Neogene changes in land surface reactivity and implications for Earth system sensitivity to carbon cycle perturbations

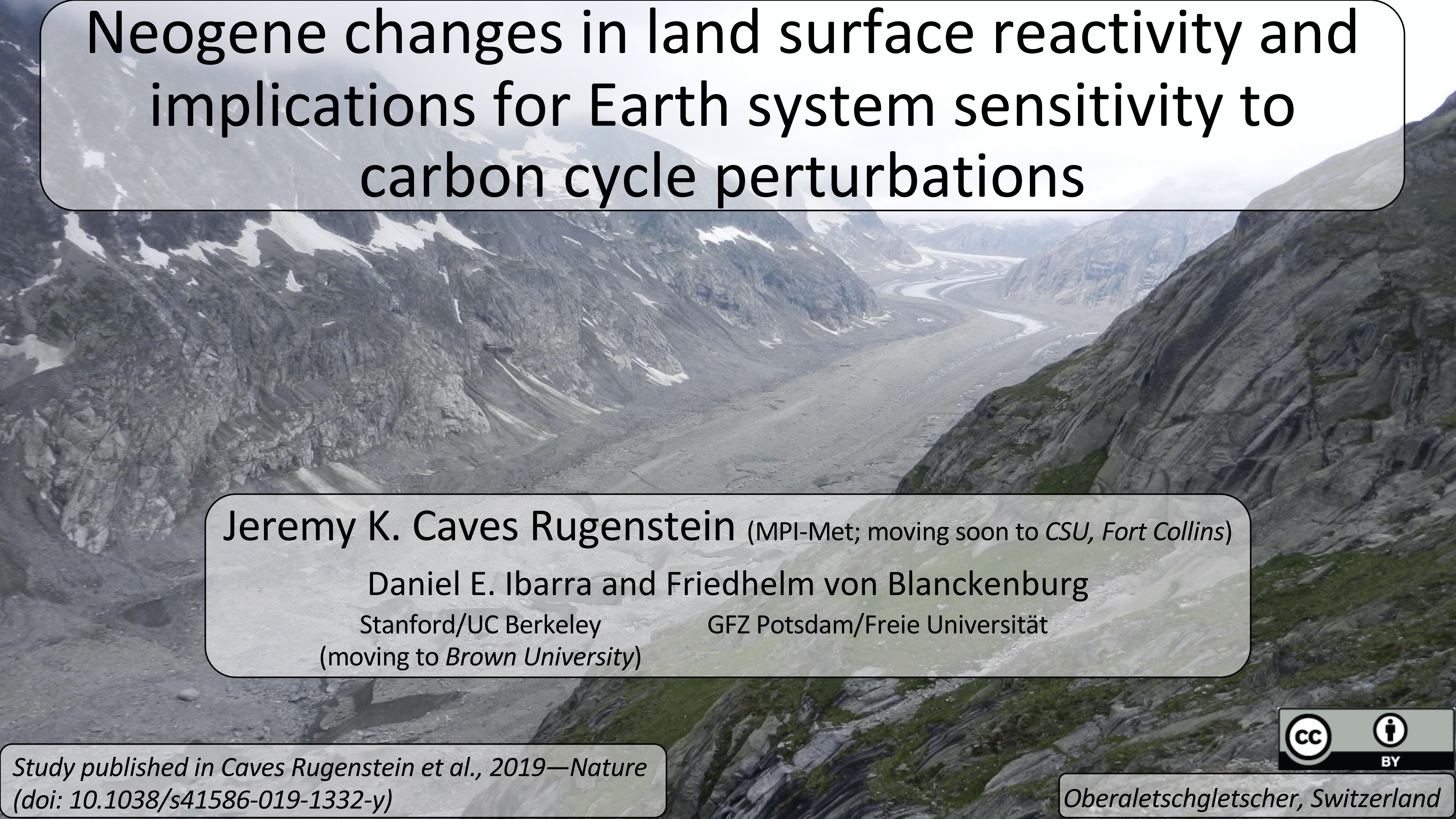
Jeremy K. Caves Rugenstein (MPI-Met; moving soon to *CSU, Fort Collins*)

Daniel E. Ibarra and Friedhelm von Blanckenburg

Stanford/UC Berkeley (moving to *Brown University*)

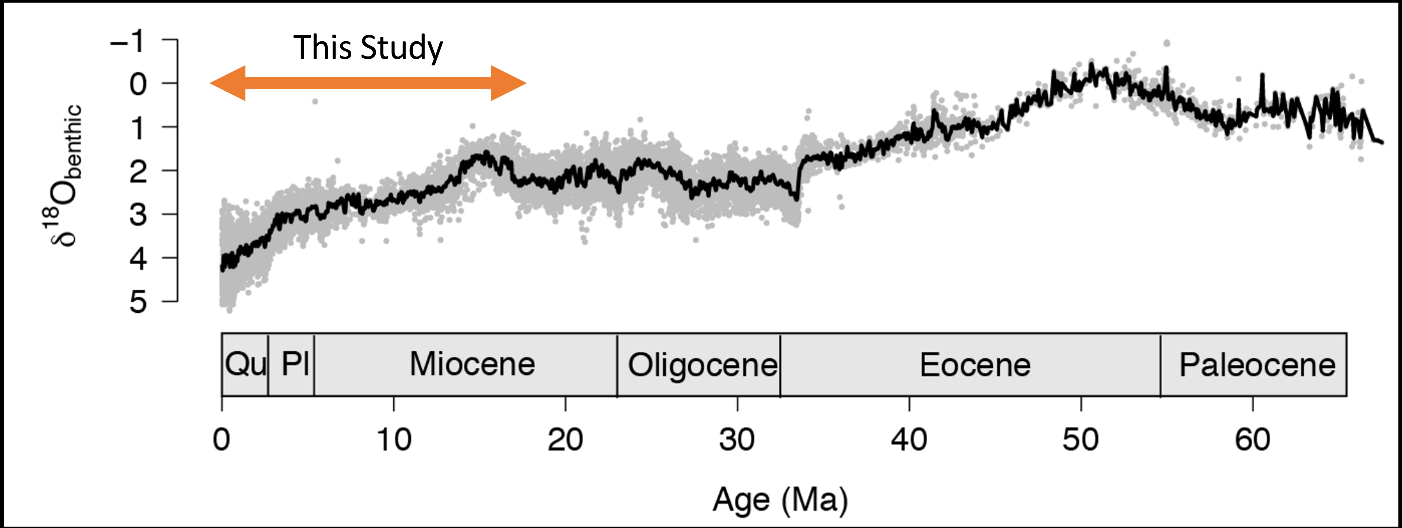
GFZ Potsdam/Freie Universität

Study published in Caves Rugenstein et al., 2019—Nature (doi: 10.1038/s41586-019-1332-y)



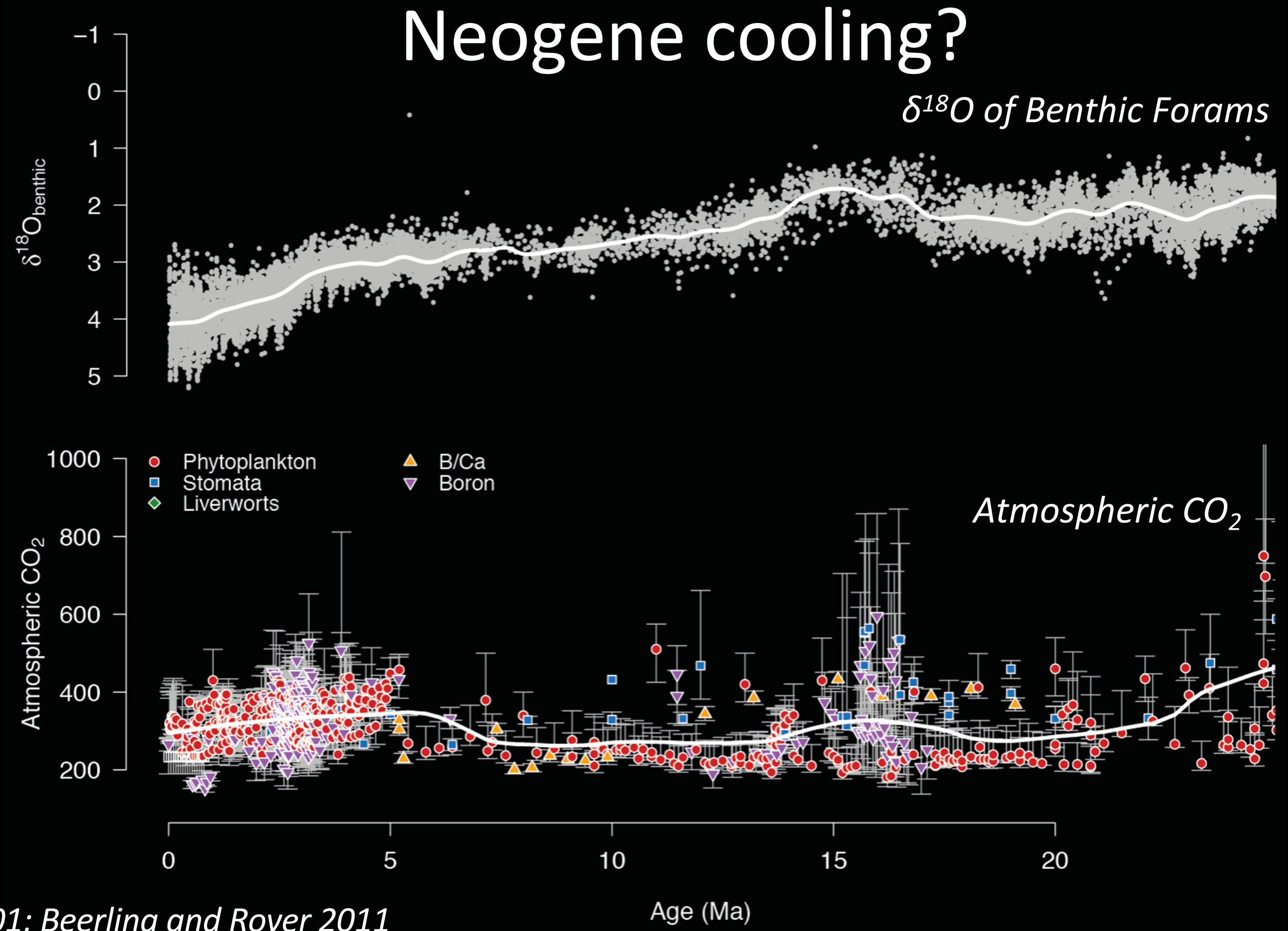
Oberaletschgletscher, Switzerland

Cenozoic Cooling



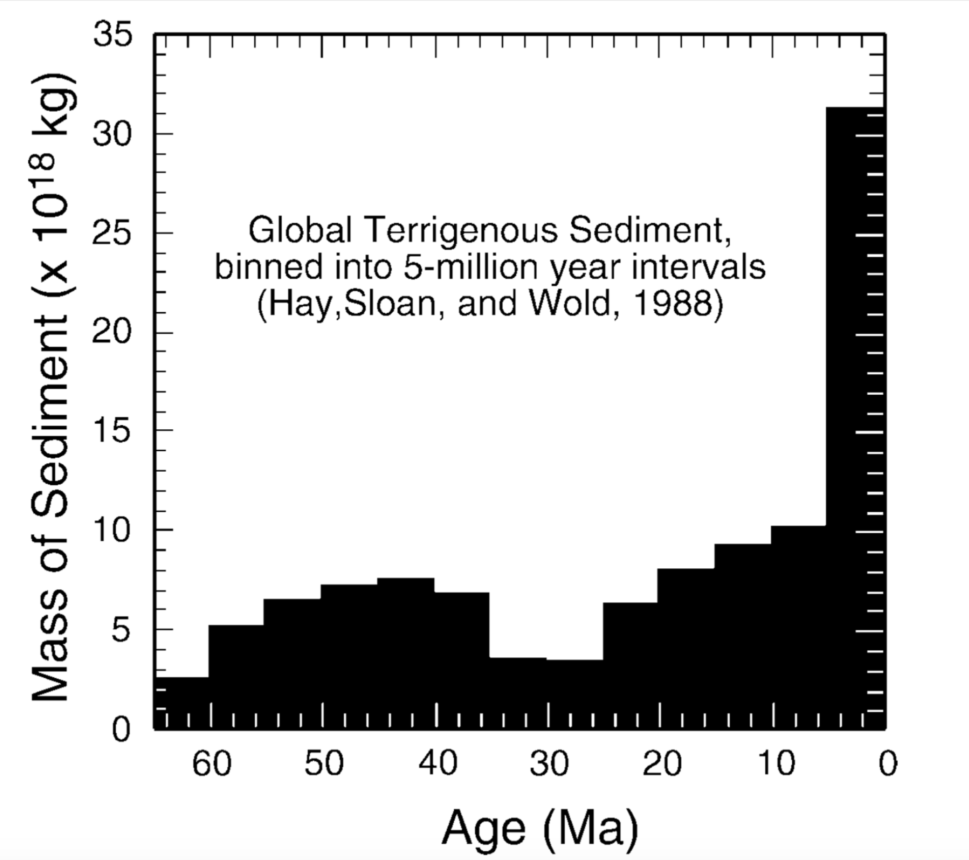
Zachos et al. 2001

Motivating Question: What drove Neogene cooling?



