

Testing the impacts of early land plants on the Earth System

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Note regarding research team participants: We are still finalizing our list of participants for each camp based on this list of 14 possible people. This will be finalized after we receive our final aircraft dates from the Polar Continental Shelf Project.

Our first camp at Read Bay, Cornwallis Island will be a maximum of 9 people. This will definitely include Drs. Sperling, Tarhan, Hodgskiss, Brazeau, Leslie, and wildlife monitor Devon Manik. The remaining three participants will be chosen from the other participants listed above.

Our second camp at Twilight Creek, Bathurst Island (in Qausuittuq National Park, under a Parks Canada research permit) will be a maximum of 6 people. This will definitely include Drs. Sperling and Tarhan and wildlife monitor Devon Manik. The remaining three participants will be chosen from the other participants listed above. This is the camp that may work at Truro Island should we not be able to land at Twilight Creek (described below). Two to three participants (those not going to Twilight Creek) may travel to the mineral exploration camp on Somerset Island to work on pre-existing drill cores (if we can obtain permission to visit that camp) (note this work is focused on our academic scientific research using these pre-existing drill cores and is not focused on mining; we are simply taking advantage of these existing geological resources).

Thus, although we have listed 14 possible participants and dates from July 15th to August 15th, these represent our possible list of field geologists and our maximum date window.

Long term objectives:

The goal of this proposed work is to provide a new view—from a joint geochemical, paleontological, and Earth-system modeling approach—on how land plants impacted global phosphorus cycling, primary productivity, redox balance, and surface oxygenation. We will target five central questions:

- 1) To what extent did the emergence and radiation of early land plants drive shifts in the magnitude of organic carbon burial in the oceans?
- 2) What was the impact of the emergence and initial radiation of land plants on the magnitude and intensity of weathering on the continents, and did the expansion of the terrestrial biosphere prompt shifts in the delivery of phosphorus to the oceans?
- 3) What was the effect of any land plant-mediated changes in phosphorus delivery on marine ecosystems and nutrient cycling?
- 4) Are major changes in the terrestrial biosphere across the Silurian-Devonian transition coupled with changes in the average redox state of the oceans (i.e., a switch from ferruginous to euxinic episodic anoxia, against a backdrop of increasing oxygenation)?
- 5) To what extent is the radiation of early land plants mechanistically linked to changes in atmospheric oxygen levels through the middle Paleozoic?

We will tackle these questions by providing new key constraints on the biogeochemical and ecological impact of the rise of land plants. We will:

- 1) Provide a new, expanded record of burial of terrestrial organic carbon across this interval.
- 2) Track changes in the magnitude and intensity of terrestrial weathering and how these change would have shifted phosphorus inputs into marine settings.
- 3) Provide new constraints on how the radiation of early land plants shaped the marine phosphorus cycle.
- 4) Provide a new view of how the marine redox landscape changed with the rise of land plants.
- 5) Reconstruct long-term changes in the oxygenation of Earth's surface environments.

We seek to use a multidisciplinary approach to tackle a fundamental question about the evolution of Earth's surface environments: how did the emergence and radiation of land plants impact the Earth system, from changes in continental weathering processes to the planetary hydrologic budget and climate state, marine nutrient cycling and ecosystem structure, the redox structure of the oceans and the oxygenation of the atmosphere? We propose to generate new, field-based

geochemical, sedimentological, and paleontological records, focusing on the Silurian-Devonian transition—an under-characterized but key interval for both land plant evolution and marine redox state—in order to reconstruct first-order ecological and environmental changes concurrent with the radiation of early land plants. Further, we will couple these empirical records to biogeochemical and climate modeling over a range of scales—from local critical zone and seafloor diagenesis to global scale weathering and carbon-oxygen cycle modeling—in order to develop a more robust process-based understanding of plant-biogeochemical feedbacks and reconstruct the long-term consequences of early land plant evolution for the broader Earth system.

Short term objectives (2026):

In 2023, our research team studied the Cape Phillips and Bathurst Island Formations at Grant Point, Bathurst Island, Nunavut (in Qausuittuq National Park). We collected samples for geochemistry and biostratigraphy and are currently in the process of preparing a paper on the geological framework for publication. Figure 1 shows our overall study plan across the 2023 and proposed 2026 field seasons, aiming to study both shallow- and deep-water depositional settings through the Silurian-Devonian transition in the southern Queen Elizabeth Islands. Specifically, in 2026 we will study the shallow-water carbonate formations (Allen Bay, Cape Storm, Douro, Barlow Inlet, Sophia Lake, Snowblind Bay, and Disappointment Bay formations) on Cornwallis (primary field area), Somerset, and potentially Truro Island. We will also study the shallow-water Blue Fiord and Bird Fiord formations, and the deeper-water Eids formation, in the Twilight Creek area, Bathurst Island, Qausuittuq National Park (we are applying for a separate Parks Canada research permit for this work and it is not described here in detail.) Overall, this fieldwork will result in a complete record spanning all depositional environments through this critical interval of Earth history.

