# The Role of Calcification in Carbonate Compensation



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# Warning!

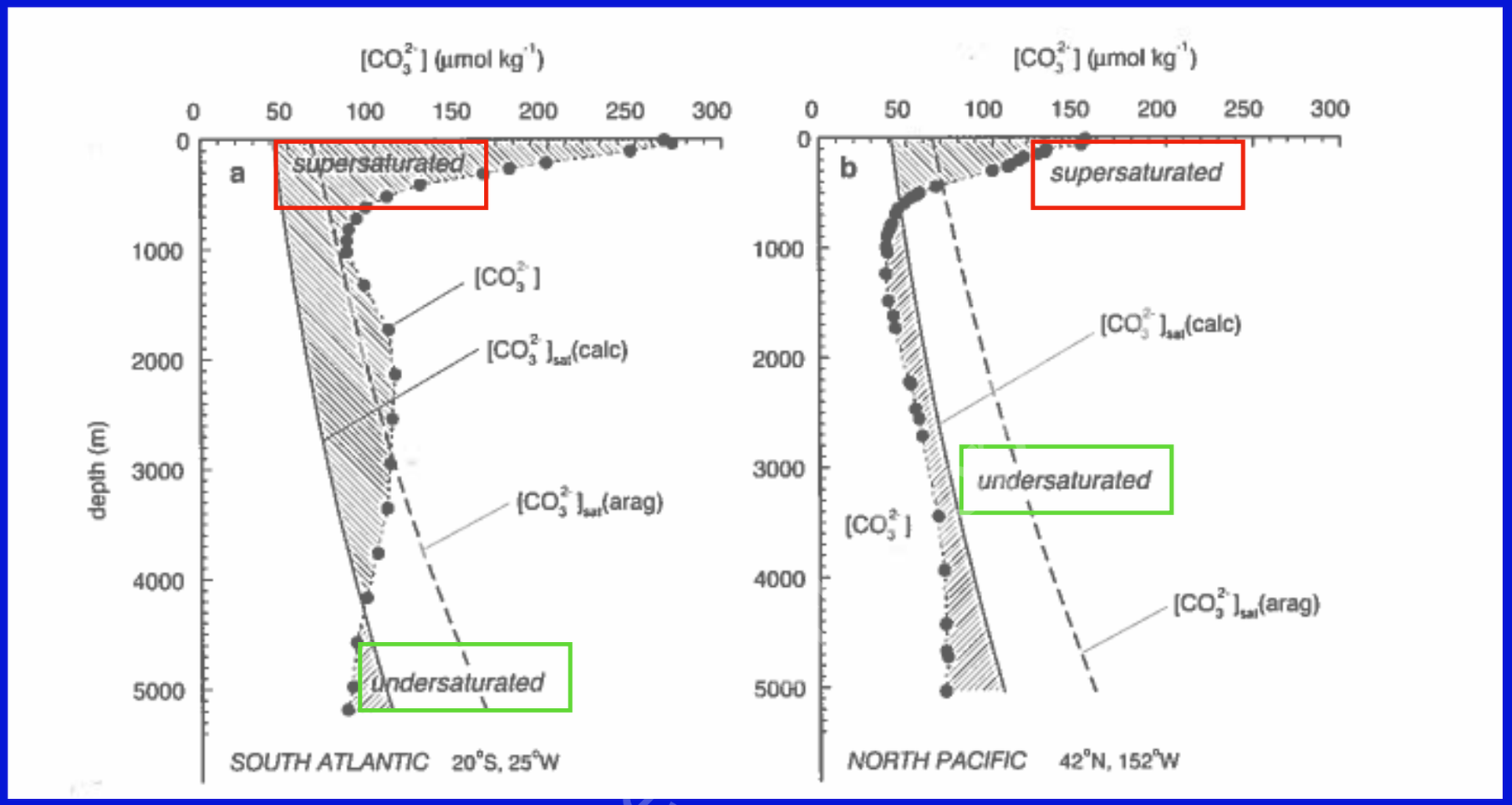
This is about the both short and LONG term evolution of the oceans

(After all, I’m a geologist!)

# What is Carbonate Compensation?

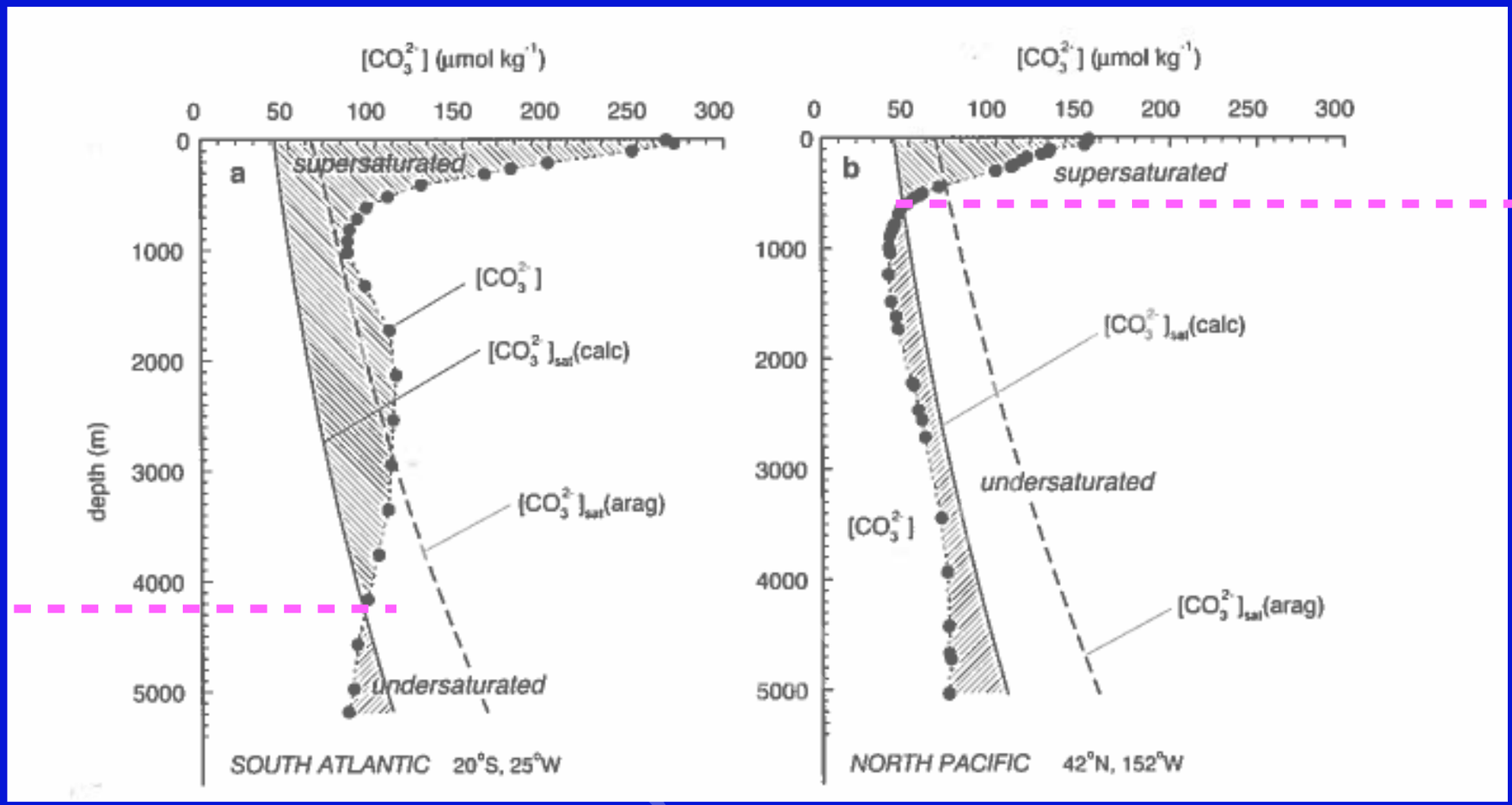
# What is Carbonate Compensation?

It is the ability of the oceans to regulate changes its carbonate chemistry, and consequently pH, by dissolving or preserving biogenic $CaCO_3$ in sediments.




