BayesReef: Bayesian inference for estimation and uncertainty quantification of parameters in geological reef evolution model

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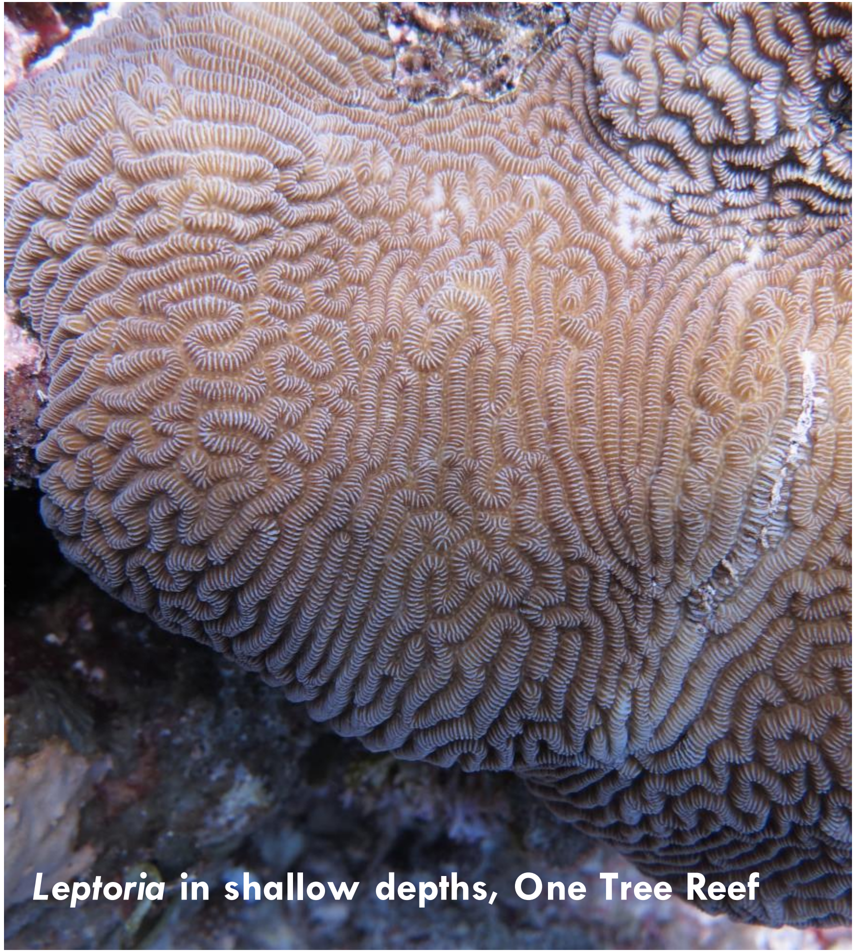
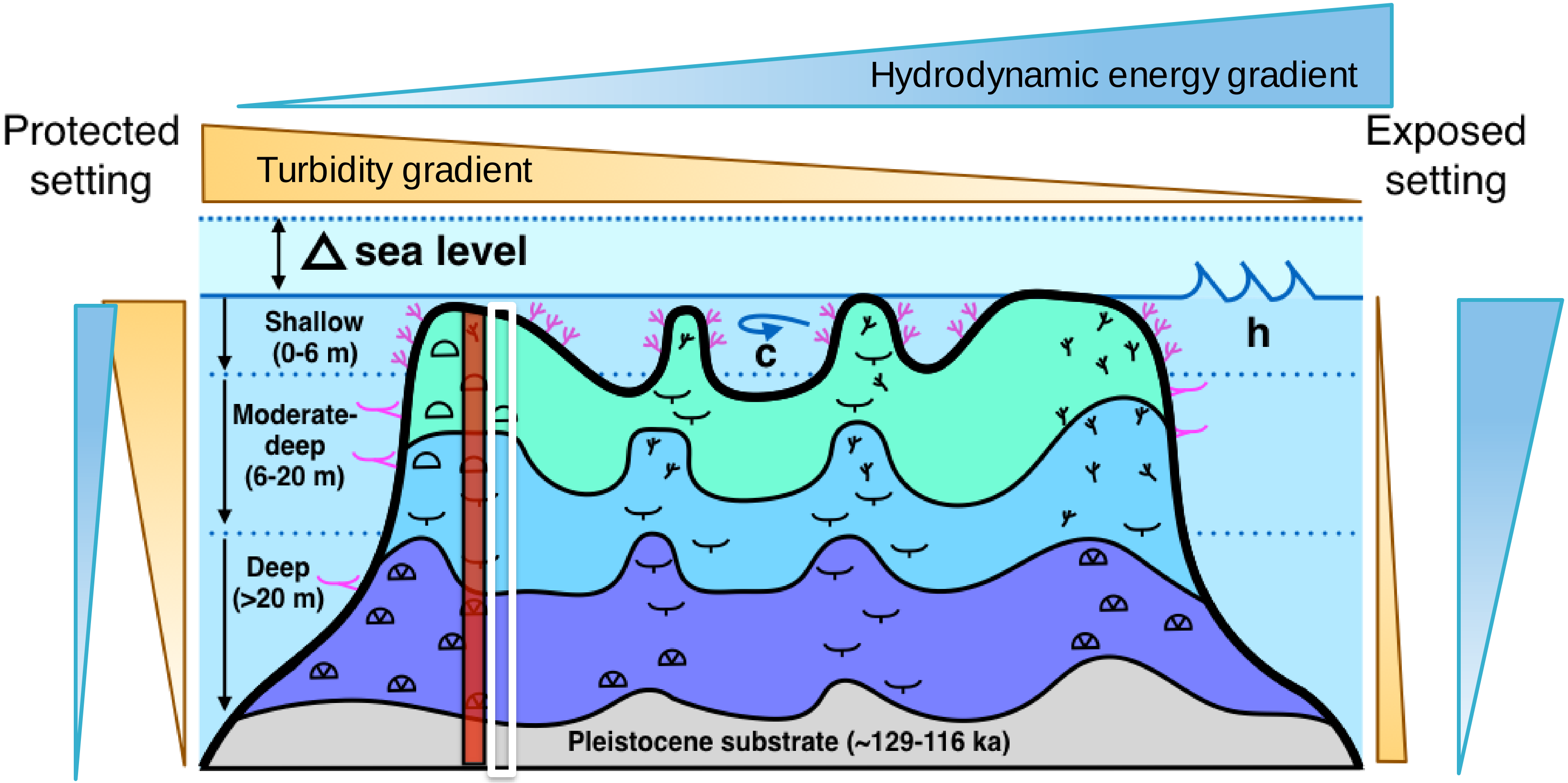


