Interdisciplinary Research Opportunities in Island Landscape Evolution

Taylor Perron (MIT)

Islands as natural experiments in landscape evolution

Taha’a, French Polynesia

Volcanic ocean islands have advantages over continents as natural experiments in landscape evolution:

- Within-island controls: Lithology, vertical motion, age, initial topography
- Inter-island variability: Climate, age, biogeography, geodynamics

Perron (Annual Reviews, 2017)

How do geodynamical processes shape topography?

SCIENCE ADVANCES | RESEARCH ARTICLE

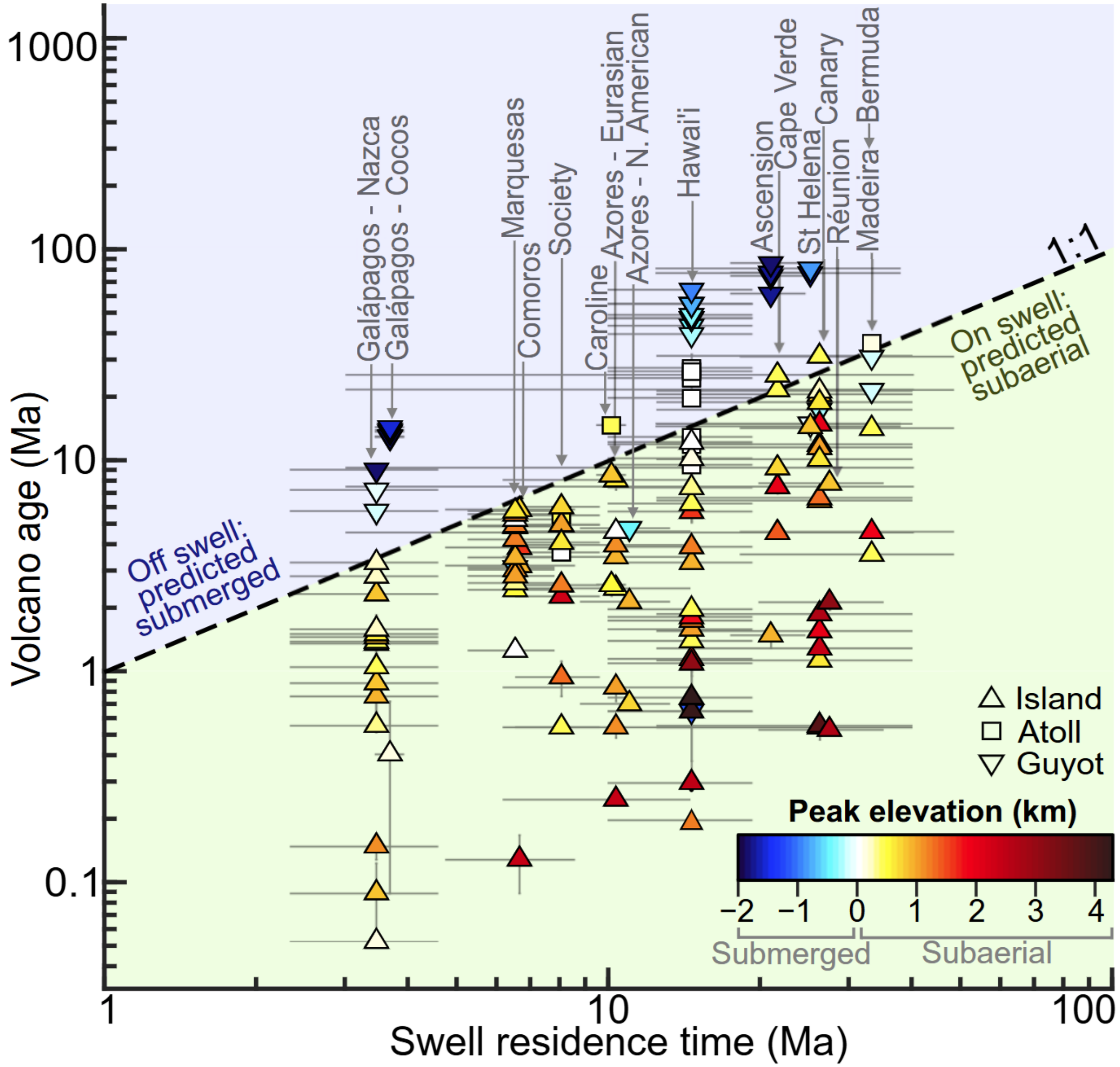
EARTH SCIENCES

Hotspot swells and the lifespan of volcanic ocean islands

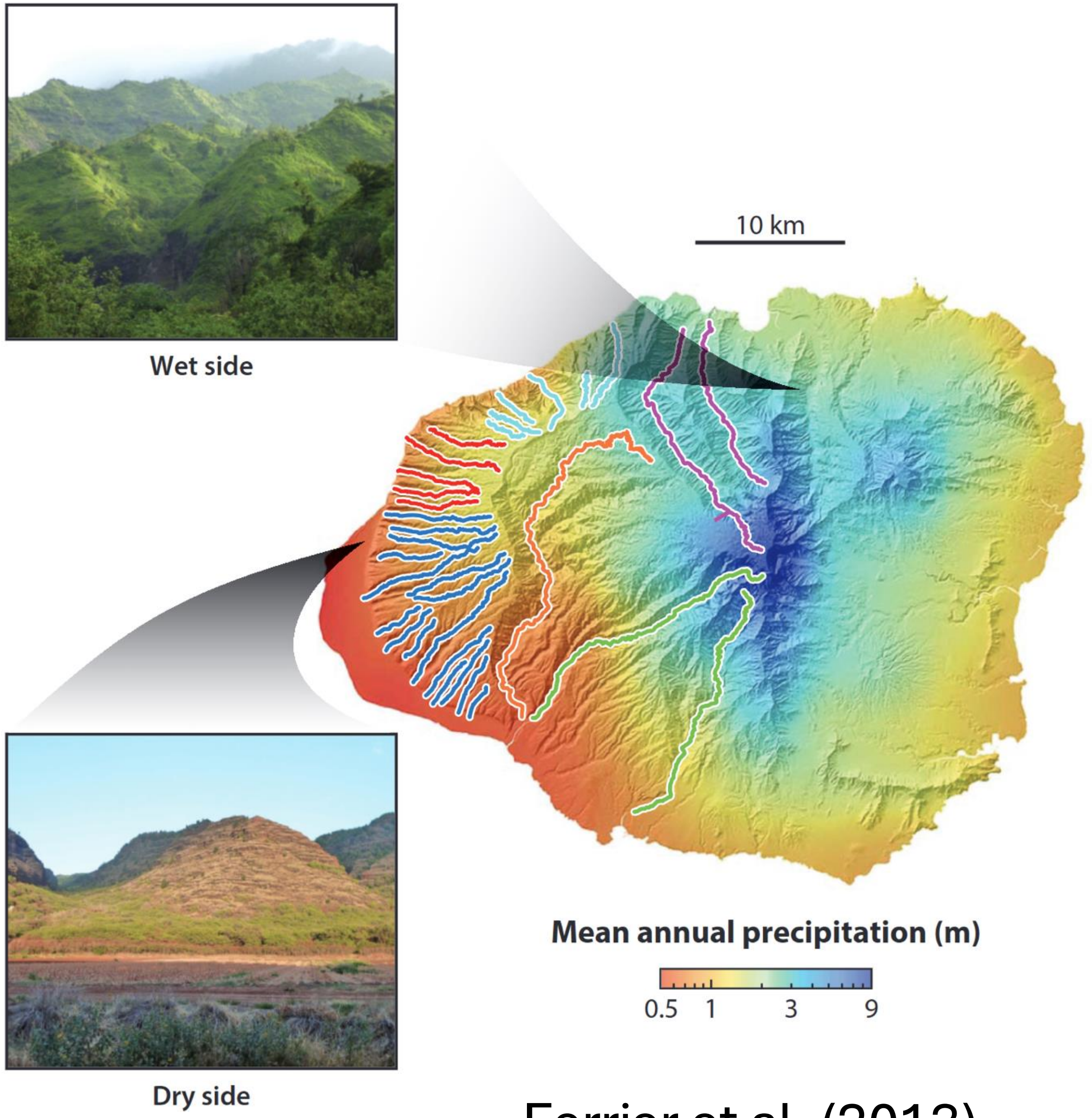
Kimberly L. Huppert[1,2]*, J. Taylor Perron[1], Leigh H. Royden[1]

Swell residence time predicts the lifetime of hotspot islands

Huppert et al. (2020)



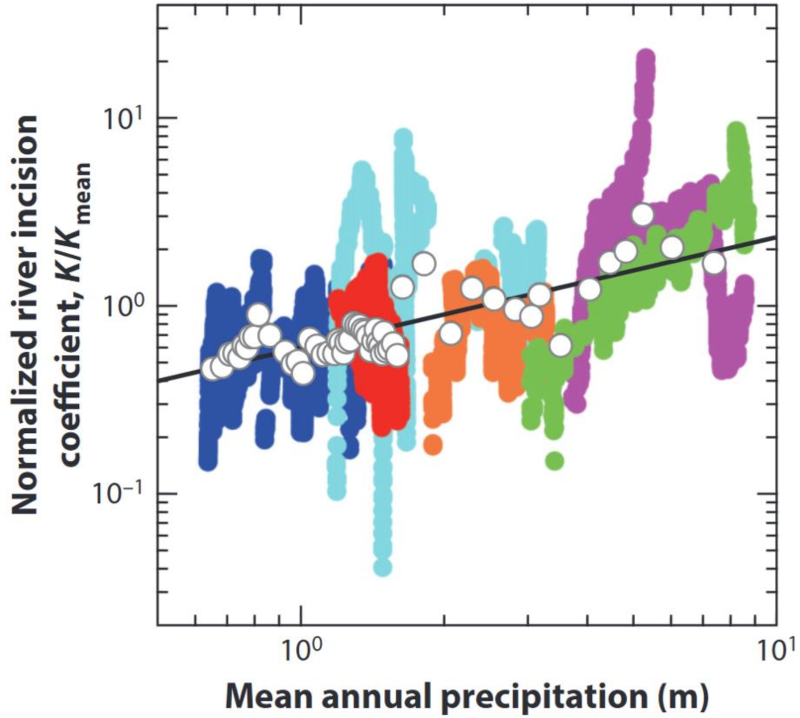
How does climate influence erosion?



LETTER

Climatic control of bedrock river incision

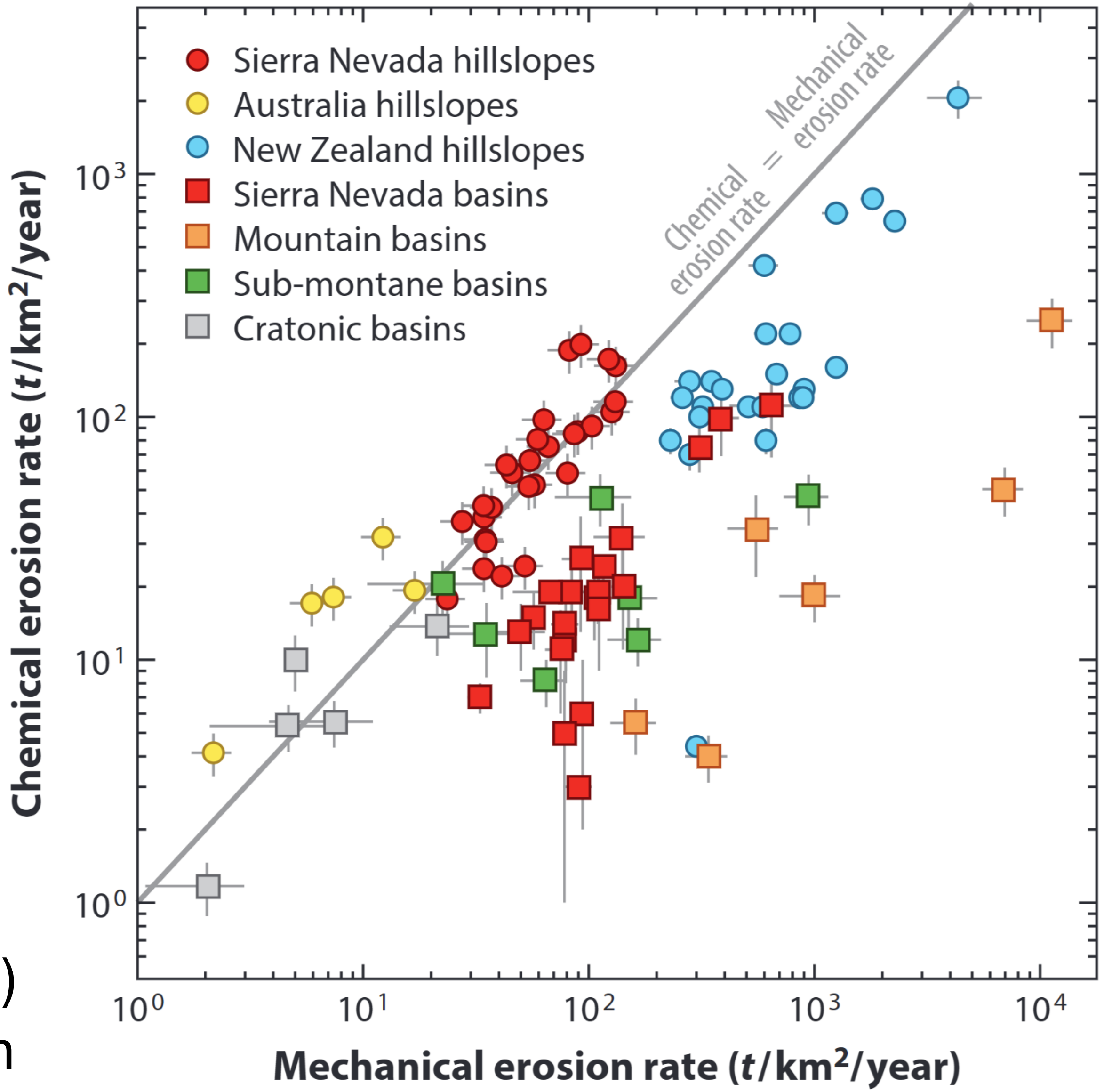
Ken L. Ferrier[1]†, Kimberly L. Huppert[1] & J. Taylor Perron[1]



Ferrier et al. (2013)

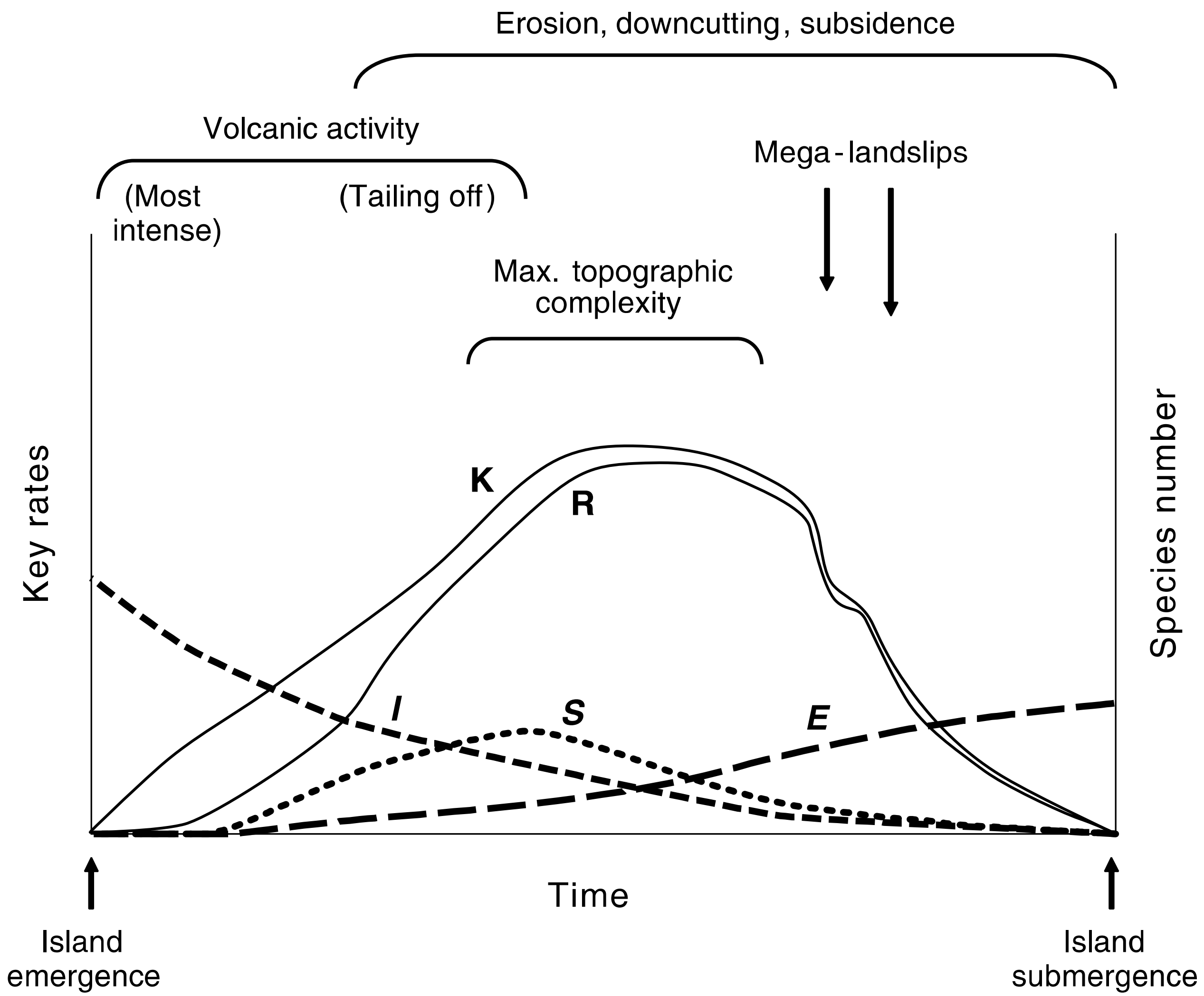
What controls the balance of mechanical and chemical erosion?

Interiors of young, basaltic islands are permeable, reactive, and hot



Perron (2017)
Data from Dixon, West, Riebe, Larsen

How does topography influence biogeography and biodiversity?



Whittaker et al. (2007, 2008)

Need quantitative geological models that can be tested with biological data

How do terrestrial and marine landscapes co-evolve?