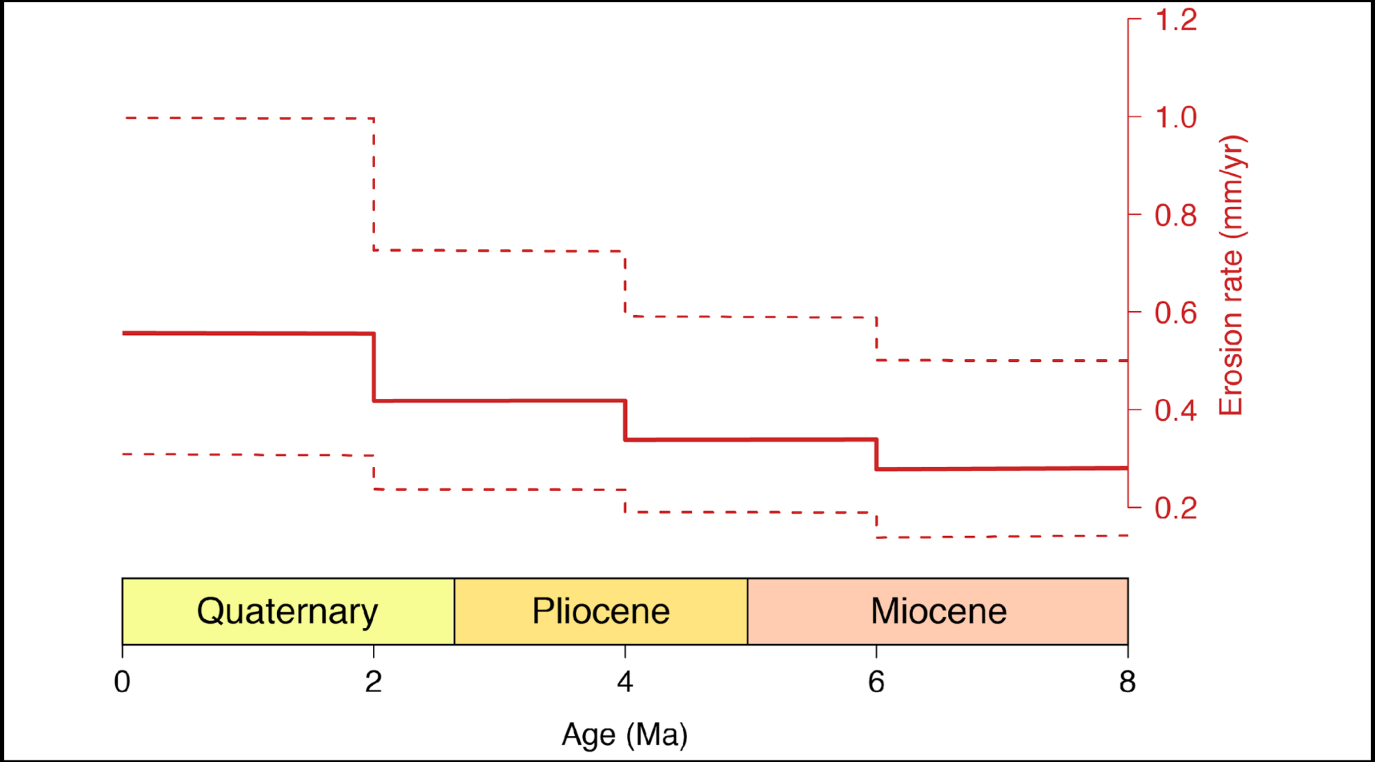
Zachos et al. 2001; Beerling and Royer 2011

Global Increase in Erosion?



Molnar 2004—*Ann. Rev. EPS*

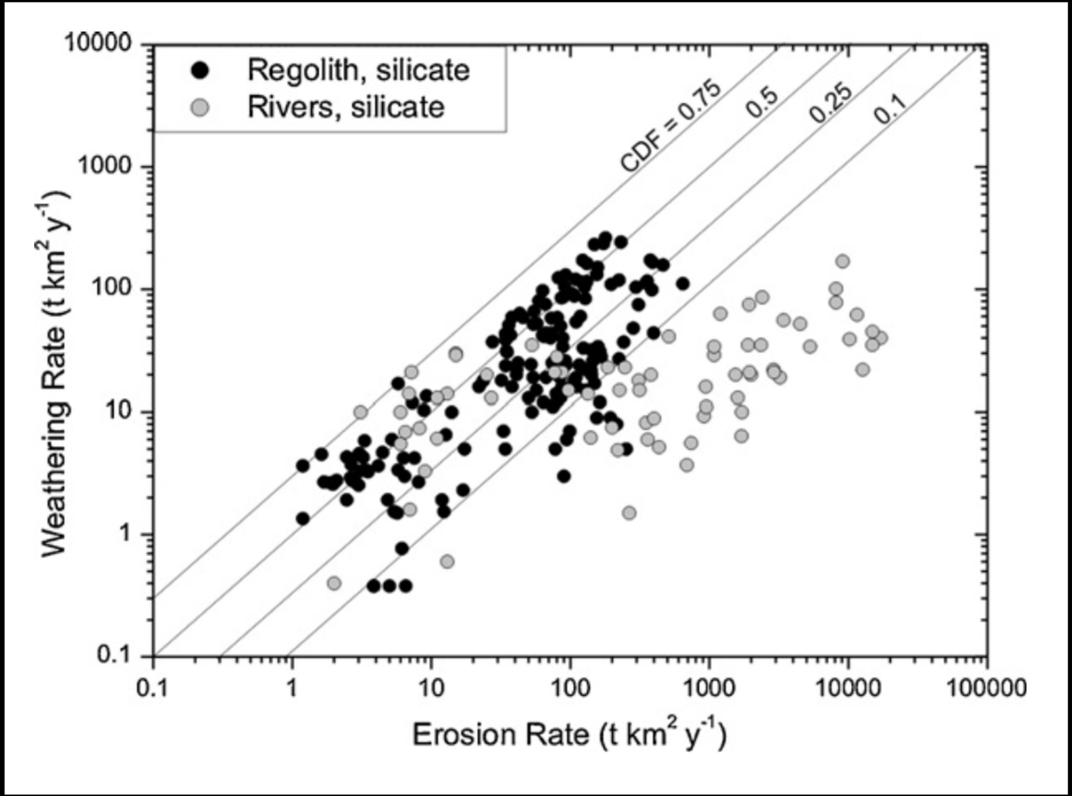
Mountain Increase in Erosion?



Thermochronometry Data

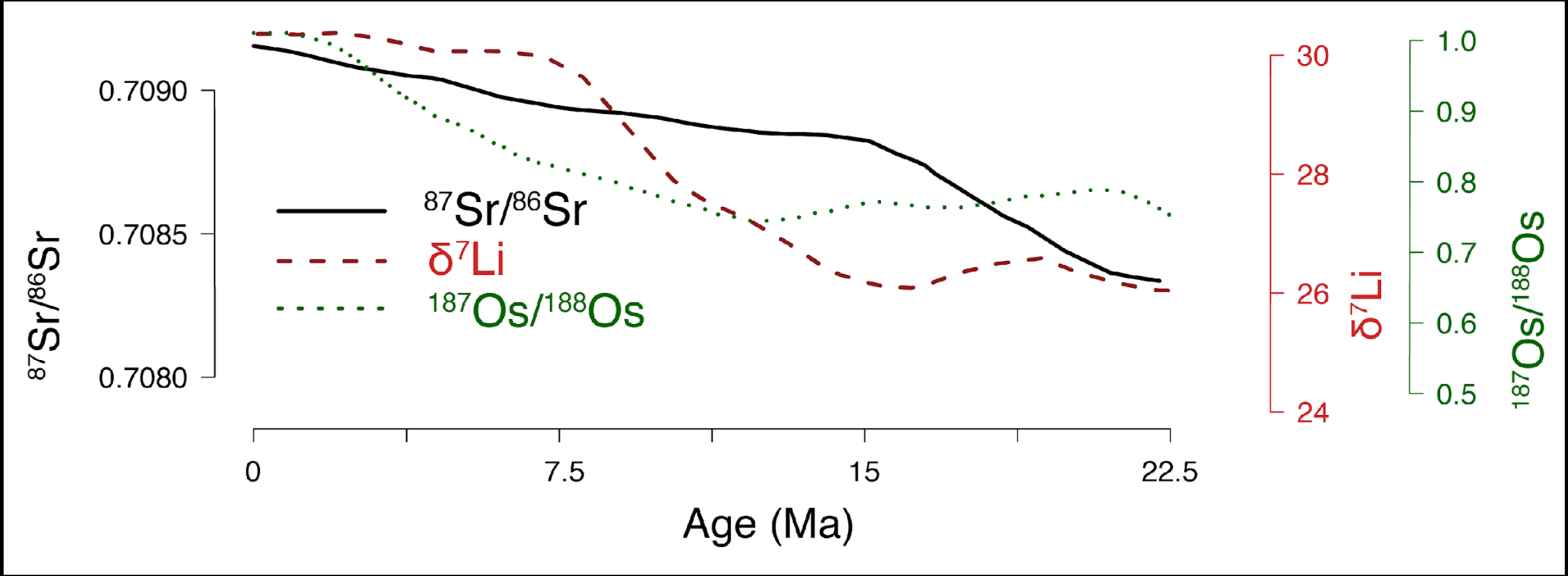
Herman et al. 2013—*Nature*

Erosion & Weathering are Coupled



Dixon and von Blanckenburg 2012—*CRG*

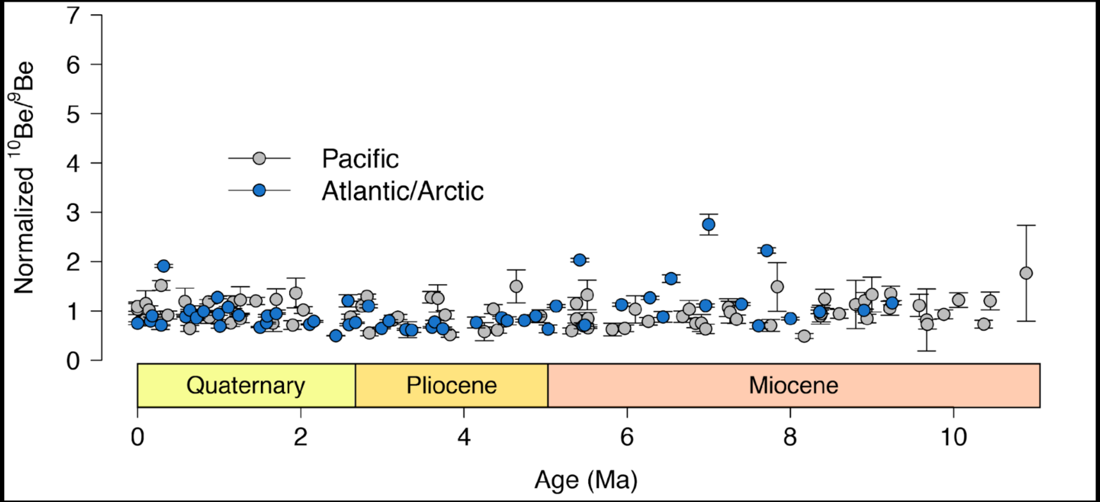
Was there a corresponding increase in weathering?



Raymo et al. 1988; Misra and Froehlich 2012; McCauley and DePaolo 1997; Torres et al., 2014

Arguments against an erosional/weathering increase

- Sadler Effect (timescale artifact)
- Spatial Averaging Bias (Schildgen et al., 2018—*Nature)*
- No large weathering change possible without a change in degassing
  - Carbon cycle models (Kump and Arthur, 1997; Li and Elderfield, 2013; Caves et al., 2016)
  - Marine $^{10}Be/^{9}Be$



Willenbring and von Blanckenburg 2010—*Nature*

The marine isotope records indicate increasing reactivity of the land surface—sustained by increasing erosion—that drove cooling, at constant weathering fluxes

Supported by:
Increasing and then constant δ^7Li
Constant $^{10}Be/^{9}Be$

We develop a parsimonious carbon cycle model (CLiBeSO-W) to solve for the required increase in erosion to explain seawater δ^7Li, seawater $^{10}Be/^{9}Be$, and atmospheric CO_2 over the Neogene

C | Li | Be | S | O — W Model

Adapted from GEOCARB and COPSE

1) Weathering fluxes sensitive to erosion *and* climate
2) Li isotopes
   – Tracks weathering intensity
3) Be isotopes
   – Tracks weathering flux

Approach: Solve for the required increase in erosion that can match Neogene $p\mathrm{CO_2}$, $\delta^7\mathrm{Li}$, and $^{10}\mathrm{Be}/^{9}\mathrm{Be}$ data while maintaining carbon mass balance

Model: Silicate Weathering Flux

- Climate (CO_2) and Erosion (E) dependencies

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$$W_{sil} =$$

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$$W_{sil} = k\underbrace{\left(E_R^{\alpha_{sil}}\right)}_{\text{Erosional dependency}}$$

- E_R is ratio of erosion
- $\alpha_{sil} < 1$ and provides non-linear response

See Shields and Mills 2017–PNAS

Model: Silicate Weathering Flux

- Climate (CO_2) and Erosion (E) dependencies

$$W_{sil} = k\underbrace{\left(E_R^{\alpha_{sil}}\right)}_{\text{Erosional dependency}}\underbrace{\left[Log_2(R_{CO2}) + 1\right]}_{\text{Climatic dependency}}$$