Leptoria in shallow depths, One Tree Reef

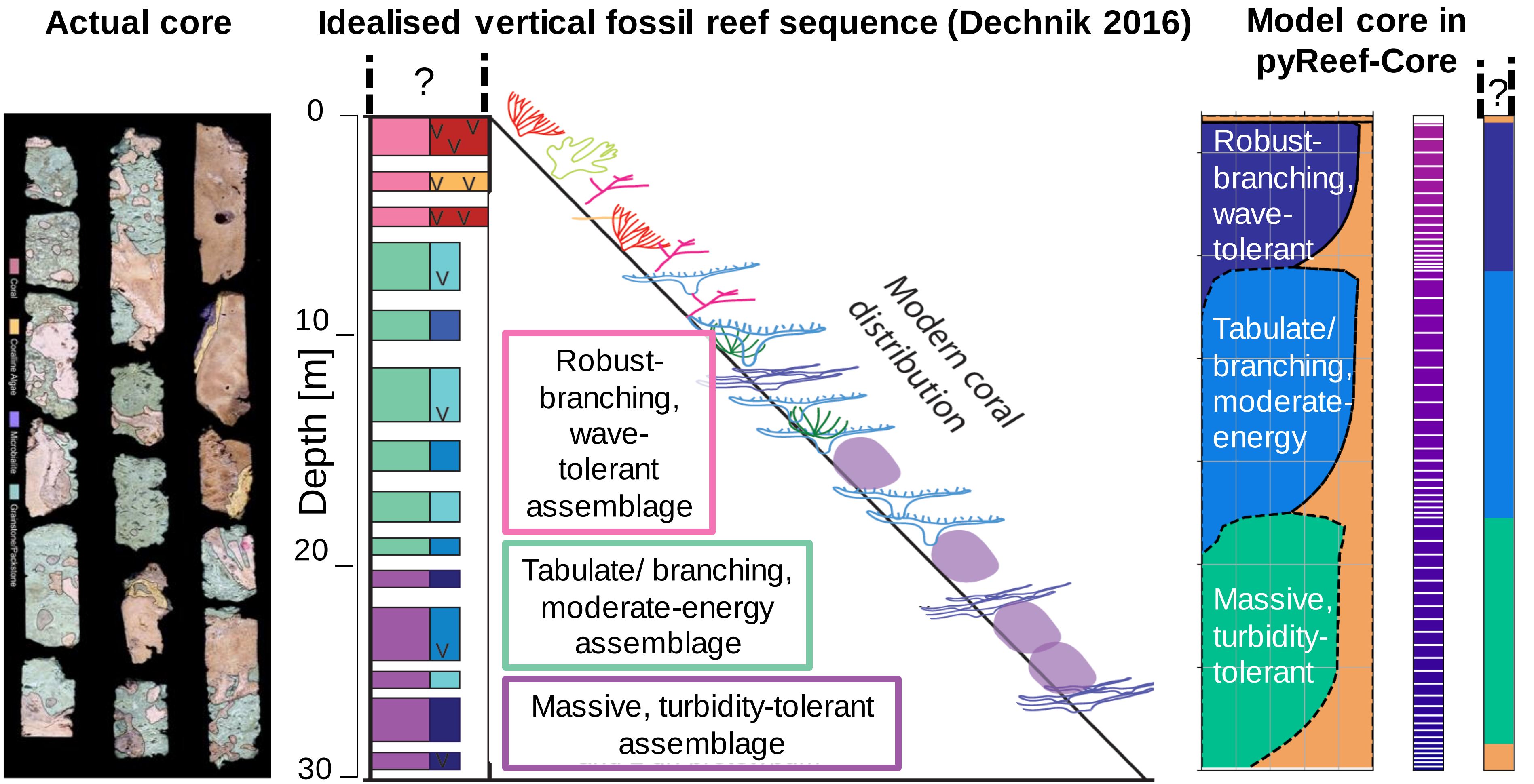
Environmental controls on reef growth

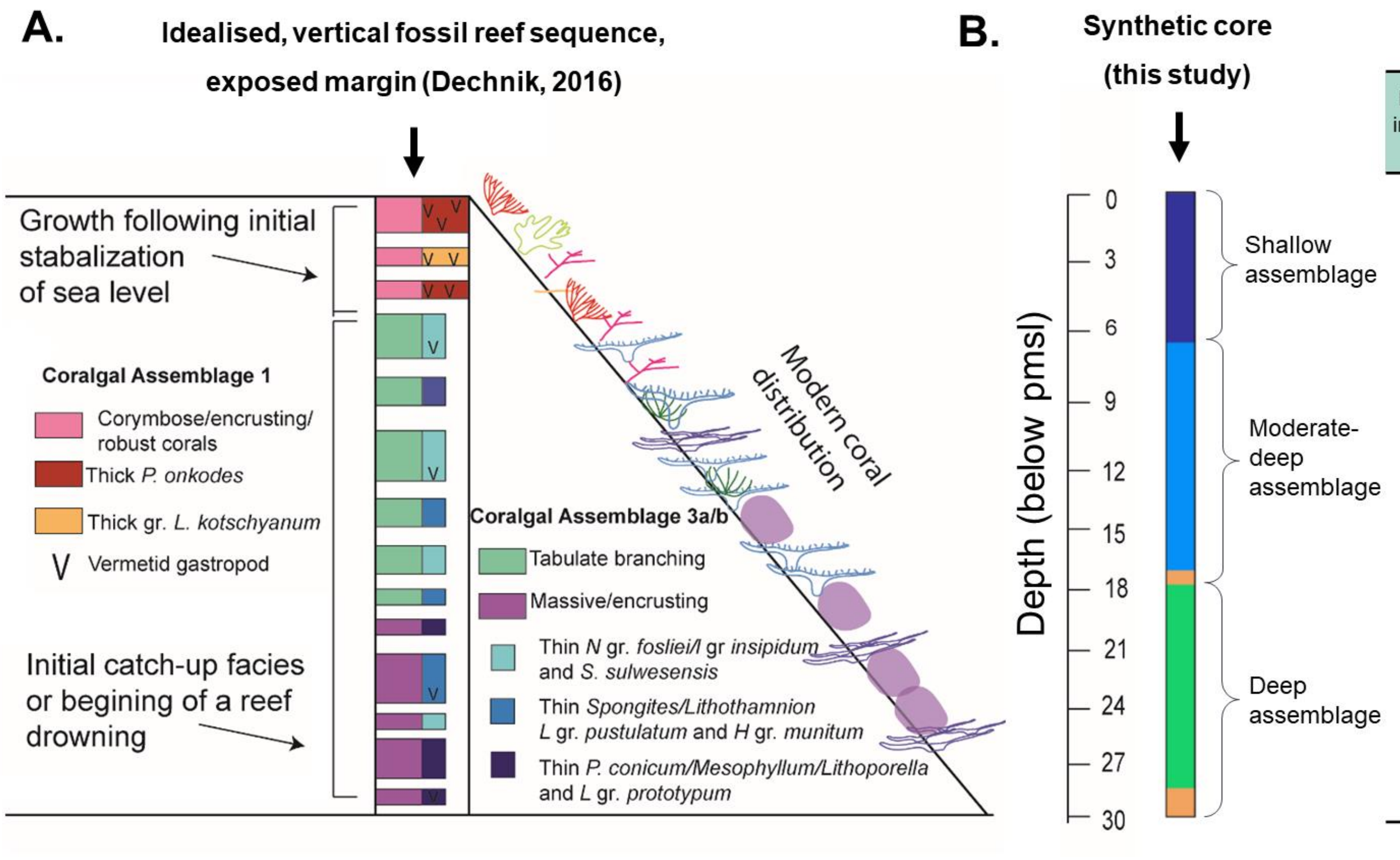


Shallow, high-energy assemblage

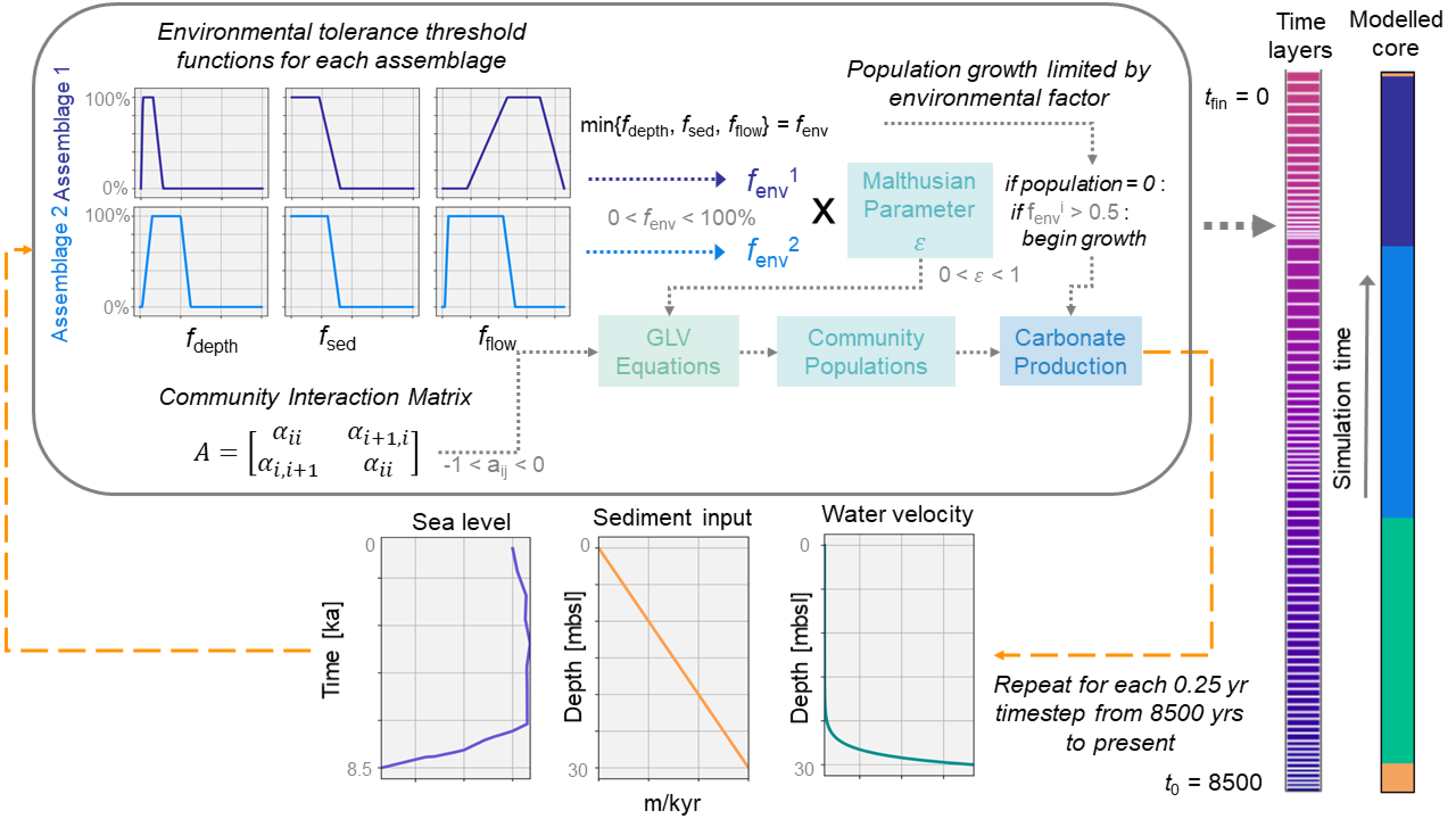
Adapted from Chappell (1980)

