Joshua Murray - Research Statement

The long-term carbon cycle of planets is fundamentally governed by mineral reactions. Carbon sources are produced by the oxidation and decarbonation of mineral-bound carbon in the subducting slab and mantle. Carbon sinks are governed by incongruent weathering of silicates to form carbonate minerals (with structural inorganic carbon) and clays (capable of sequestering organic carbon). I work to understand those mineral reactions, in order to:

1. Constrain the forces that govern Earth's climate through time.
2. Interrogate the processes that create and maintain a habitable planet.
3. Find geologically inspired solutions to carbon dioxide removal.

Tectonics and climate

The obduction of mafic and ultramafic rocks within the tropical rain belt coincides with times of global cooling (Jagoutz et al., 2016; Macdonald et al., 2019). The increased weatherability due to Ca- and Mg-rich lithologies exposed to high surface temperatures, high runoff, and steep topography is invoked as the mechanism that drives cooling (Kump and Arthur, 1997). In this framework, carbon is removed when Ca and Mg, dissolved from their primary minerals, and precipitated as carbonate minerals. However, my work on Ordovician basin sediments in Newfoundland, combining fieldwork, geochemistry, and statistical inference, suggests that the total CO_2 consumption from the Bay of Islands ophiolite peaked at around $\sim$1% of modern global values (Murray, Bergmann, et al., In Prep.). In Murray and Jagoutz, 2023, I demonstrate an alternative pathway by which ophiolite obductions modulate Earth's climate. Mafic and ultramafic rocks preferentially weather to high surface area clays with heightened capacity to preserve organic carbon from remineralisation (Harder, 1972; Hedges and Keil, 1995; Wilson, 2004). I use carbon cycle and weathering models, alongside analysis of shale geochemistry, to show that the changing clay mineralogy during an ophiolite obduction is enough to account for Palaeozoic glaciations and the contemporaneous carbon isotope excursions (Murray and Jagoutz, 2023).

My research will further test the linkage between ophiolite obduction, weathering, and climate through interrogating sediments derived from those terranes. Deeper in time, I will continue studying basin sediment derived from ophiolites, building a full picture of changing carbon fluxes prior to the onset of icehouse climates. In the modern, I will study the regolith, riverine sediment, and IODP cores derived from the modern 'hotspots' of weathering in New Guinea and Indonesia. Despite their outsized role in the global carbon cycle, silicate weathering and organic carbon burial are poorly constrained (Milliman and Farnsworth, 2013; Hartmann et al., 2009). If we do not understand the modern geologic carbon cycle, palaeoclimatological inferences will remain enigmatic.

The long-term fate of weathering products is poorly understood. Mass balance at subduction zones finds that subducting carbon is not completely recycled during volcanic outgassing (Dasgupta and Hirschmann, 2010; Kelemen and Manning, 2015). On continental margins, organic carbon is clay-bound, yet models of subducting sediment ignore low-temperature metamorphic reactions in clays (Kerrick and Connolly, 2001; Van Keken et al., 2011). To evaluate the transfer of carbon from subducting sediments to the foreland basin I will analyse the mineralogy and geochemistry of metapelites across a transect of low-grade metamorphic facies (Aleutian and Shimanto accretionary prisms). I will use that data to constrain organo-mineral relationships during the initial subduction of sediment.

The rate and nature of mineral reactions is likely to have changed during abrupt and secular changes to the Earth system. For example: the continental crust has become more exposed and more felsic since the Archean (Tang et al., 2016; Lee et al., 2018); oxygen in the modern atmosphere is intimately linked to granite weathering (Bazilevskaya et al., 2015); and the evolution of planktonic foraminifera has shifted the location of carbonate production (Wilkinson and Walker, 1989). I will mentor students capable of interrogating the major changes to the Earth system in an interdisciplinary manner, considering the relationships between tectonics, life, igneous processes, sedimentary mineral formation, and climate. The interconnectedness of our planet necessitates the careful consideration of each aspect from the nucleation of the inner core to the extracellular enzymes of bacteria (Al Asad and Lau, 2024; Rothman and Forney, 2007).

Planetary carbon cycling

On the Martian surface, mafic and ultramafic rocks are more abundant than on Earth and, in the absence of plate tectonics, crustal carbon accumulates and is not recycled back to the atmosphere. Given the right conditions, carbonates may form sub-aerially, removing CO_2 (Murray, Kelemen, et al., In Prep.). However, the extent of CO_2 in carbonate deposits on Mars appears substantially smaller than the mass of CO_2 inferred in the early Martian atmosphere (Edwards and Ehlmann, 2015). My work suggests that the alteration of olivine played a fundamental role in the cooling of Mars: I show that large-scale alteration of ultramafic rocks, abiotic reduction of CO_2 during serpentinization, and subsequent storage of organic carbon in clays can account for both cooling and the carbon isotopic record, consistent with best estimates of clay volumes and compositions (Murray and Jagoutz, 2024).

Ophiolite alteration on Earth can inform processes that occur on Mars. Conversely, Mars preserves altered material from ancient weathering of a largely mafic planetary surface, which may be similar to early Earth. It follows that comparison between the two planets is mutually beneficial to unravel the role of tectonics, crustal differentiation, and atmospheric composition on the fate of carbon and climate. I will use the wealth of data from rovers, landers, and orbiters (e.g., Curiosity, Perseverance, Phoenix, Mars Express, ExoMars, CRISM) to further constrain the origin and distribution of carbon reservoirs, both organic and inorganic, within the Martian crust. In particular, I will explore the spatial and temporal links between igneous composition, humidity, and climate with hydrated silicates, carbonate, and methane detections, all grounded in an understanding of alteration processes on Earth.

Applications to carbon dioxide removal

My research into silicate weathering and clay-driven organic carbon burial has timely implications for carbon dioxide removal. The application of my fundamental science opens further funding channels from the National Science Foundation, the Department of Energy, and non-governmental research funding.

I will investigate the conditions that promote organic carbon preservation by clays over human timescales. Of interest is the secondary products of enhanced rock weathering (ERW): inorganic carbon sequestration has huge potential but can be limited by rates of bicarbonate uptake in water, rather than by mineral weathering rate (McDermott et al., 2024). Organic carbon preservation could provide a second mechanism for carbon dioxide removal (Manning, 2022) but requires an understanding of mineral formation, nutrient cycling, and organo-mineral reactions. I will conduct benchtop experiments on secondary mineral formation and organic carbon adsorption from basalt and peridotite weathering. I will then extend this research to include natural laboratory experiments deploying clays and rock powder into favourable environments for organic carbon storage, from agriculture to vulnerable carbon reservoirs such as permafrost and wetlands.

My work on mafic and ultramafic provenance (Murray, Bergmann, et al., In Prep.) gives me further skills that are applicable to ERW research. One of the major costs associated with ERW lies in the analysis of samples of partially weathered material in order to monitor the extent of carbon sequestration and to accurately issue carbon credits. Current best-practice relies upon mobile:immobile elemental ratios, e.g., Ca/Ti (Reershemius et al., 2023). However, I have found that a multivariate approach provides tighter constraints with the same analytical costs by utilising the entire suite of major and trace elements. I will detail new frameworks for improved ERW monitoring and apply them to preliminary ERW geochemical data, working in tandem with nonprofit organisations and local stakeholders.

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