- E_R is ratio of erosion
- $\alpha_{sil} < 1$ and provides non-linear response
- RCO_2 is ratio of CO_2 to modern

Modified from Caves et al. 2016 – *EPSL*
See Myhre et al. 1998 – *GRL* for $\log_2$ response

Model: Lithium Isotopes in Rivers (δ^7Li)—Weathering Intensity

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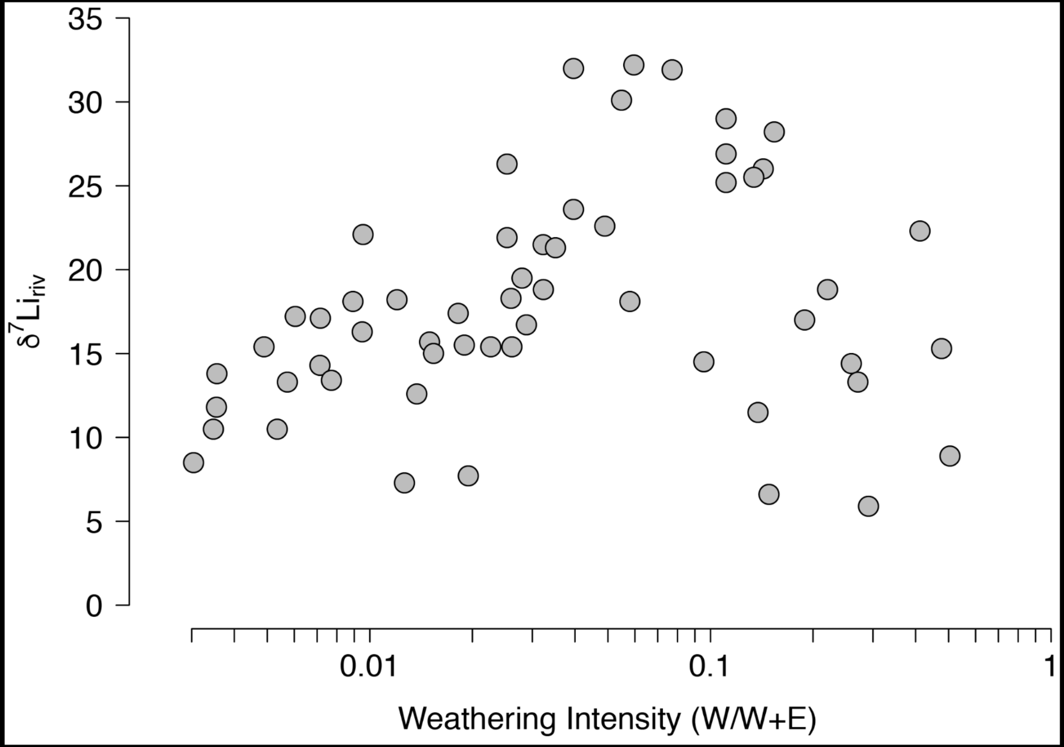

Dellinger et al. 2015—*GCA*

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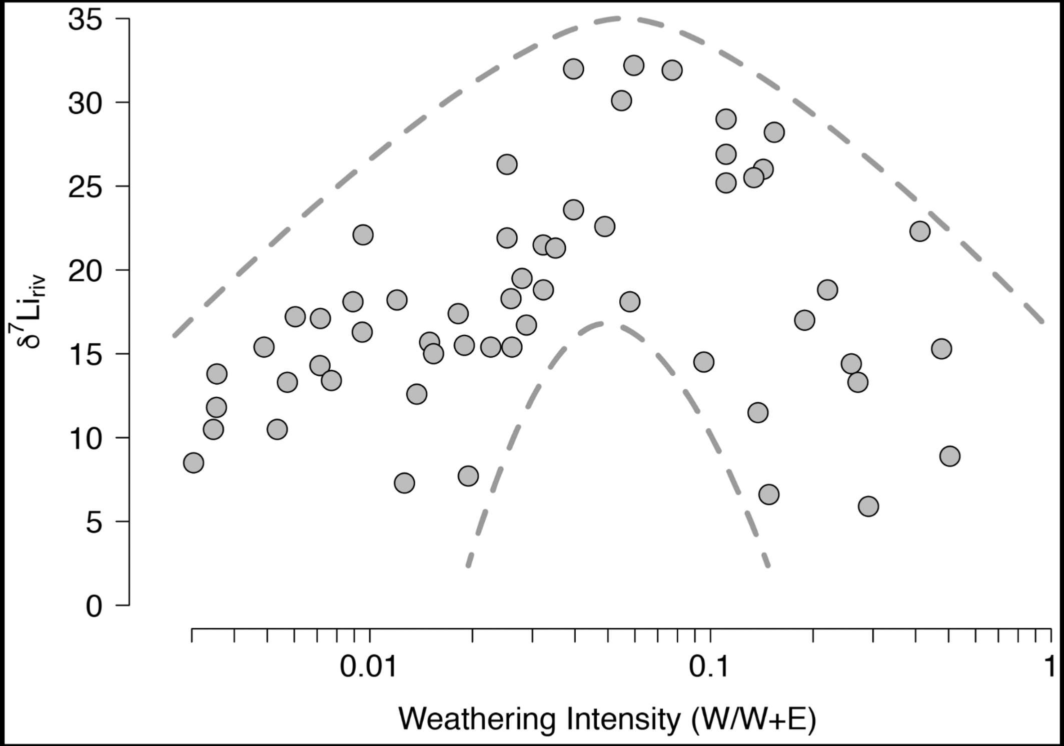

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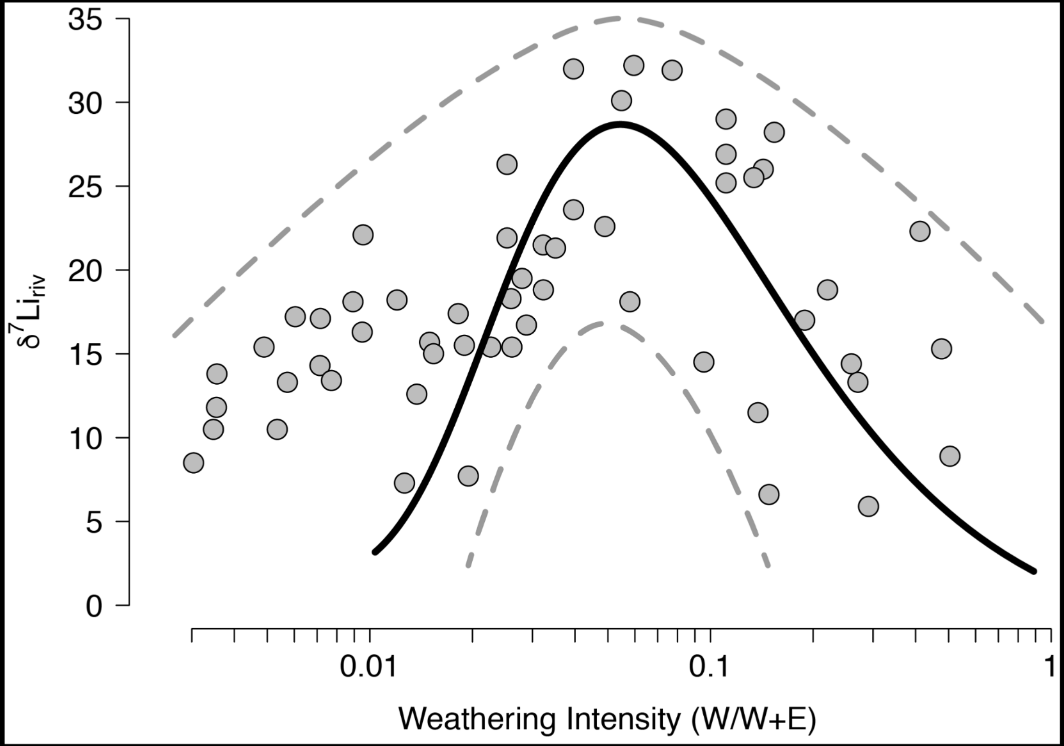

For equations see Dellinger et al. 2015—*GCA*; Bouchez et al. 2013–*AJS*

Model: Beryllium Isotopes ($^{10}Be/^{9}Be$)—Weathering Flux

Continents

von Blanckenburg et al. 2012—*EPSL*

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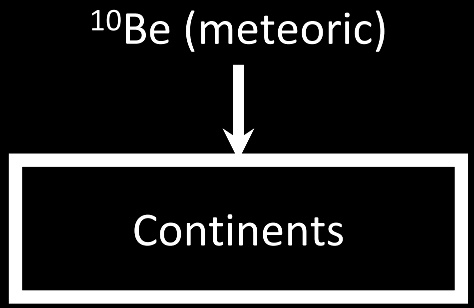

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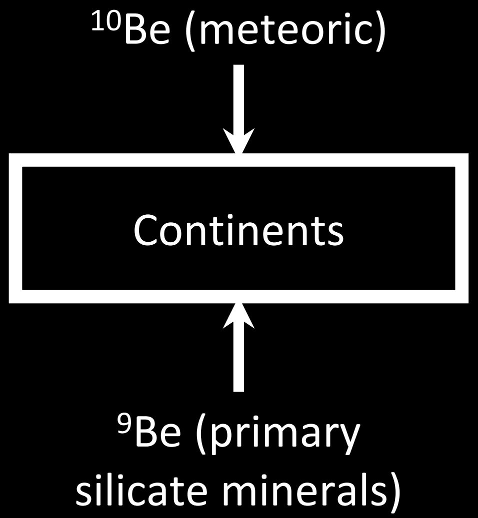

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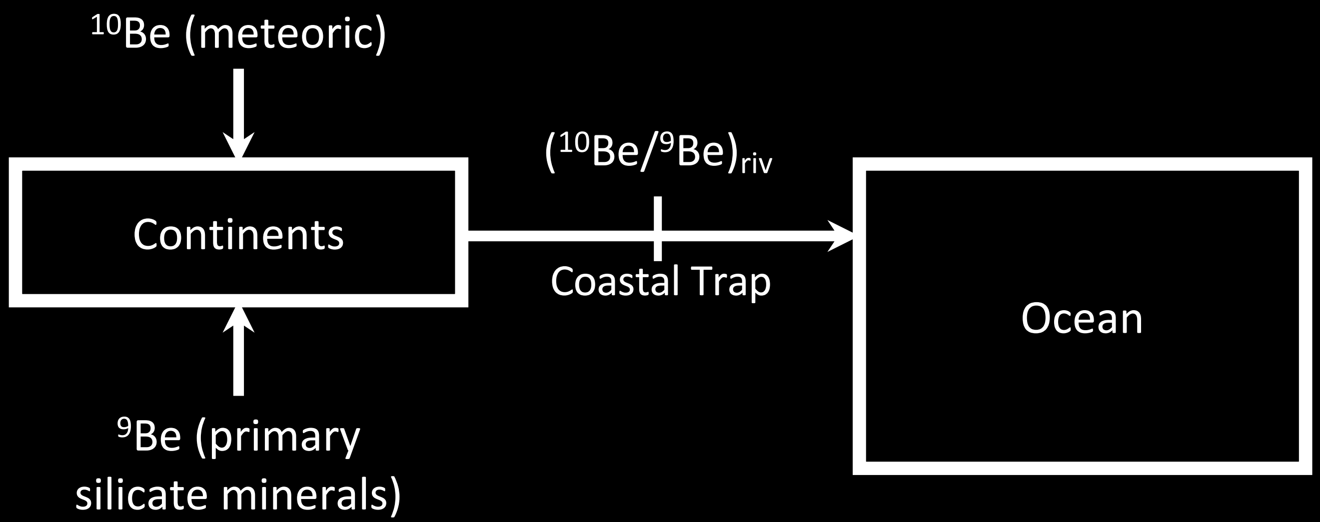

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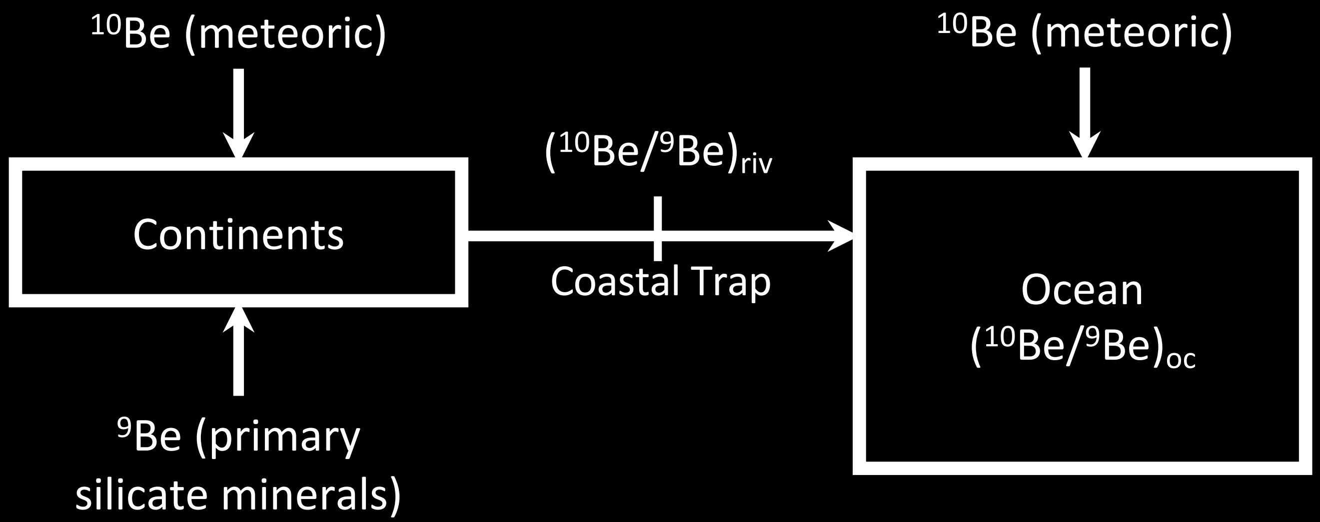

