A new framework to quantify carbon cycle perturbations using trace metal isotopes

Markus Adloff, Fanny M. Monteiro, Andy Ridgwell, Sarah E. Greene

May 4, 2020

markus.adloff@bristol.ac.uk

School of Geographical Sciences, University of Bristol
Department of Earth Sciences, University of California Riverside
School of Geography, Earth and Environmental Sciences, University of Birmingham

Interpreting past Carbon cycle events

Geologic record contains evidence of past Carbon (C) emissions accompanied by extensive environmental change

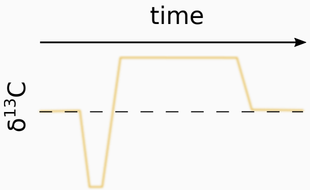
- In particular, Large Igneous Province emplacements caused largest pre-industrial C emissions (e.g. Ontong Java Plateau eruption coincident with Oceanic Anoxic Event 1a $\sim$120 Ma)
- Studying the Earth system response to these events requires knowledge of the strengths of forcing and feedbacks

Image by Adrian Malec from Pixabay

Reconstructing C fluxes from C isotopes

- C isotope excursions are evidence for altered C fluxes

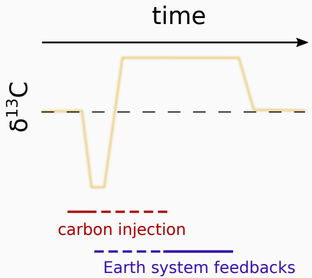
Example: Oceanic Anoxic Event 1a (∼120 Ma)



Reconstructing C fluxes from C isotopes

- C isotope excursions are evidence for altered C fluxes
- The sign of the excursion holds information about likely nature of dominant C fluxes

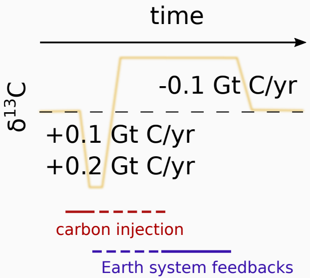
Example: Oceanic Anoxic Event 1a (∼120 Ma)



Reconstructing C fluxes from C isotopes

- C isotope excursions are evidence for altered C fluxes
- The direction of the excursion holds information about likely nature of dominant C fluxes
- C fluxes from to assumed sources/sinks can be estimated with C cycle models
- But: C sources/sinks cannot be identified unambigously
- And: Temporally overlapping C fluxes cannot be distinguished

Example: Oceanic Anoxic Event 1a (∼120 Ma)



Why are Sr, Os, Li and Ca isotopes useful?

Proxy-pontential of Sr, Os, Li and Ca

- processes that govern C cycle on long timescales also control metal cycles (e.g. mantle emissions, continental weathering)
- **source of metal fluxes** can be identified due to **distinct isotopic composition** of continental run-off and mantle
- local sediment cores can yield **global signals** because of **long residence times** in the ocean and inter-basinal isotopic homogeneity
- apart from Ca, little biological relevance, hence **less complex vital effects**?

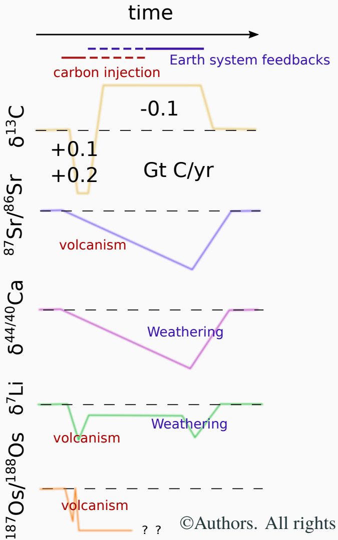
These metal isotopes are used to understand periods of environmental change

- Glacials - Interglacials
- Eocene/Oligocene Transition
- Paleocene-Eocene Thermal Maximum
- ...

