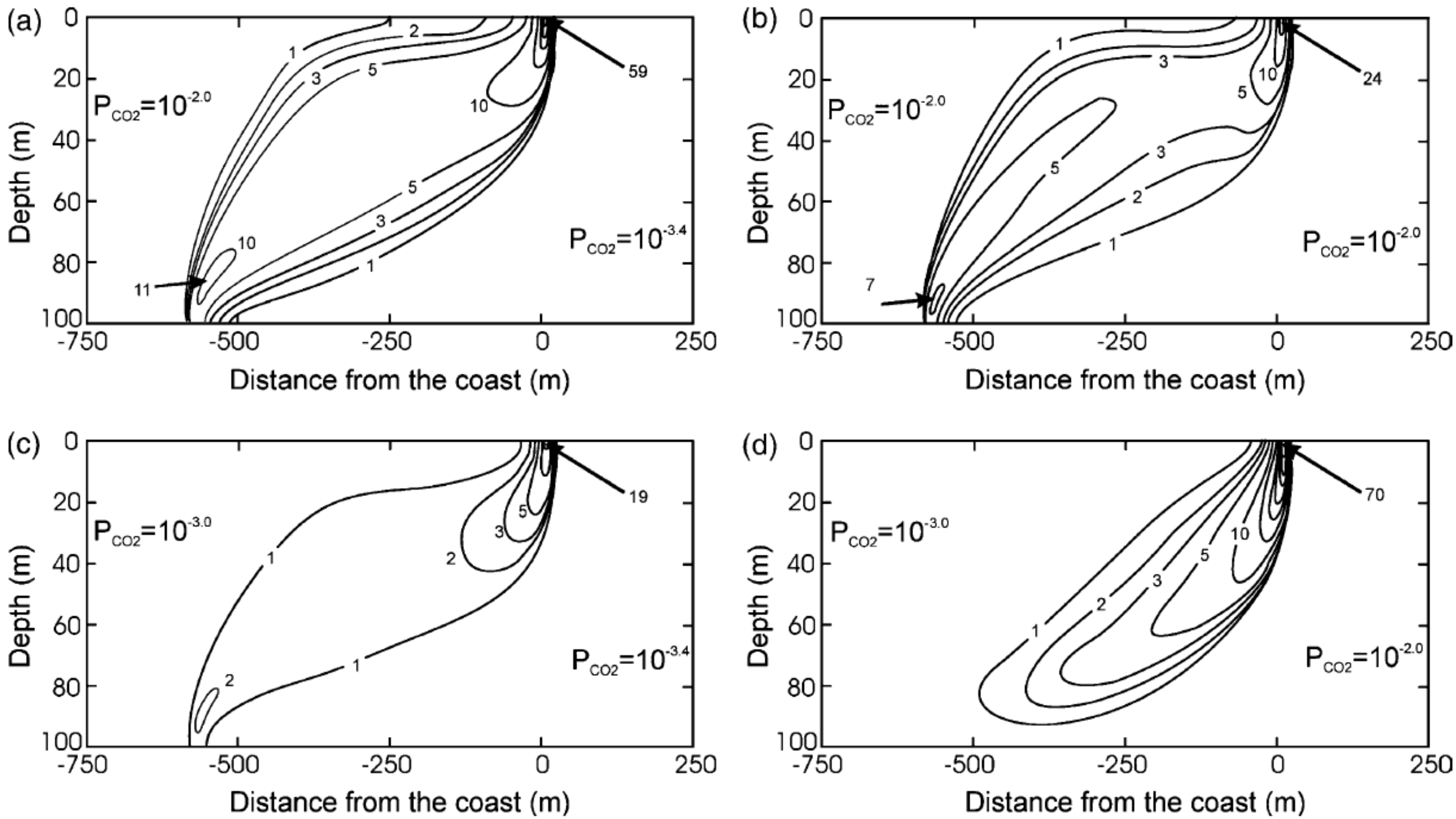
Sea Level depth

$$v = 100\left(\frac{v - v_0}{v_0}\right)$$



Calcite Dissolution – Coastal Aquifers

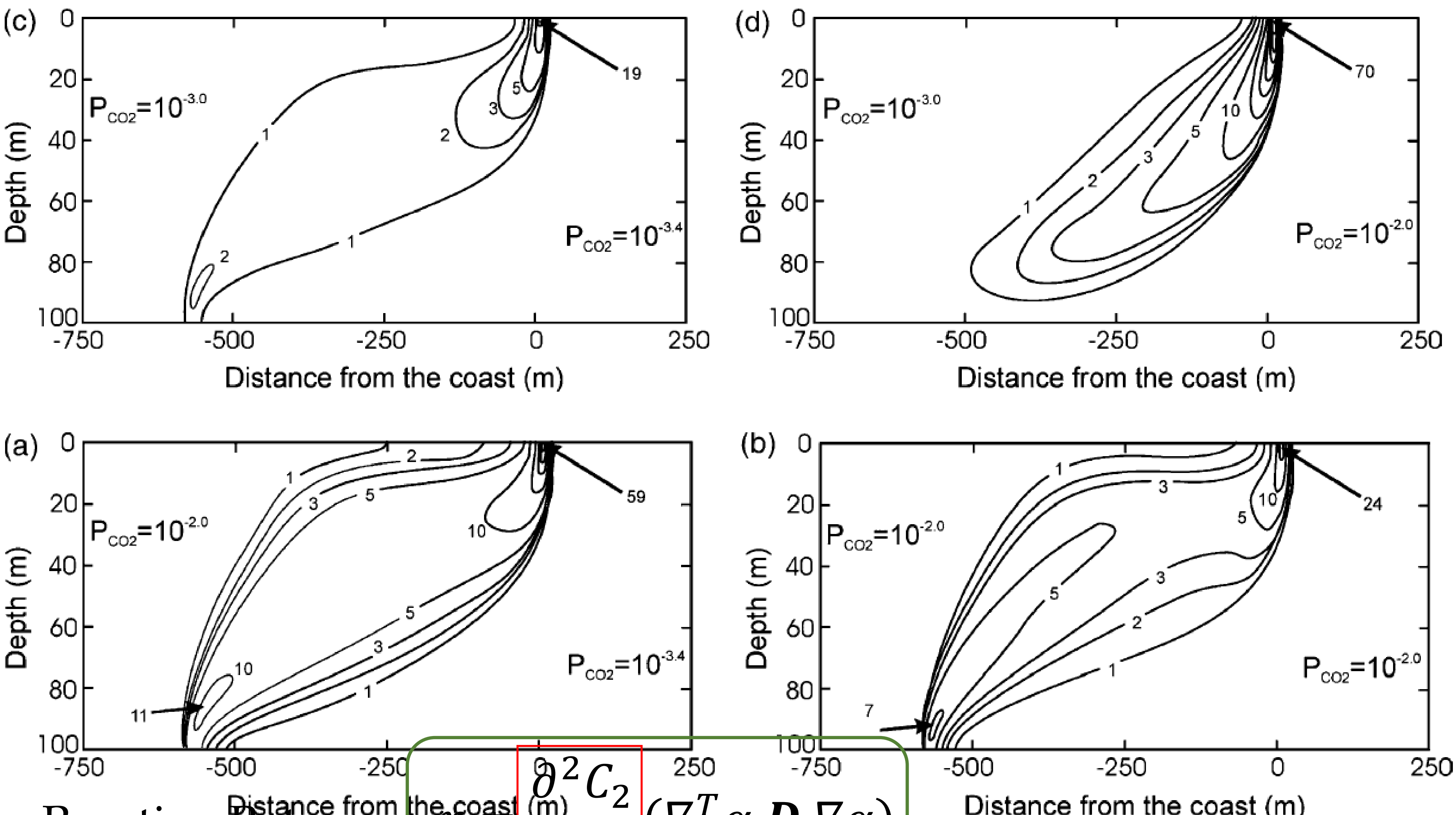
The PCO2 of both end-members control the rate of dissolution



- The larger PCO2 the more reactive
- Differences in PCO2 between the endmember solutions results in an increase of total accumulated calcite dissolution