Taha'a, French Polynesia
PlanetScope

Landscape evolution and biological evolution

An example from the continents

Terrestrial and marine landscapes

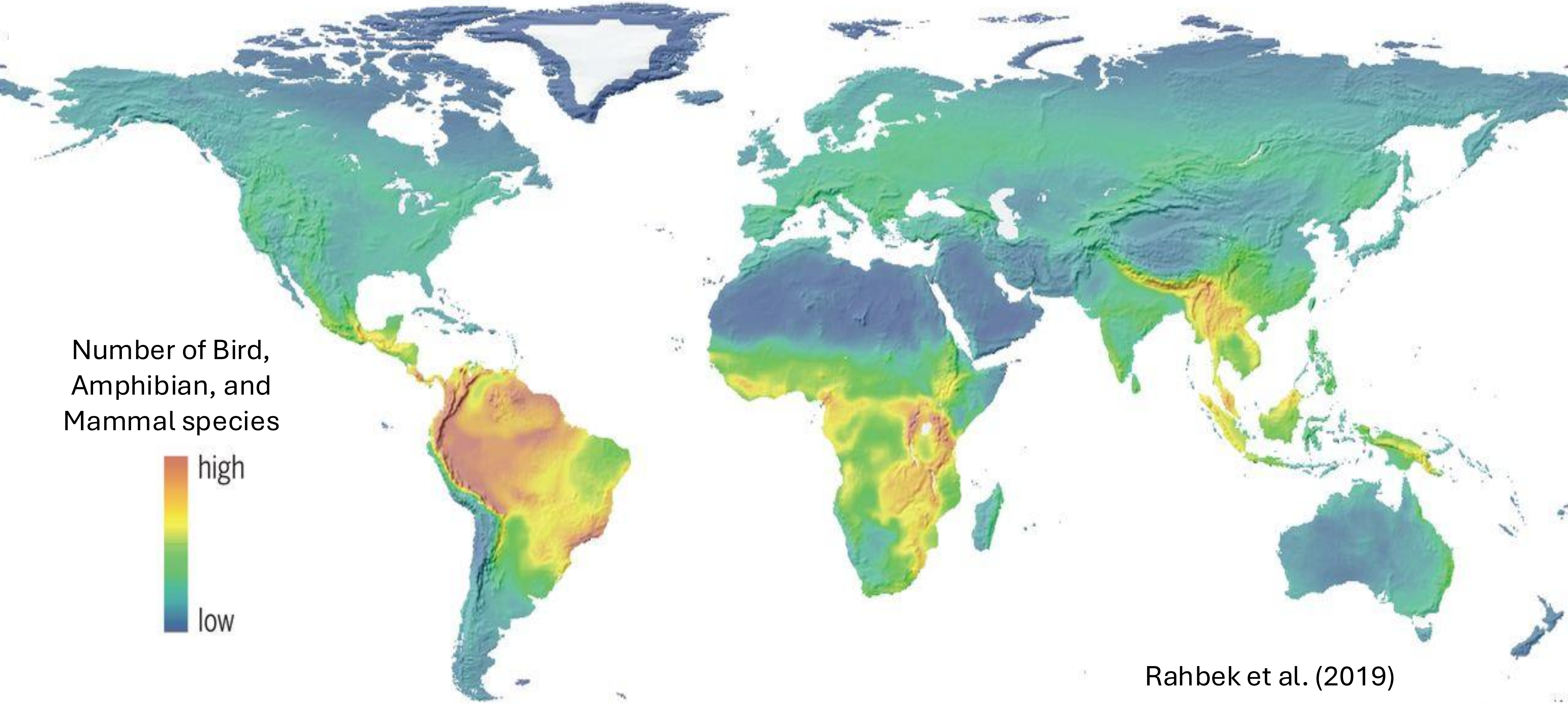
Coral reefs, subsidence, and sea level cycles

Landscape evolution and biological evolution

An example from the continents

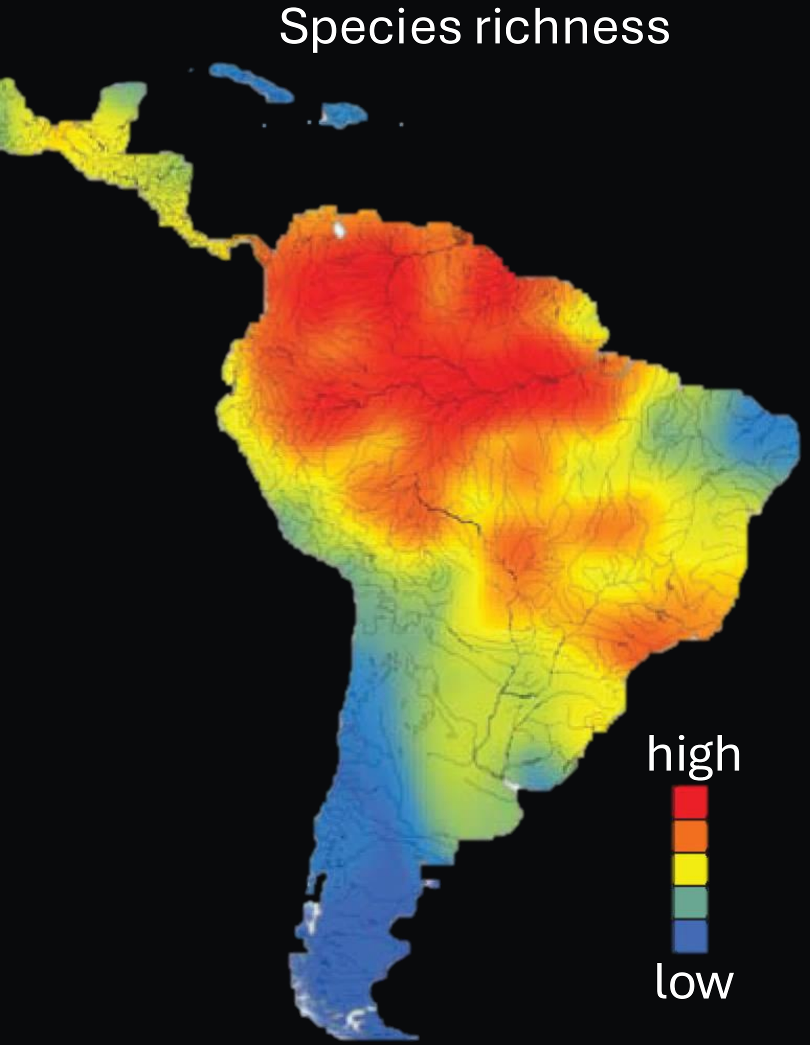
High biodiversity in many active mountain ranges:

A consequence of rapidly changing topography?



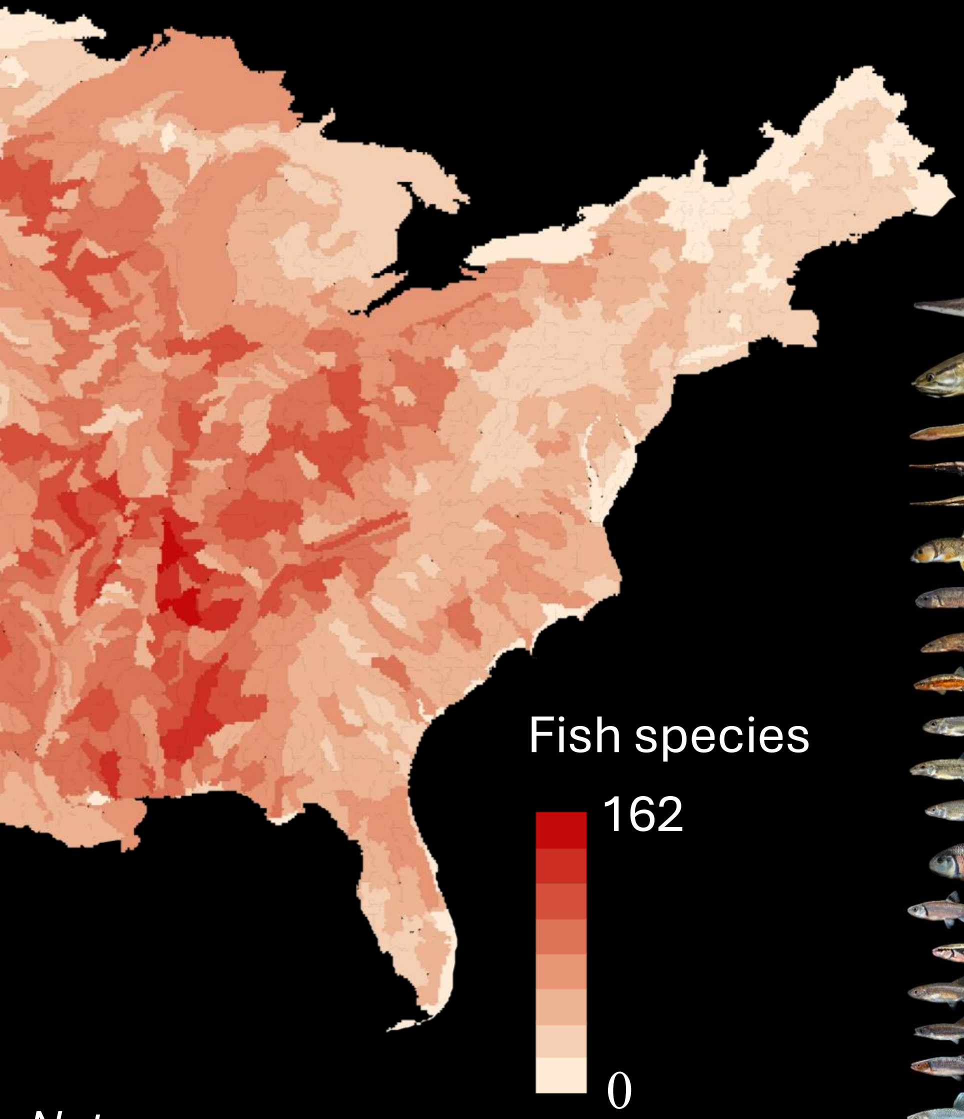
Rahbek et al. (2019)

Freshwater biodiversity is high in tectonically *inactive* regions

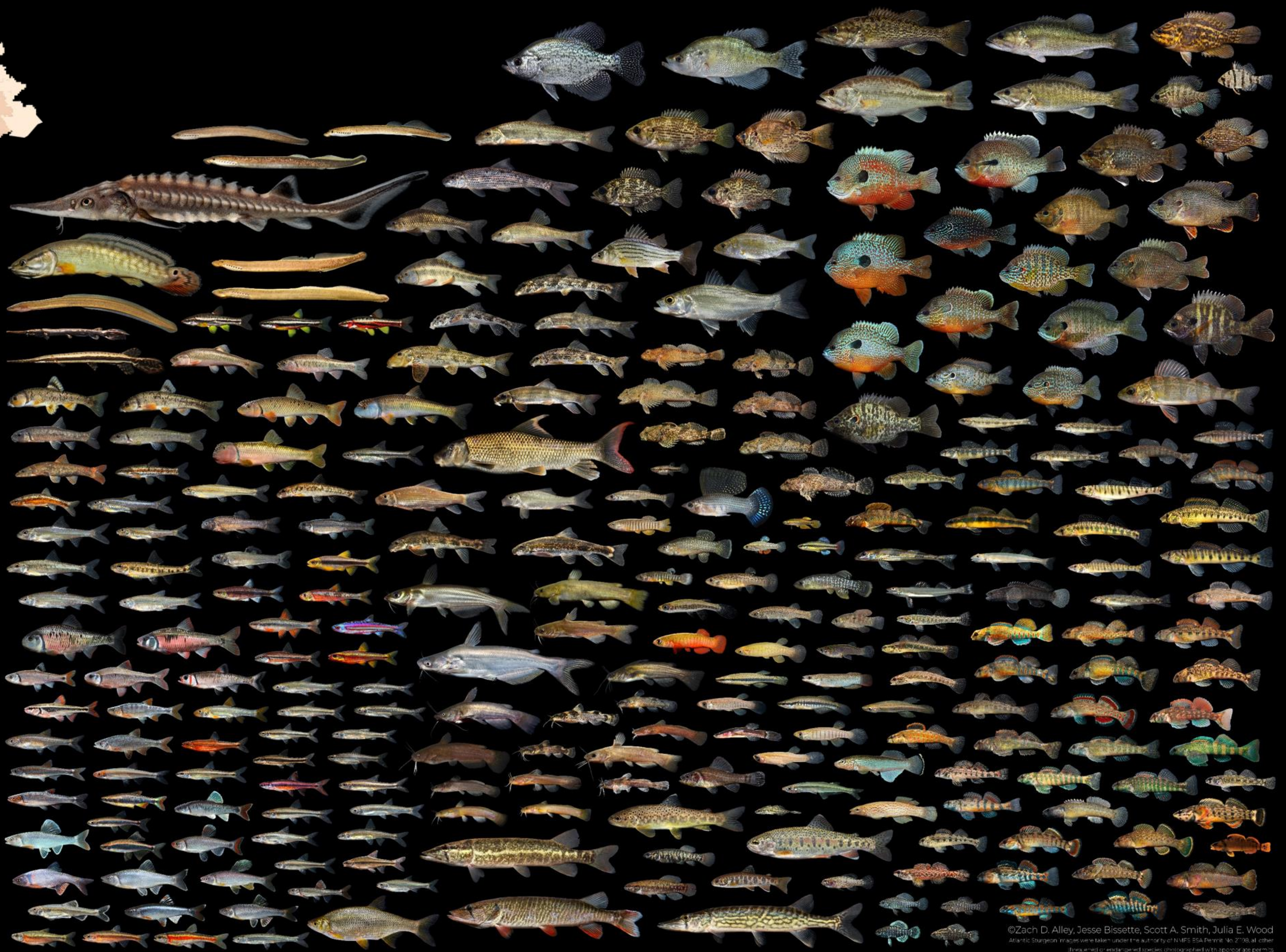


Albert et al. (2018, 2020)

Freshwater biodiversity is high in tectonically *inactive* regions



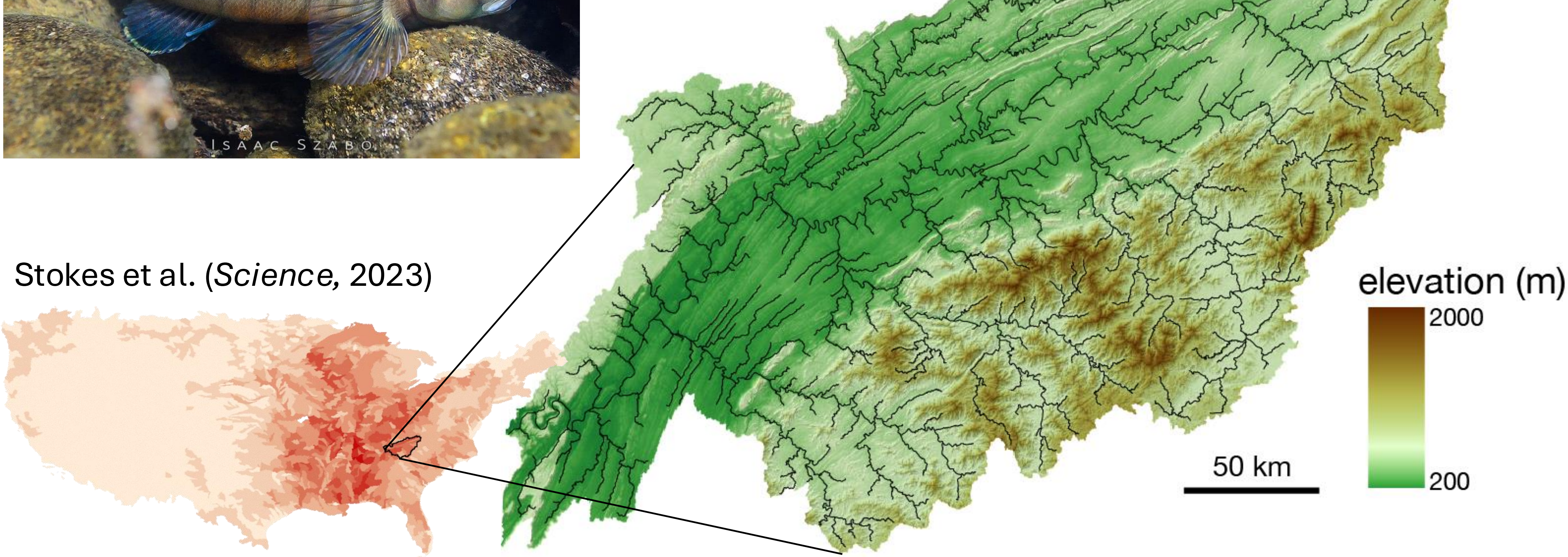
Natureserve



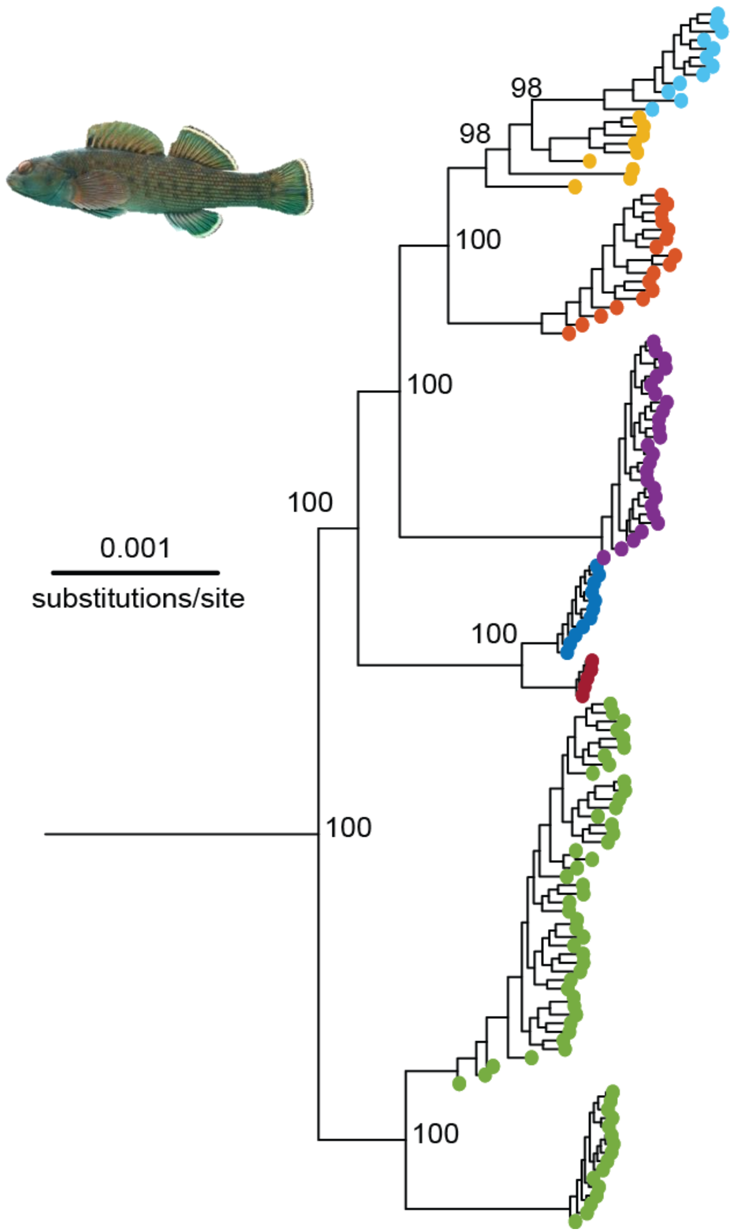
Case study: Greenfin Darter, endemic to the Upper Tennessee River

Maya Stokes (PhD '21)
Tom Near (Yale)

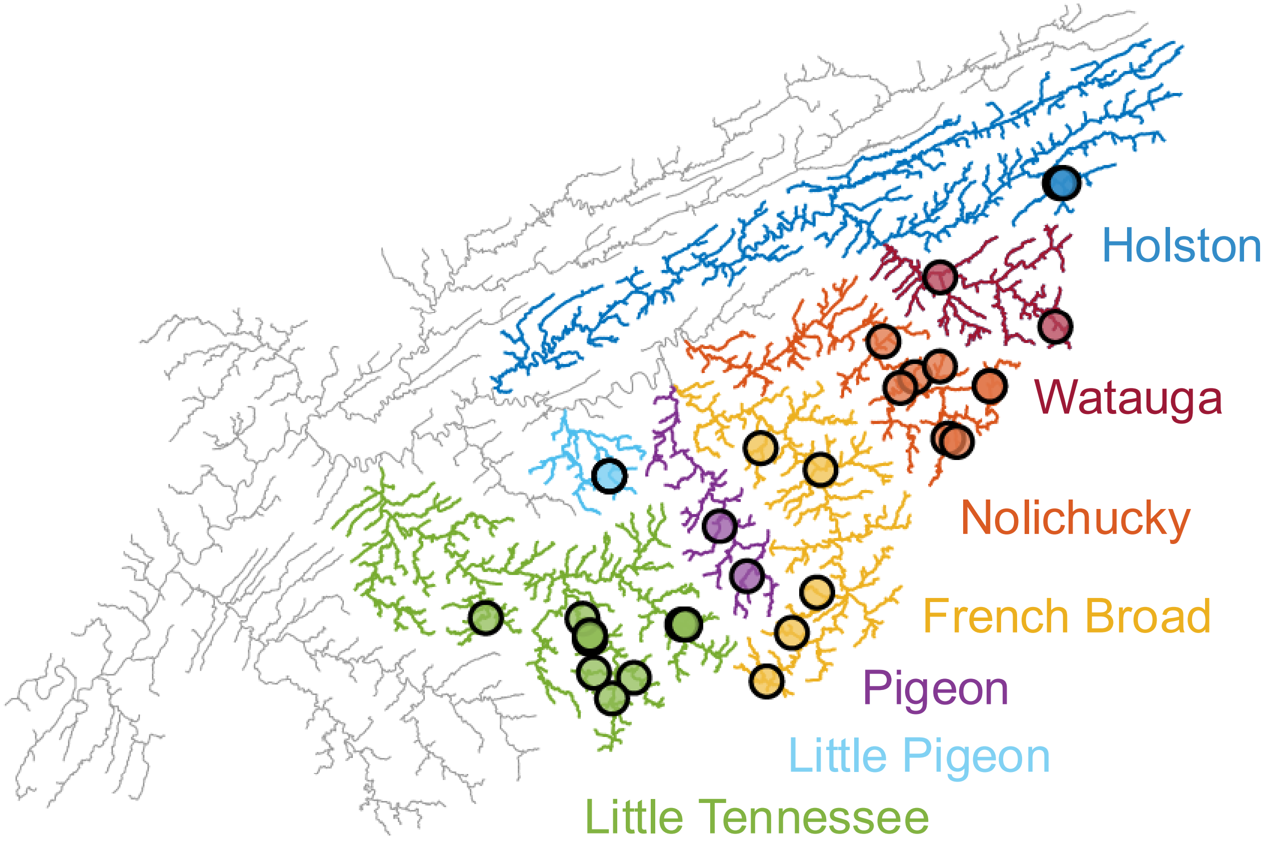
Stokes et al. (*Science*, 2023)