The added value of metal isotopes for reconstructing C fluxes

- Metal isotopes are used to determine changes in metal sources/sinks

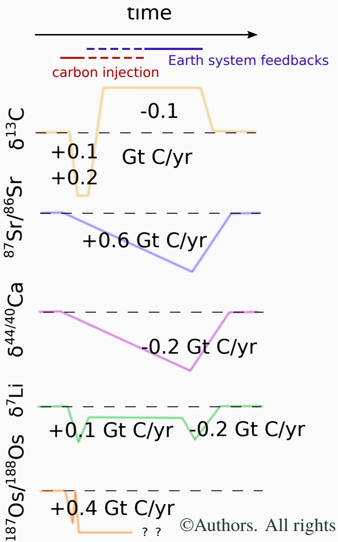
Example: Oceanic Anoxic Event 1a (∼120 Ma)



The added value of metal isotopes for reconstructing C fluxes

- Metal isotopes allow identification of specific sources/sinks
- Isotope mixing models can constrain C fluxes based on metal isotope excursions
- But: Isotope mixing models are often run without dynamic C cycle although metal cycles are sensitive to long-term C cycle changes. Does this affect estimates of external forcing/internal feedback strength?

Example: Oceanic Anoxic Event 1a (∼120 Ma)



Outline of our research for this talk:

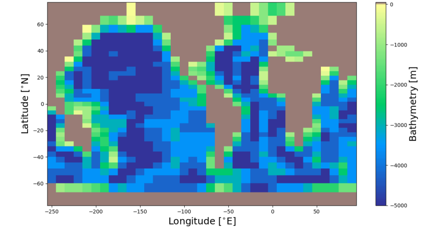
Research question

How do Carbon cycle feedbacks affect the evolution of metal isotope excursions during episodes of enhanced volcanism?

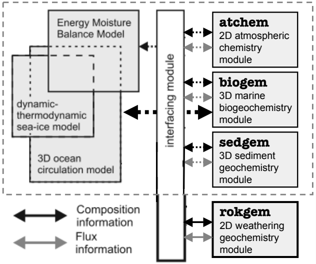
Research method

Simulations with a 3D Earth system model including dynamic cycles of C and metal isotopes

cGENIE - 3D Earth system model of intermediate complexity



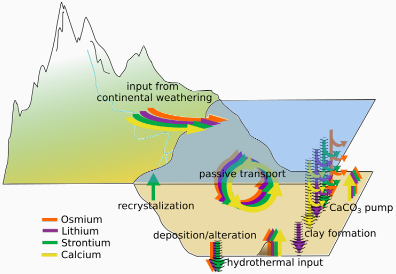
Modern-day bathymetry in cGENIE



Modular structure of cGENIE (from Colbourn et al. 2001)

Features of cGENIE

- Dynamic, isotope-enabled cycling of C, O, P, S, Si, (N, Fe), Ca^{New}, Sr^{New}, Os^{New}, Li^{New}
- Climate-sensitive terrestrial weathering
- Sediment accumulation/dissolution driven by benthic chemistry

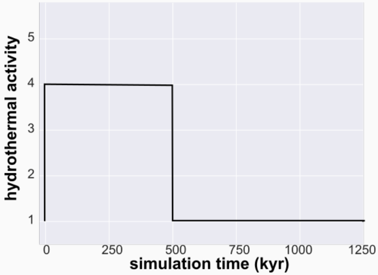


Metal cycles in cGENIE (Adloff et al. [in prep])

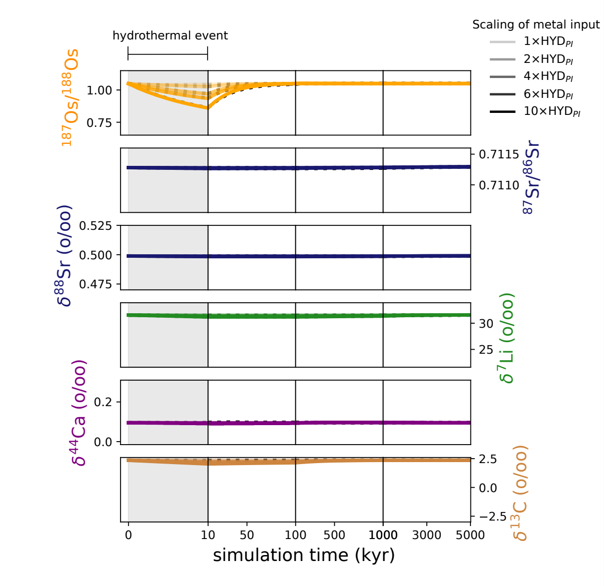
Methods: Transient increase in hydrothermal input