Central to the operation of that process is the fact that the surface ocean is supersaturated with respect to calcite (and aragonite) and the deep ocean is undersaturated

Zsat



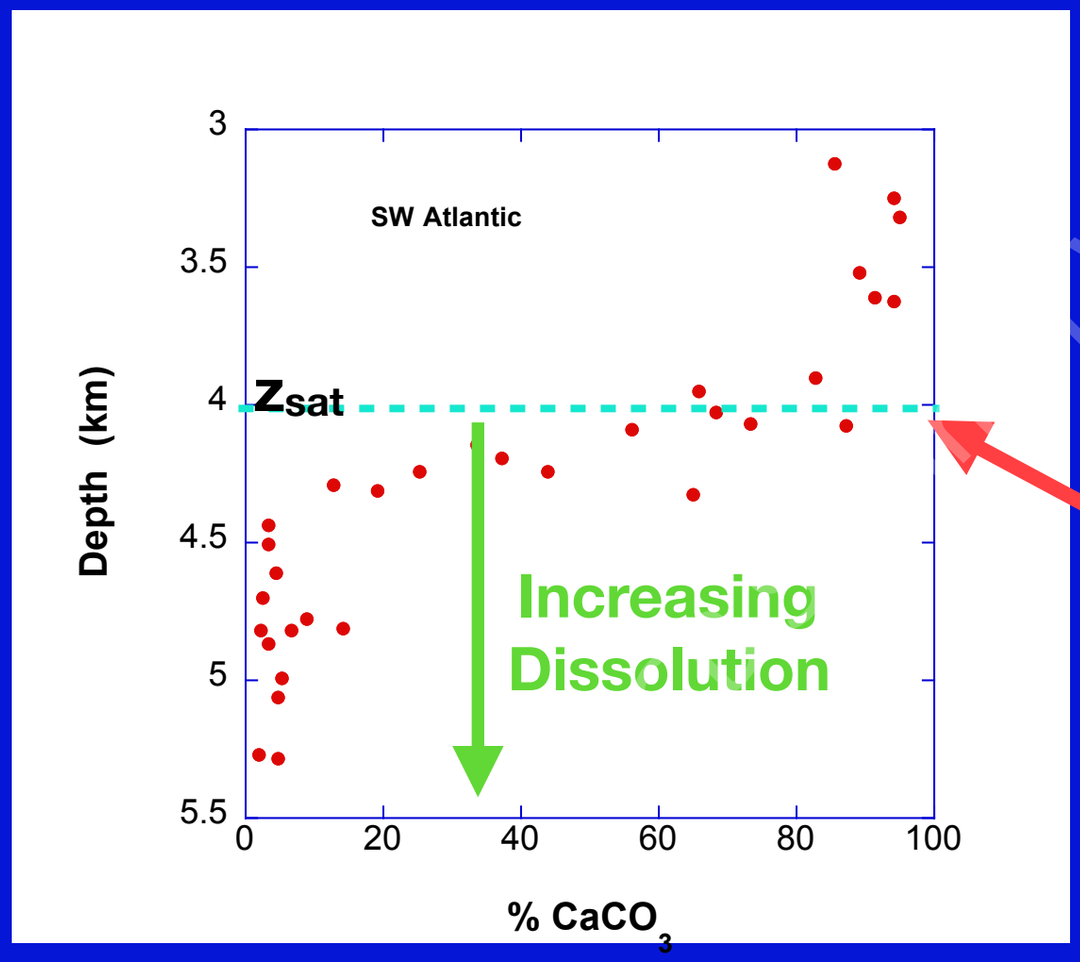

Zsat

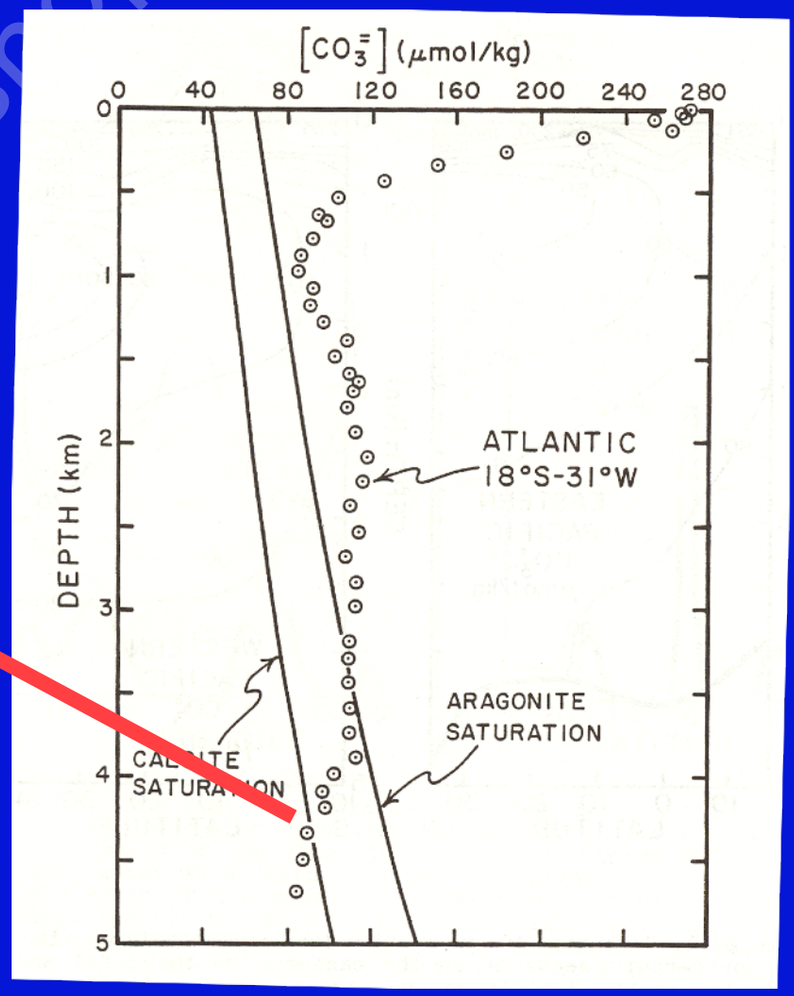


The surface (depth) that separates supersaturated and undersaturated waters is the

Saturation Depth ($z_{sat}$)