Greenfin darter phylogeny from ddRAD DNA sequencing

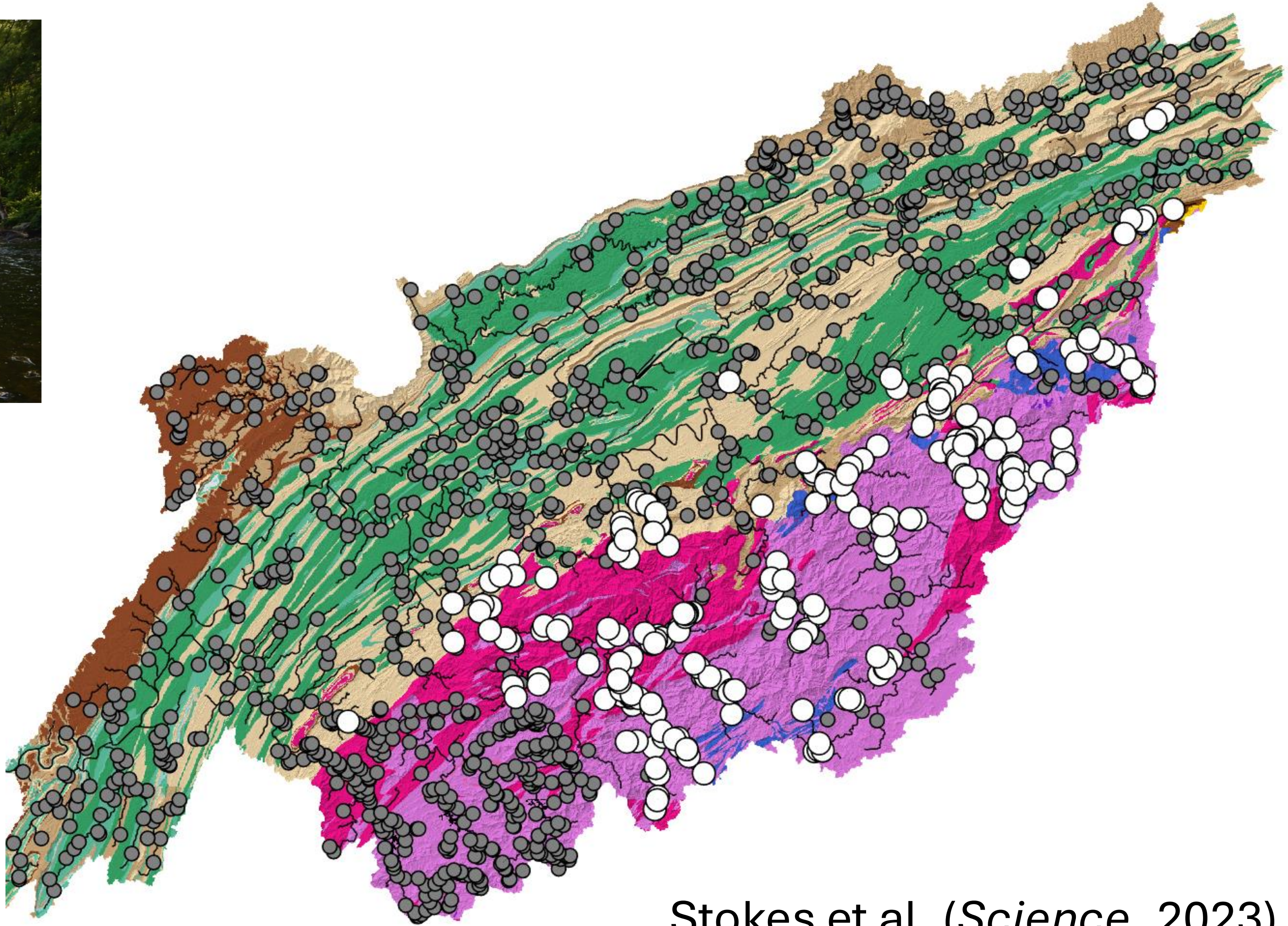


Genetically isolated sub-species correspond to sub-basins. What are the barriers?



Stokes et al. (*Science*, 2023)

Greenfin Darters don’t like to live in sedimentary rocks



- Greenfin Darter Absence
- Greenfin Darter Presence

Simplified geologic units

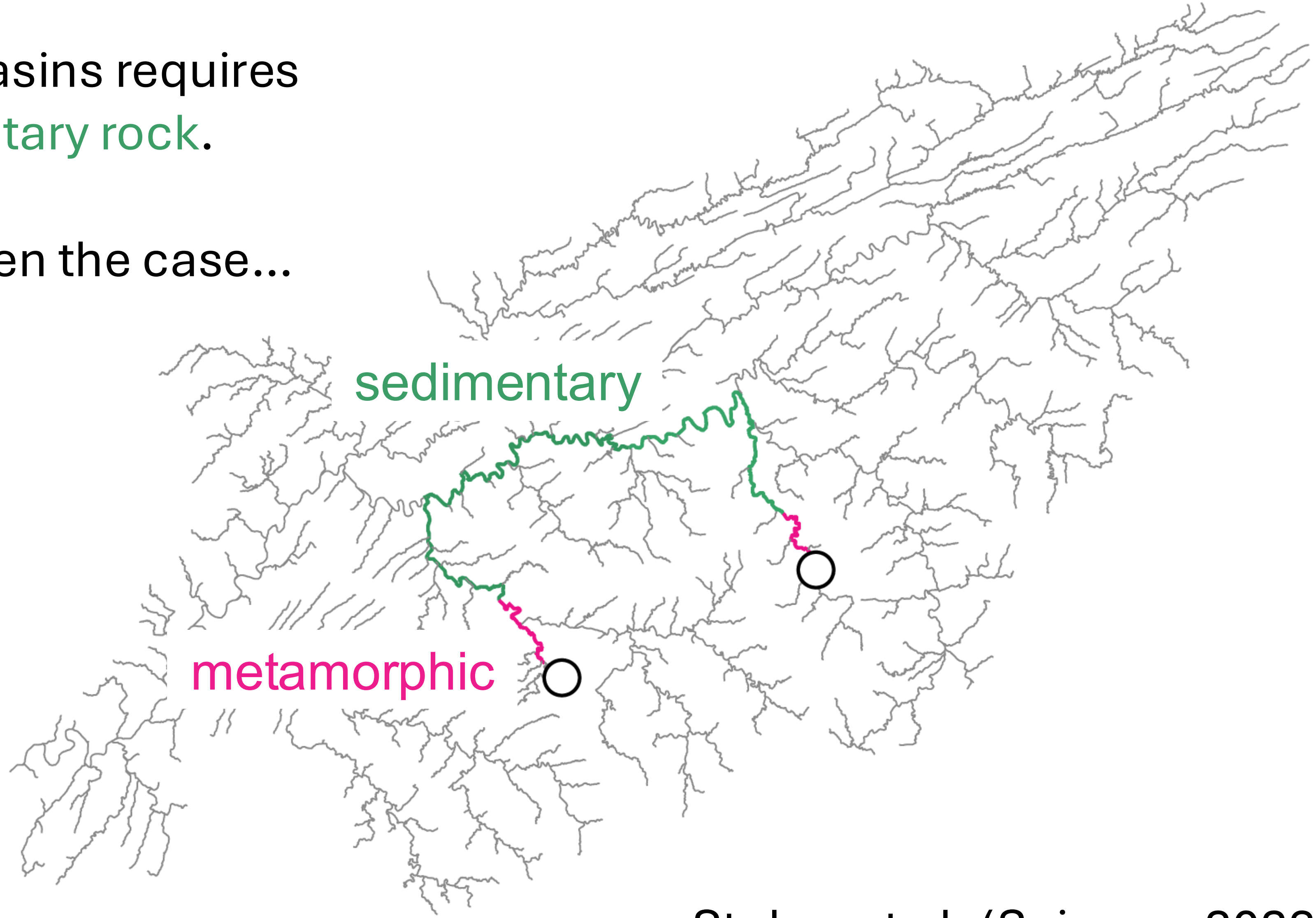
- Siliciclastic (coarse)
- Siliciclastic (fine)
- Limestone & dolostone
- Metasedimentary
- Metamorphic
- Igneous

Stokes et al. (*Science*, 2023)

Greenfin Darters don’t like to live in sedimentary rocks

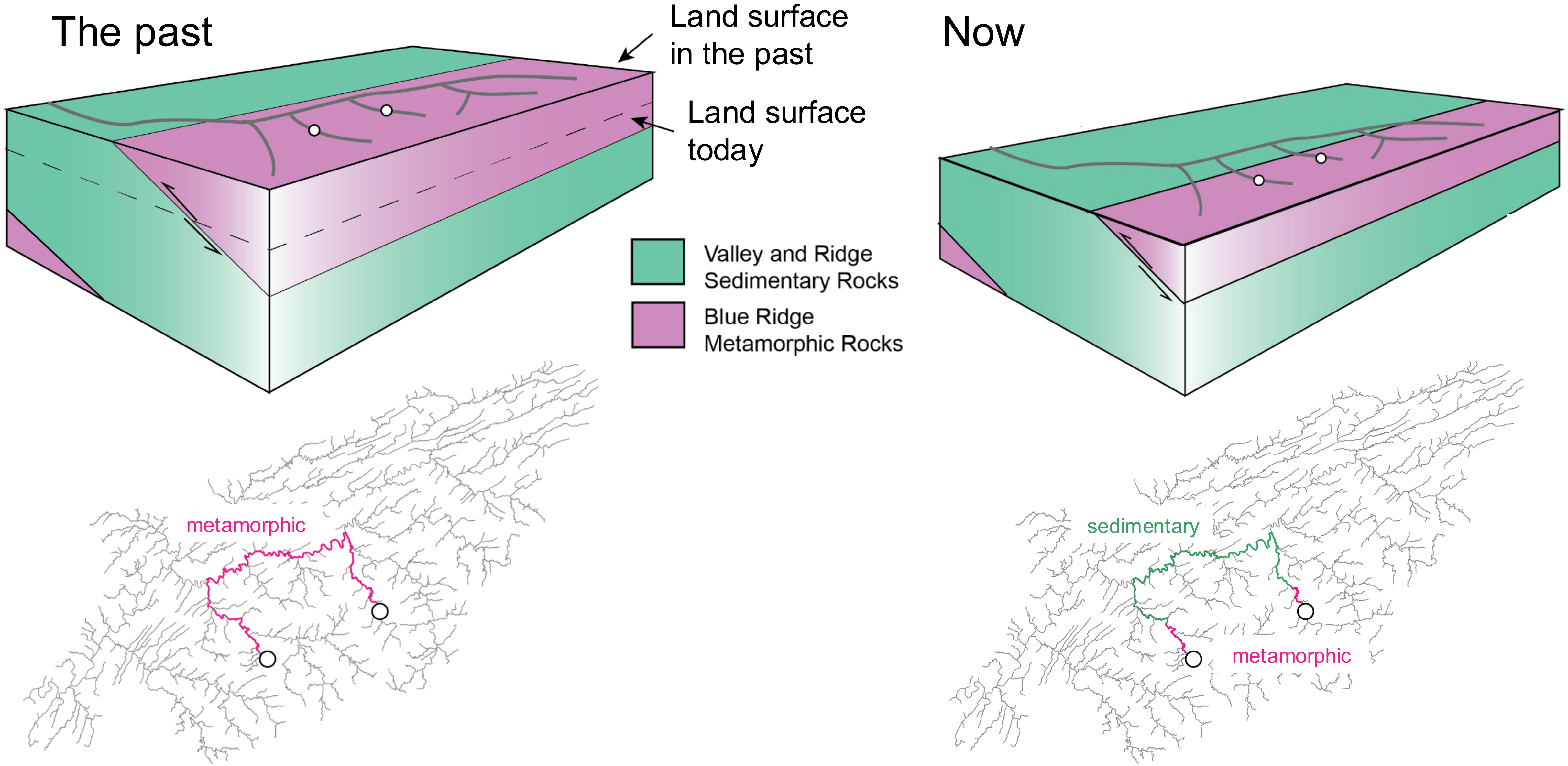
Swimming between sub-basins requires travel through sedimentary rock.

But this has not always been the case…



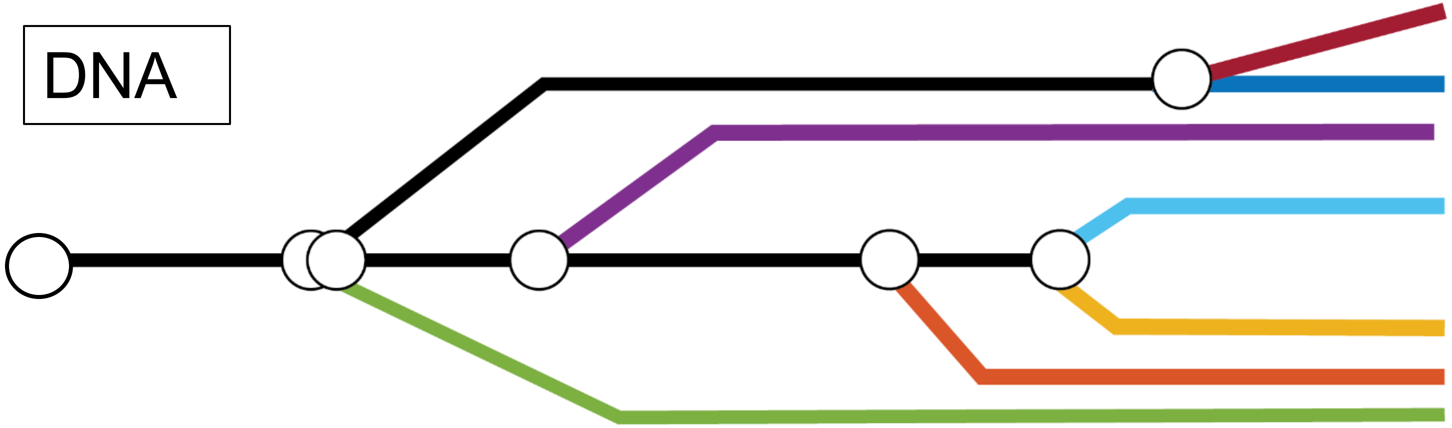
Stokes et al. (*Science*, 2023)

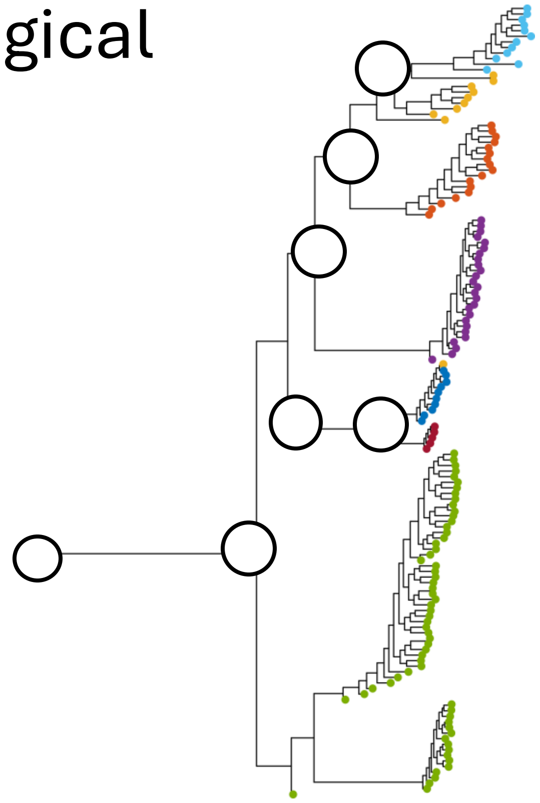
Rock contact (the barrier) moved across the landscape as it eroded



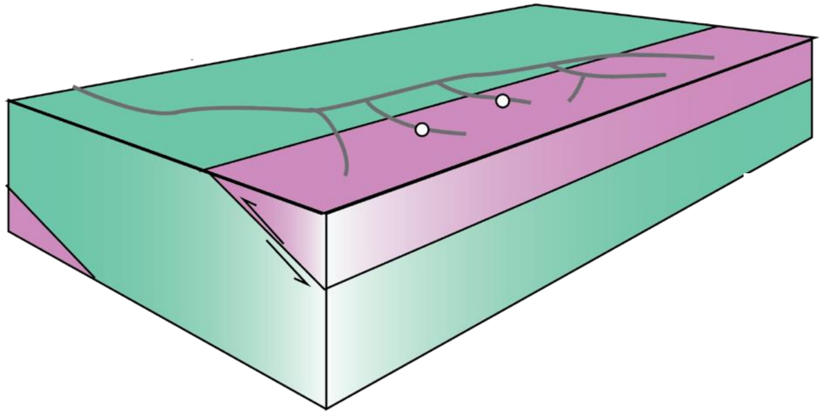
Test: Compare predicted divergence trees for geological models with the DNA-based divergence tree