Geological perspective on reef growth



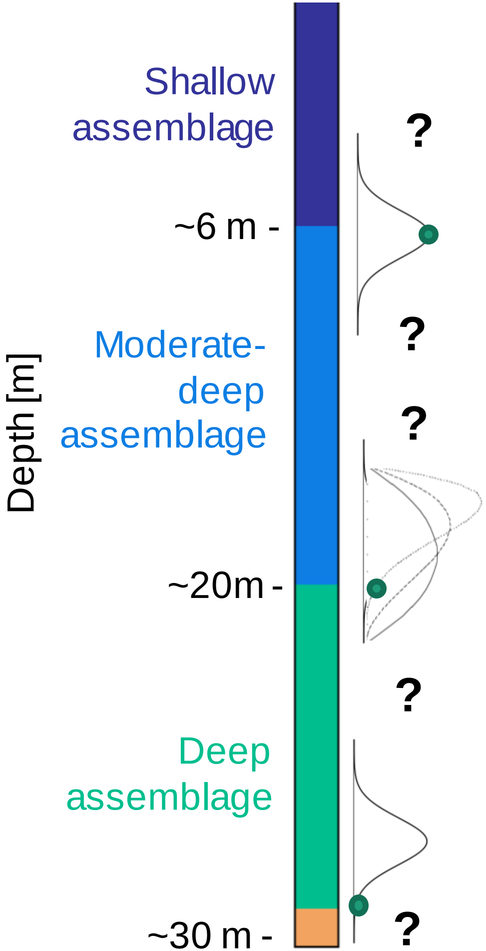


Depth interval [m]	Assemblage	**Num. ID**
0	Shallow, exposed	**0.143**
…	…	**…**
…	…	**…**
…	…	**…**
4	Shallow, exposed	**0.143**
6	Mod-deep, exposed	**0.286**
…	…	**…**
…	…	**…**
…	…	**…**
…	…	**…**
…	Mod-deep, exposed	**0.286**
16	Carbonate sediment	**0.581**
18	Deep, exposed	**0.429**
…	…	**…**
…	…	**…**
…	…	**…**
…	…	**…**
28	Deep, exposed	**0.429**
30	Carbonate sediment	**0.581**



Environmental tolerance threshold functions for each assemblage
Assemblage 1
Assemblage 2
100%
0%
f_depth
f_sed
f_flow
min{f_depth, f_sed, f_flow} = f_env
f_env^1
f_env^2
0 < f_env < 100%
X
Malthusian Parameter ε
0 < ε < 1
Population growth limited by environmental factor
if population = 0 :
if f_env^i > 0.5 :
begin growth
GLV Equations
Community Populations
Carbonate Production
Community Interaction Matrix
A = [α_ii α_i+1,i ; α_i,i+1 α_ii]
-1 < a_ij < 0
Sea level
Time [ka]
0
8.5
Sediment input
Depth [mbsl]
0
30
m/kyr
Water velocity
Depth [mbsl]
0
30
Repeat for each 0.25 yr timestep from 8500 yrs to present
Time layers
Modelled core
t_fin = 0
t_0 = 8500
Simulation time

pyReef-Core output



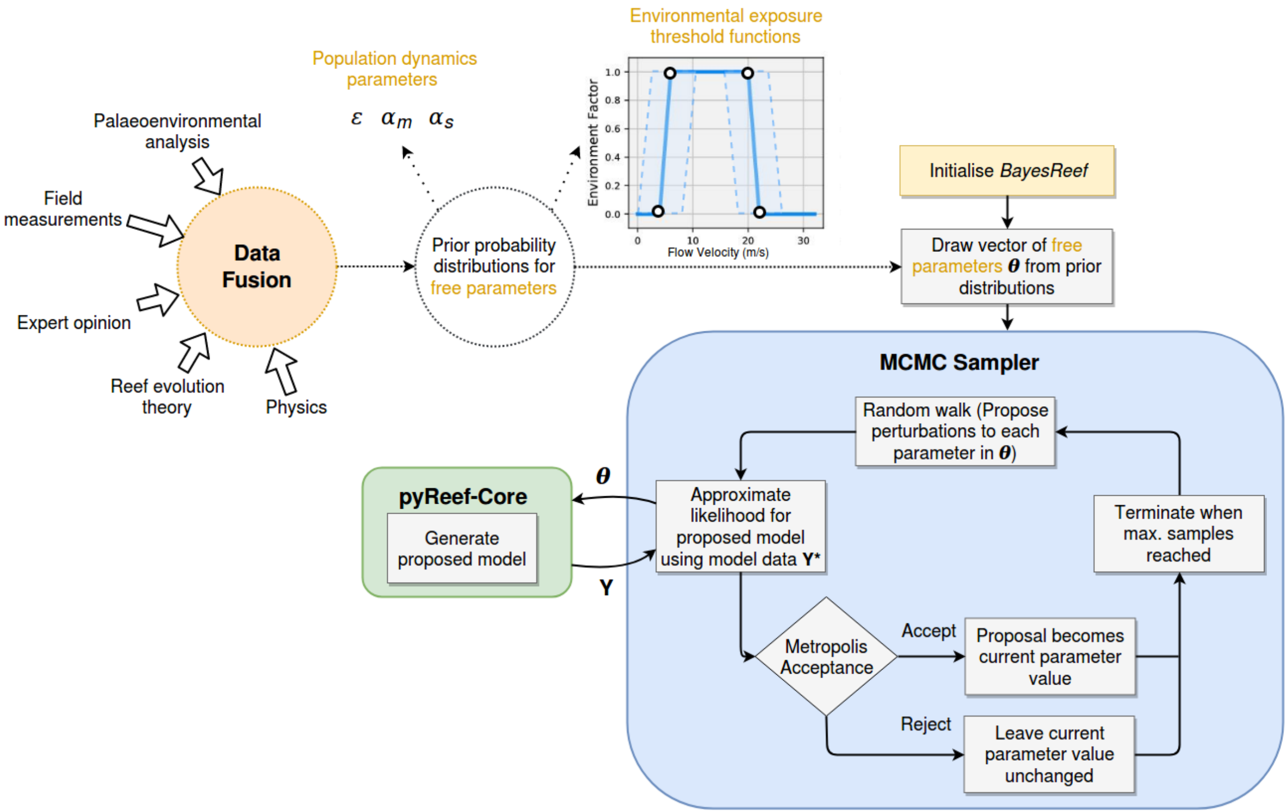
Predator-prey model

Ecological Dynamics

Sediment input
Hydrodynamic energy
Accommodation

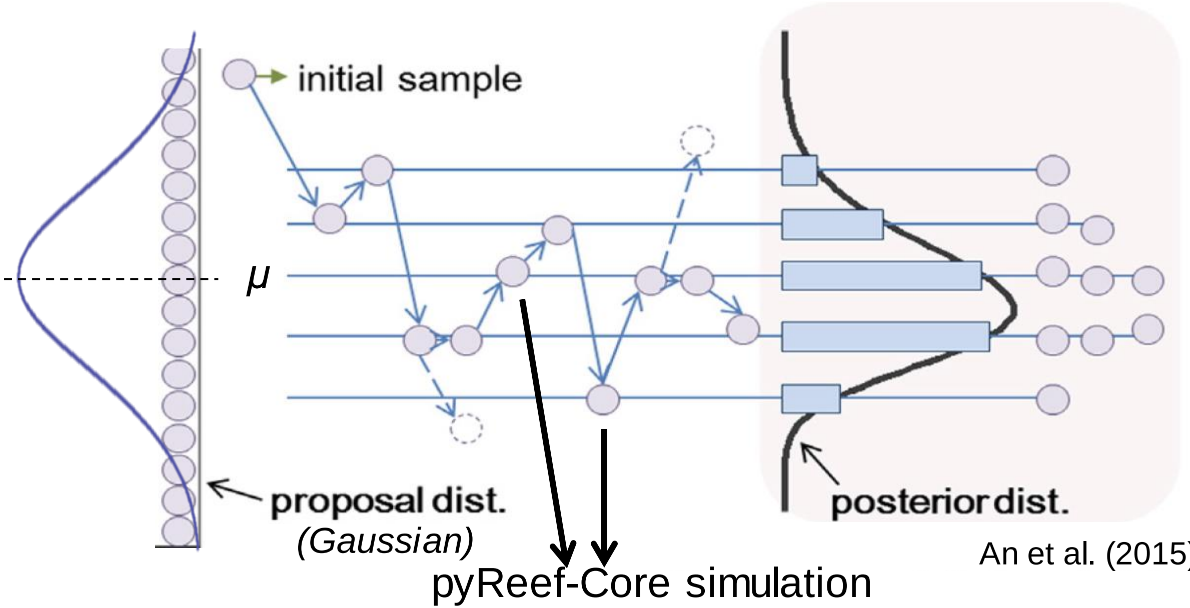
- Markov Chain Monte Carlo (MCMC) is a **Bayesian Inference method** that accommodates complex models and missing data problems.
- **BayesReef** uses MCMC methods to
  1. calibrate models to core data;
  2. quantify uncertainty in models; and
  3. estimate model parameters.