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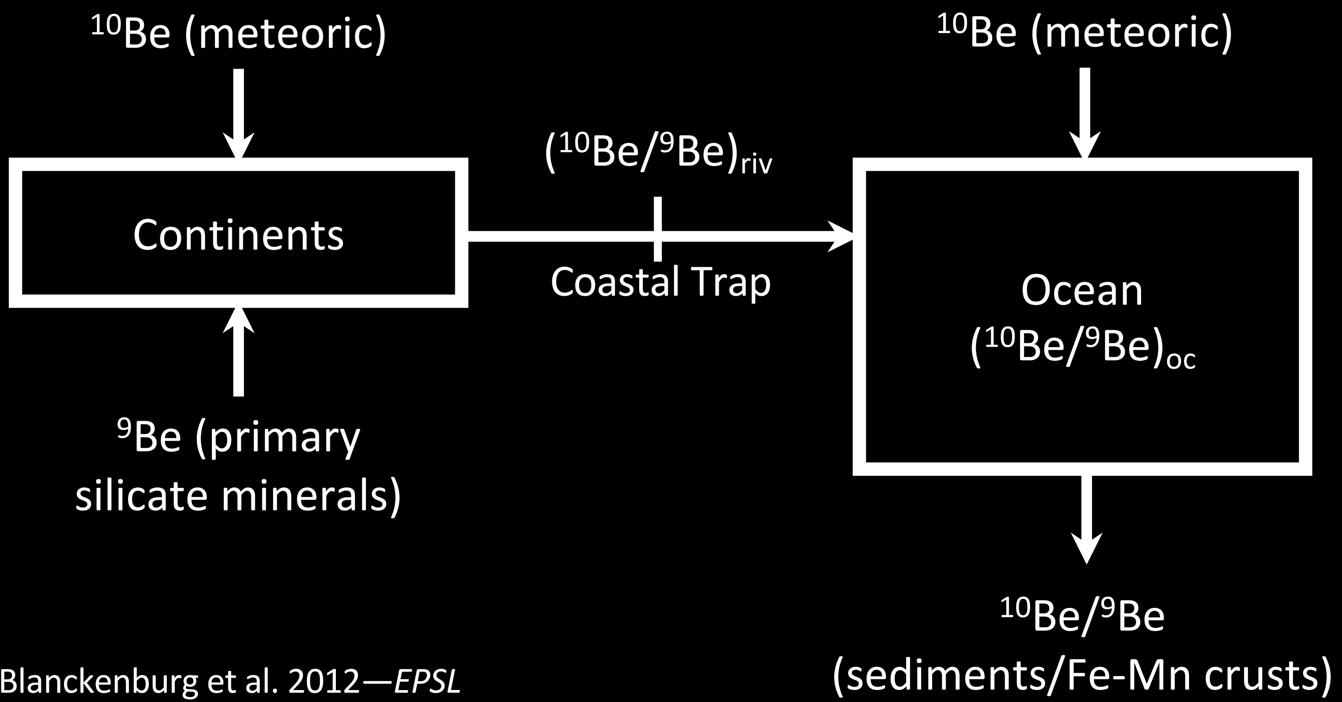

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Monte Carlo Model Inversion

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Monte Carlo Model Inversion

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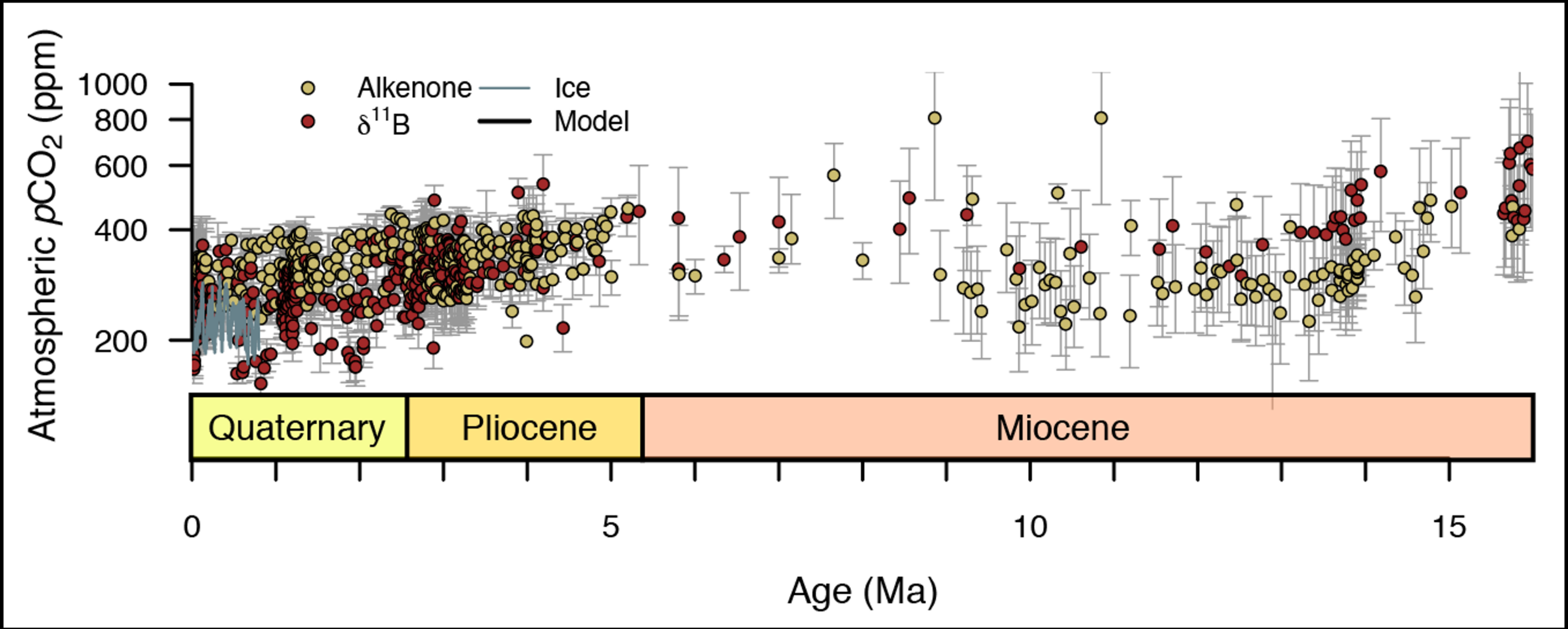
- Simulate 10,000s changes in erosion
- Filter for changes in erosion that best match $\delta^{7}\mathrm{Li}$, $^{10}\mathrm{Be}/^{9}\mathrm{Be}$, and $p\mathrm{CO}_2$ data

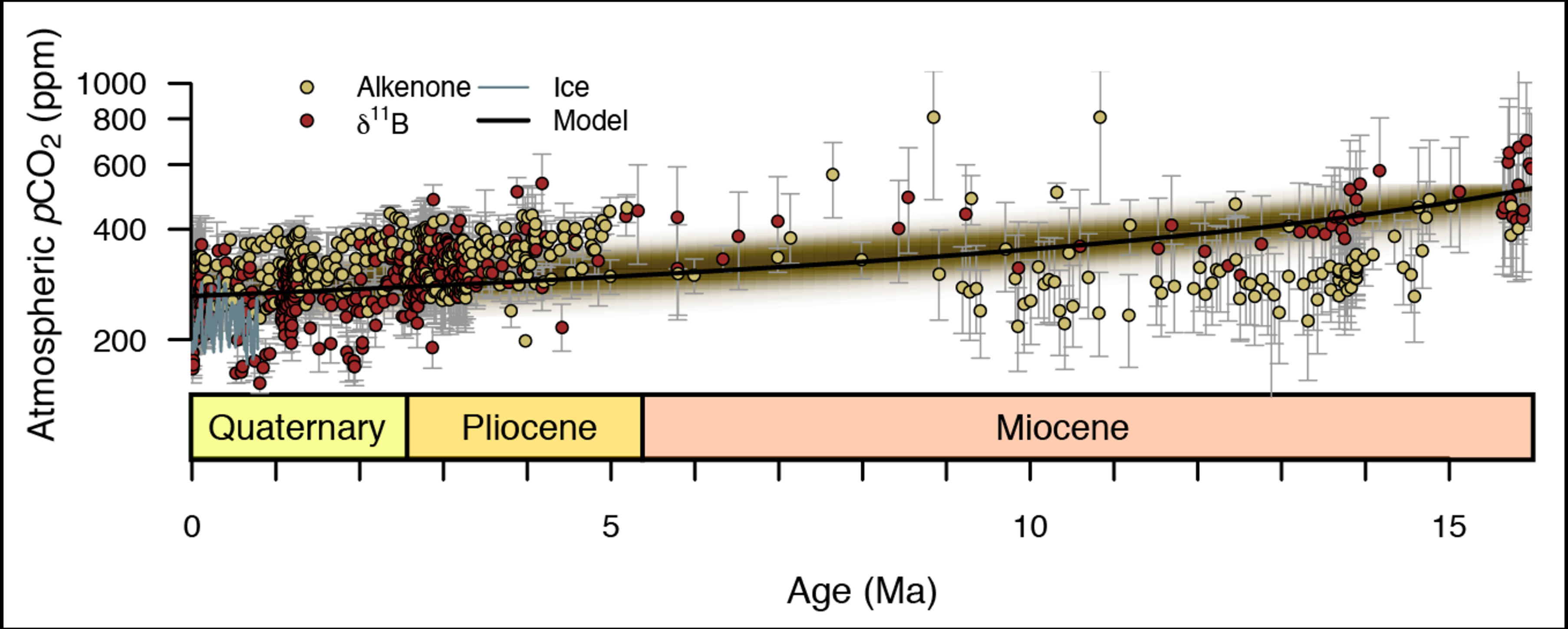
Result: 3.3x (1.9–5.0x)
change in erosion

Erosional Increase—CO_2



Many pCO_2 studies (with thanks to Clara Bolton)

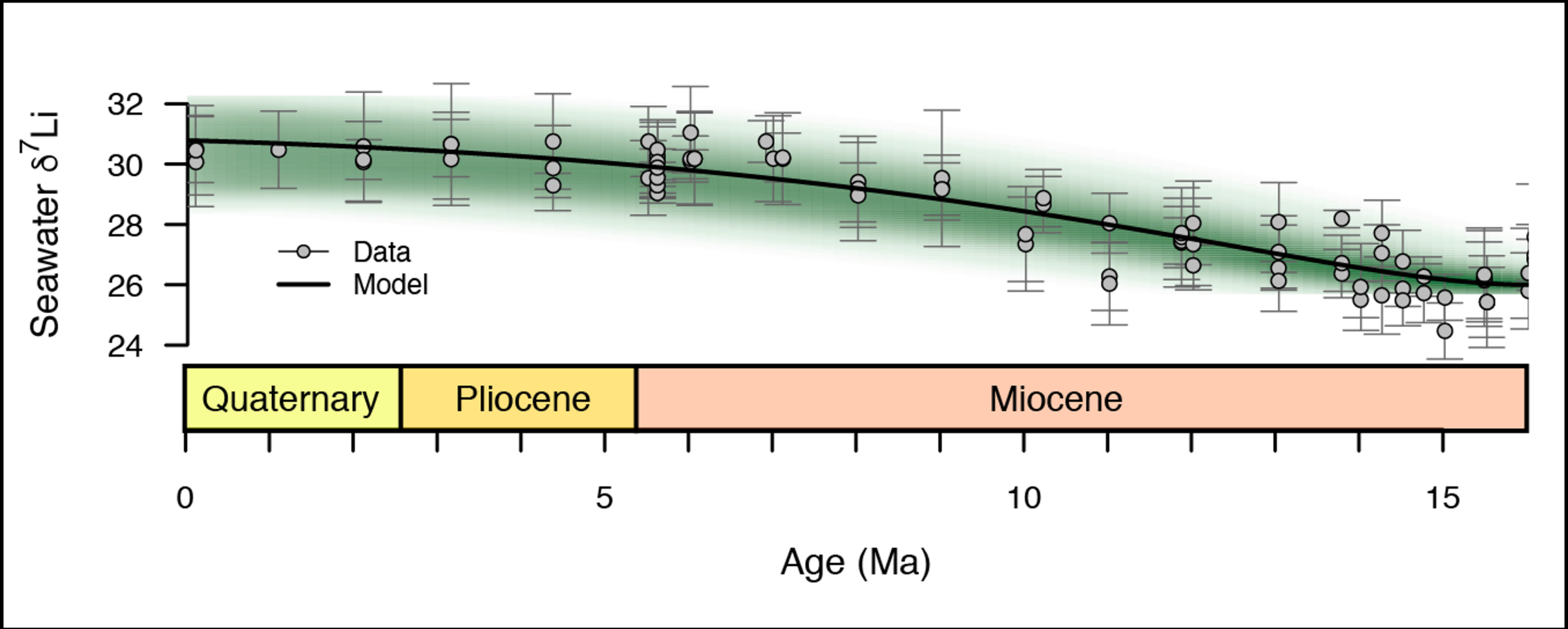
Erosional Increase—CO_2



Solid line is the mean model result; shading indicates all plausible solutions

Caves Rugenstein et al. 2019—*Nature;* Many pCO_2 studies (with thanks to Clara Bolton)