DNA

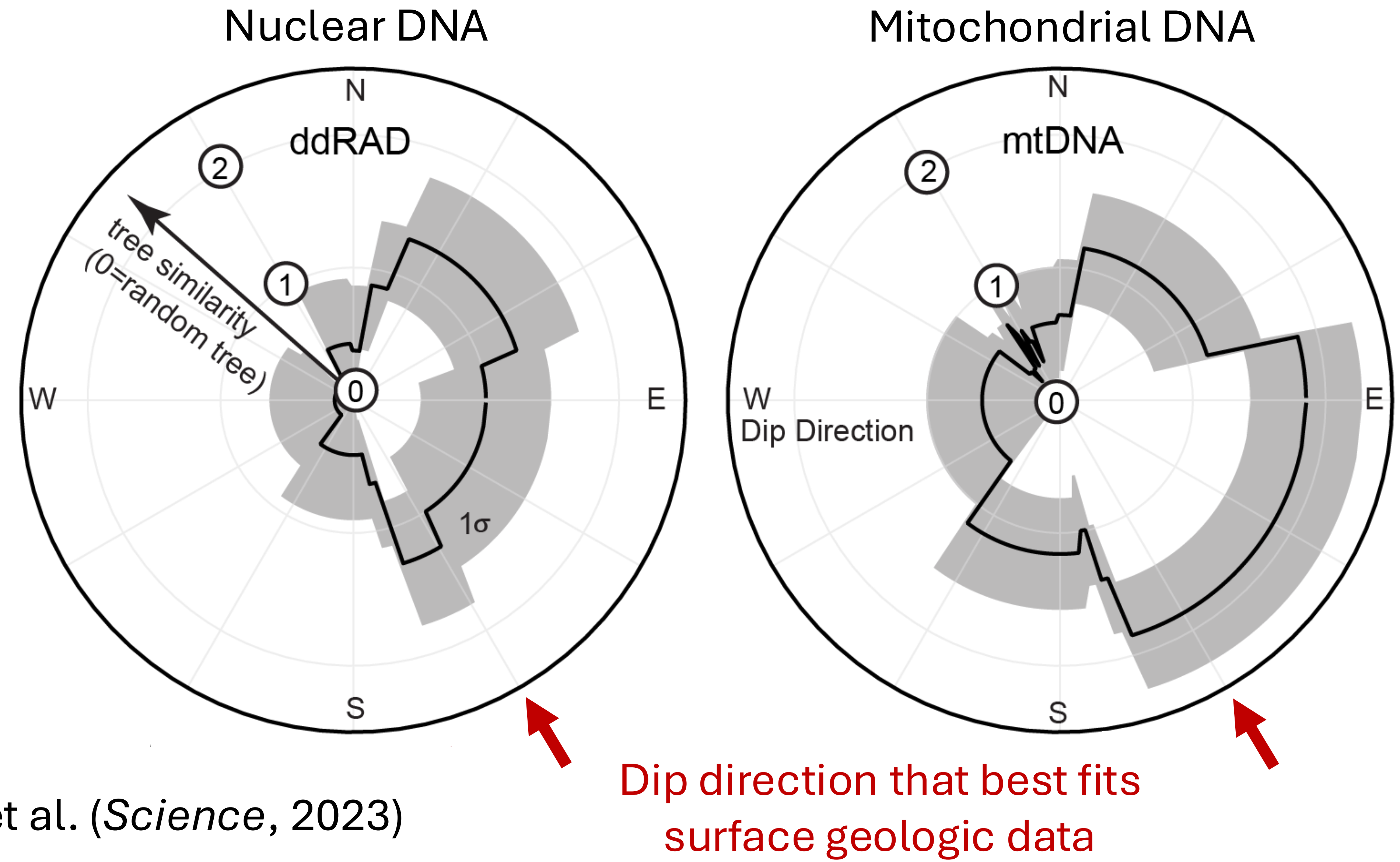




Geologic Model

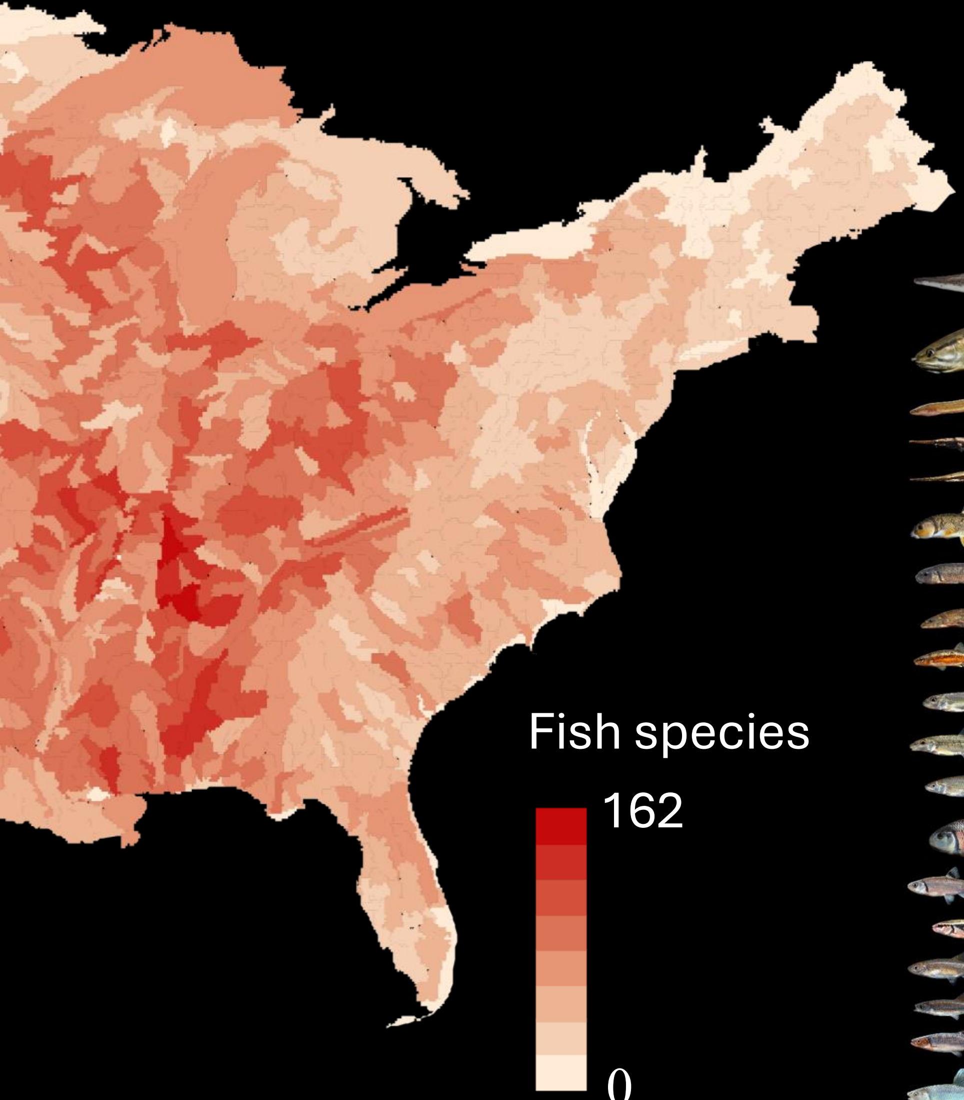


Genetic trees are most consistent with a rock contact sloping down to the S/SE, which is also the best fit to surface geologic data

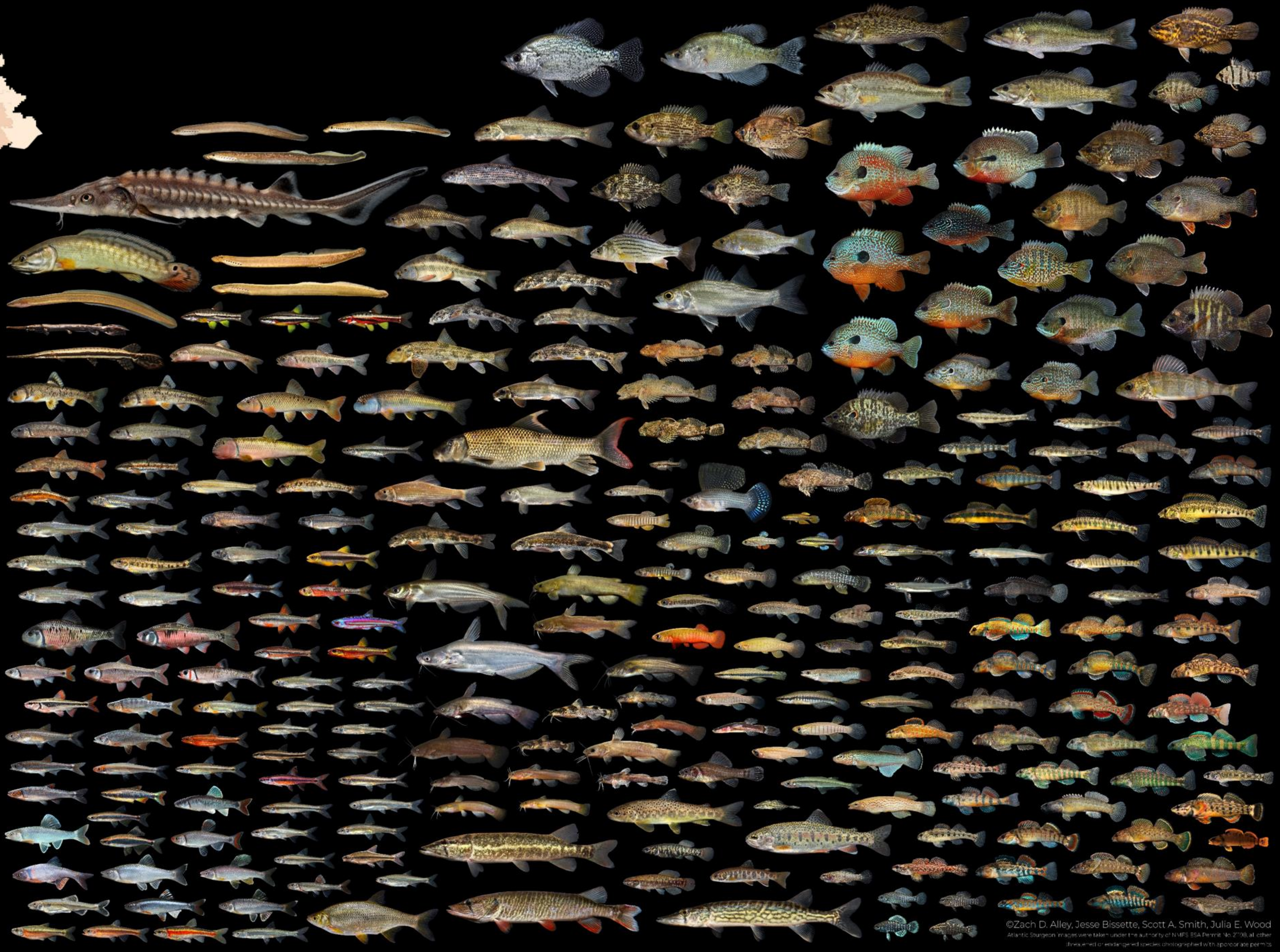


Stokes et al. (*Science*, 2023)

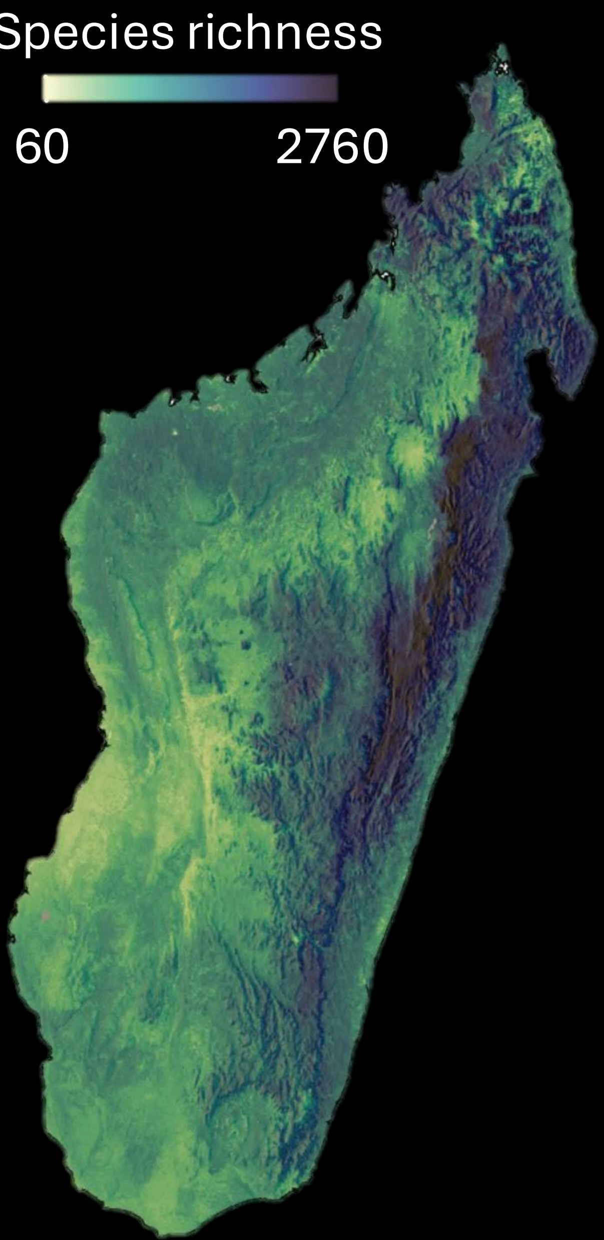
Unsteady landscape evolution can drive fish diversification, even without active mountain-building



Natureserve



An example from another tectonically “quiet” landscape: Madagascar



Liu et al. (*Science*, 2024)

How do terrestrial and marine landscapes co-evolve?

Taha'a, French Polynesia
PlanetScope

Terrestrial and marine landscapes

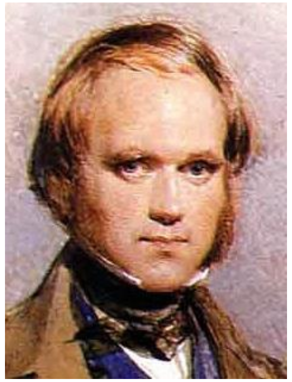
Coral reefs, subsidence, and sea level cycles


Michael Toomey
PhD 2013
Andrew Ashton
(WHOI)
What controls the morphologic evolution of coral reefs?
Moorea, French Polynesia
David Hiser / Stone-Getty Images

As ocean islands subside, some follow a predictable sequence:

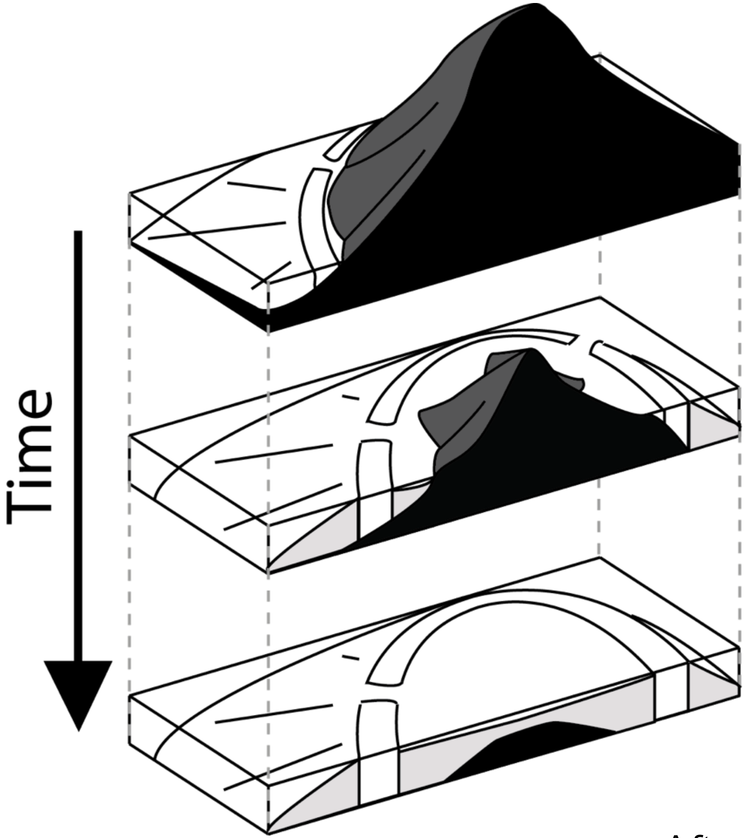
From fringing reefs… …to barrier reefs…

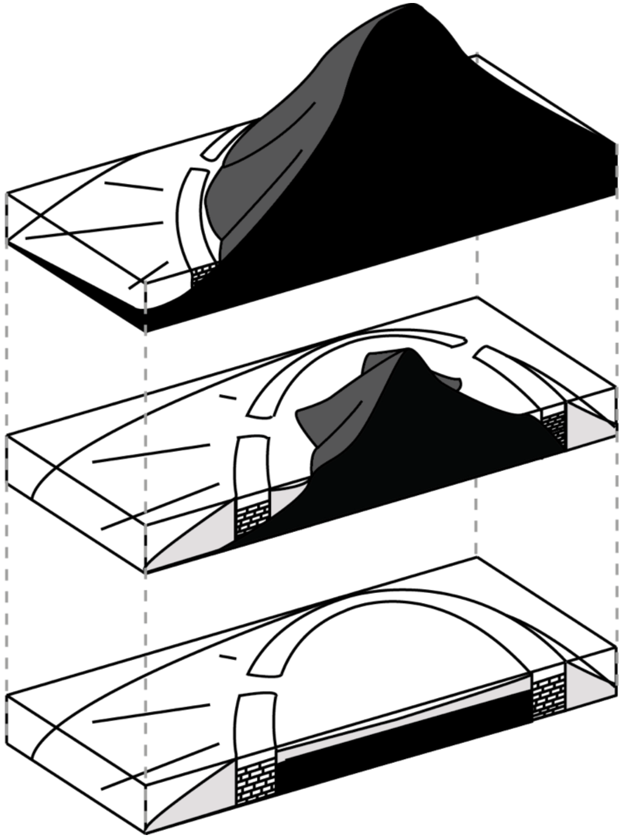
…and eventually to atolls.



Darwin:
Island subsidence forms barrier reefs, then atolls

Daly:
Variable erosion at LGM lowstand explains reef types





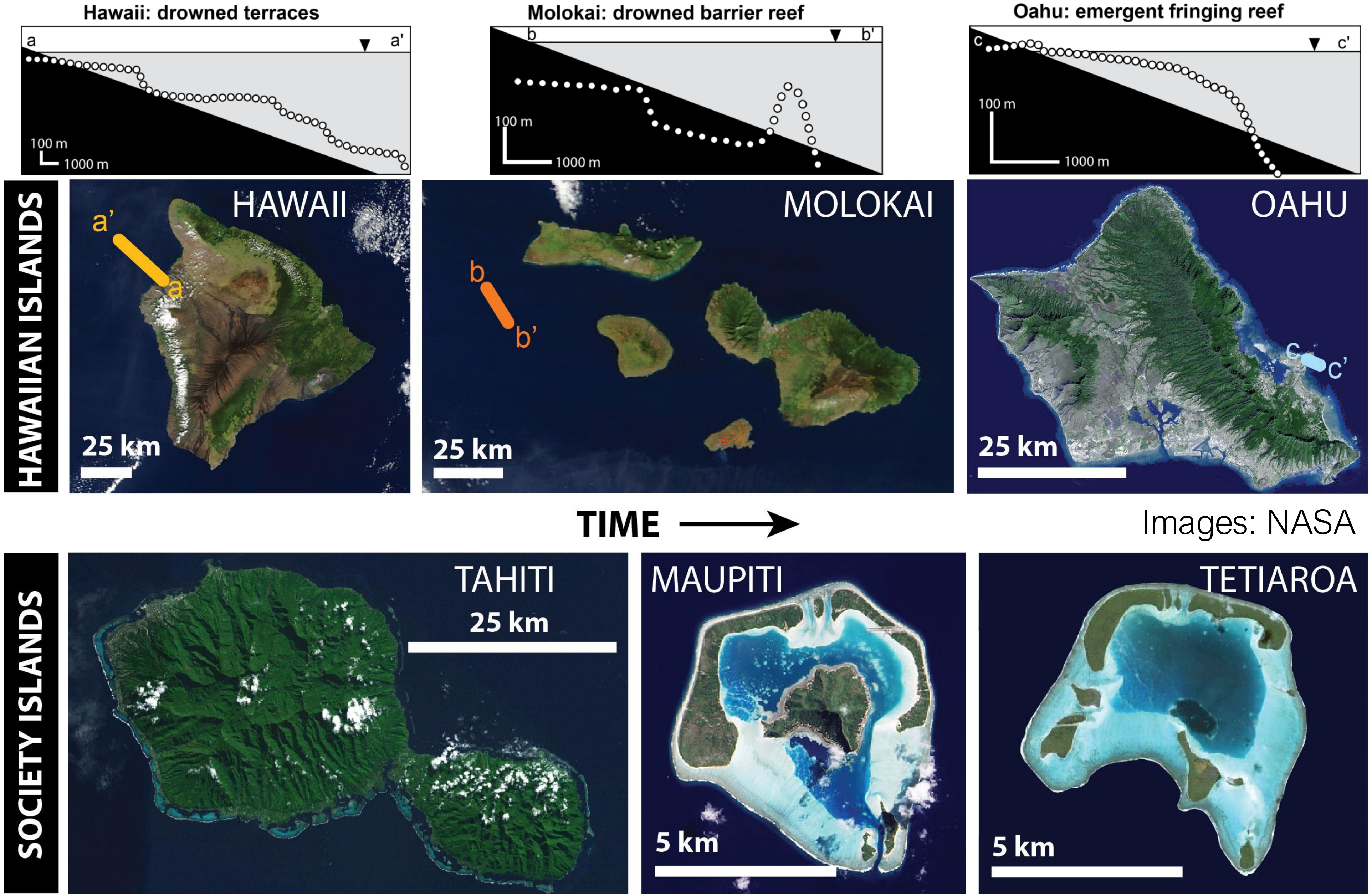
Fringing reef

Barrier reef

Atoll

After Purdy [1974]

Subsidence alone cannot explain the variety of Pleistocene reef profiles. And sea level cycles must matter.