Data Fusion and Bayesian inference in *BayesReef*



BayesReef

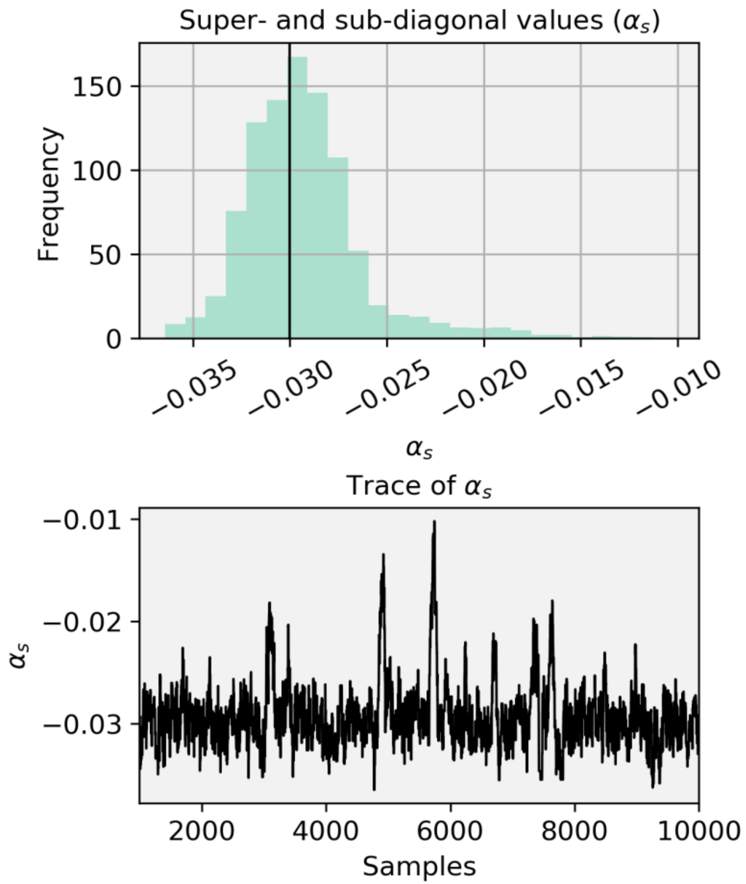
Using Monte Carlo Markov Chain ($MCMC_{PL}$)

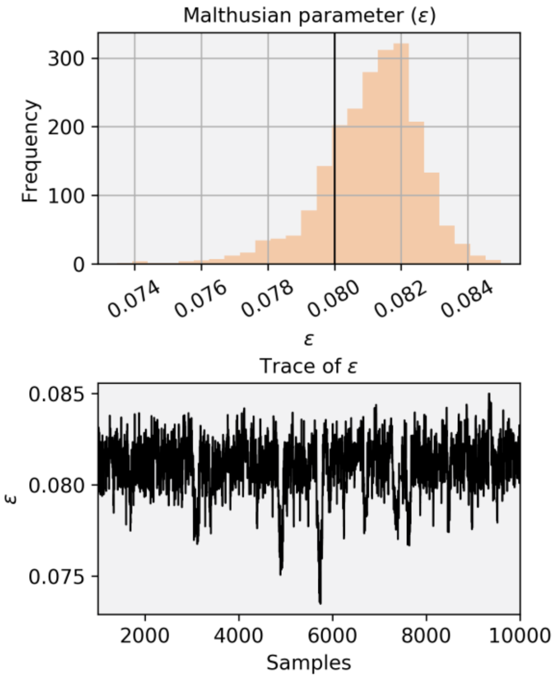


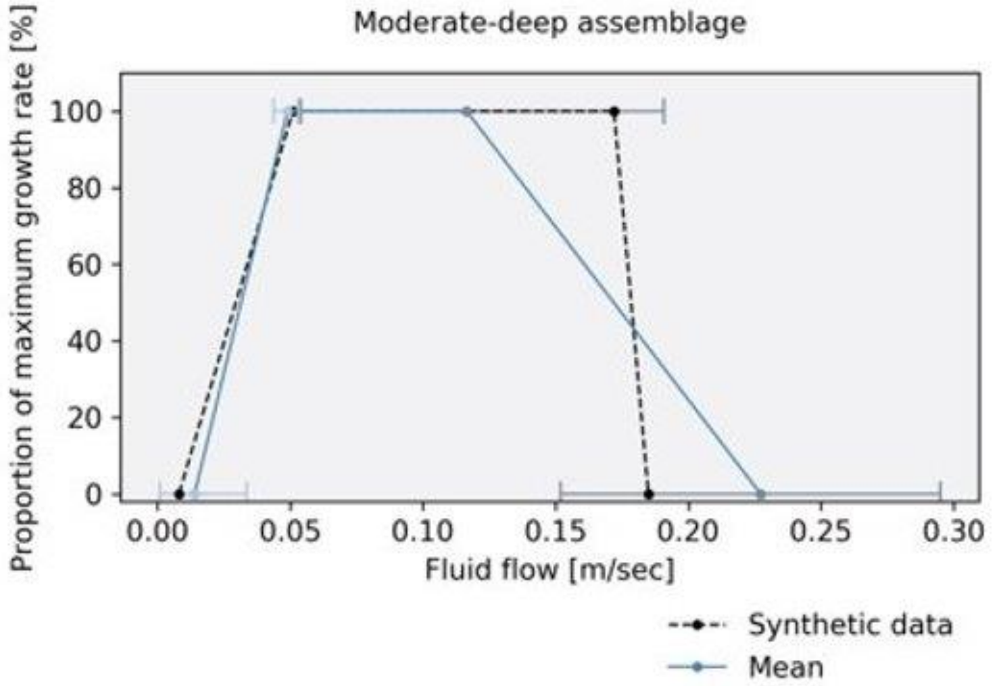
An et al. (2015)

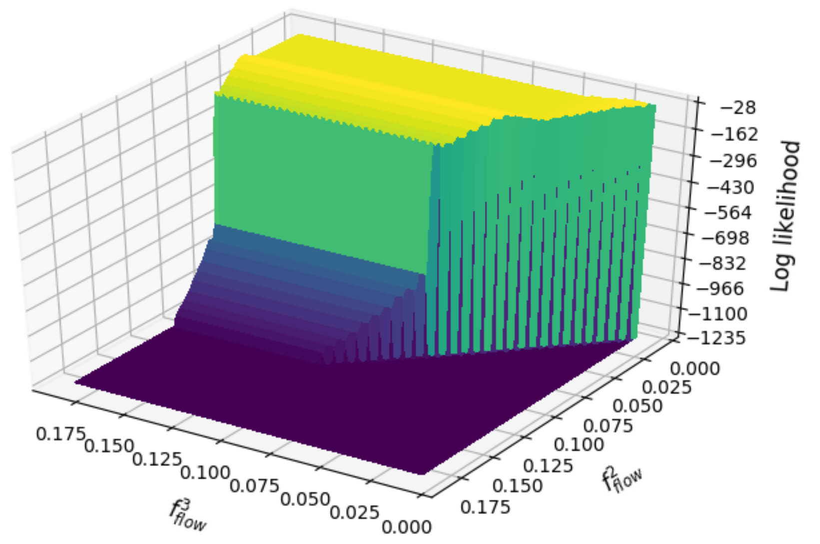
Synthetic reef-core experiments (Part 1)

- Tested for ability of py-Reef-core to predict synthetic core.
- 4 'free parameters'
  - Community Matrix – Super and Sub-diagonals
  - Malthusian parameter
- Ran chains 10,000 samples long (~ 1 day)
- Use Multinomial Likelihood in MCMC

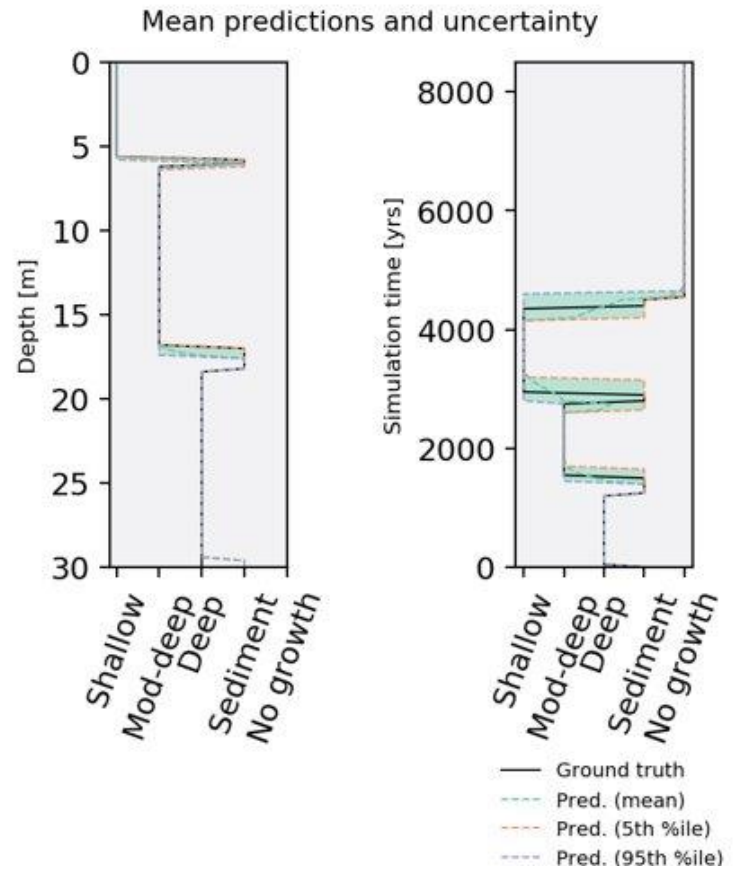



Malthusian parameter (ε)
Frequency
300
200
100
0
0.074
0.076
0.078
0.080
0.082
0.084
ε
Trace of ε
0.085
0.080
0.075
ε
2000
4000
6000
8000
10000
Samples