Calcite Dissolution – Coastal Aquifers

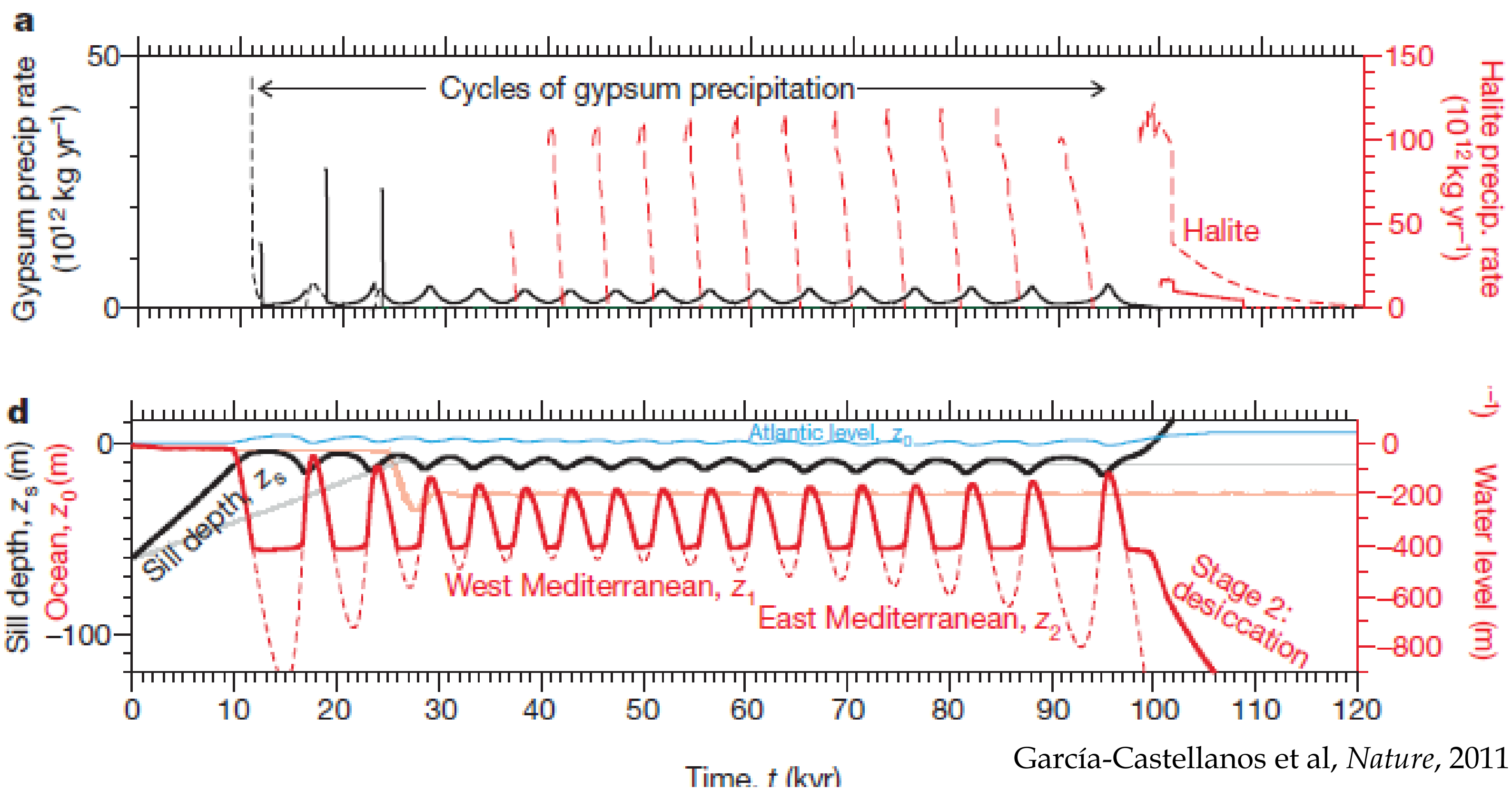
The PCO2 of both end-members control the rate of dissolution



Reaction Rate

$$r = \frac{\partial^2 C_2}{\partial \alpha^2} \left(\nabla^T \alpha \, \boldsymbol{D} \, \nabla \alpha\right)$$

Messinian Crisis (5.96 to 5.33 million years ago)



García-Castellanos et al, *Nature*, 2011