1-D model of Pleistocene reef evolution

$$\frac{\partial z}{\partial t} = \frac{\partial c}{\partial t} + \frac{\partial s}{\partial t} + V$$

Island vertical motion

Coral thickness

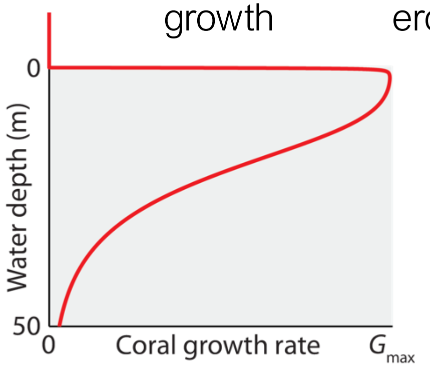
$$\frac{\partial c}{\partial t} = G(h,x) - W(h,x)$$

Coral growth — Wave erosion

Carbonate sediment thickness

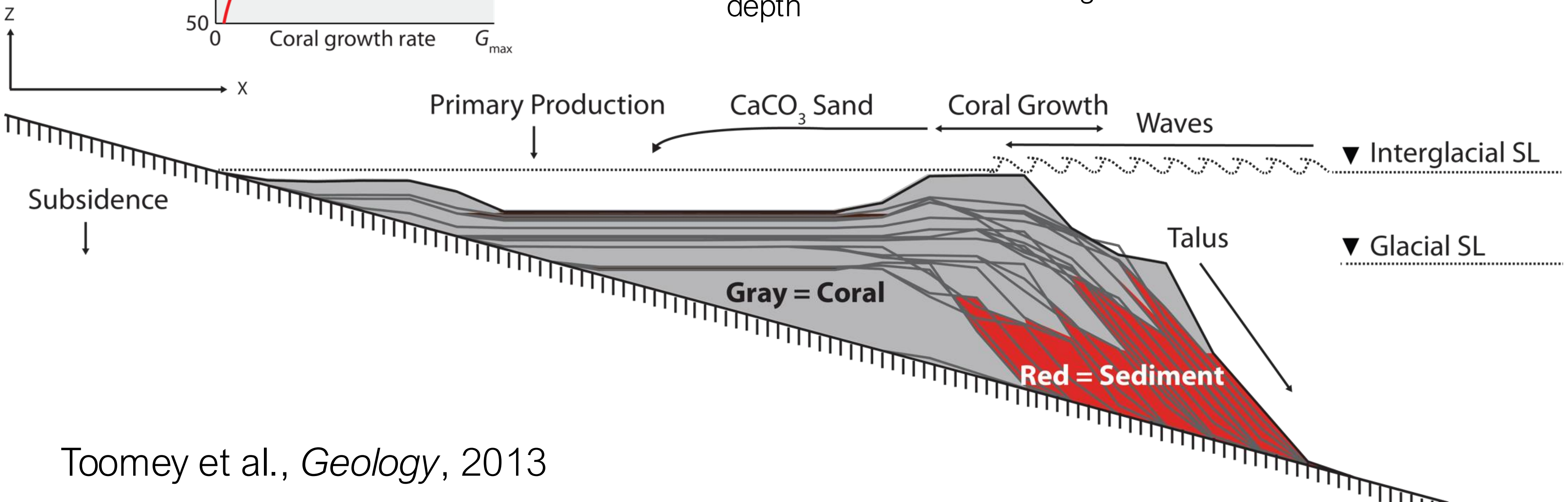
$$\frac{\partial s}{\partial t} = W(h,x) - \frac{1}{f_v}\frac{\partial q_s}{\partial x} + P(h,x)$$

Wave erosion — Sediment transport — Primary production

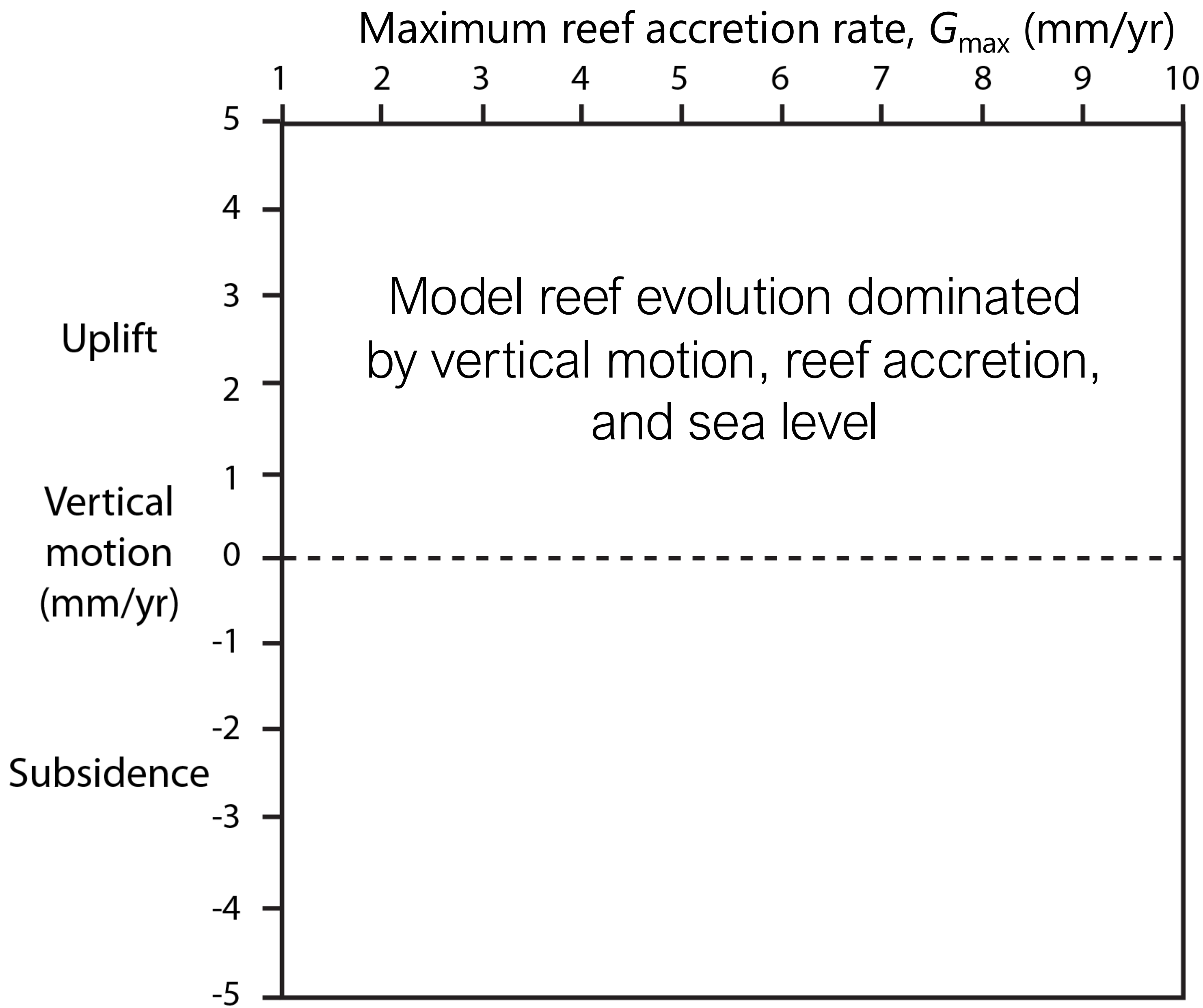


$$h = SL(t) - z(x,t)$$

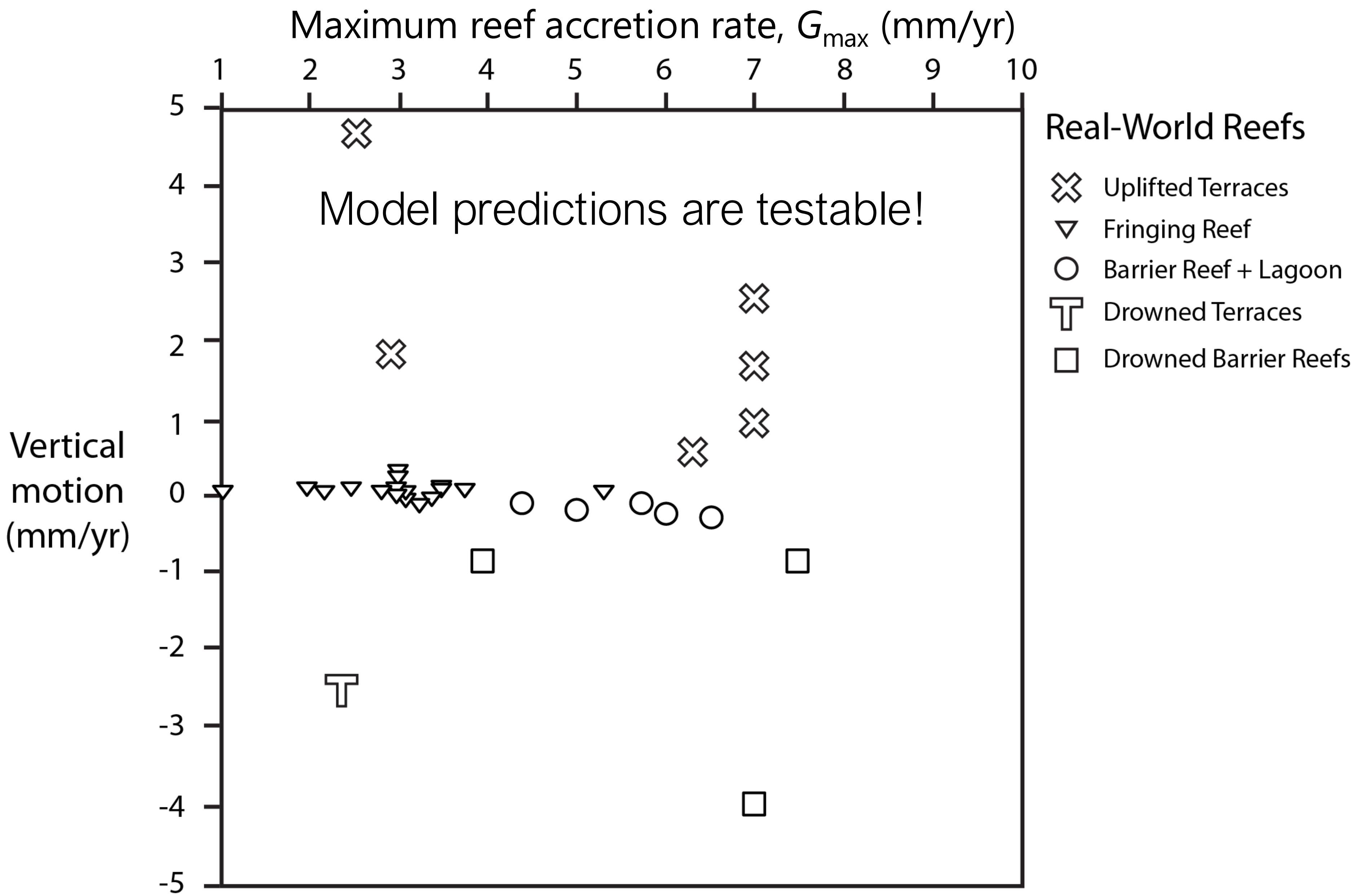
Water depth — Sea level — Reef height



Toomey et al., *Geology*, 2013



Toomey et al., *Geology*, 2013



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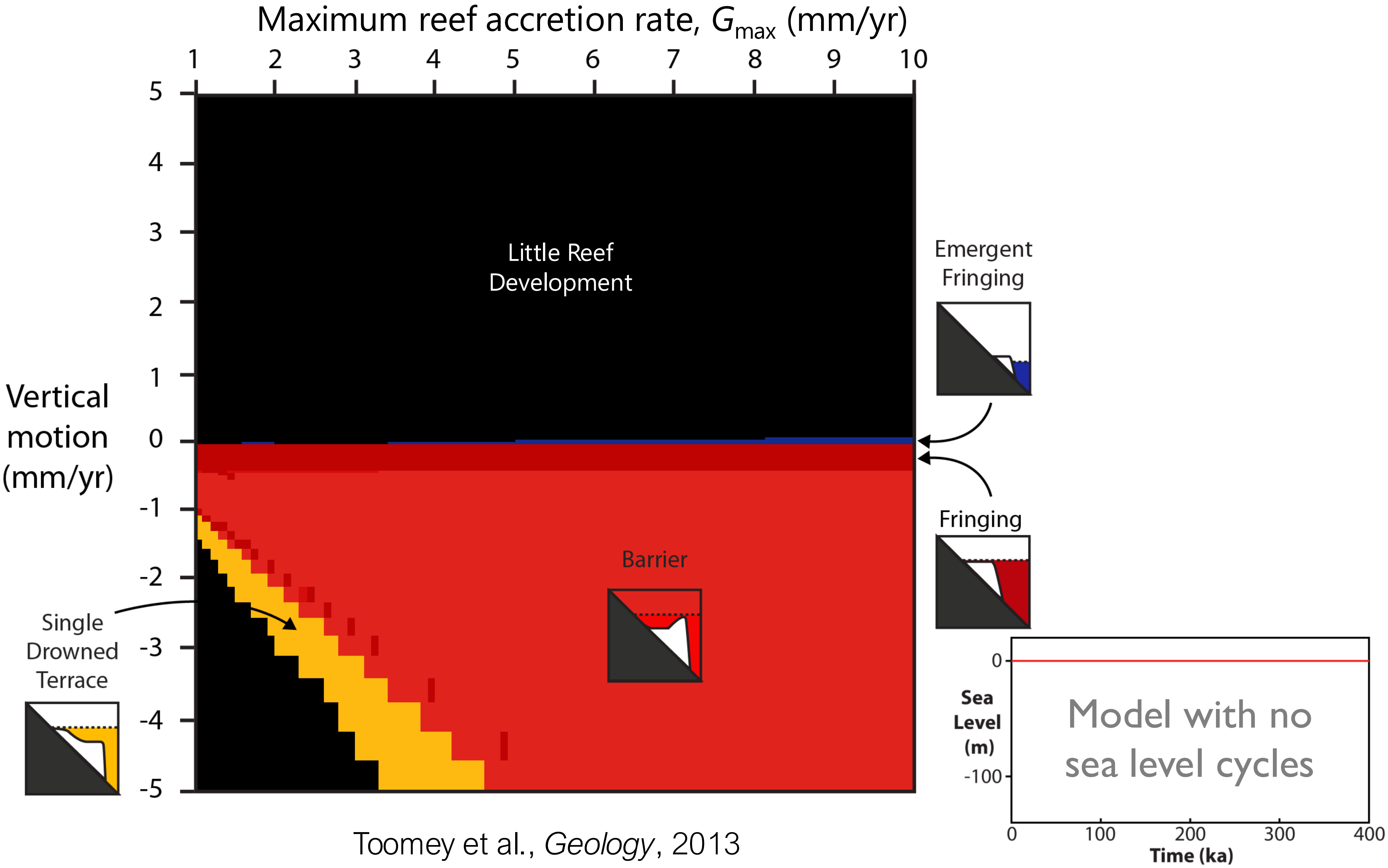
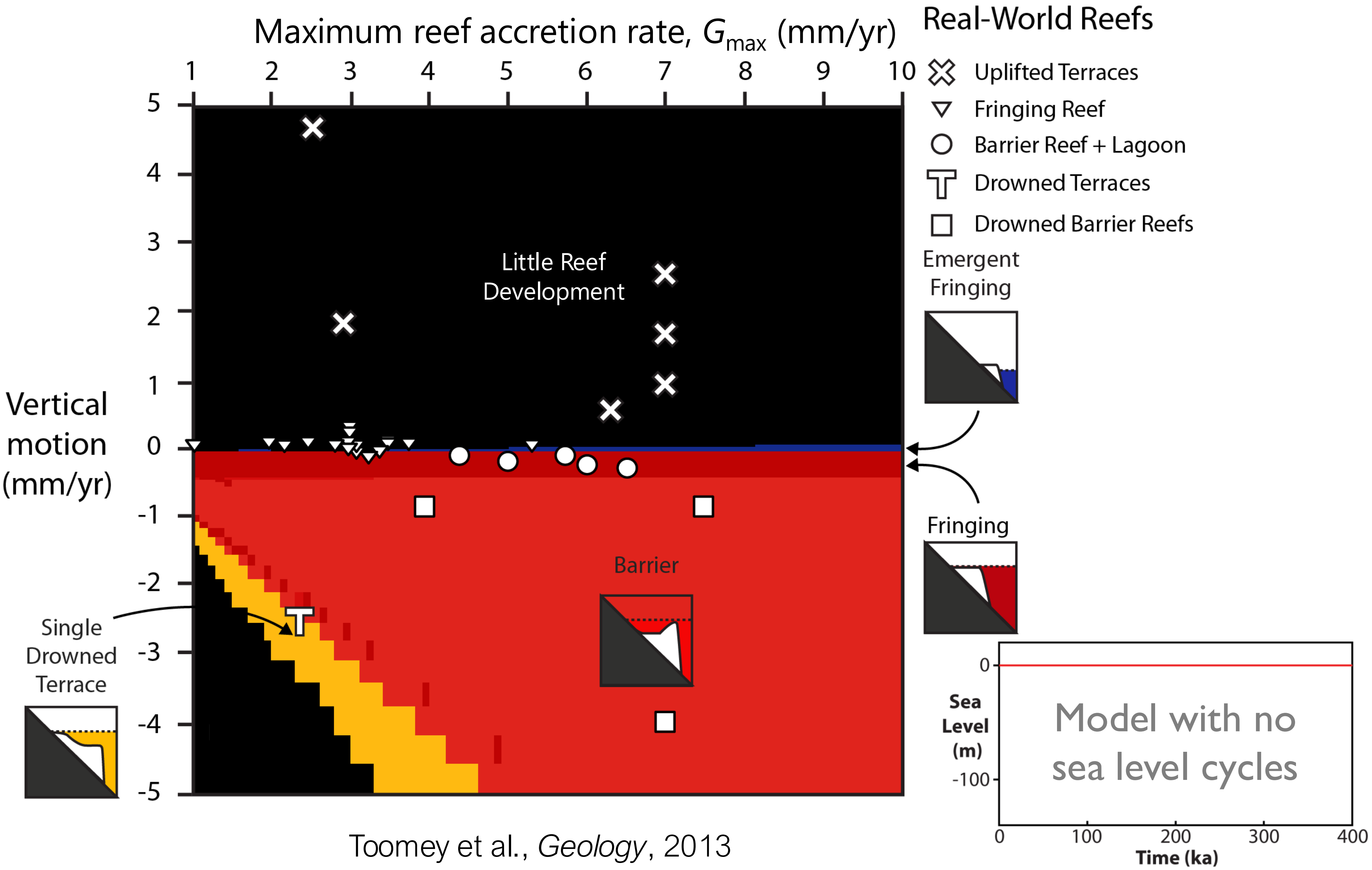
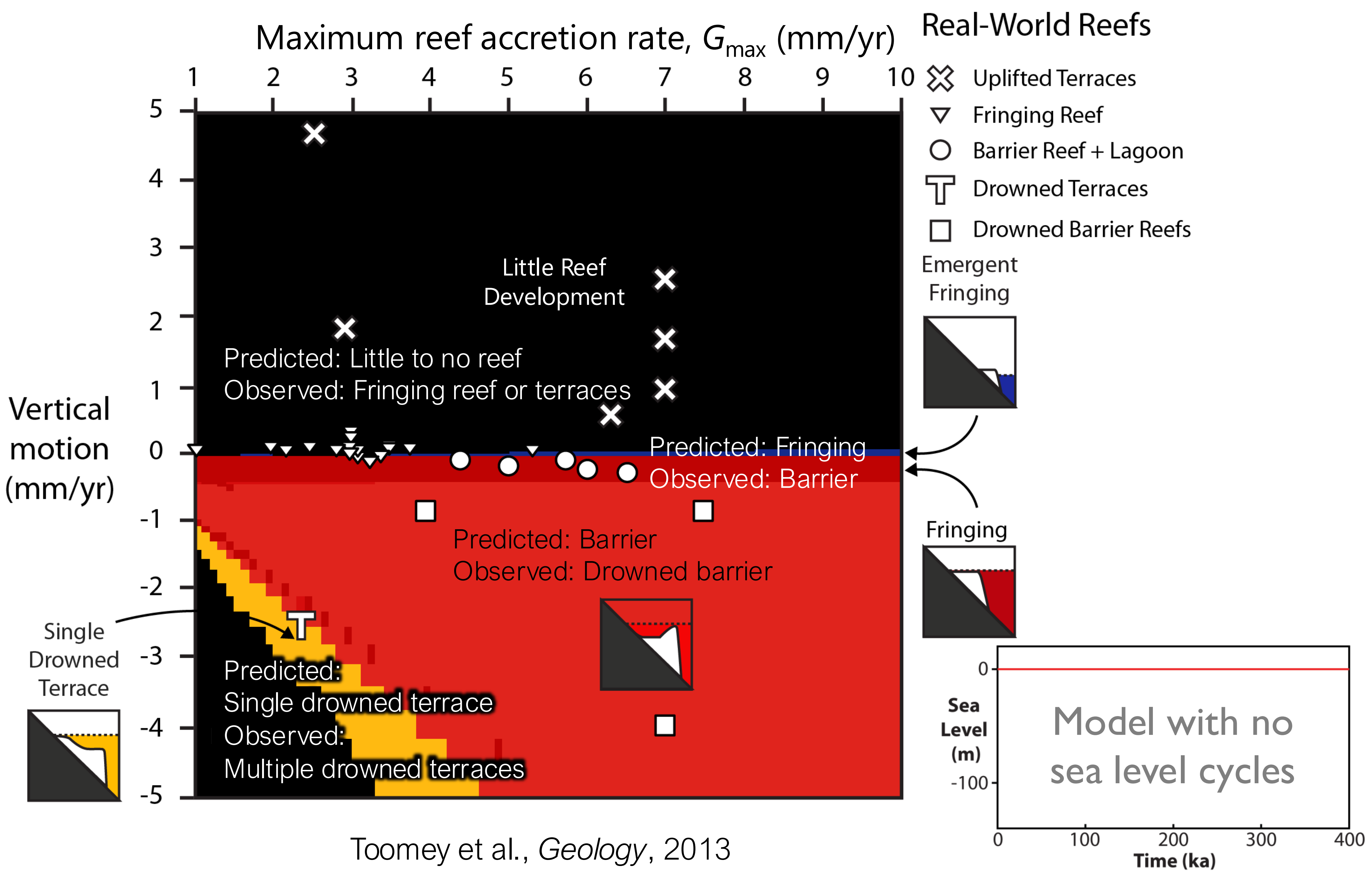