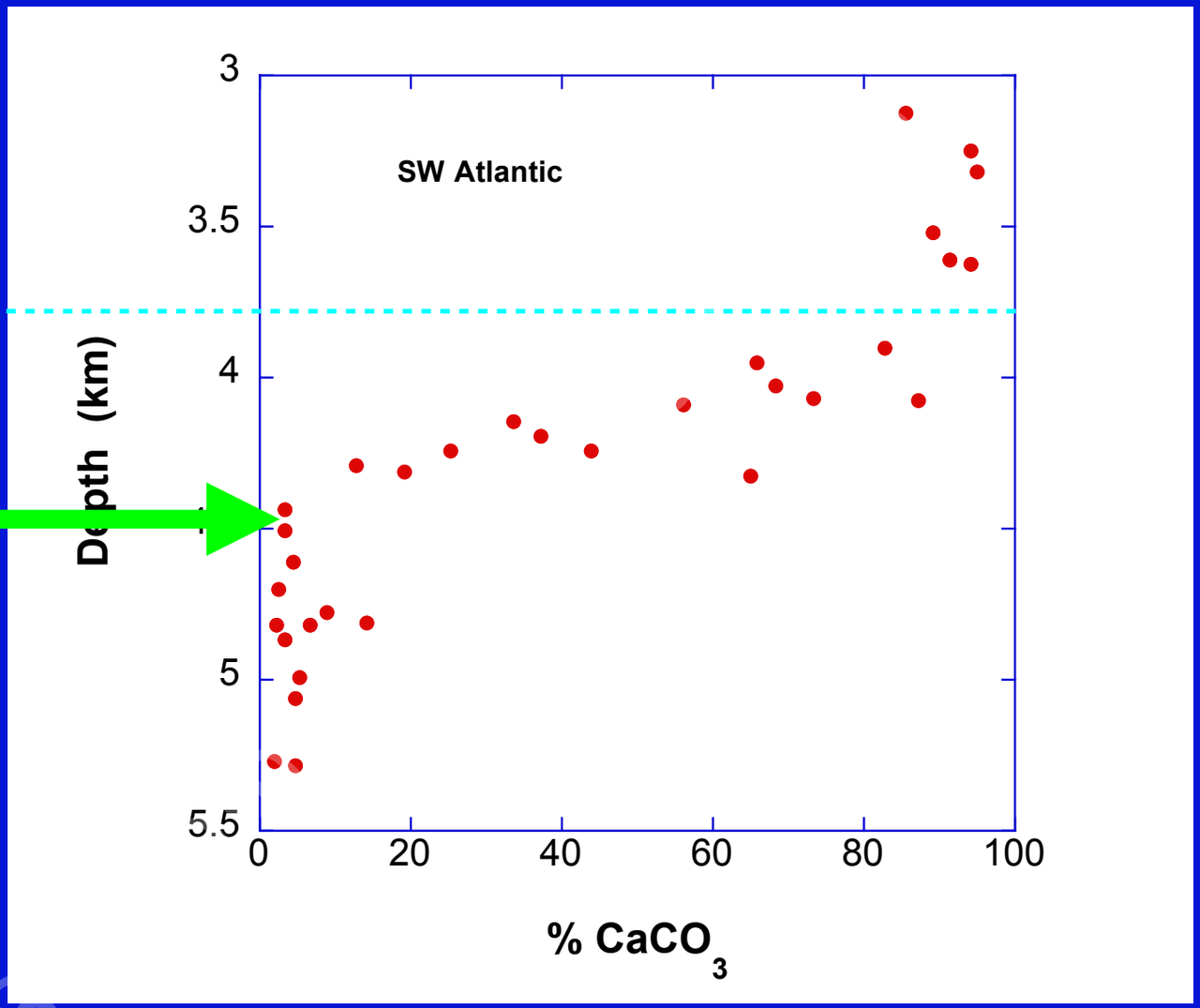
# The resulting saturation-depth trend generates $CaCO_3$ vs Depth profiles of the form:



Zsat

Snowline




Snowline = depth where % $CaCO_3$ = 0

Snowline



Snowline = depth where % $CaCO_3$ = 0

Compensation Depth = depth where the rain of $CaCO_3$ tests to sediment is exactly balanced by dissolution

At steady state:

Compensation Depth ($Z_{cc}$) = Snowline

# Can we predict $Z_{sat}$ and $Z_{cc}$?

For the Saturation Depth $Z = Z_{sat}$:

$$z_{sat} = z^{0}_{sat}\, ln\left(\frac{[Ca^{2+}][CO_3^{2-}]}{K^{1}_{sp}}\right)$$

For the CCD:

$$z_{cc} = z^{0}_{sat}\, ln\left( \frac{F_B\,[Ca^{2+}]}{K^{1}_{sp} k^{*}} + \frac{[Ca^{2+}][CO^{2-}_{3}]}{K^{1}_{sp}} \right)$$

*$F_B$ = rain (flux) of $CaCO_3$ reaching the seafloor!*

*$F_B \propto$ calcification ( rate )*

How much do $Z_{sat}$ and $Z_{cc}$ change with an acidification event ?

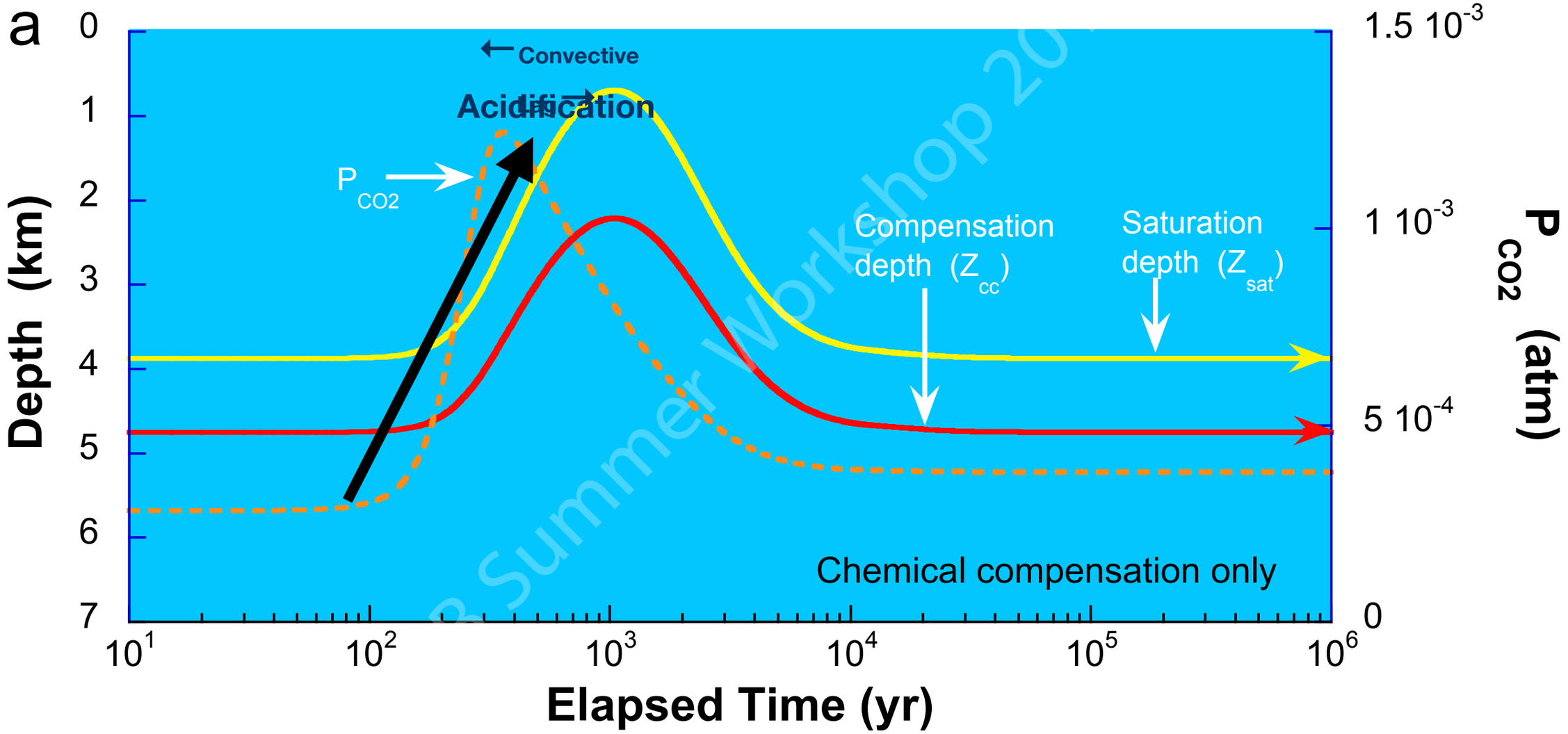
**(Assuming calcification is constant)**