Experiment set-up

- different increase factor: 2, 4, 6, 10 $\times$ pre-industrial (PI)
- simulations of **increased metal input without C emissions** and of **combined C and metal input increases** (1, 2 $\times$ C:metal ratio in PI hydrothermal systems)
- higher input is sustained for 10, 100 or 500 kyr and is then returned to pre-event value



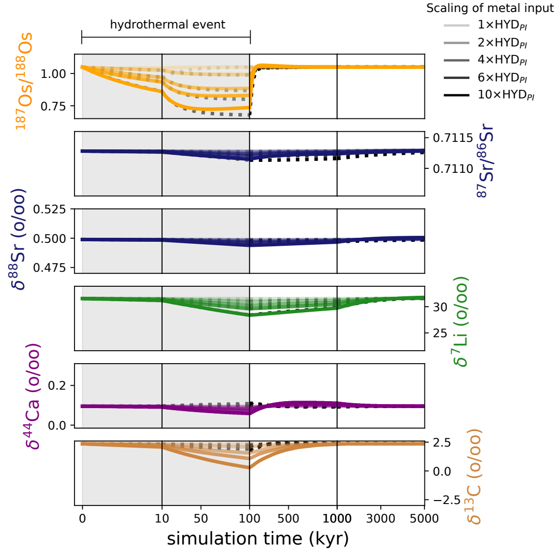
Hydrothermal event (10 kyr) & recovery



Observations:

- The mantle-derived metal injection rates we probed are too small to cause isotopic excursions in any metal system except Os, which has the shortest residence time.
- ^{187}Os/^{188}Os excursions evolve similarly with (coloured lines, $1\times$C:metal$_{hyd,PI}$) and without (black dotted lines) simultaneous C emissions

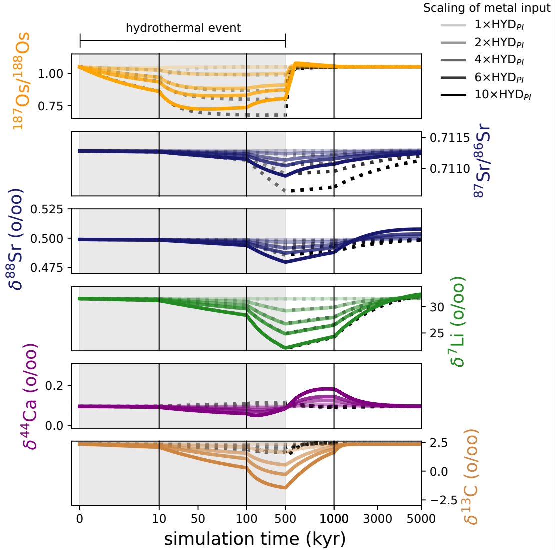
Hydrothermal event (100 kyr) & recovery



Observations:

- For 100 kyr-long events, all metal systems start to show perturbations
- At the same time, metal isotope excursions in simulations with (coloured lines, 1×C:metal$_{hyd,PI}$) and without (black dotted lines) simultaneous C emissions start to differ because of increased metal delivery from land and dissolving sediments