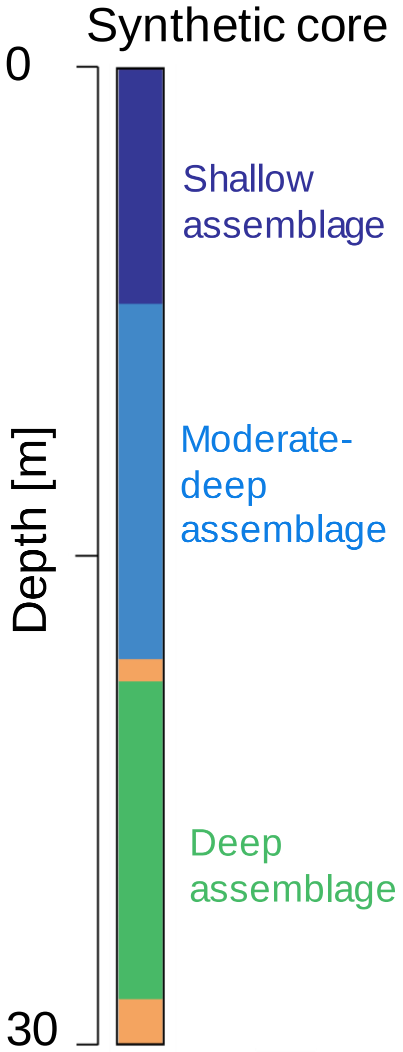

Moderate-deep assemblage
Proportion of maximum growth rate [%]
100
80
60
40
20
0
0.00
0.05
0.10
0.15
0.20
0.25
0.30
Fluid flow [m/sec]
Synthetic data
Mean



Log likelihood
−28
−162
−296
−430
−564
−698
−832
−966
−1100
−1235
0.175
0.150
0.125
0.100
0.075
0.050
0.025
0.000
f^3_{flow}
f^2_{flow}



Mean predictions and uncertainty
Depth [m]
0
5
10
15
20
25
30
Simulation time [yrs]
8000
6000
4000
2000
0
Shallow
Mod-deep
Deep
Sediment
No growth
Ground truth
Pred. (mean)
Pred. (5th %ile)
Pred. (95th %ile)

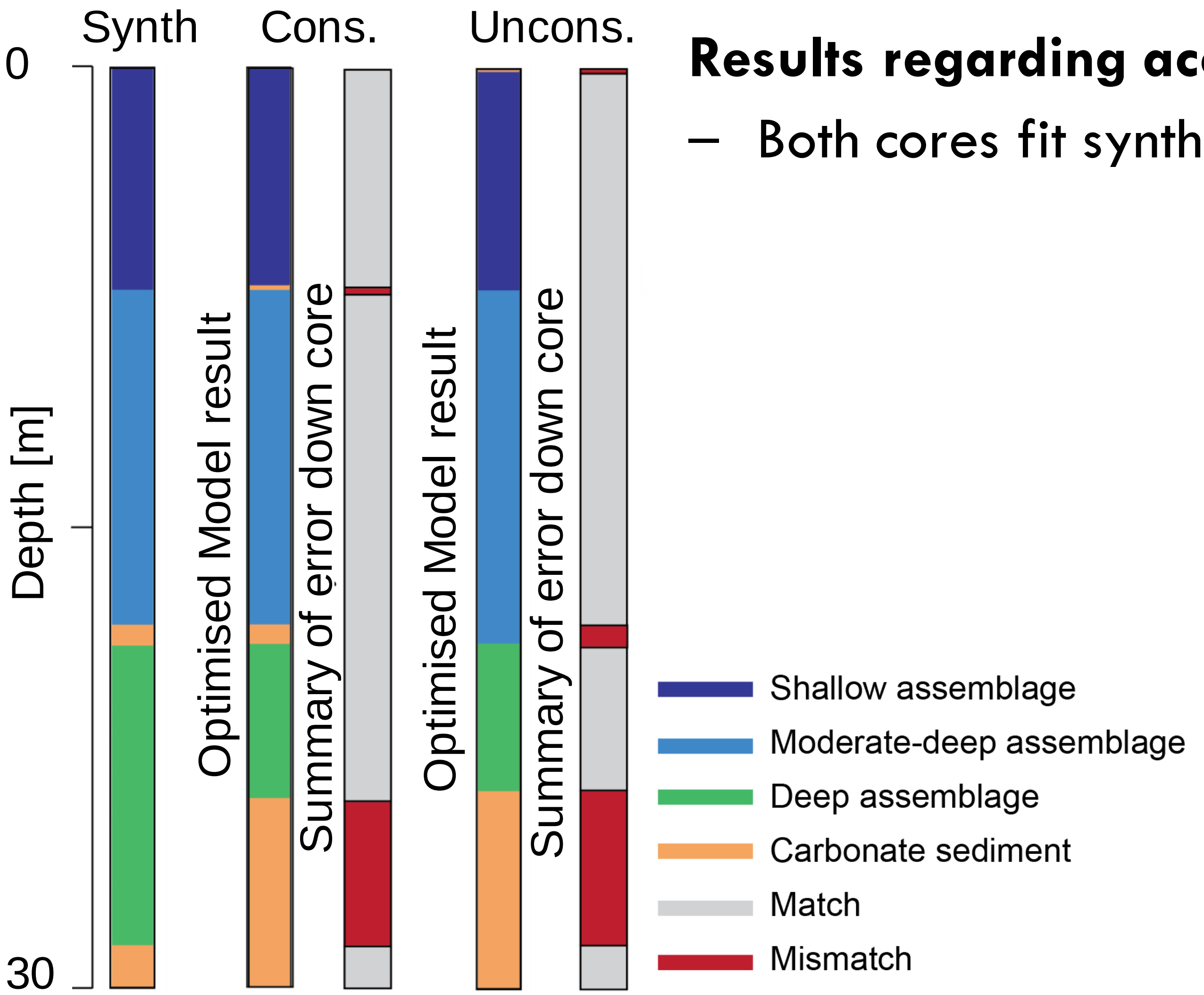


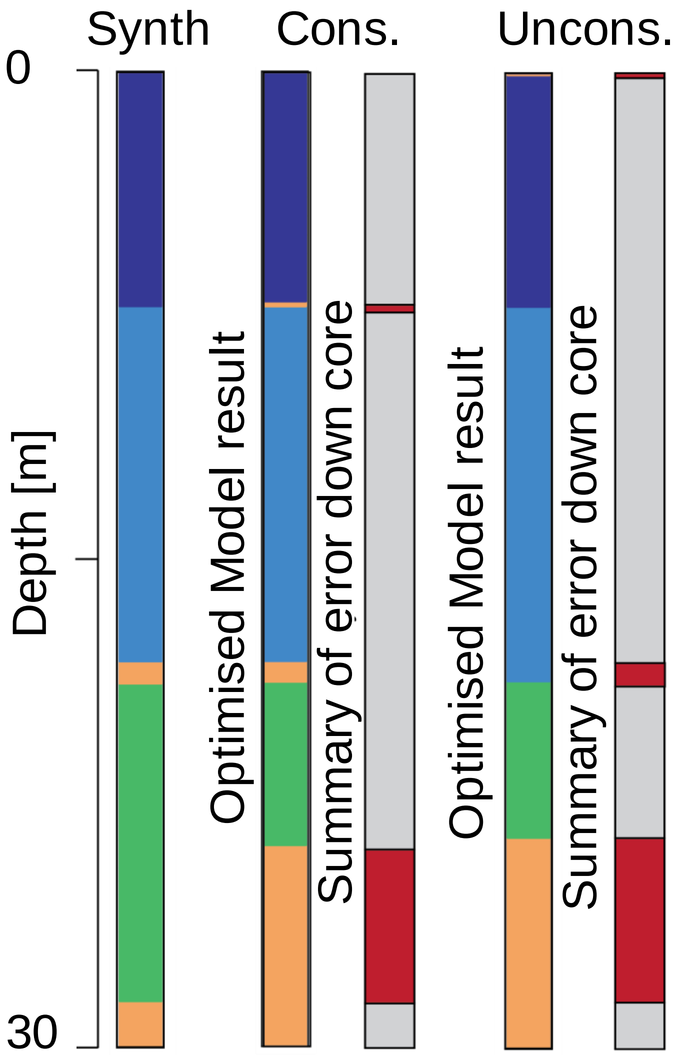
Synthetic reef-core experiments (Part 2)

- Tested for ability to predict (converge on) synthetic core.
- 15 vs 27 'free parameters'
  - Exposure thresholds of assemblages
  - Assemblage interactions
- Ran chains 50,000 samples long (~ 5 days)
- Use Gaussian Likelihood in MCMC

Results regarding accuracy

– Both cores fit synthetic data well.