This falls

$$CO_2 + CO_3^{2-} + H_2O \longleftrightarrow 2\ HCO_3^-$$

Add $CO_2$

Causes Dissolution of $CaCO_3$

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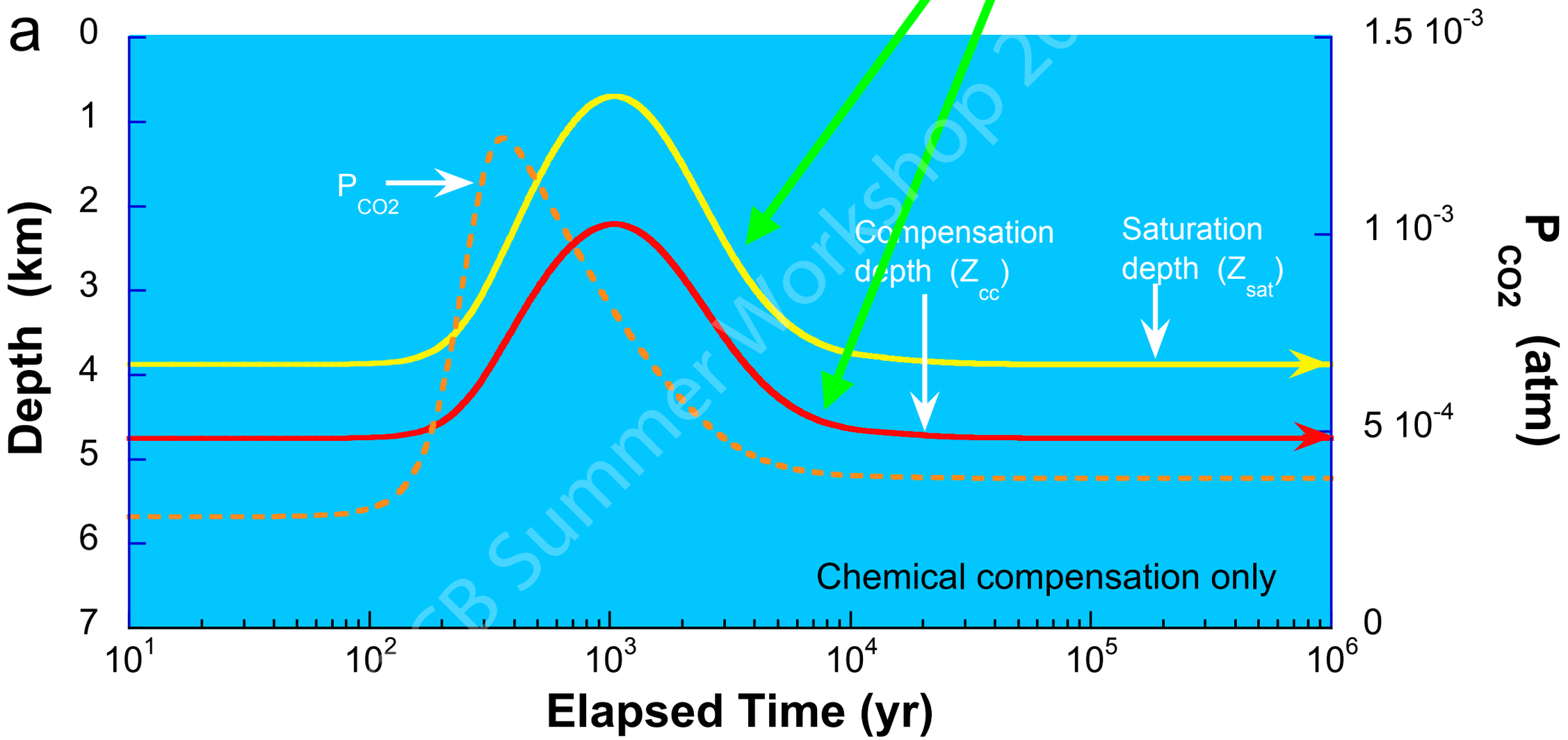
Post-acidification return




Boudreau, Middelburg and Luo (2018)

What new ideas can I give you about compensation?

Rain/Flux of $CaCO_3$ to sediment falls

$$z_{cc} = z^{0}_{sat}\, ln\left(\frac{F_B\,[Ca^{2+}]}{K^{1}_{sp}k^{*}} + \frac{[Ca^{2+}][CO_3^{2-}]}{K^{1}_{sp}}\right)$$

gets smaller = shallows

# Biological Compensation:

Based on the idea that calcification rate is sensitive to saturation state of surface waters

Operates at the same time as chemical compensation

## Biological Compensation during Acidification:

- Loss of calcification ($F_B$) makes $z_{cc}$ move up, just like chemical compensation

- Loss of removal of surface alkalinity ($HCO_3^-$)

- Alkalinity will build-up in the oceans

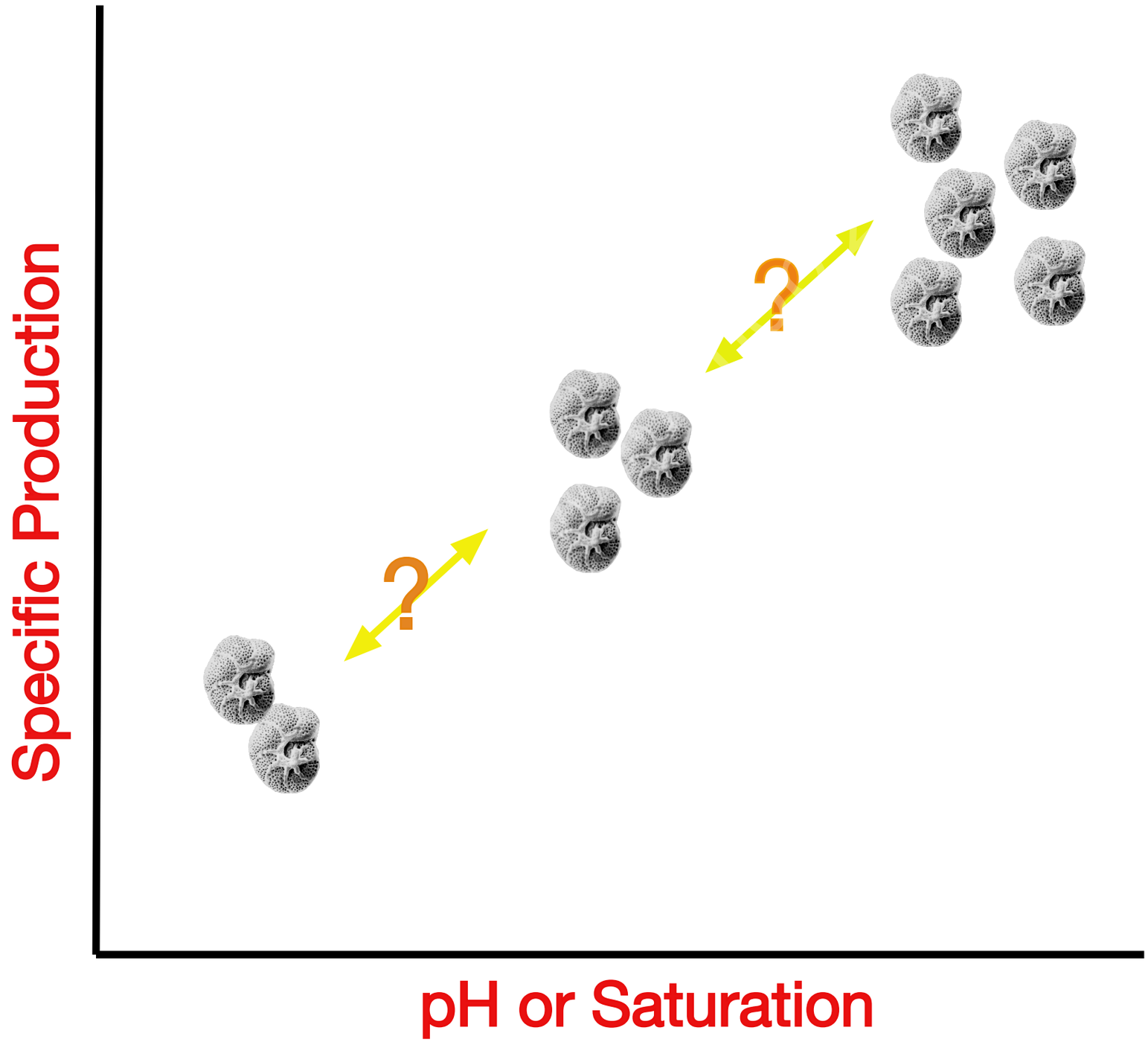
- That build-up will counteract the added $CO_2$

$$CO_2 + CO_3^{2-} + H_2O \quad <—> \quad 2\ HCO_3^-$$

## Biological Compensation during Acidification:

How do $Z_{sat}$ and $Z_{cc}$ change with added biological compensation?