Erosional Increase—δ^7Li



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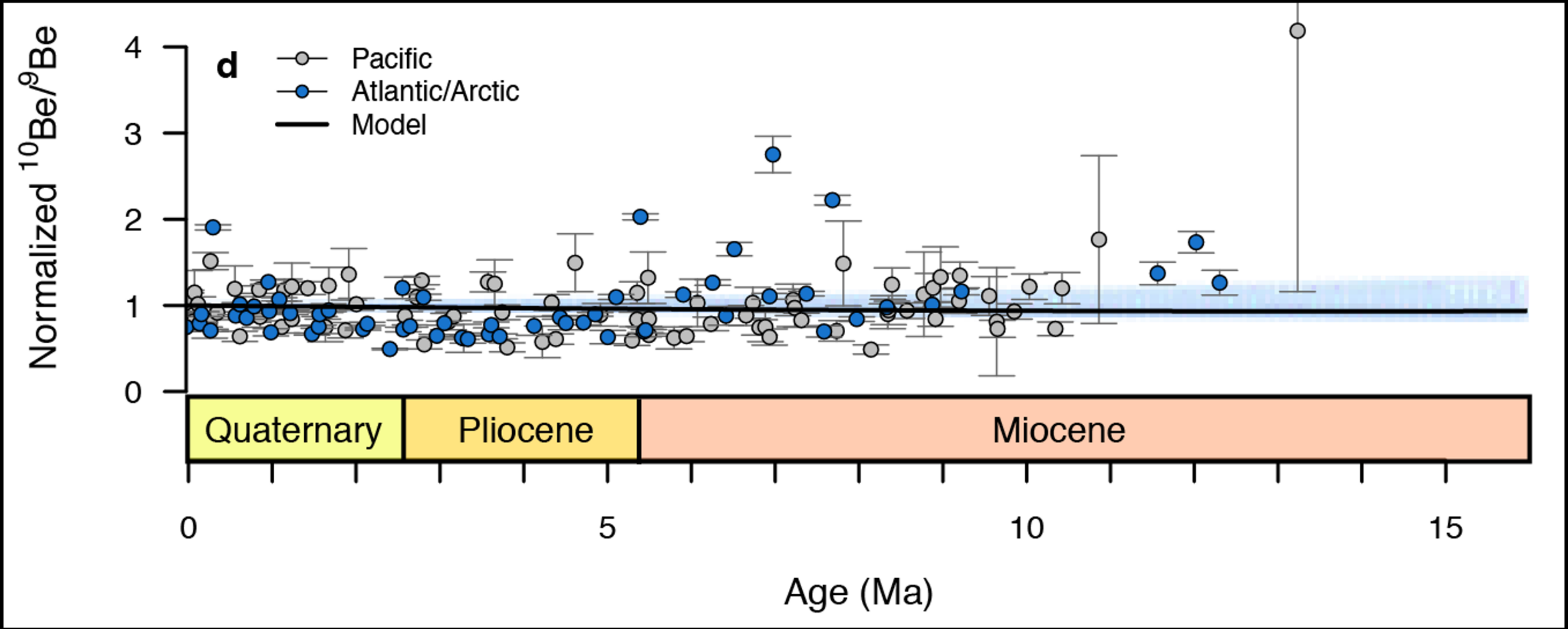
Caves Rugenstein et al. 2019—*Nature*

Erosional Increase—$^{10}Be/^{9}Be$



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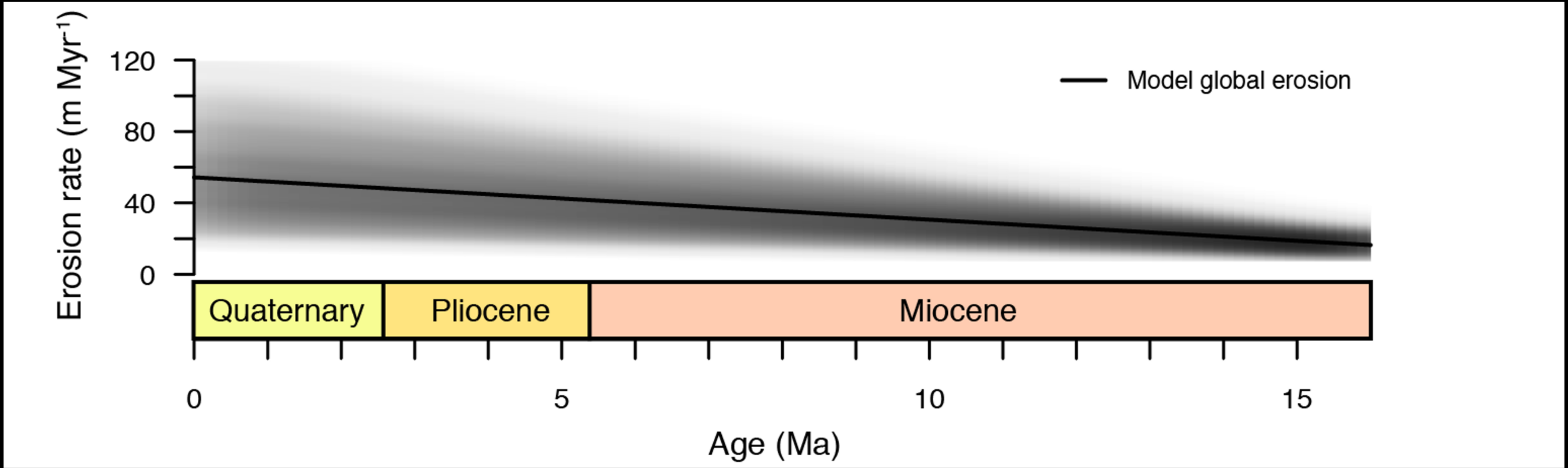
Caves Rugenstein et al. 2019—*Nature*

Erosional Increase—data

- 3.3x (1.9x–5.0x)



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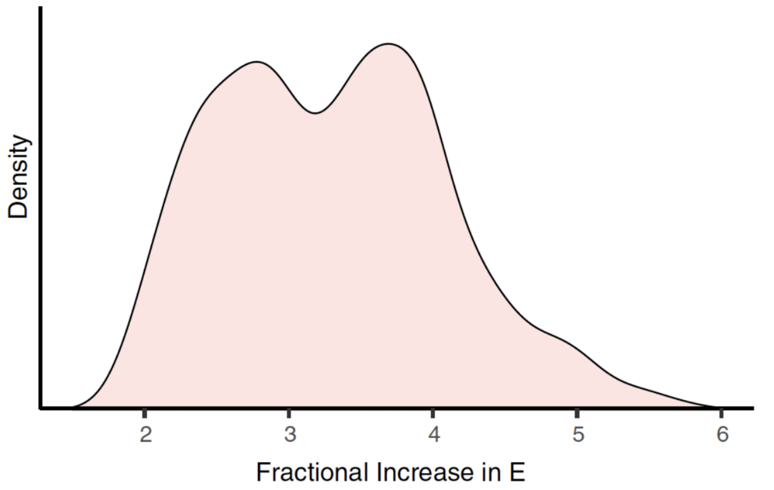

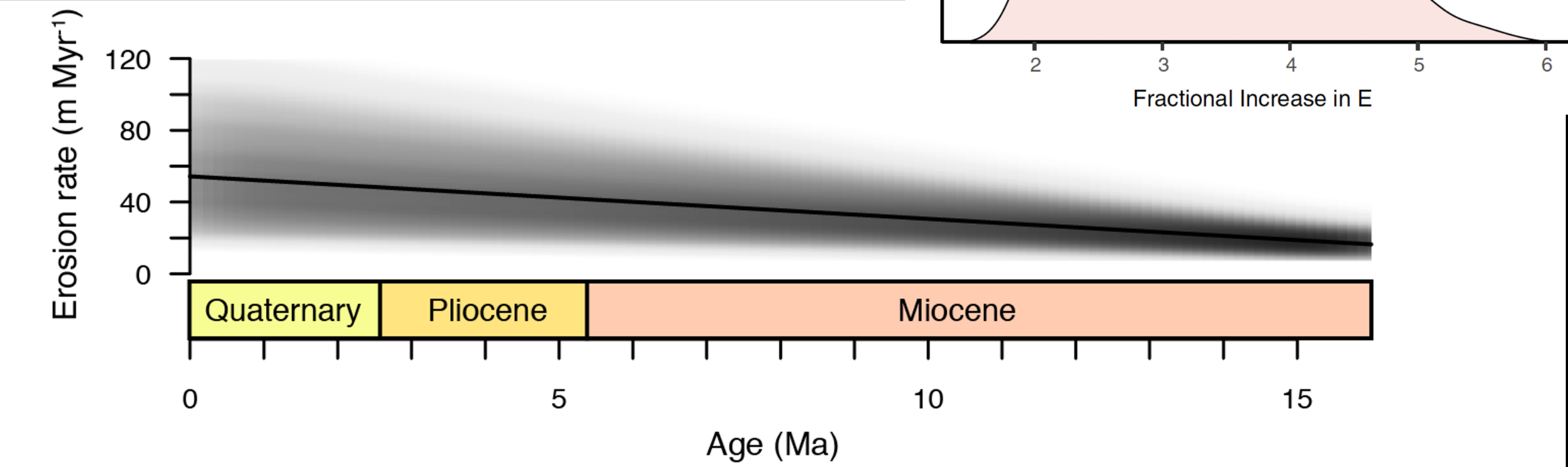

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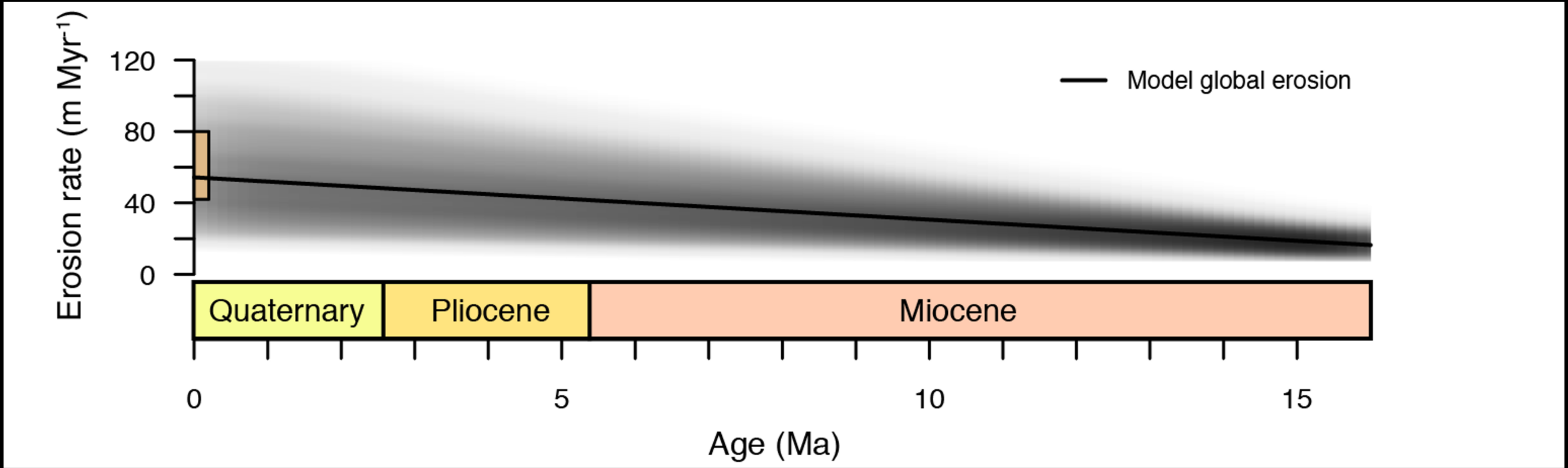