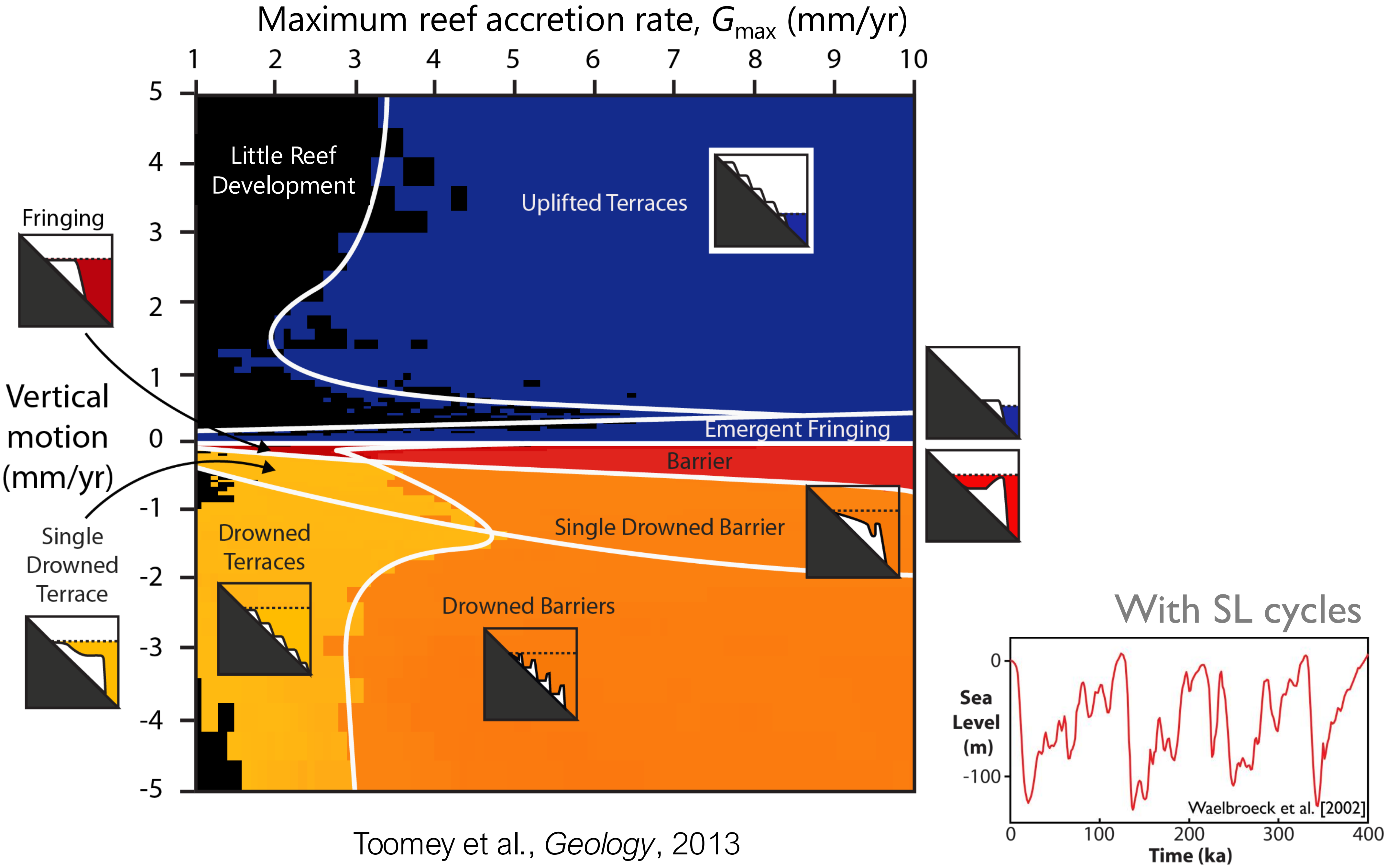
Toomey et al., *Geology*, 2013



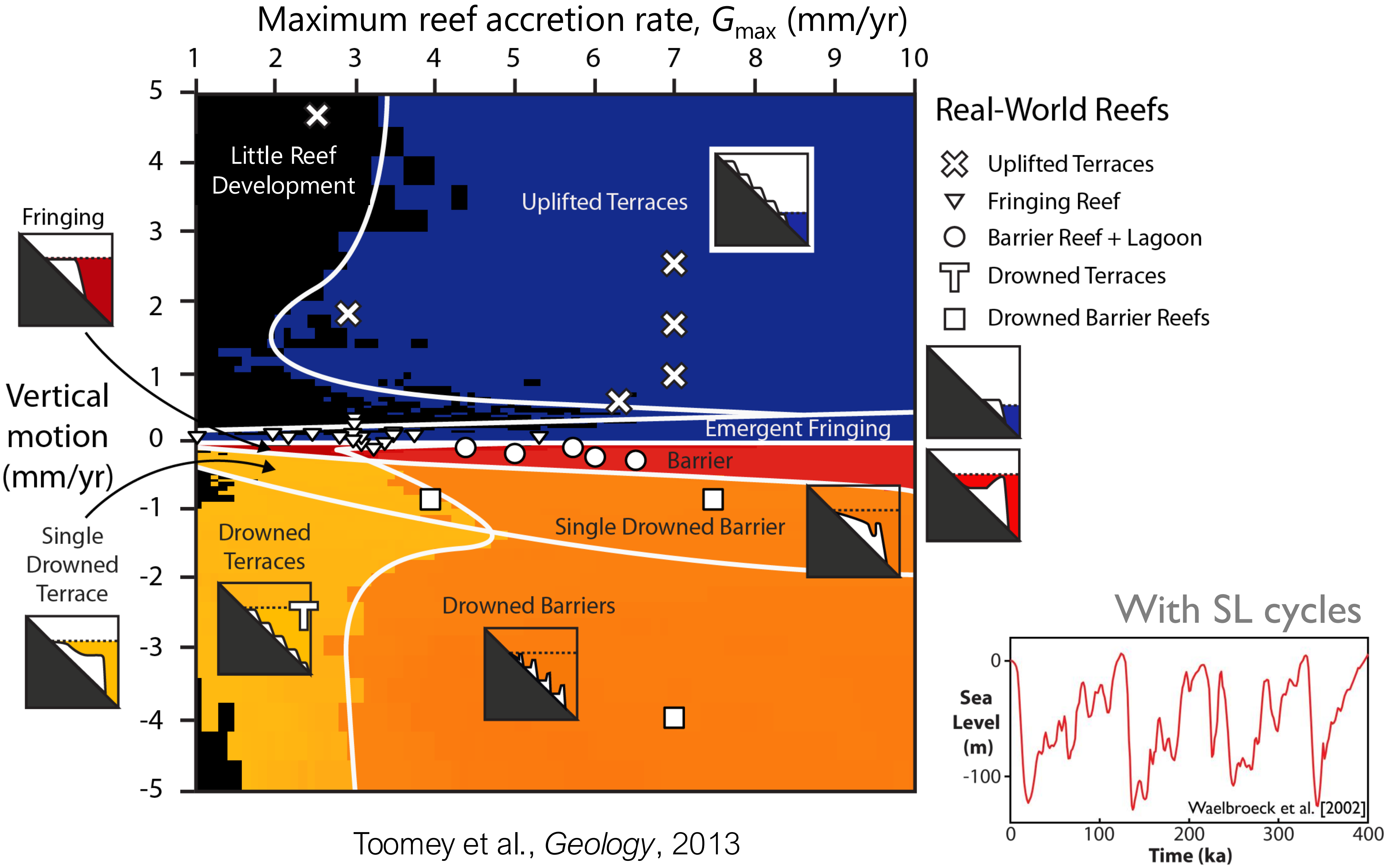
Toomey et al., *Geology*, 2013



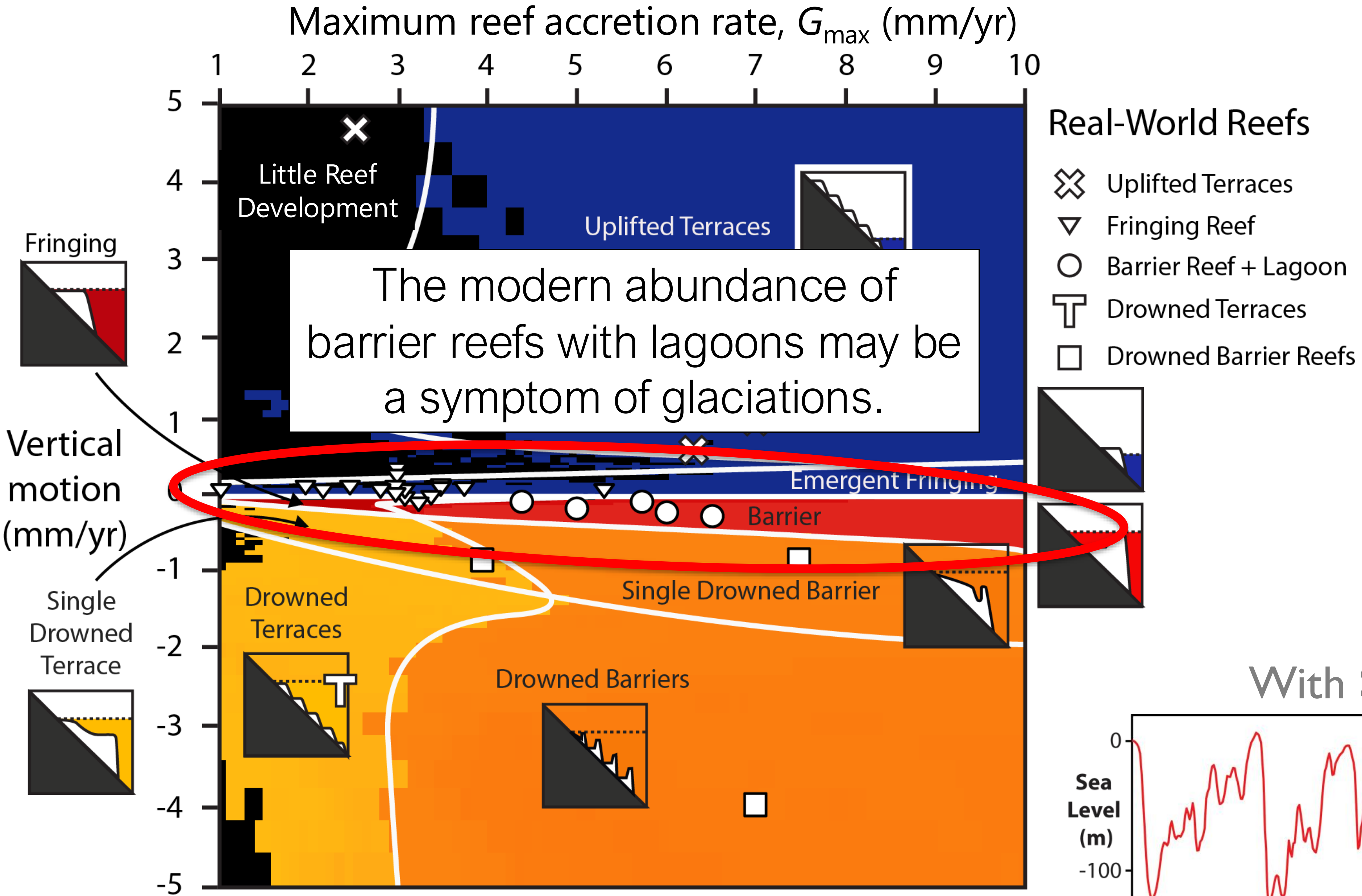
Toomey et al., *Geology*, 2013



Toomey et al., *Geology*, 2013

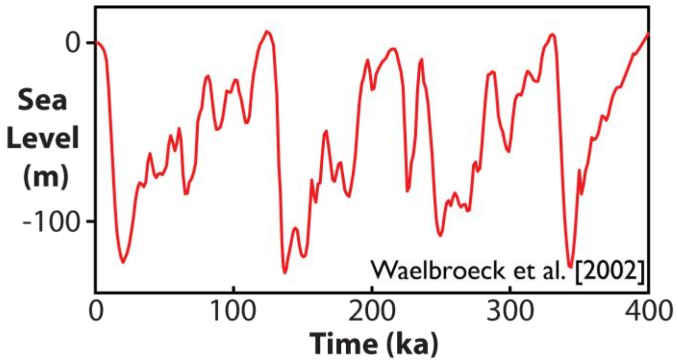


Toomey et al., *Geology*, 2013

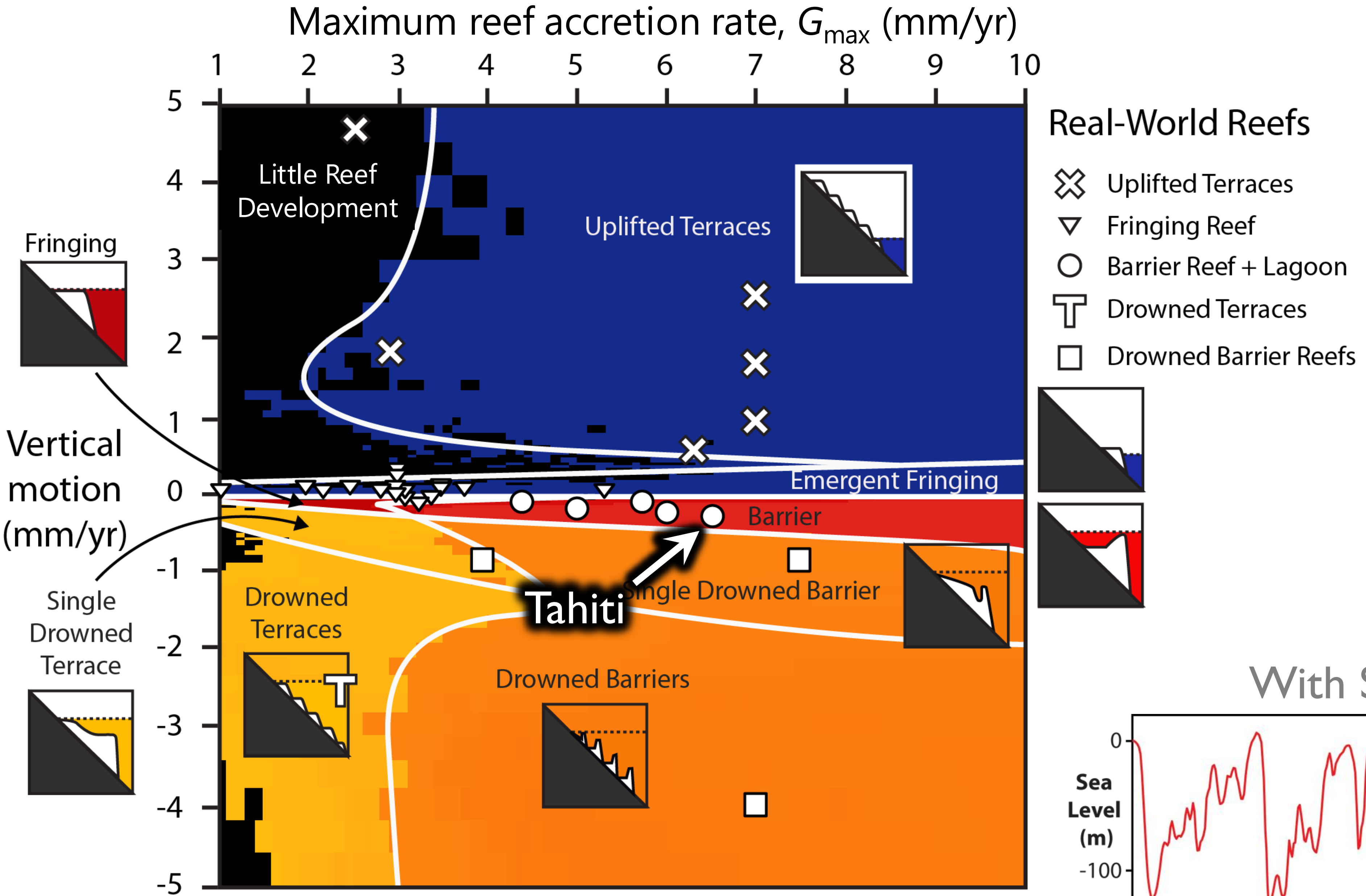


The modern abundance of barrier reefs with lagoons may be a symptom of glaciations.