# Longterm Ecological Function Unknown

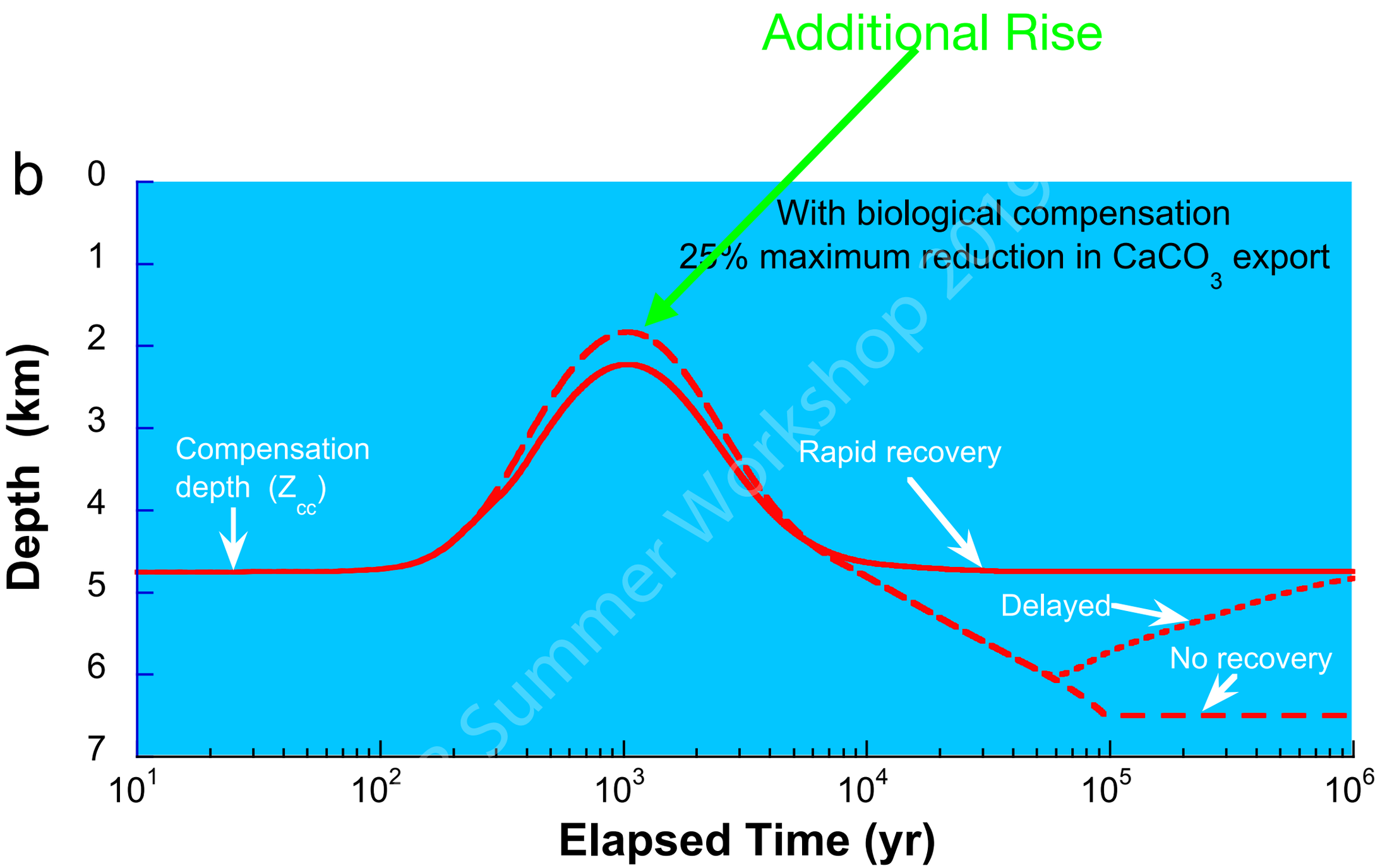


# Biological Compensation during Acidification:

**Rapid Recovery: $F_B$ inversely mirrors $CO_2$ in the ATM**
**(calcifier ecology in equilibrium with surface pH)**

**No Recovery: Loss of $F_B$ is permanent**
**(calcifier populations permanently reduced)**

**Delayed Recovery: Loss for a while, but later recovery**
**(calcifiers eventually increase and reoccupy ecological niche)**

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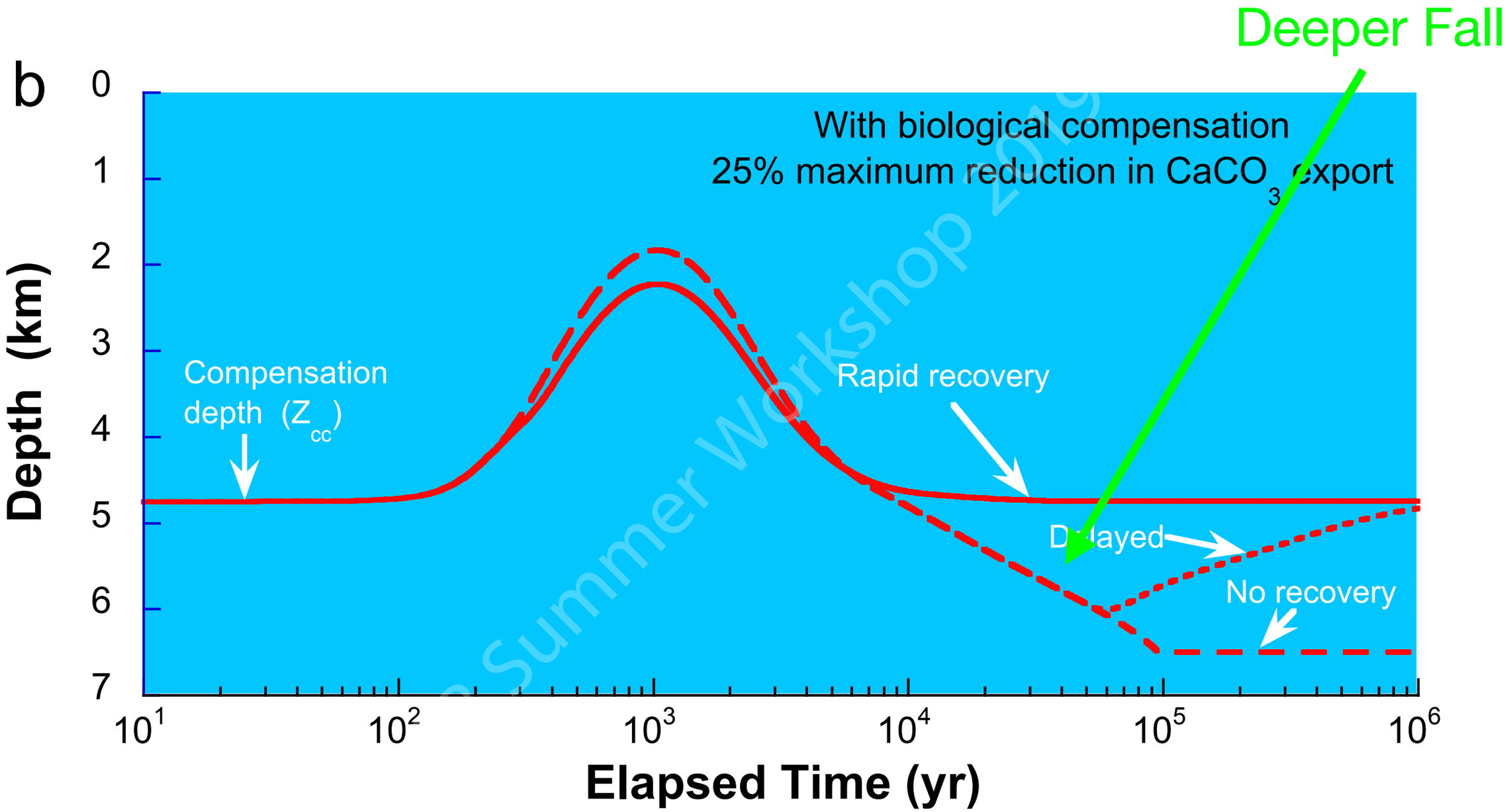


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# Biological Compensation:

Once the $CO_2$ input stops:

- If calcifiers return slowly or don't return:
- then alkalinity accumulation from reduced calcification will induce a greater deepening of both $Z_{sat}$ and $Z_{cc}$