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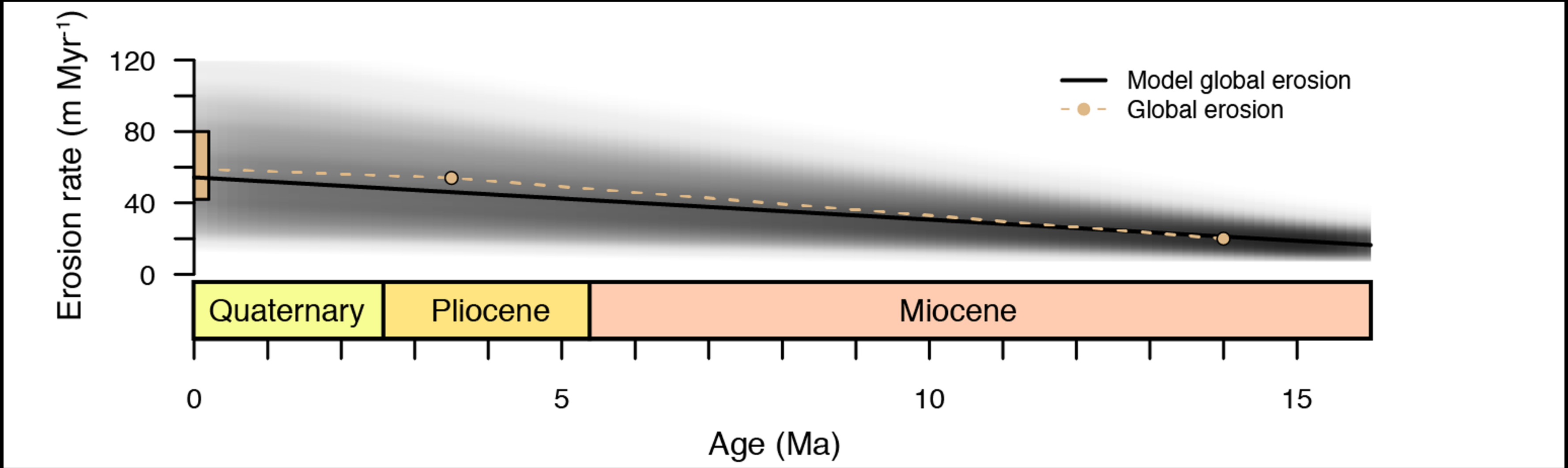

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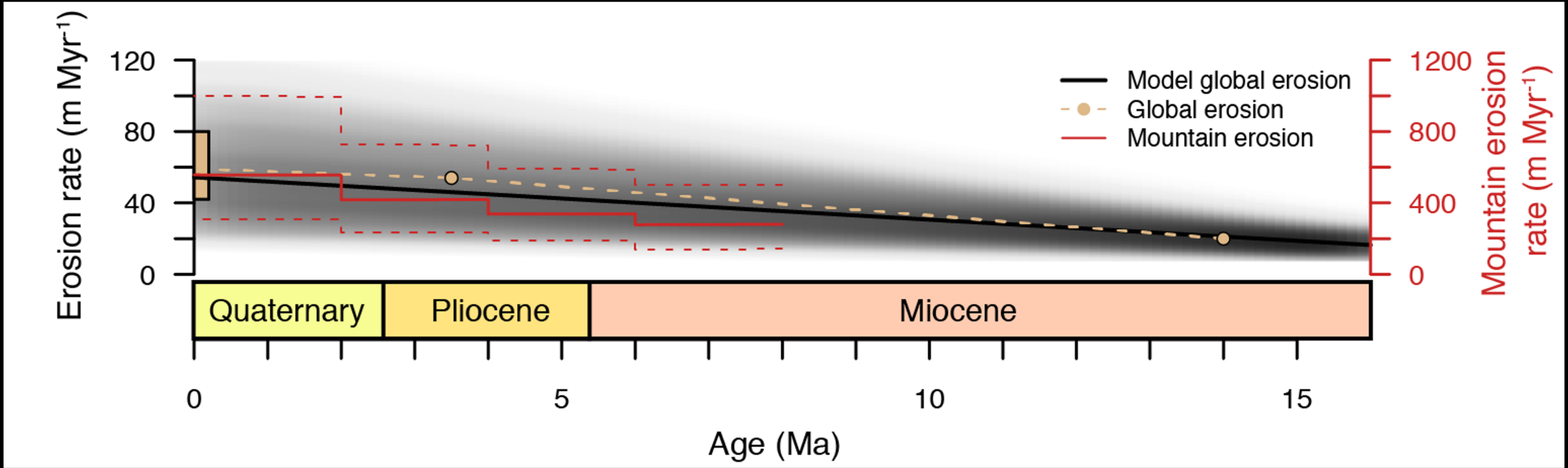

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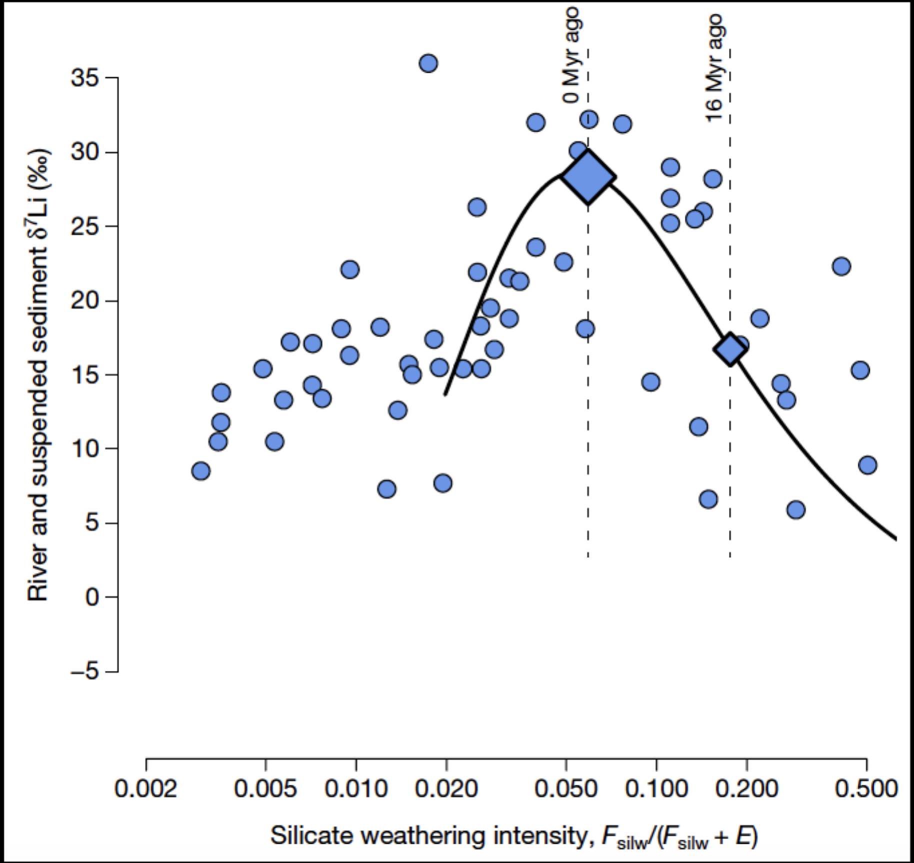
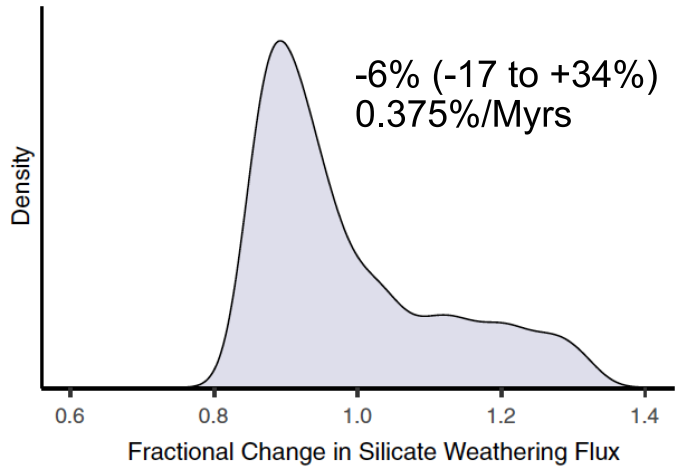
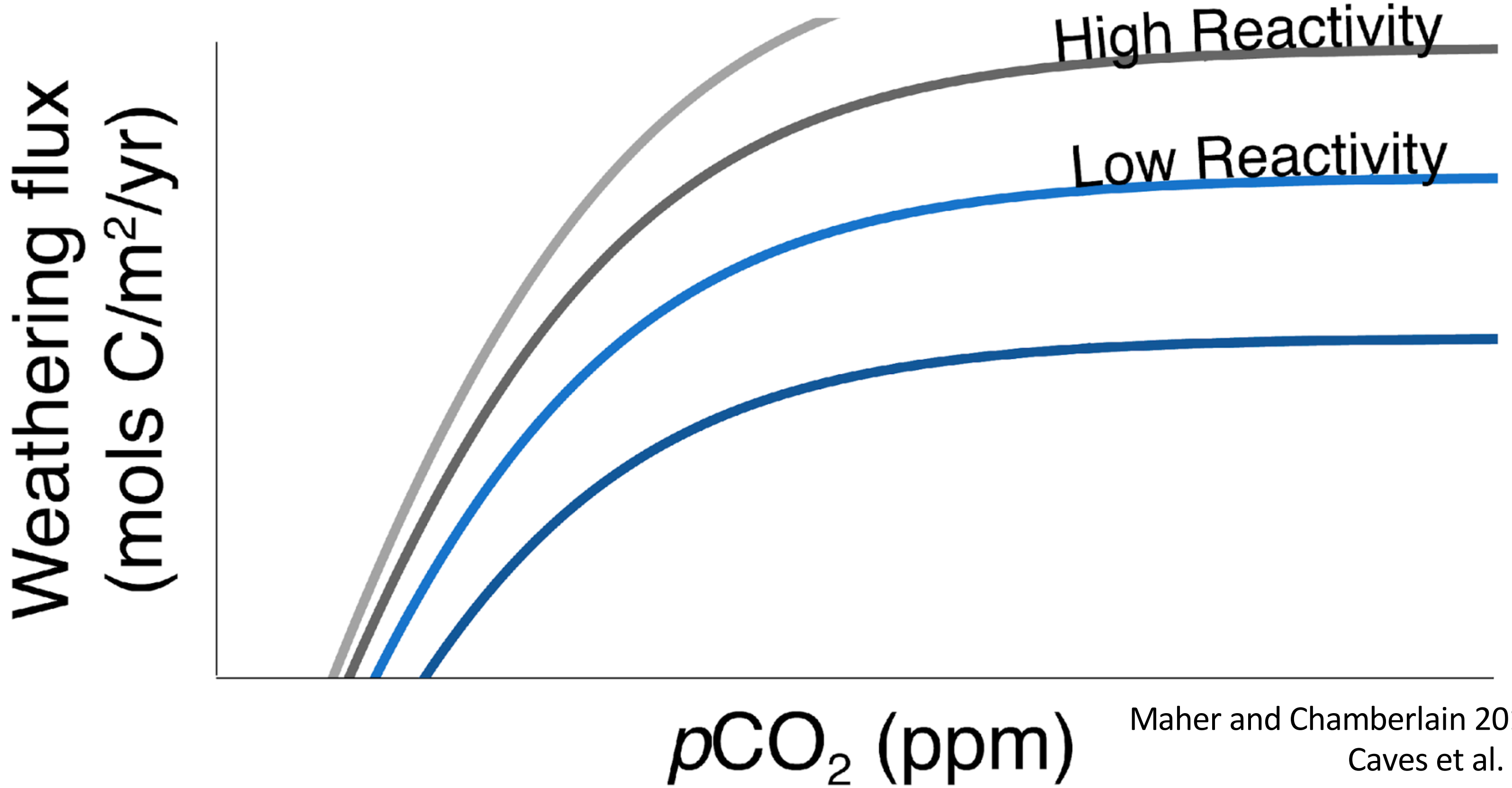
Change in Silicate Weathering Intensity





Caves Rugenstein et al. 2019—*Nature*

Process to remove CO_2



After:
Maher and Chamberlain 2014–*Science*
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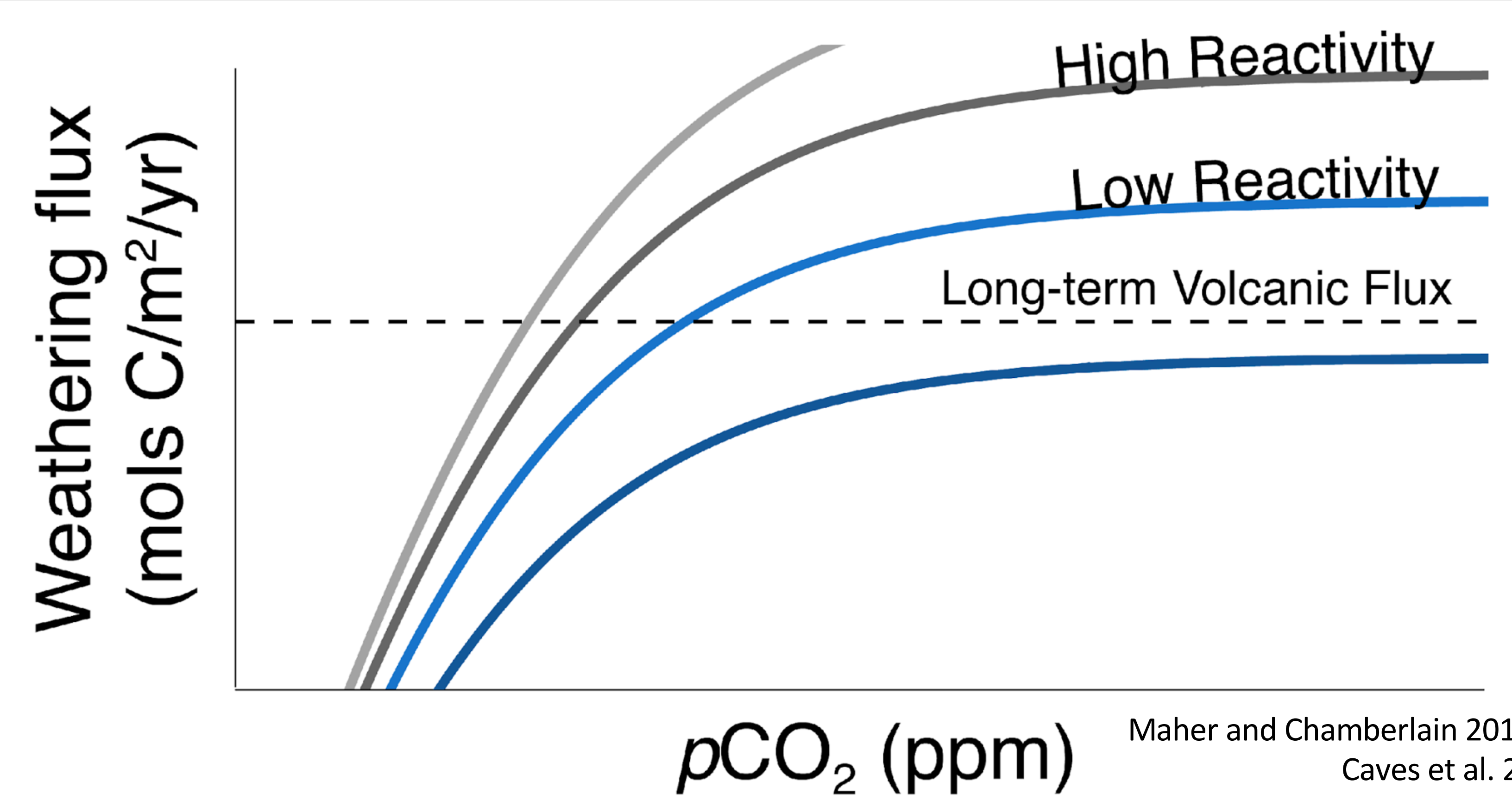