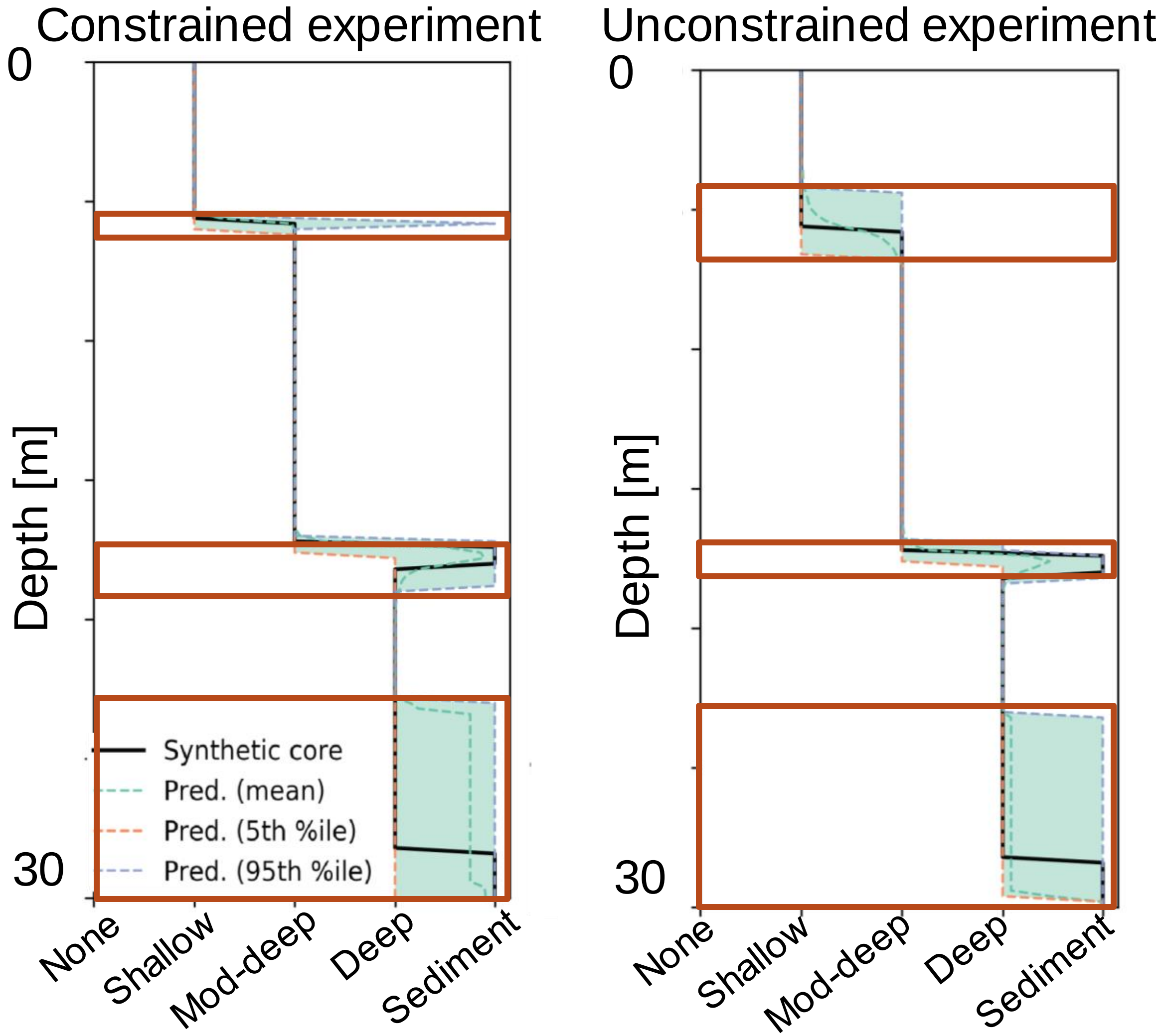




Results regarding accuracy

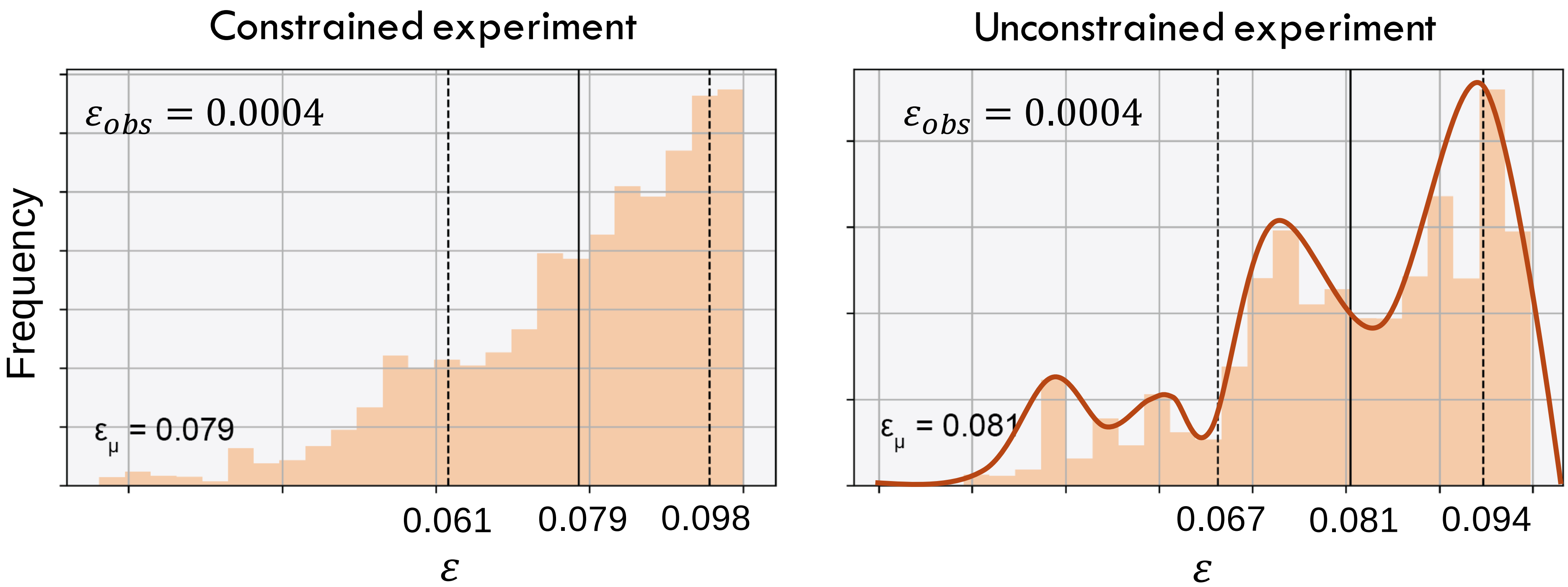
- Both cores fit synthetic data well.
- Constrained experiment converged marginally better model prediction.

	Constrained experiment	Unconstrained experiment
No. of free parameters	15	27
RMSE	0.066	0.076



Results regarding uncertainty

- Uncertainty focused at assemblage transitions.
- Comparable level of uncertainty.