## Biological Compensation:

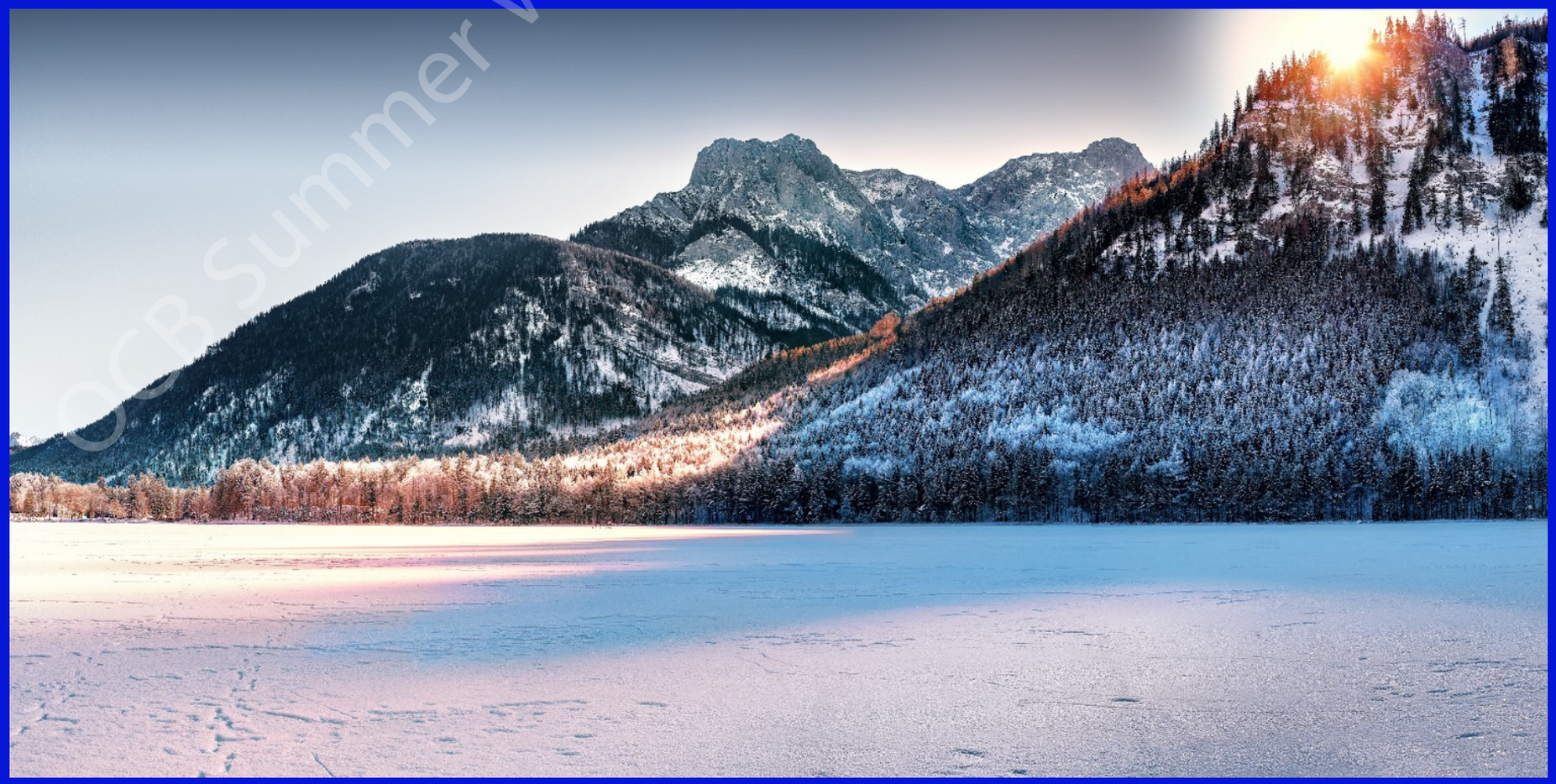
- The deepening can exceed the pre-perturbation positions

We will transition from:

← This

THIS!

↓



b

With biological compensation
25% maximum reduction in $CaCO_3$ export

Compensation depth ($Z_{cc}$)

Rapid recovery

Overdeepening

Delayed

No recovery

Depth (km)

0
1
2
3
4
5
6
7

$10^1$ $10^2$ $10^3$ $10^4$ $10^5$ $10^6$

Elapsed Time (yr)



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Anthropogenic acidification may lead to alkalinization and overdeepening depending on the response of calcifiers

Has this ever happened?

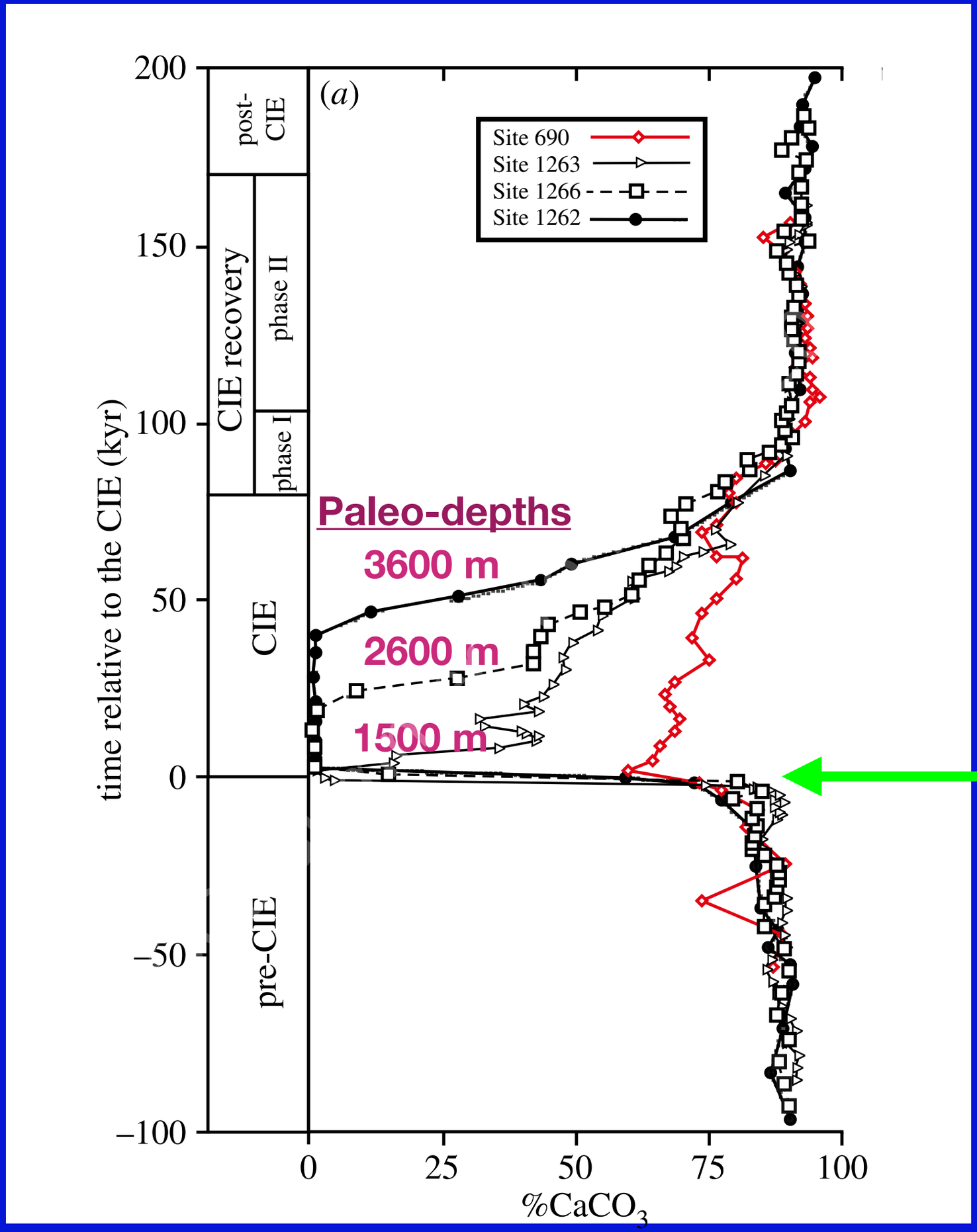
Perhaps the PETM

PETM:

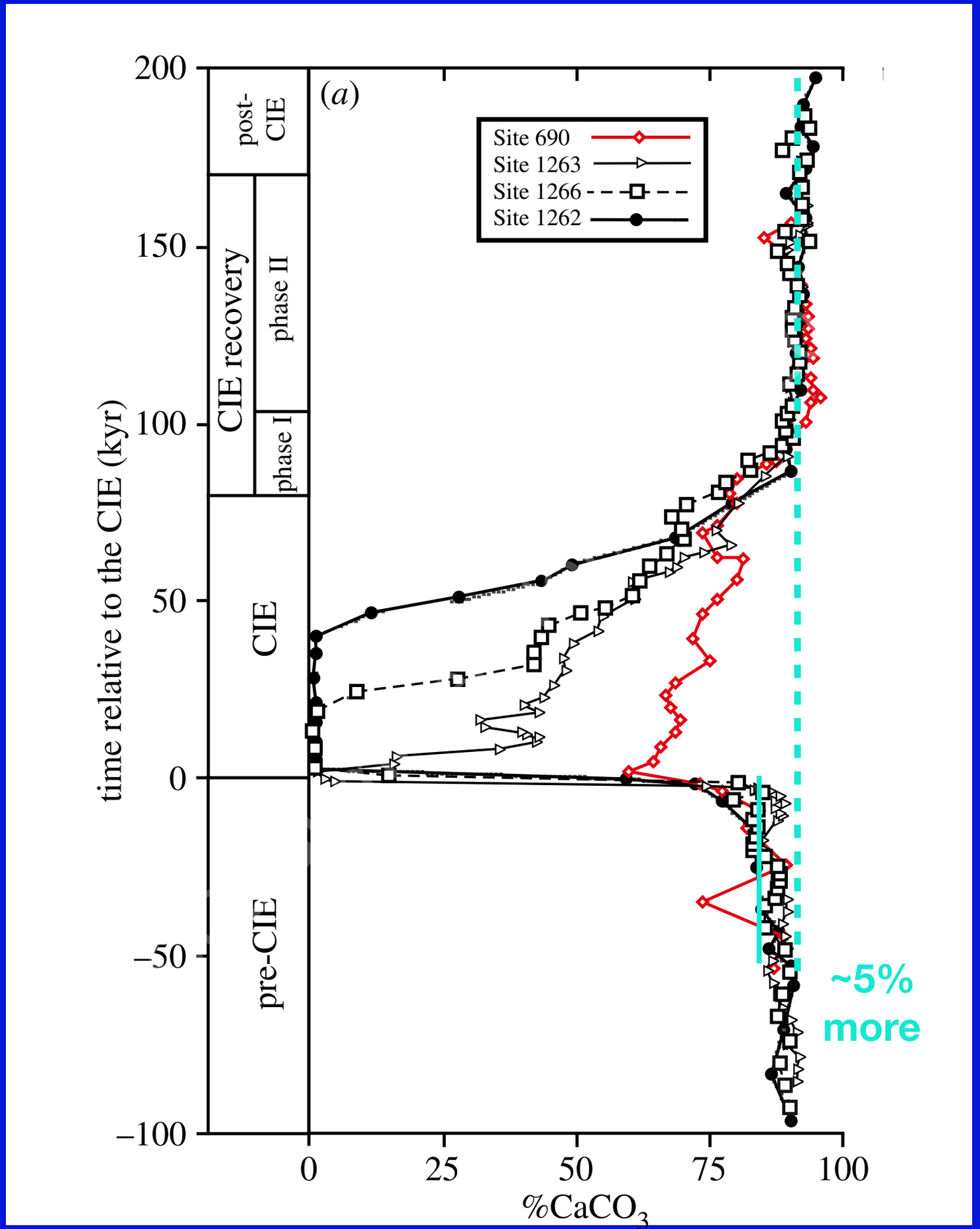
- 55 Ma
- Period of extra warming in a warm period
- High $CO_2$ with a $CO_2$ release event from dissociating hydrates

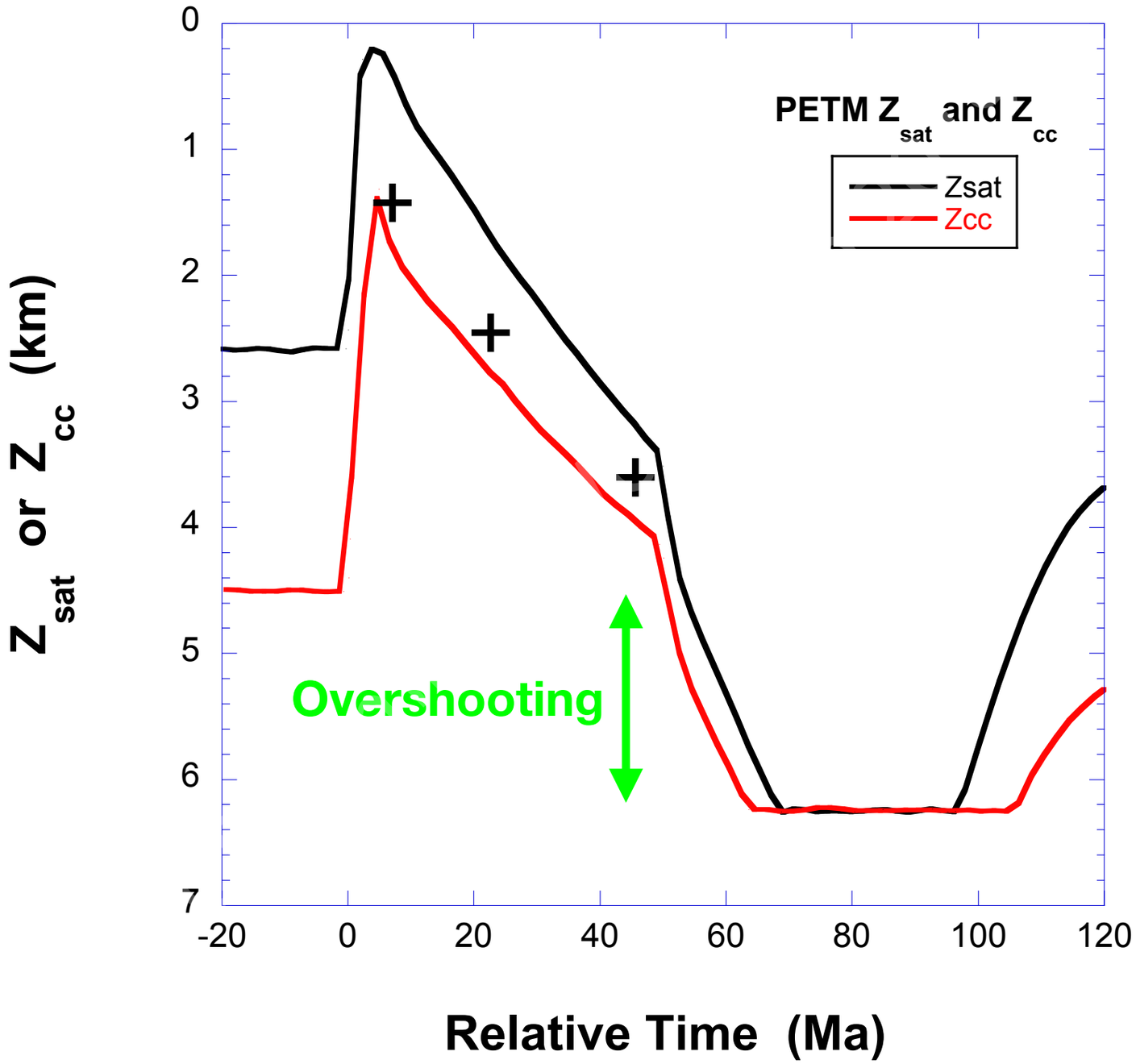
## Sample sediments of that age:

Walvis Ridge



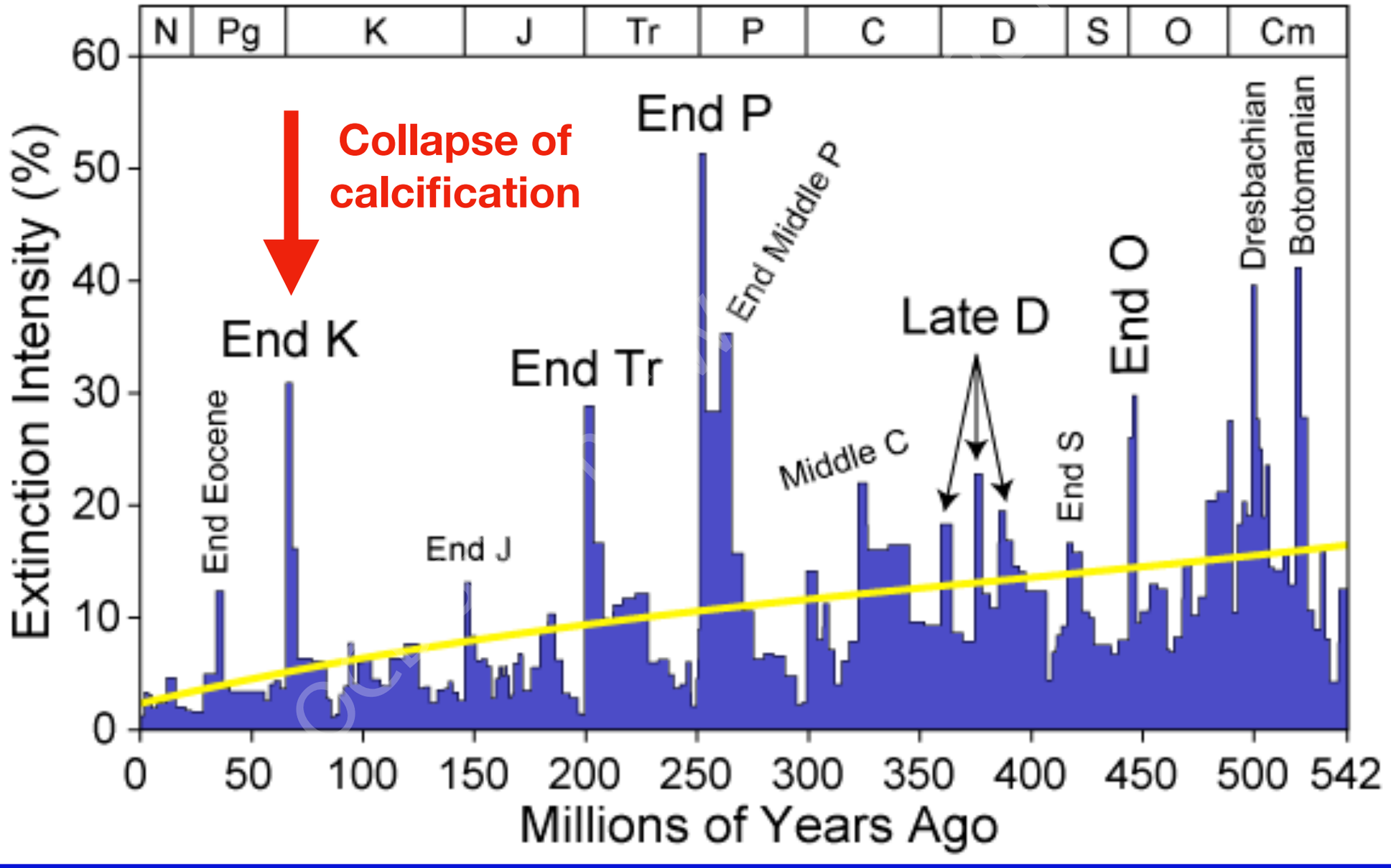
Walvis Ridge

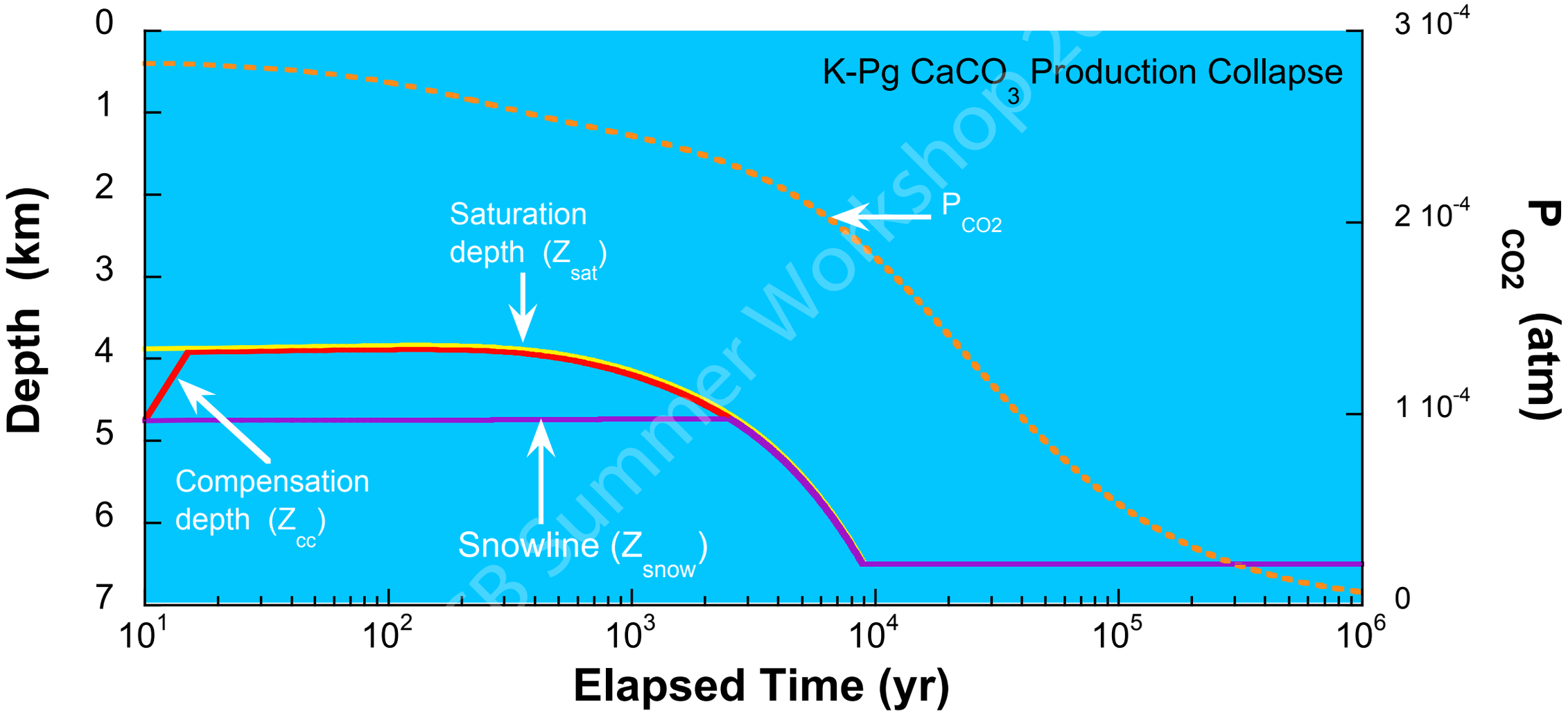



PETM Z sat and Z cc
Zsat
Zcc
Overshooting
Z sat or Z cc (km)
Relative Time (Ma)
0
1
2
3
4
5
6
7
-20
0
20
40
60
80
100
120

# Is there an Example of extreme Biological Carbonate Compensation?

# Marine Genus Biodiversity: Extinction Intensity



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# MAIN CONCLUSIONS

- There are 2 forms of carbonate compensation: chemical and biological (which is due calcification and is instantaneous)

- Biological compensation can explain the overshooting of the PETM (55 M years ago)

- Anthropocene acidification may or may generate overshooting, as our models so far lack mechanistic parametrization of calcification