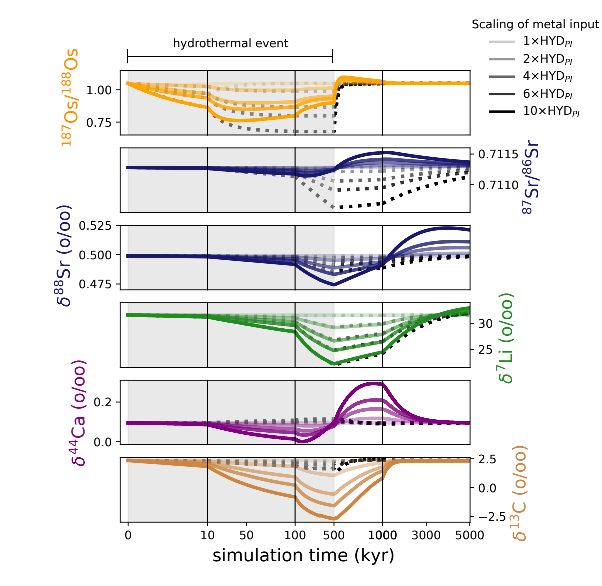
Hydrothermal event (500 kyr) & recovery



Observations:

- For even longer events, all metal systems are substantially perturbed by the magmatic input. Increased metal delivery from land also affects all isotope systems.
- With simultaneous C emissions (coloured lines, 1×C:metal$_{hyd,Pl}$) unradiogenic excursions recover more quickly than without (black dotted lines) and positive overshoots appear during stable isotope recoveries

Hydrothermal event (500 kyr) & recovery - larger C emissions ($2 \times$ C:metal$_{hyd,PI}$)



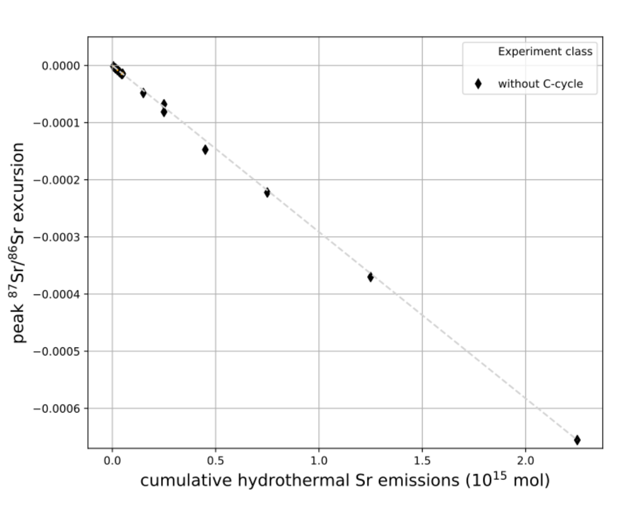
Observations:

- If the C:metal ratio in hydrothermal emissions is increased ($\times 2$), the previously noted effects are amplified
- Positive overshoots during recovery now also occur in radiogenic systems

Example 1: C cycle effects on $^{87}Sr/^{86}Sr$ exursion amplitude

Static CO_2 (no extra C emissions):

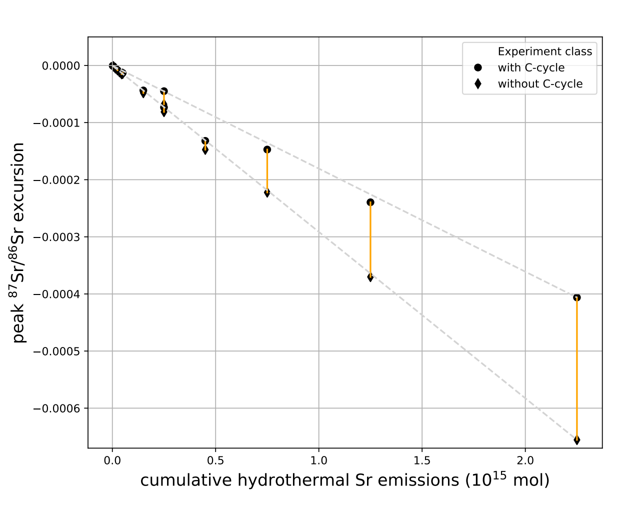
- Without C cycle feedbacks, there is a good correlation between $^{87}Sr/^{86}Sr$ exursion amplitude and the total amount of Sr emitted from the mantle



Example 1: C cycle effects on $^{87}Sr/^{86}Sr$ exursion amplitude

Dynamic CO_2, 1×C:metal$_{hyd,PI}$:

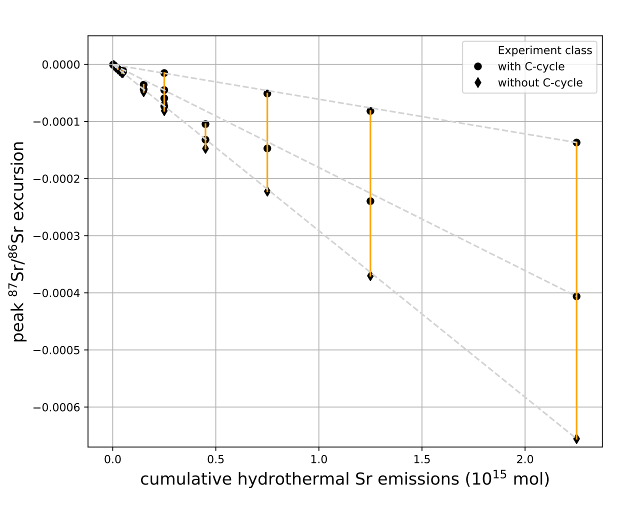
- C cycle feedbacks reduce the $^{87}Sr/^{86}Sr$ exursion amplitude through increased delivery of continental Sr



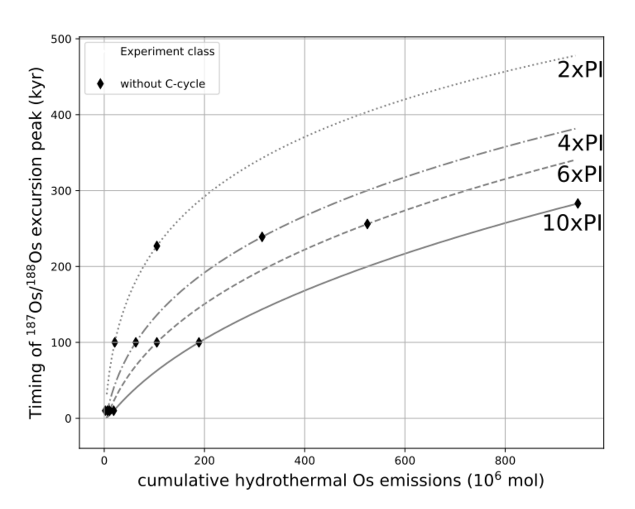
Example 1: C cycle effects on $^{87}Sr/^{86}Sr$ exursion amplitude

Dynamic CO_2, 2×C:metal$_{hyd,PI}$:

- C cycle feedbacks reduce the $^{87}Sr/^{86}Sr$ exursion amplitude through increased delivery of continental Sr
- In simulations with doubled C emissions, the negative $^{87}Sr/^{86}Sr$ exursion is reduced by up to 85%. Interpreting this isotopic excursion without accounting for the dampening effect of C cycle feedbacks would lead to substantial underestimation of the magmatic forcing.



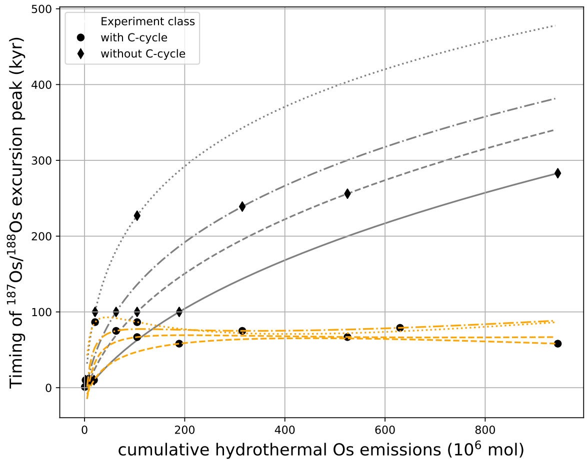
Example 2: C cycle effects on $^{187}Os/^{188}Os$ peak excursion timing



Static CO_2 (no extra C emissions):

- Without C cycle feedbacks, the $^{187}Os/^{188}Os$ peak excursion occurs later if the emission is slower