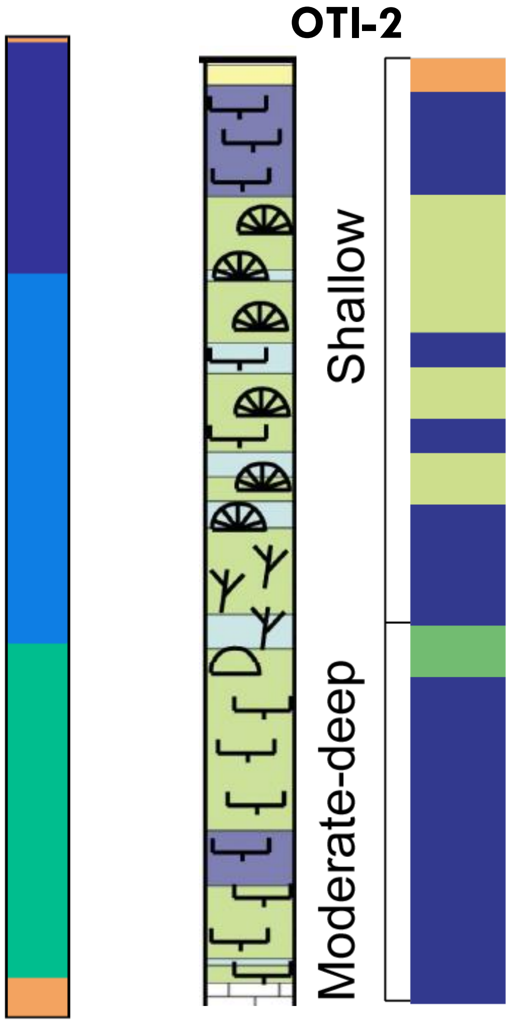
Results regarding parameter estimation

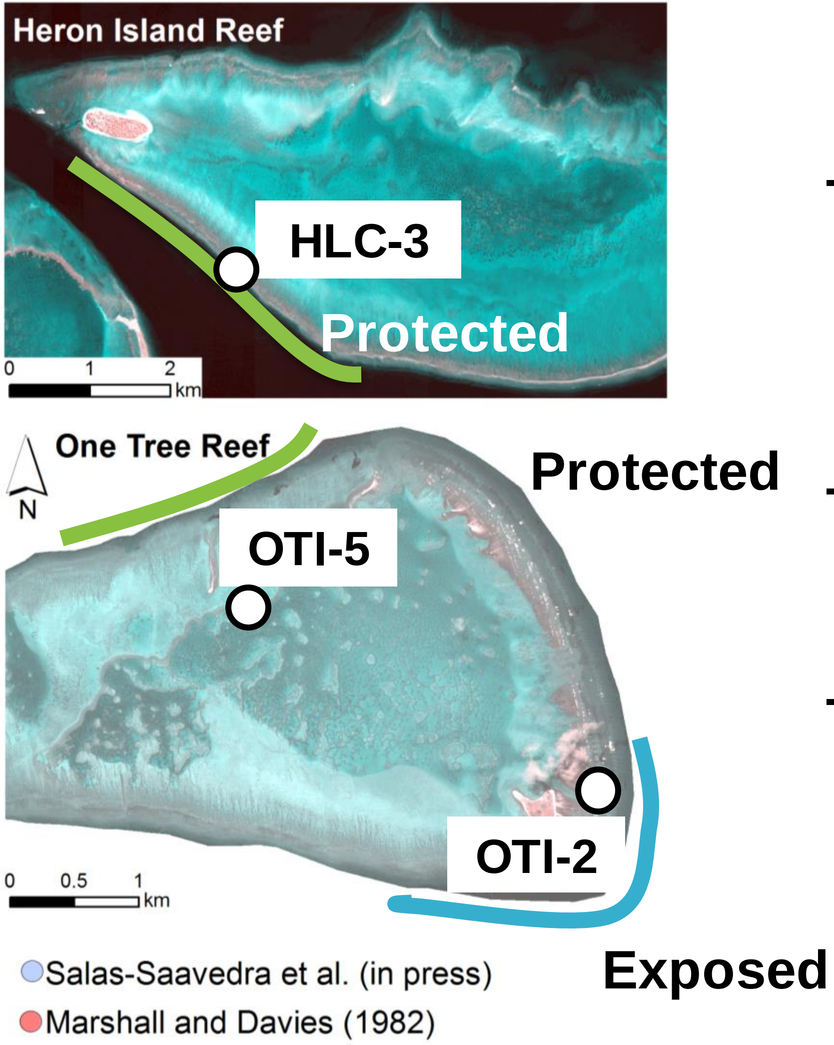
- Observed parameter not within credible interval of point-estimate values.
- Multi-modal distributions

Model predictions approximate the data well, but not the parameters.

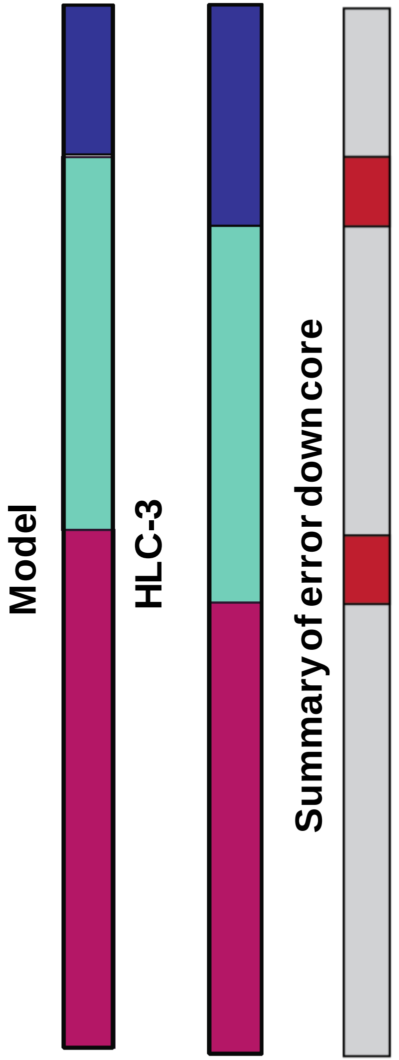
Preliminary experimental results for real world reef-core similations

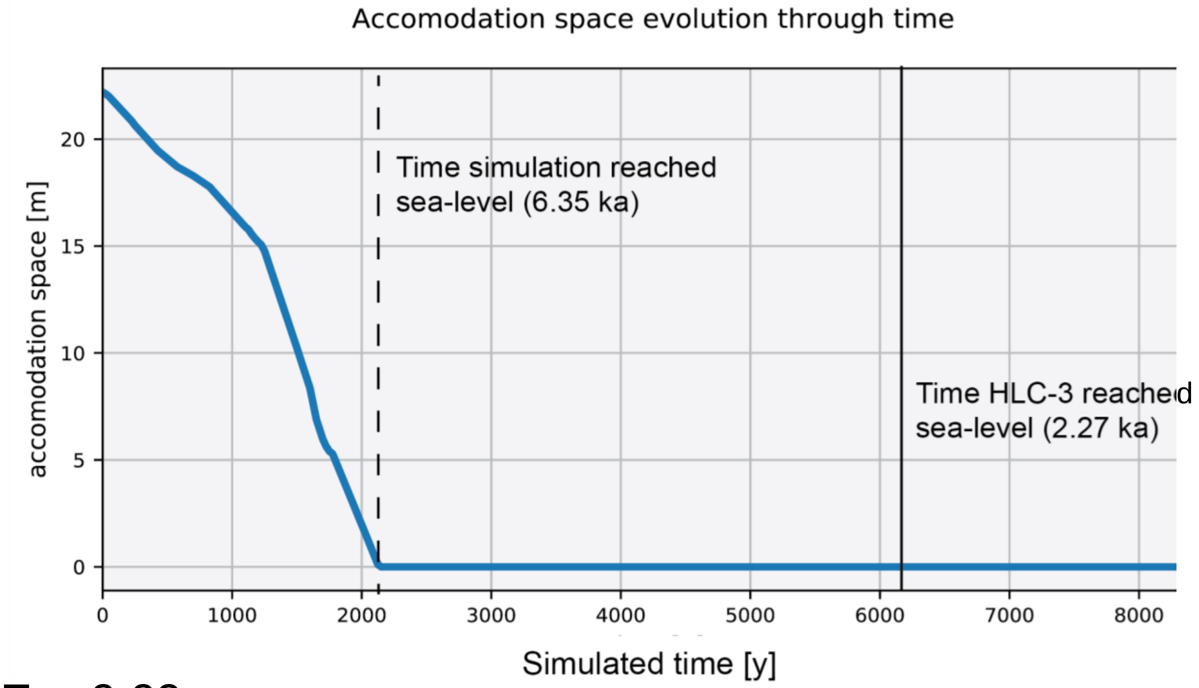
- Real-world reef development is far more complex than synthetic case.
- **Objectives:**
  - Using **BayesReef** on noisy data, predict exposure threshold of assemblages to:
    - Hydrodynamic energy
    - Sediment input





- Three reef cores selected from exposed and sheltered margins of **One Tree** and **Heron Island Reefs.**
- Both cores exhibit similar coralgal assemblages (Dechnik, 2016; Dechnik, unpublished)
- **Experiment:** Run MCMC chain of 50,000 samples using BayesReef to calibrate model to core data.