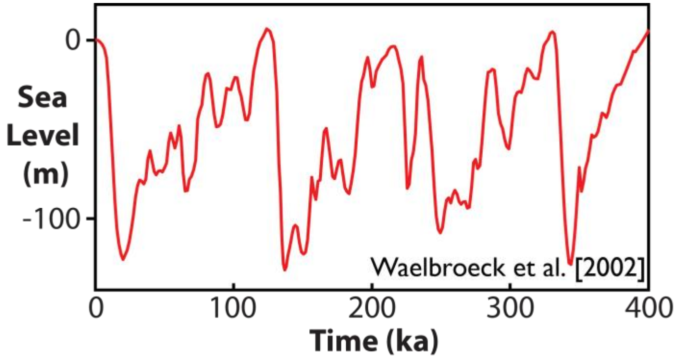
With SL cycles



Toomey et al., *Geology*, 2013

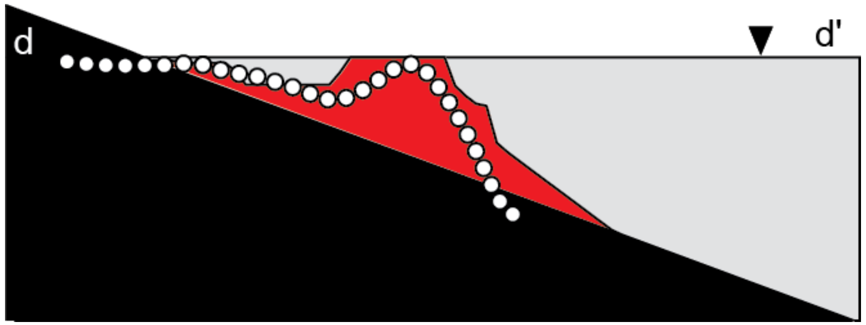


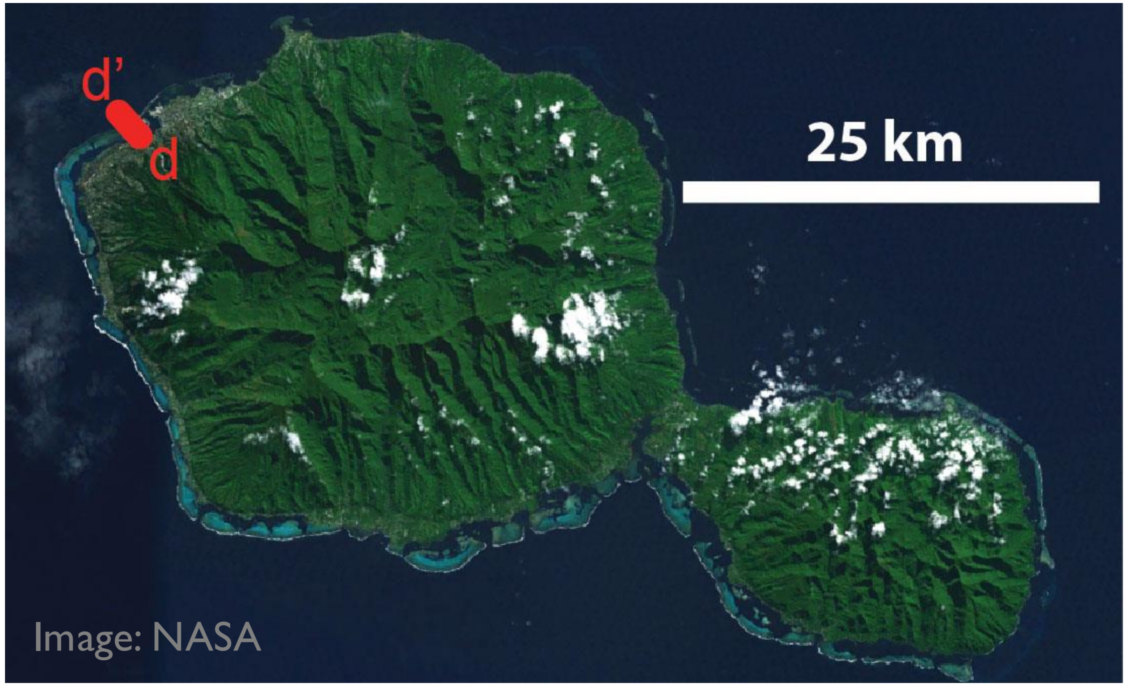
With SL cycles



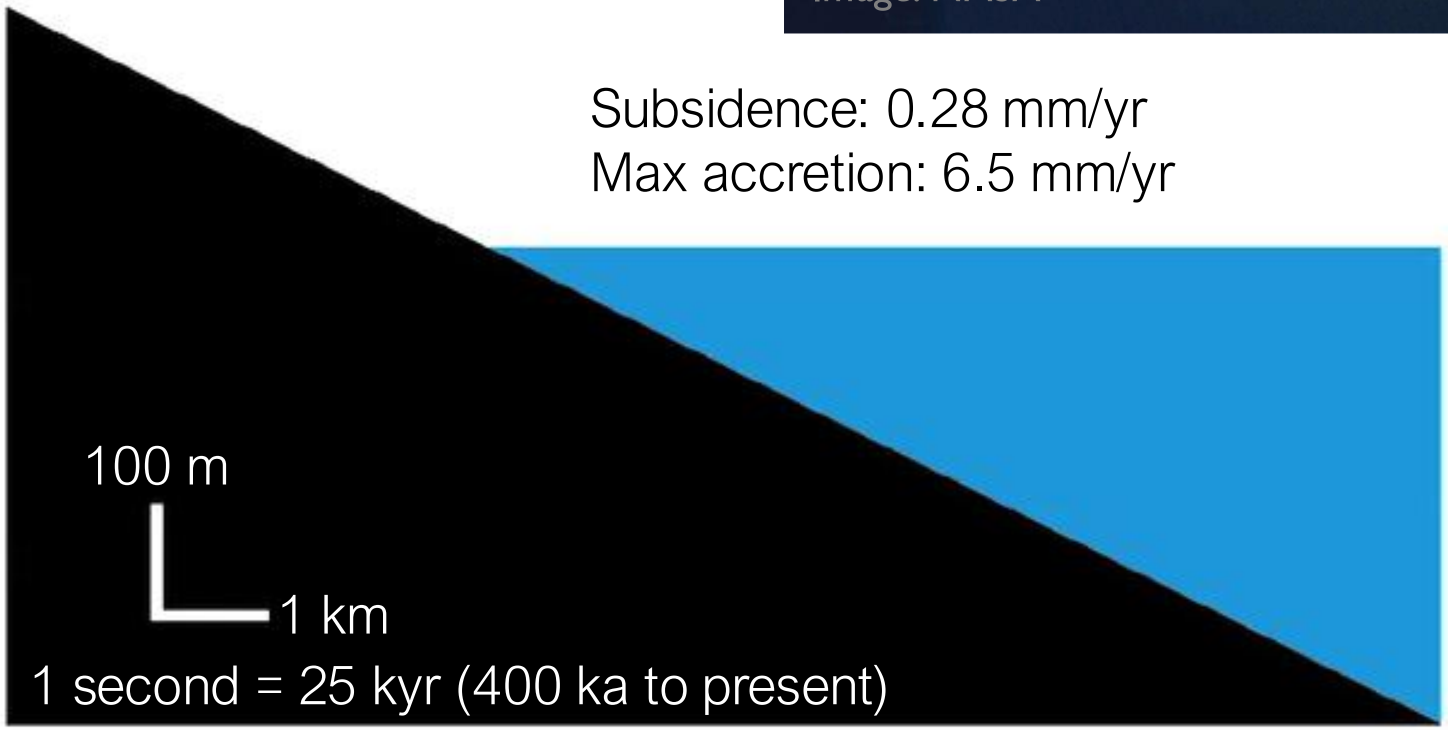
Toomey et al., *Geology*, 2013

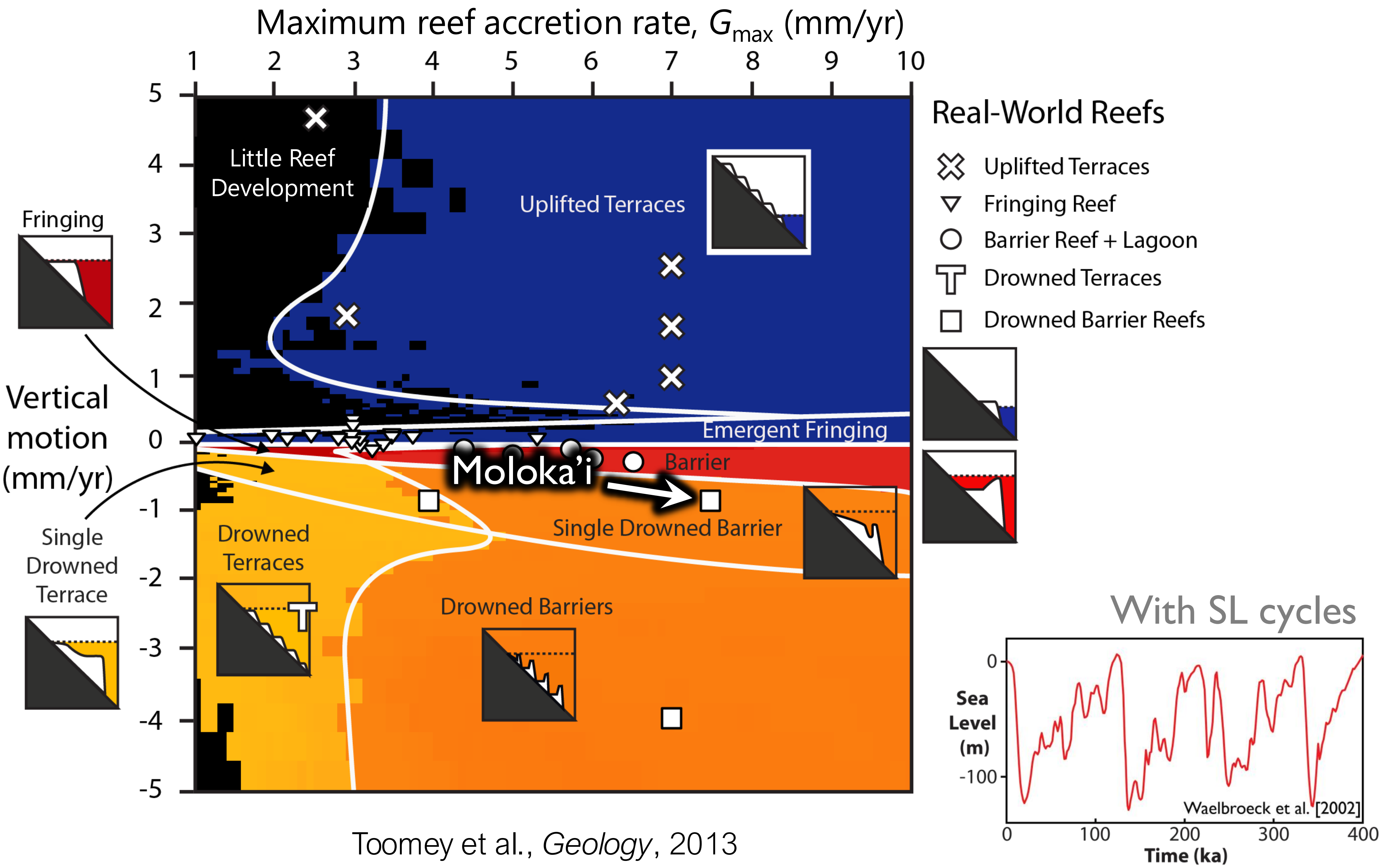
Tahiti: Slow subsidence and moderate accretion rate maintain a barrier reef with a 90 m deep lagoon.





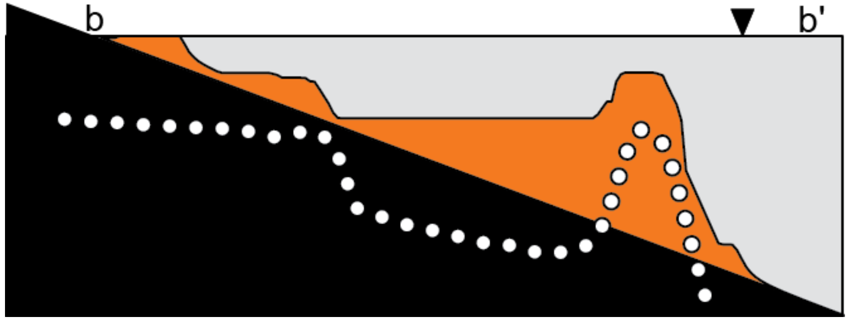
Subsidence: 0.28 mm/yr
Max accretion: 6.5 mm/yr

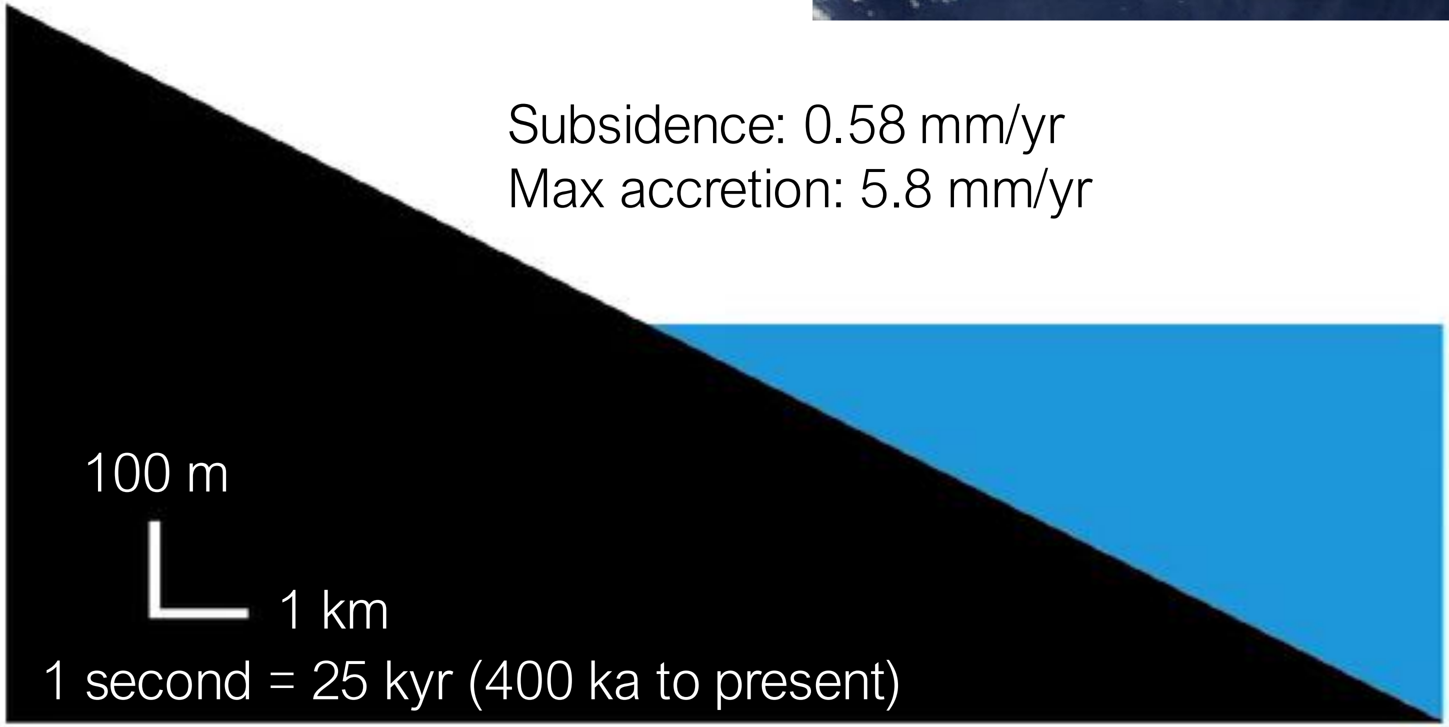


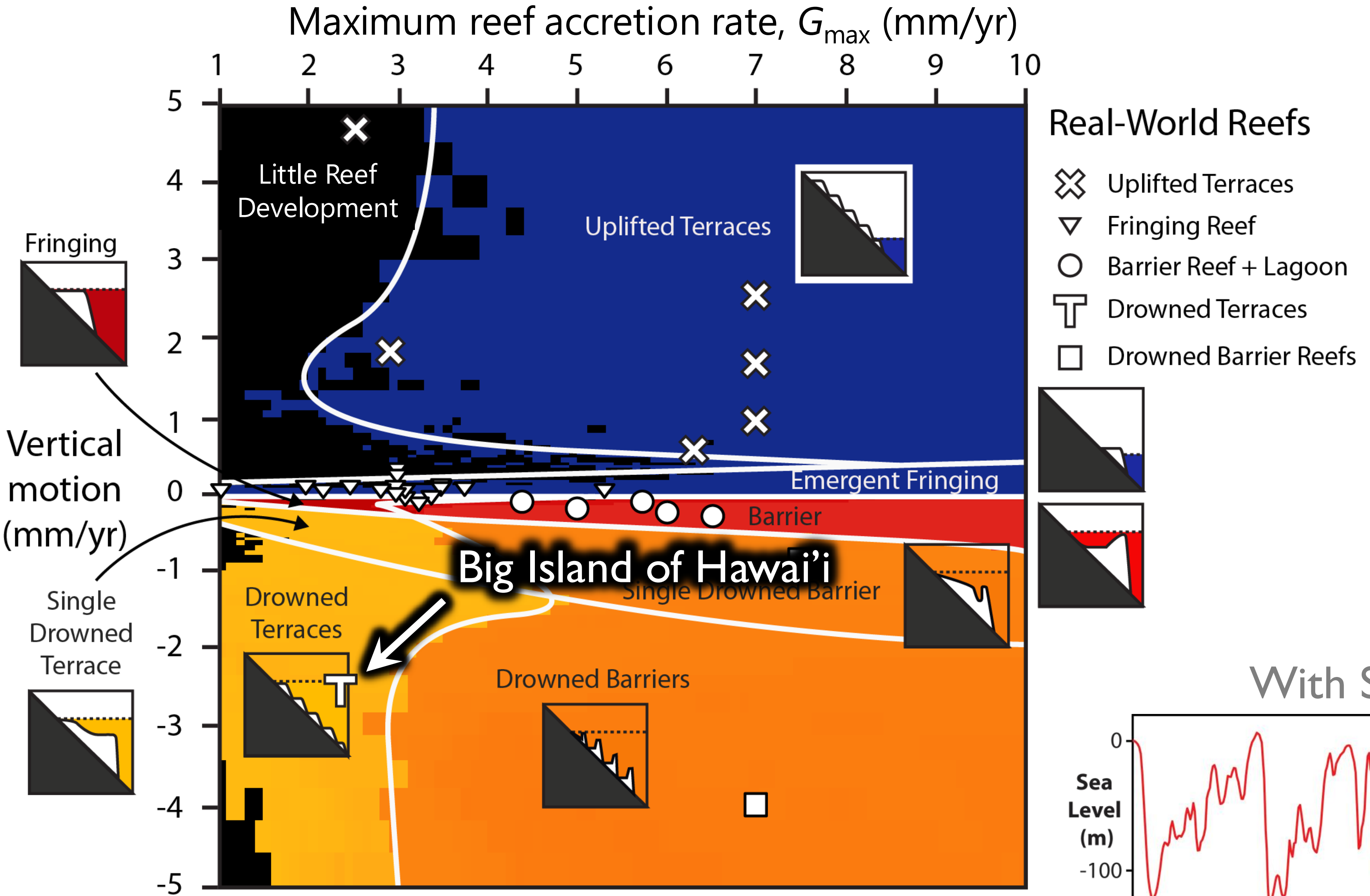


Toomey et al., *Geology*, 2013

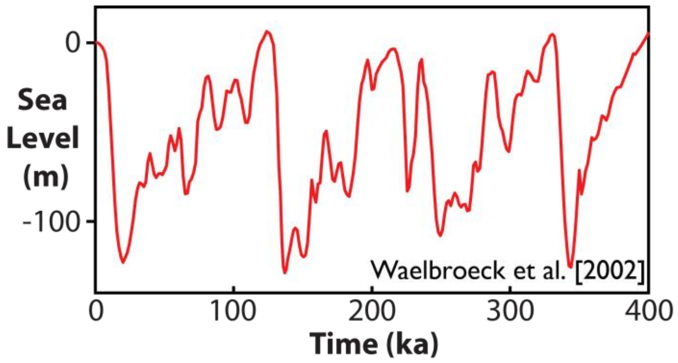
Molokai: Rapid subsidence drowns barrier reef during transgressions at glacial terminations.