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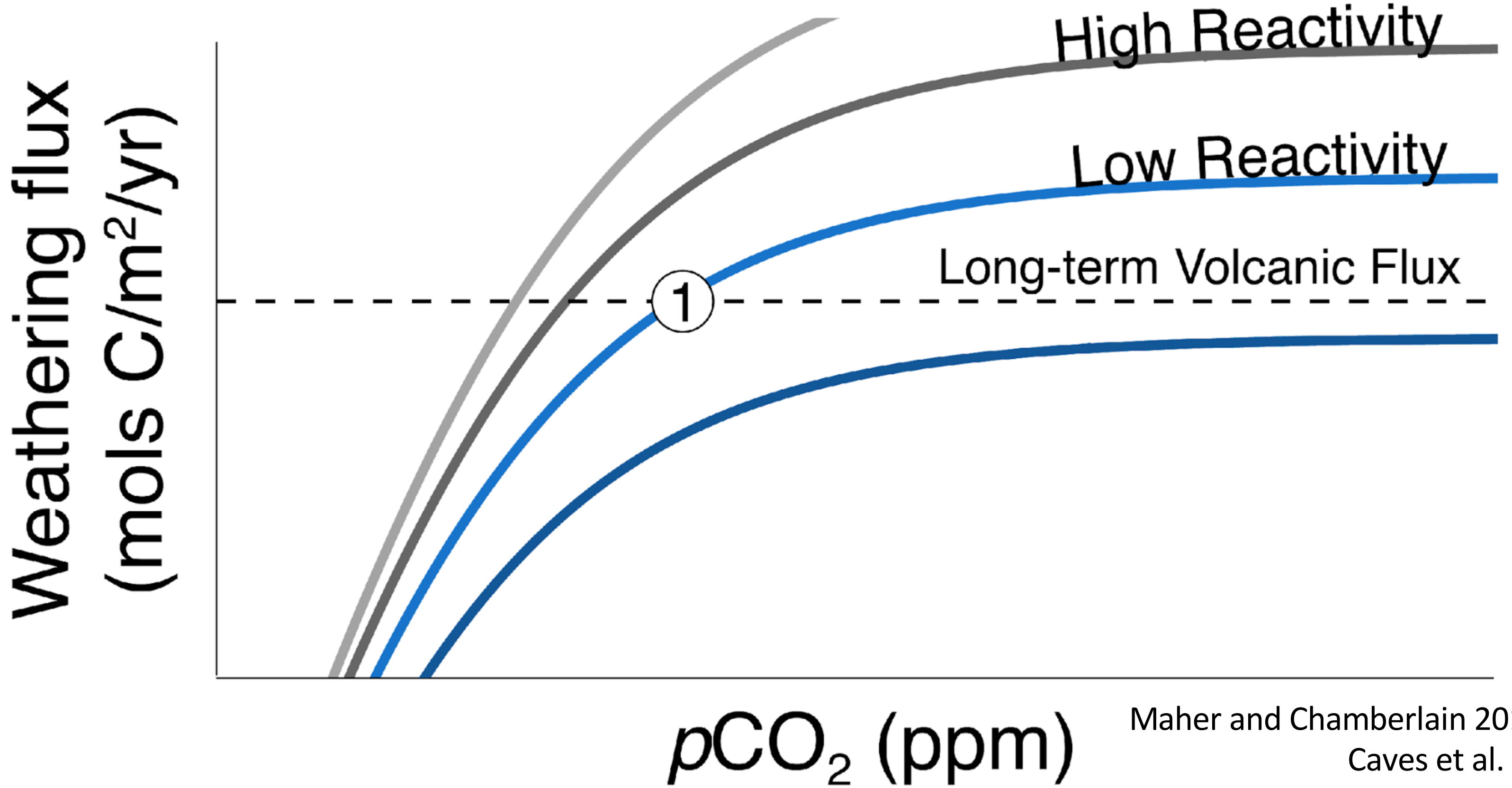

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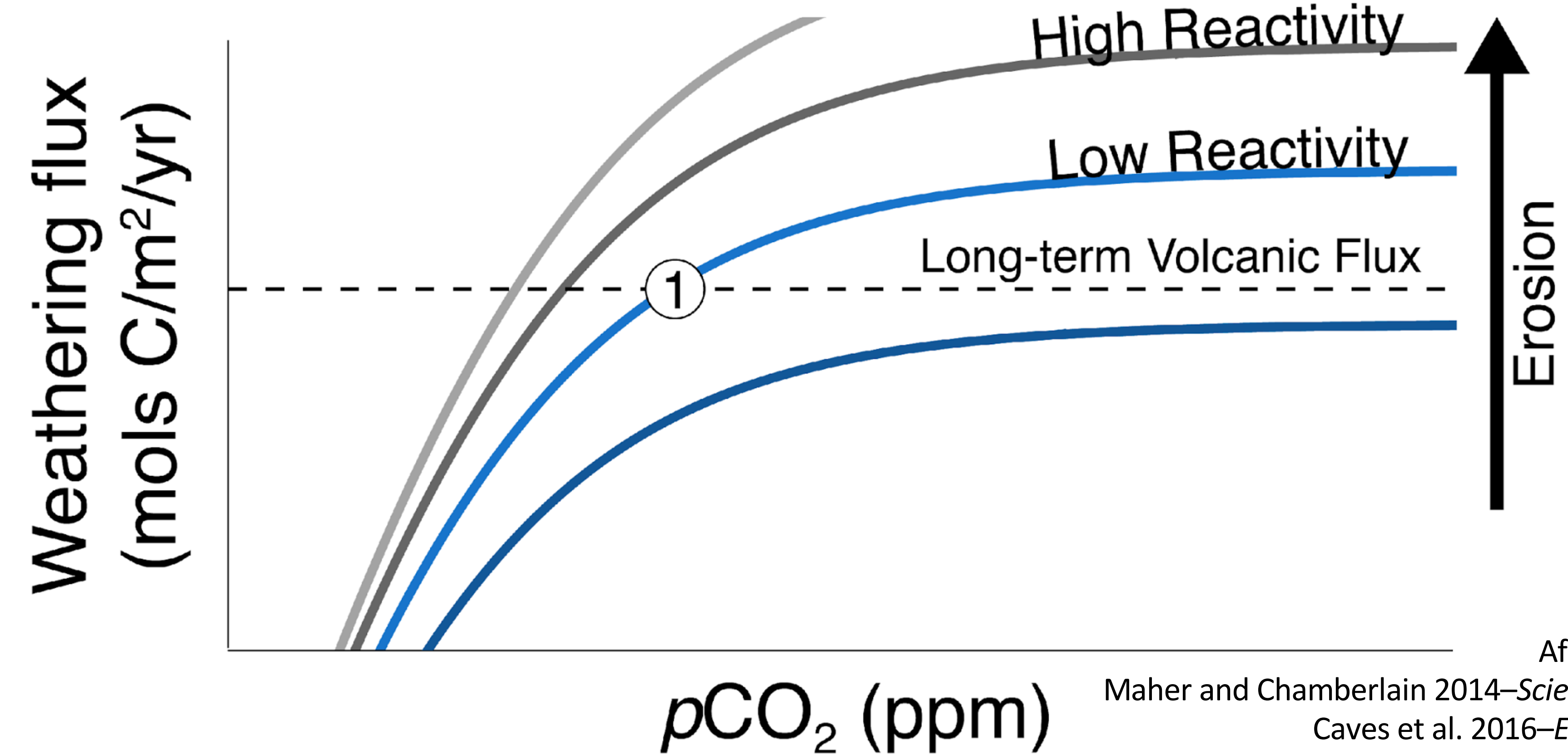

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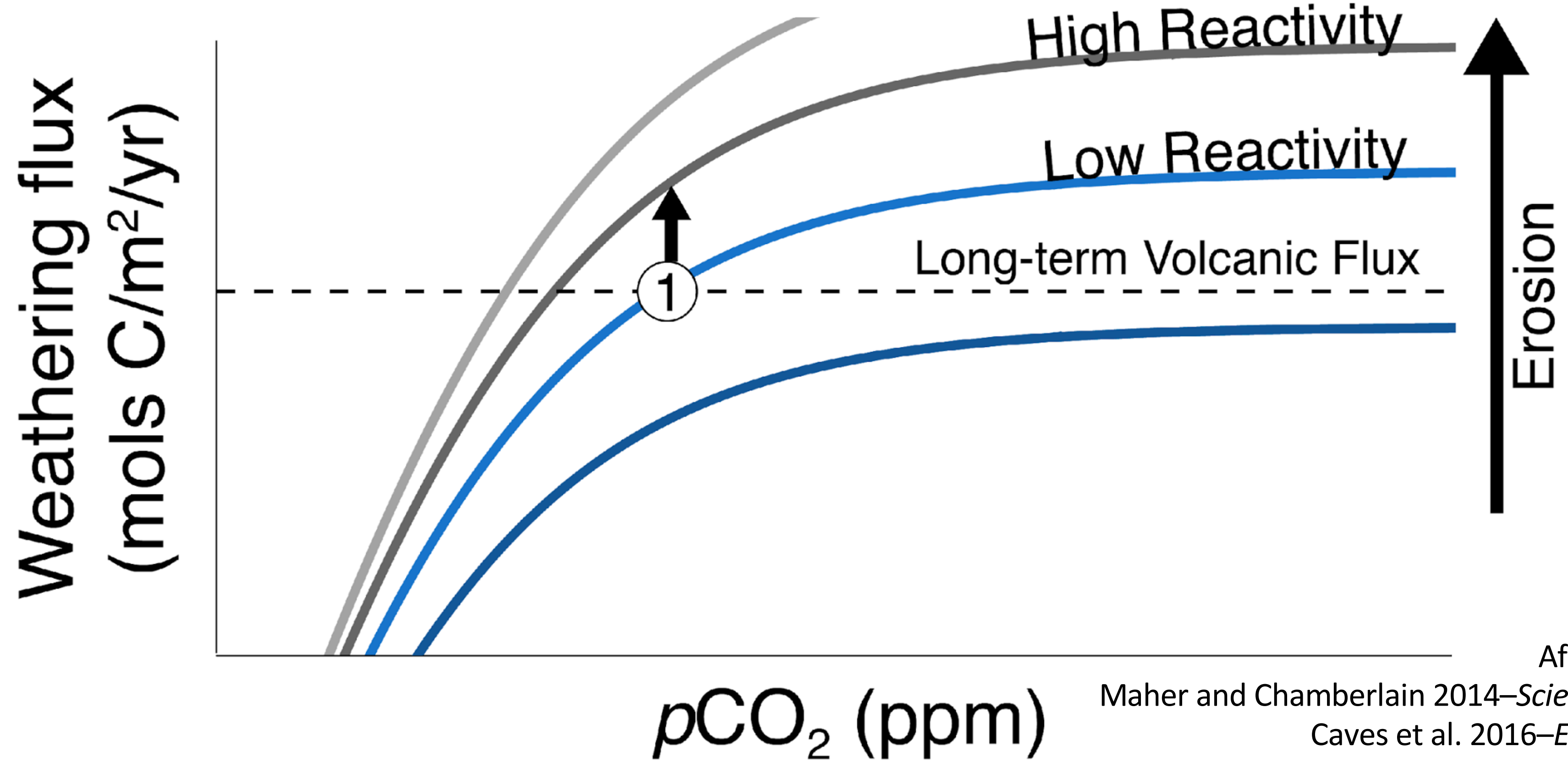