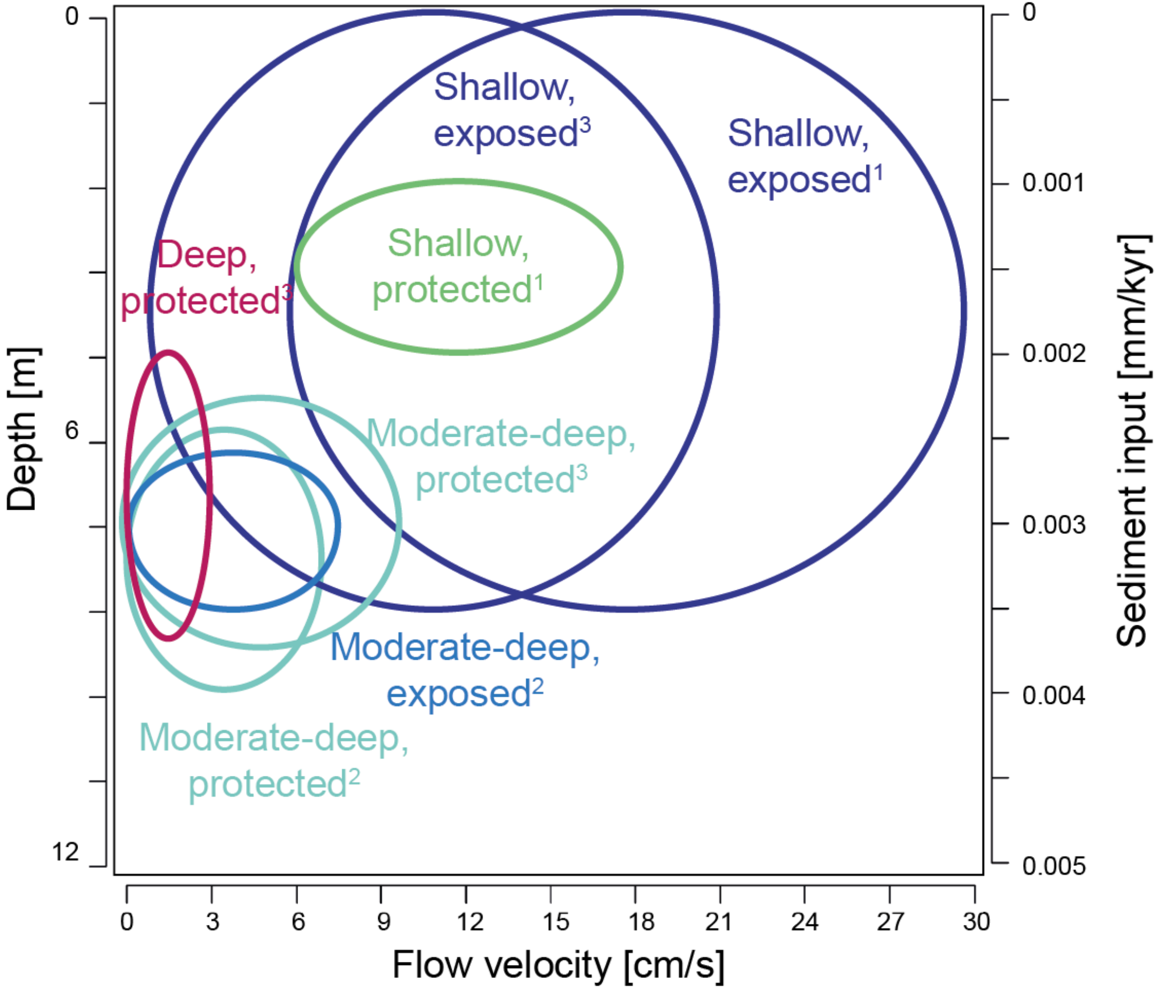




RMSE = 0.09

Results

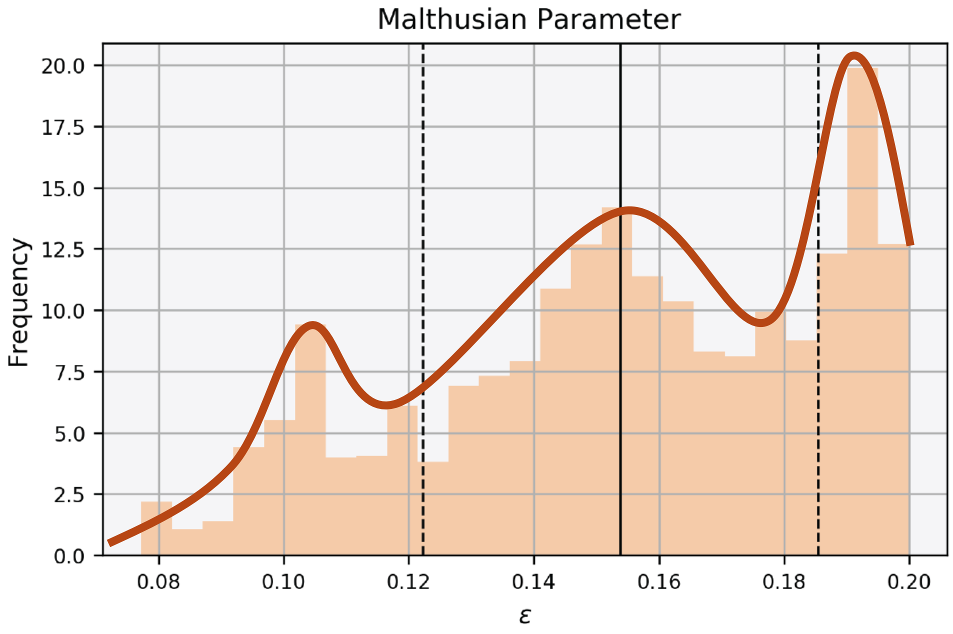
- Very good fit with data
- Reached sea-level ~4 ky sooner than actual core

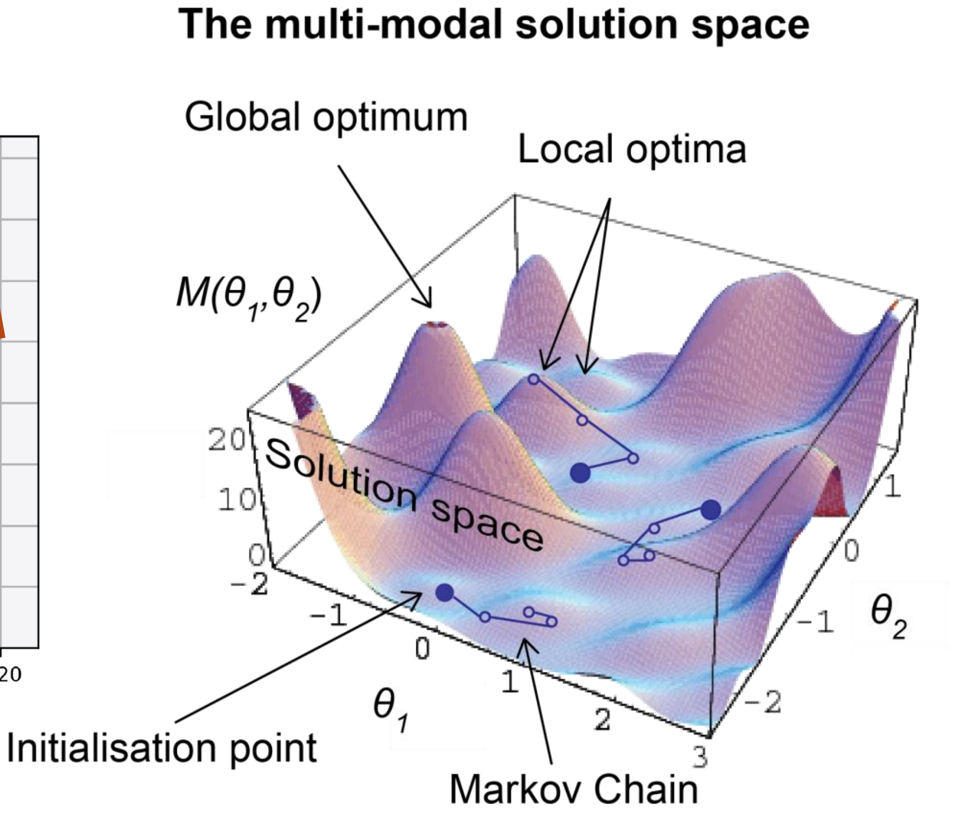


Palaeo-environmental analysis

- Shallow, exposed assemblages are relatively insensitive to sediment input and flow velocity.
- Deeper assemblages have tighter environmental niches

Multi-modal distributions

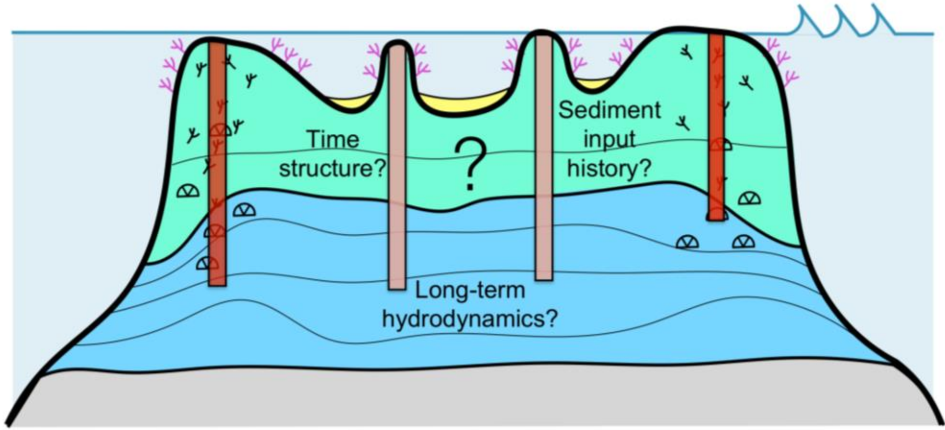




Conclusions and future work

1. The MCMC sampler in BayesReef is accurate, robust and efficient with fewer free parameters, but less so when calibrating models to noisy data.
2. Current work focuses on BayesReef for high performance computing and parallel tempering for sampling multi-modal distributions

3. Future work will feature BayesReef for 3D Reef-Core and for the Great Barrier Reef Model (T. Salles, 2018)



Questions welcome

- Acknowledgements

Jodie Pall, Tristan Salles, Sally Cripps, and Jody Webster

- Technical Report:

Jodie Pall, **Rohitash Chandra**, Danial Azam, Tristan Salles, Jody M. Webster, Sally Cripps: BayesReef: A Bayesian inference framework for modelling reef growth in response to environmental change and biological dynamics, https://arxiv.org/abs/1808.02763

- Github:

https://github.com/pyReef-model/BayesReef

https://github.com/pyReef-model/pt-BayesReef/settings/collaboration

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Acropora at 2 m depth, One Tree Reef