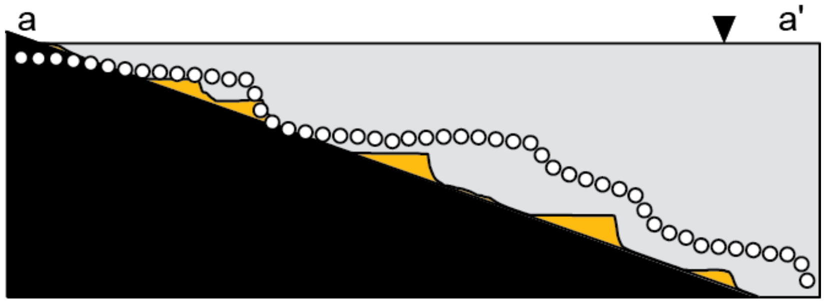


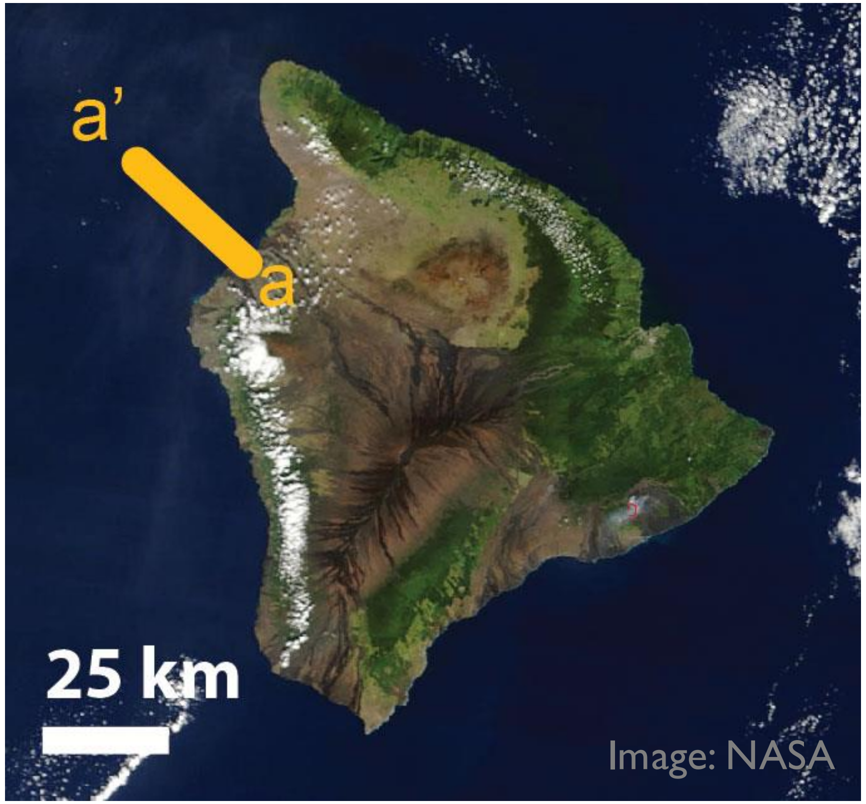
With SL cycles



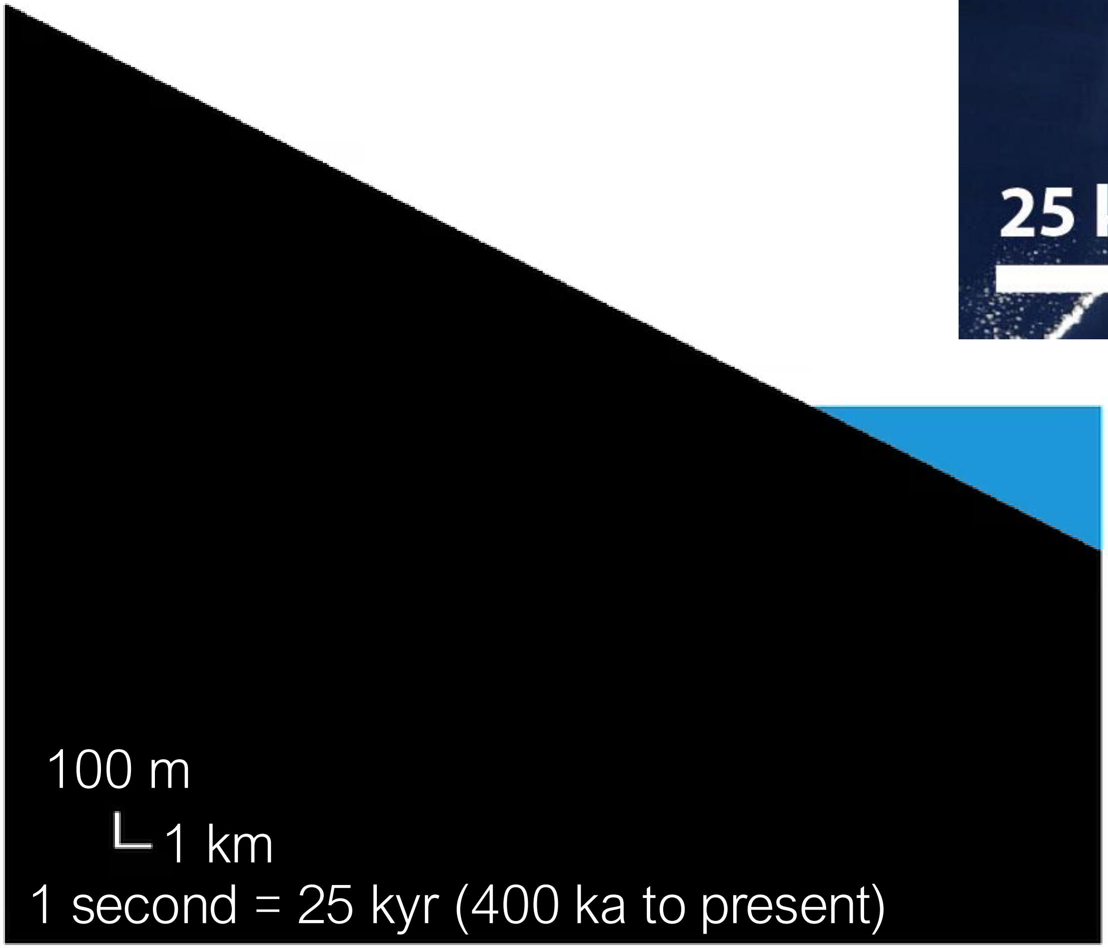
Toomey et al., *Geology*, 2013

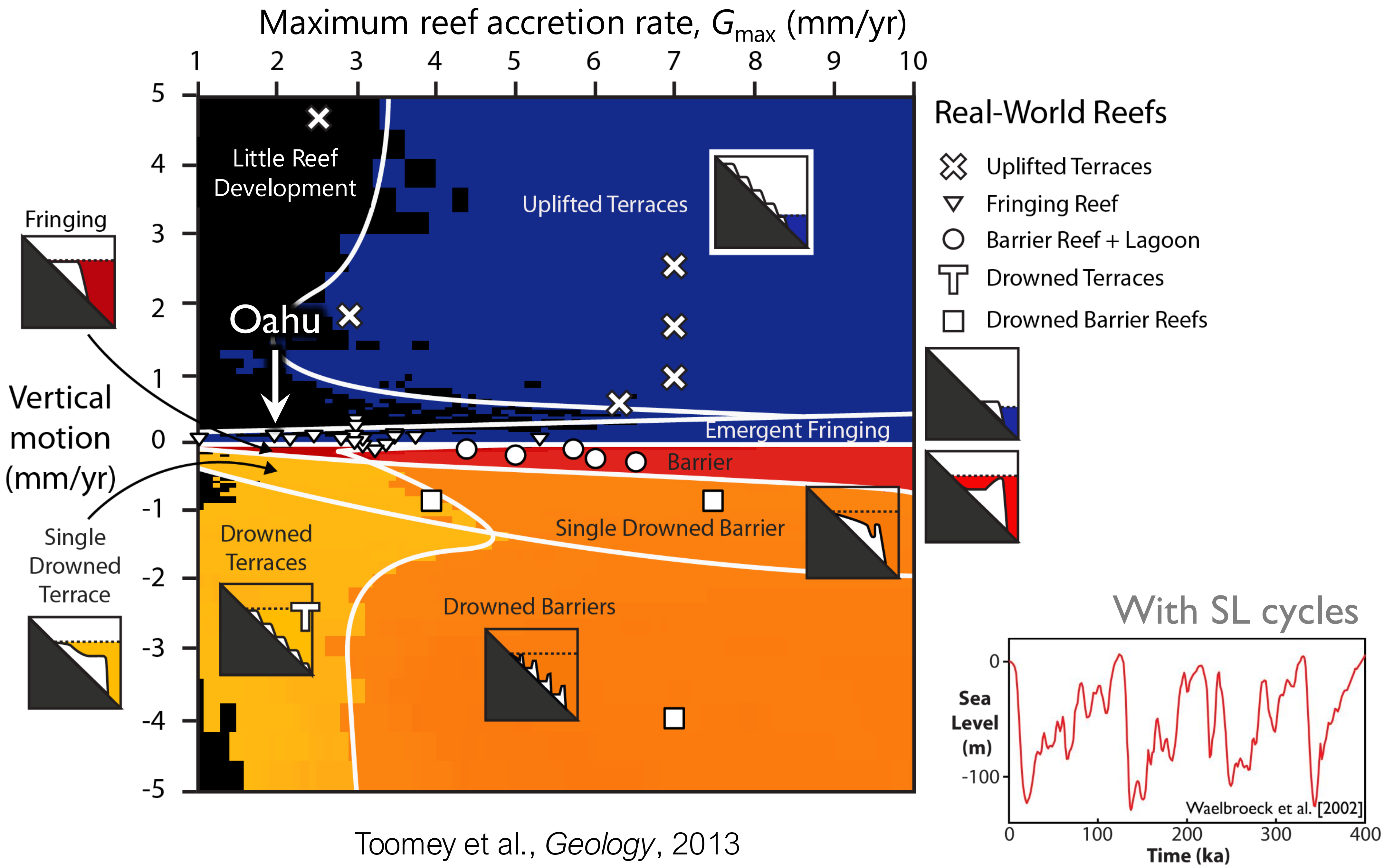
Big Island of Hawaii: Very rapid subsidence and slow accretion creates a flight of drowned terraces.





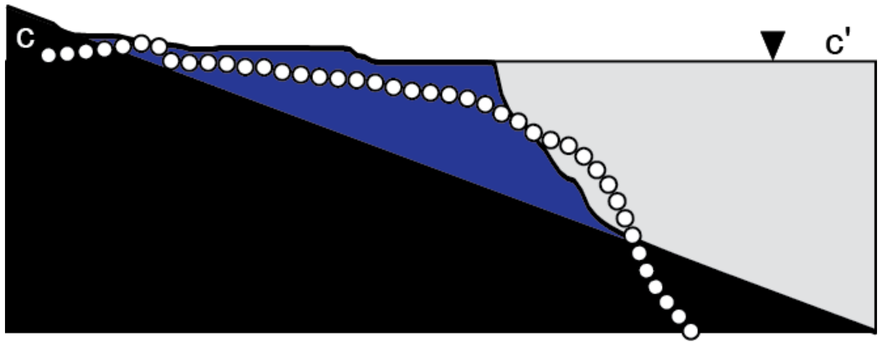
Subsidence: 2.6 mm/yr
Max accretion: 2.7 mm/yr

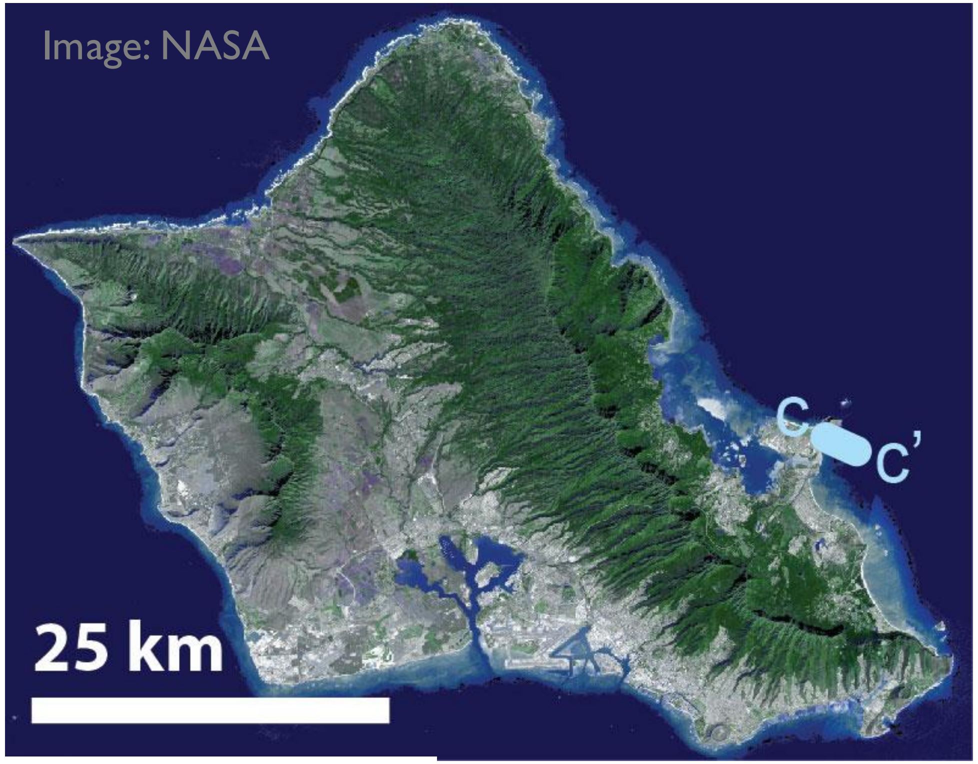




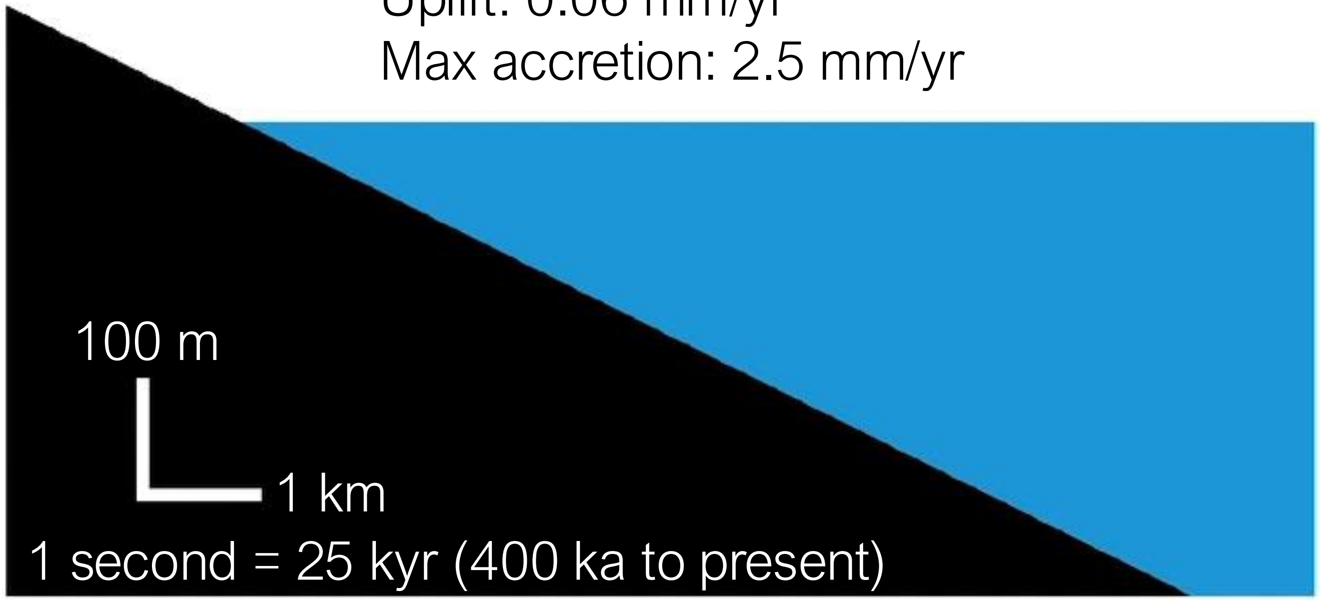
Toomey et al., *Geology*, 2013

Oahu: Slight uplift due to Big Island's flexural bulge allows back-reef to fill with sediment and exposes fringing reef above sea level.

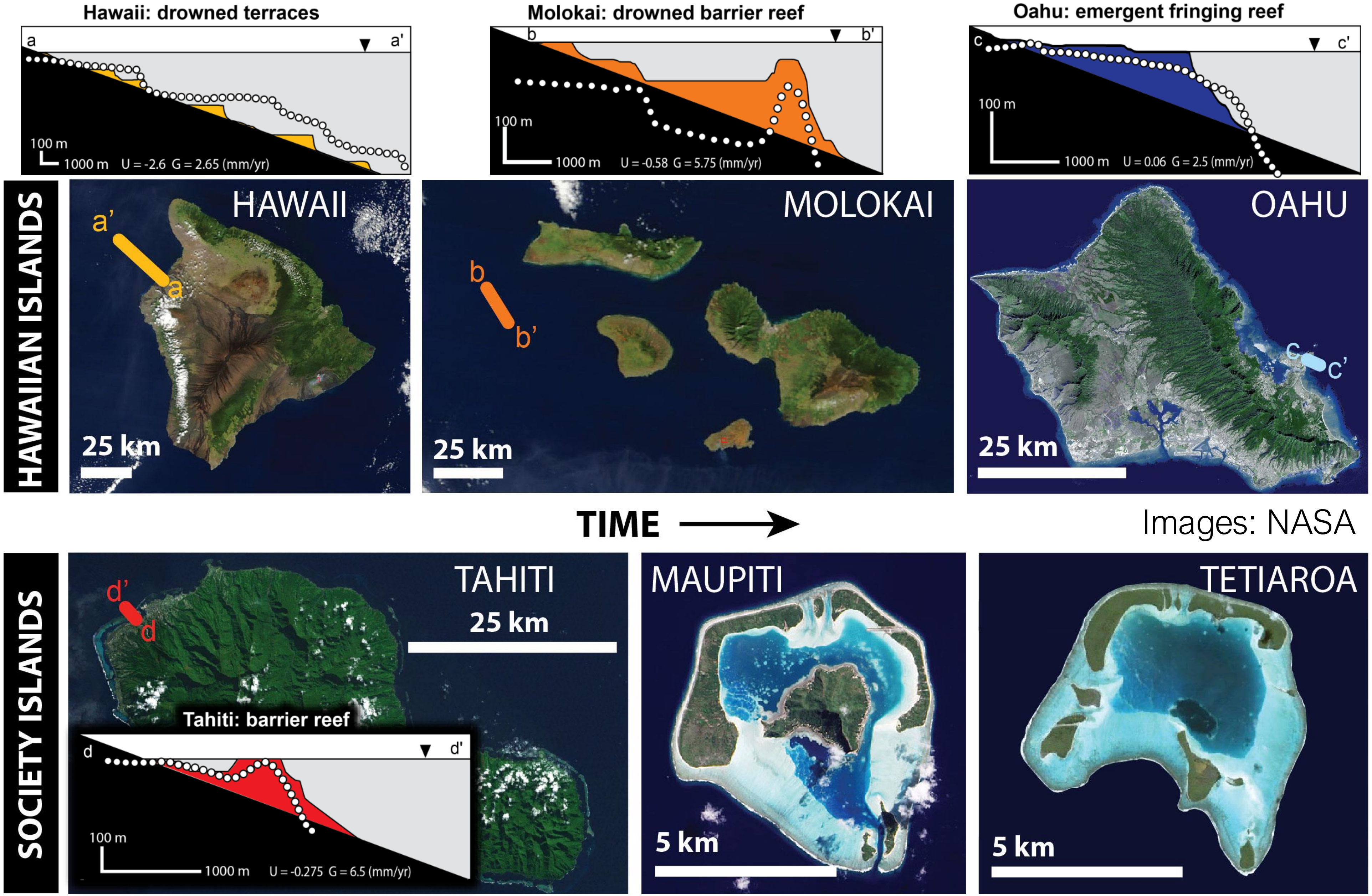




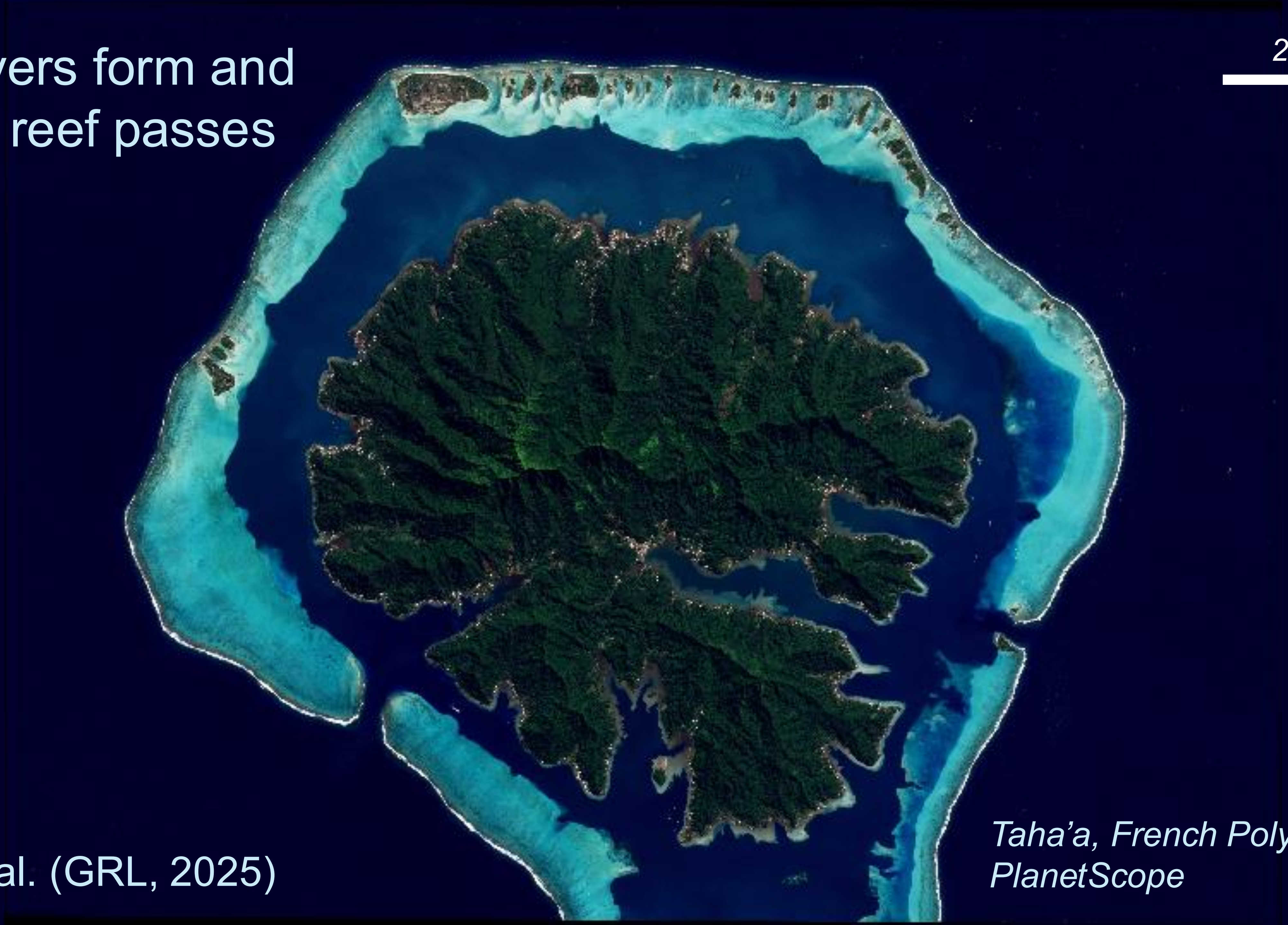
Uplift: 0.06 mm/yr
Max accretion: 2.5 mm/yr



Reconciling Darwin and Daly: Pleistocene reefs bear a prominent signature of glacial sea level cycles



Island rivers form and maintain reef passes



Gillen et al. (GRL, 2025)

Islands as natural experiments in landscape evolution

Geodynamics

Climate

Land-ocean interactions

Biological evolution

Taha'a, French Polynesia