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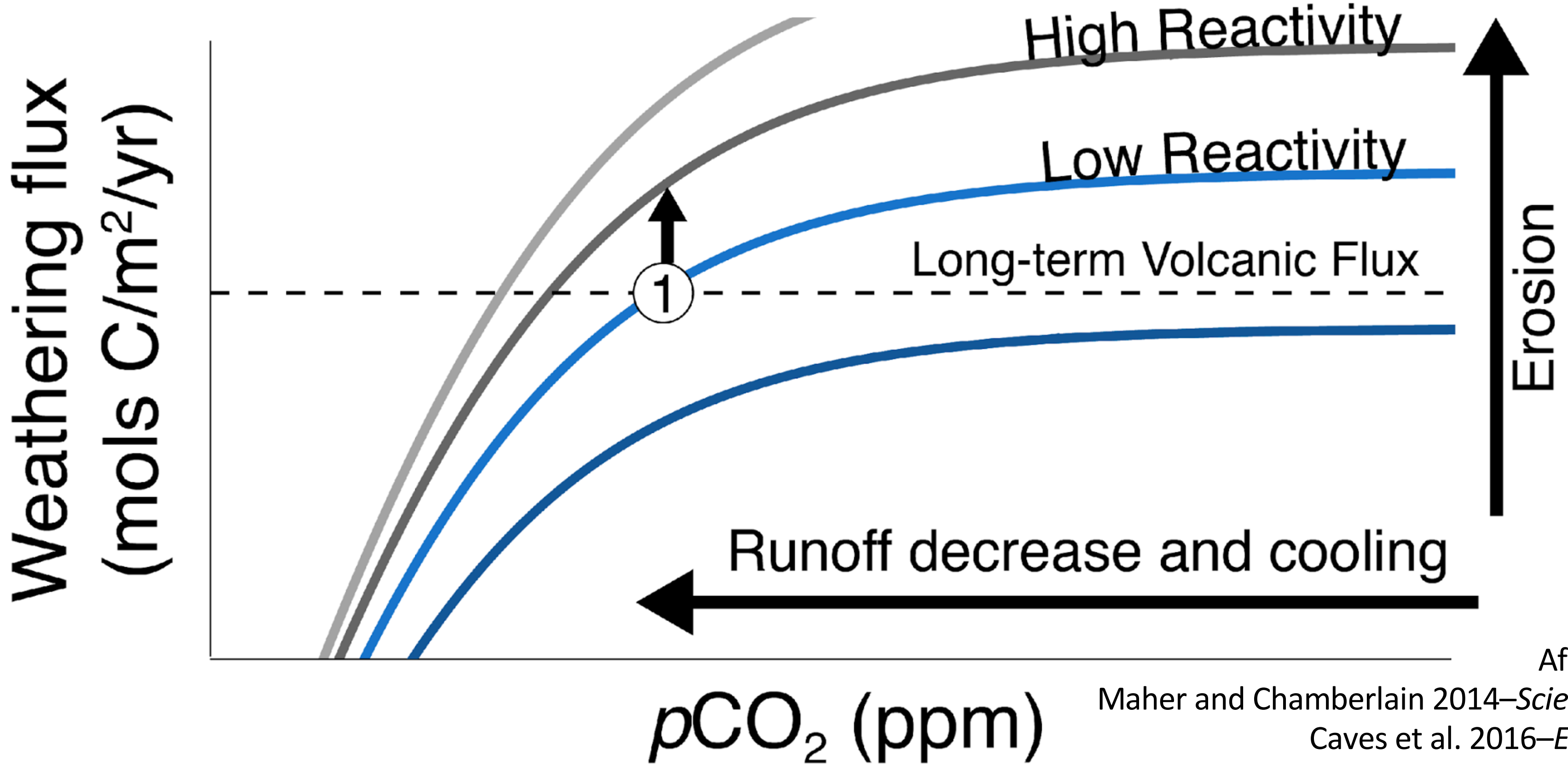

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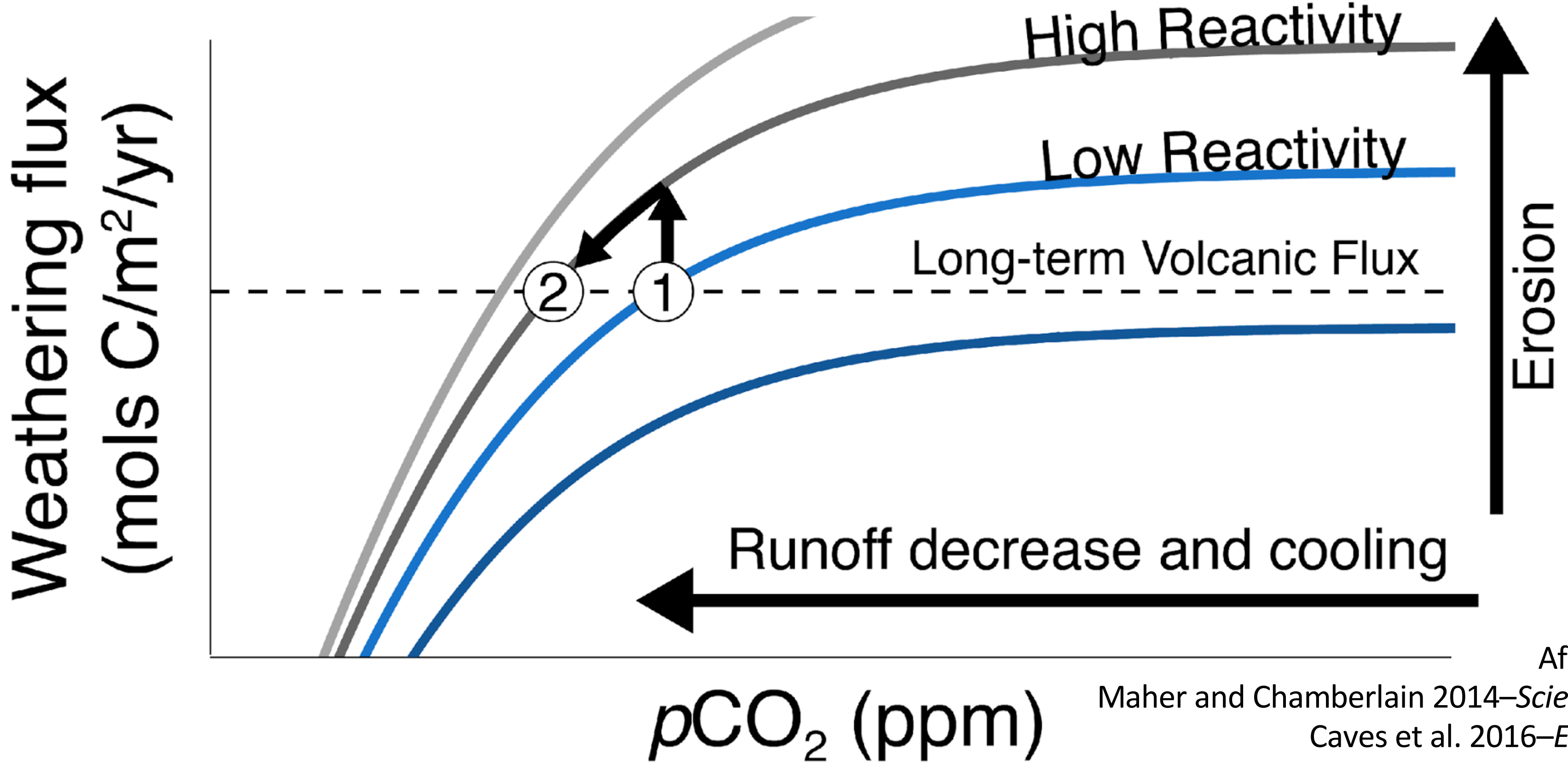

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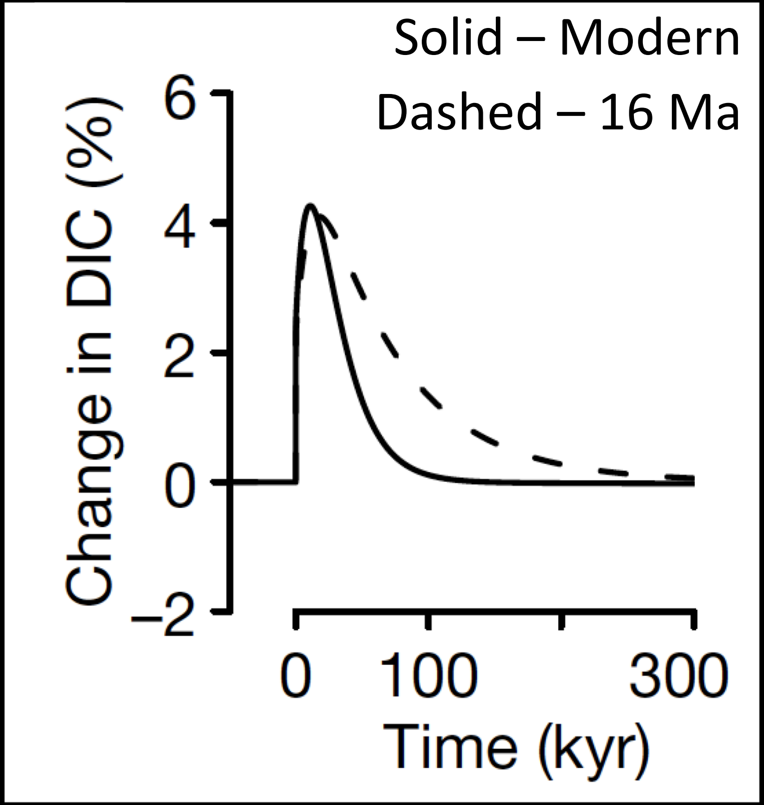
Implications: Transient Perturbations

- "Reactive land surfaces" remove carbon faster than "less reactive land surfaces".
- *e*-folding time ~50% faster



Caves Rugenstein et al. 2019—*Nature*

Conclusions

- Erosion-weathering relationship is non-stationary through time
  - Lower weathering flux per eroded material in Quaternary
- Li & Be isotopes and pCO_2 support increasing land surface reactivity driven by a ~3x increase in erosion
- Lower global weathering intensity results in a stronger silicate weathering feedback

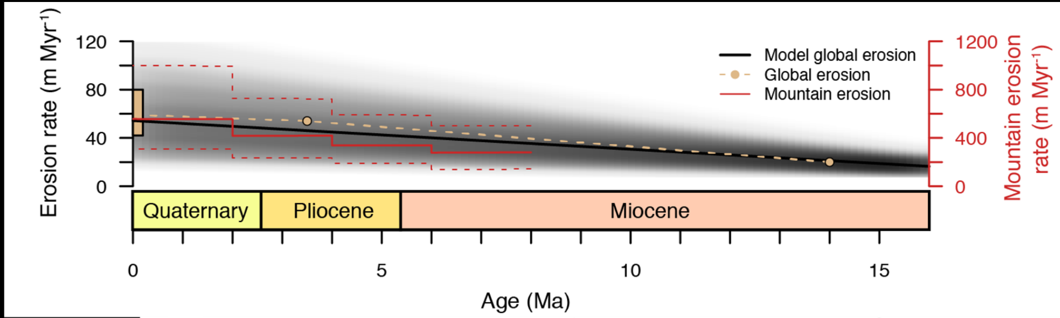
See paper sensitivity tests including: 1) pyrite weathering/burial, 2) constant erosion but declining degassing, 3) decreasing erosion/other side of the Li "croissant", 4) no reliance on Be record, etc.

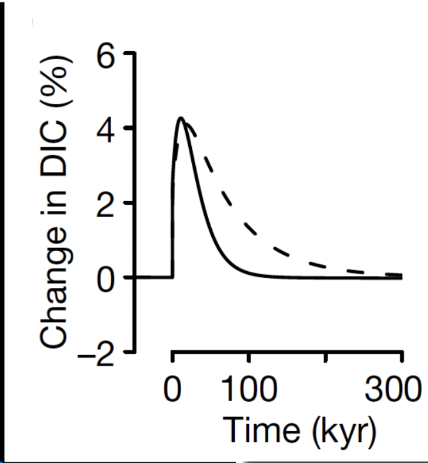
All code and model output published (paper and ETH repository)

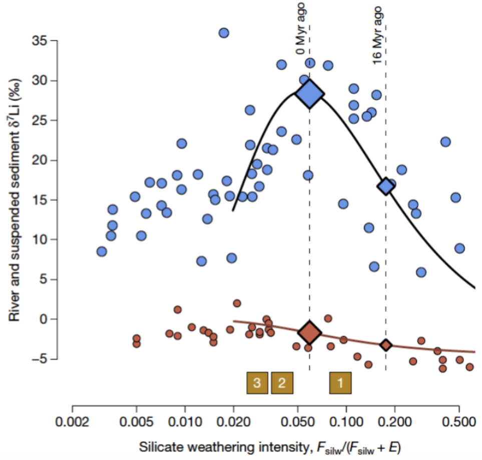
Acknowledgements

Previous institutions: ETH Zürich and Stanford University

- Sean Gallen, Kimberly Lau, Kate Maher, Daniel Stolper, Sean Willett and Matthew Winnick for thoughts and discussion.
- Clara Bolton for help with CO_2 data
- Caves Rugenstein: ETH Fellowship
- Ibarra: Heising-Simons Foundation







Emails: jeremy.rugenstein@mpimet.mpg.de and dibarra@Berkeley.edu

@Dan_E_Ibarra