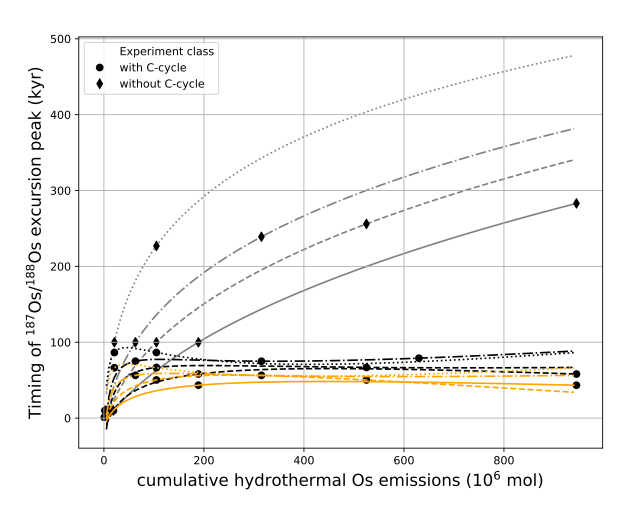
Example 2: C cycle effects on $^{187}Os/^{188}Os$ peak excursion timing



Dynamic CO_2, 1×C:metal$_{hyd,PI}$:

- Enhanced weathering prevents the negative $^{187}Os/^{188}Os$ excursion from growing further beyond 100 kyr

Example 2: C cycle effects on $^{187}Os/^{188}Os$ peak excursion timing



Dynamic CO_2, $2\times$C:metal$_{hyd,PI}$:

- A stronger weathering response further reduces the timing of the $^{187}Os/^{188}Os$ peak excursion, but the difference is smaller than compared to a scenario without weathering feedback

What we learned so far

C cycle feedbacks alter metal isotope excursions:

- dampened/increased excursion amplitudes
- earlier excursion peaks
- faster recoveries
- positive overshoots during recoveries

The size of these effects depends on:

- duration of forcing
- C:metal of forcing

} Forcing

- relative sizes of metal fluxes from mantle and run-off
- isotopic offsets between mantle, seawater and run-off
- potential for increasing metal delivery from run-off

} Background state

Other ongoing work: Simulating past background states

In a model with coupled dynamic C and metal cycles, the background state is more constrained than in offline models.

Simulating realistic a background state requires changes in boundary conditions which simultaneously satisfy differences in C and metal cycle proxies.

Example: Seawater composition and C cycle were different in Cretaceous

- $^{187}Os/^{188}Os$: **0.5 lower** (Bottini et al. 2012)
- $^{87}Sr/^{86}Sr$: **0.0015 lower** (Jones & Jenkyns 2001)
- δ^7Li: **6-10‰ lower** (Lechler et al. 2015)
- $\delta^{44/40}Ca$: **0-0.2‰ higher** (Blättler et al. 2011)
- atmosph. pCO_2: **3-5× higher** (Naafs et al. 2016)

Effect of changed boundary conditions (BC) on simulated seawater:

Proxy	$^{187}Os/^{188}Os$	$^{87}Sr/^{86}Sr$	$\delta^{88}Sr$	δ^7Li	$\delta^{44/40}Ca$	$\delta^{13}C$	CO_2
changing BC 1	=	-	-	-	-	+	-
changing BC 2	+	+	+	-	-	-	+
changing BC 3	+	+	+	+	+	=	+
changing BC 4	-	-	-	-	-	-	-
⋮	⋮						

Proxy evidence:

PI –> Cretaceous	-	-	?	-	=	?	+

Conclusions

Metal isotope excursions co-evolve with C cycle dynamics in response to external C injections:

- C cycle feedback strength affects shape and amplitude of metal isotope excursions
- Pre-event C cycle state thus also pre-conditions metal isotope response to perturbations

This is particularly relevant if:

- Amount of injected C is large
- C:metal ratio of external sources is high
- External sources stay active across timescales of C cycle feedbacks

$\Downarrow$

Quantitative constraints on external forcing or internal feedback strength from metal isotopes can be improved with coupled C- and metal dynamics