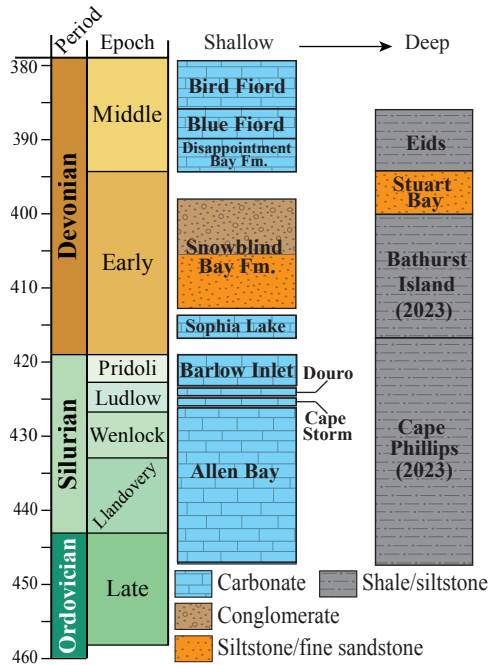


Figure 1: Geological units in the Canadian Arctic across the Silurian-Devonian. Our goal is to study and sample both shallow and deep-water depositional settings to understand Earth system evolution across water depth gradients. In 2023 our team studied the Cape Phillips and Bathurst Island Formations at Grant Point (Qausuittuq National Park). In 2026 we aim to study the Allen Bay, Cape Storm, Douro, Barlow Inlet, Sophia Lake, Snowblind Bay, and potentially Disappointment Bay Formations. We will also study the Eids, Blue Fiord and Bird Fiord Formations in Qausuittuq National Park (with a separate research application currently pending with Parks Canada).

Specific to the work in 2026 under this research license application, the field team led by PIs Sperling and Tarhan, along with Inuit wildlife monitor Devon Manik and several graduate student team members and/or collaborators, will travel by commercial airline to the Polar Continental Shelf Project (PCSP) base in Resolute Bay and then by chartered PCSP helicopter to the vicinity of Read Bay, Cornwallis Island. We will measure the stratigraphic section through the Silurian-Devonian Allen Bay, Cape Storm, Douro, Barlow Inlet, Sophia Lake and Snowblind Bay formations in the Read Bay vicinity by Jacobs staff, collecting geochemical samples every ~2-5 meters and graptolite, brachiopod and conodont biostratigraphic samples from appropriate lithologies. Early plant and vertebrate fossils will also be sampled to understand the evolution of those groups. Samples will then be analyzed in our laboratories for sedimentary geochemistry (iron speciation, Total Organic Carbon contents and isotopes, carbonate carbon isotopes, redox sensitive trace metal abundances, biomarkers, phosphorous speciation, and lithium isotopes and $\Delta^{17}\text{O}$ isotopes in brachiopods) by graduate students and project partners at Stanford, Yale, and the University of California, Riverside.

Background and rationale:

The diversification and geographic spread of plants on land is one of the most profound changes in the history of our planet. Modern Earth is covered by lush tropical forests, seemingly endless grasslands, and soaring redwoods—in striking contrast to Precambrian landscapes that consisted largely of bare rock and microbial mats. Today ~55% of primary productivity occurs on land (Woodward, 2007) and animals have co-evolved with plants in terrestrial ecosystems for ~450 million years. Plants have altered the landscape; for example, the emergence of plants transformed river morphologies and the distribution of mud in sedimentary systems (Gibling and Davies, 2012; Ielpi and Lapôtre, 2020; McMahon et al., 2022; McMahon and Davies, 2018; Spencer et al., 2022; Zeichner et al., 2021). They also affect Earth’s climate and the global hydrologic cycle through evapotranspiration and by altering planetary albedo ((Boyce and Lee, 2017; Dahl and Arens, 2020)). Climatic changes, especially in the Devonian, have long been linked to plant evolution (Algeo et al., 1995; Algeo and Scheckler, 1998; Berner, 1993; Donoghue et al., 2021). While early land plants in the Ordovician and Silurian were small and morphologically simple, the Late Silurian through Devonian was characterized by the explosive diversification of vascular plants, including lycophytes, ferns, gymnosperms, and angiosperms (Algeo and Scheckler, 1998; Bonacorsi et al., 2020; Donoghue et al., 2021; Gensel et al., 2001; Knoll et al., 1984; Kotyk et al., 2002; Leslie et al., 2021). The mid-Silurian to Early Devonian (~430-393 Ma) was a particularly critical interval in land plant evolutionary and ecological history, during which plant body fossils show a dramatic diversification in taxonomic richness, body size, anatomical and physiological specialization, and reproductive diversity.

Nevertheless, there are few robust constraints on the net impact of changes mediated by the emergence of land plants or the tempo with which these occurred. Two of the most fundamental—and most debated—aspects of how plants transformed our planet concern potential changes in long-term nutrient cycling and oxygen levels, both on land and in the oceans (Boyce et al., 2023; Dahl and Arens, 2020; D’Antonio et al., 2020; Donoghue et al., 2021; Elrick et al., 2022; Ibarra et al., 2019; Isson et al., 2020; Lenton et al., 2016; Sharoni and Halevy, 2023; Sproson et al., 2022). It has been argued that plants increased nutrient input to the oceans, which drove increased primary productivity that both pushed anoxic and ferruginous (ferrous iron present; sulfide limited) water masses towards euxinia (sulfide present; iron limited) and oxygenated the planet. However, it has also been argued that plants had no long-term effect. Previous hypotheses linking land plant evolution and marine geochemistry have been put forward primarily on the basis of modeling and summary figures of fossil and geochemical change from disparate paleogeographic areas. Here, we will directly test these hypotheses in a coherent stratigraphic framework based in Nunavut. Our work will be grounded in new observations and field work that feed into Earth-system modeling. These ambitious goals will be accomplished by a diverse team of paleontologists, sedimentologists, geobiologists, isotope geochemists, and biogeochemical and climate modelers.

Justification for fieldwork in Nunavut and the Canadian arctic islands:

To generate new and integrated geochemical, sedimentological, and paleontological records across the critical interval of the Silurian–Devonian transition, we will focus our field sampling

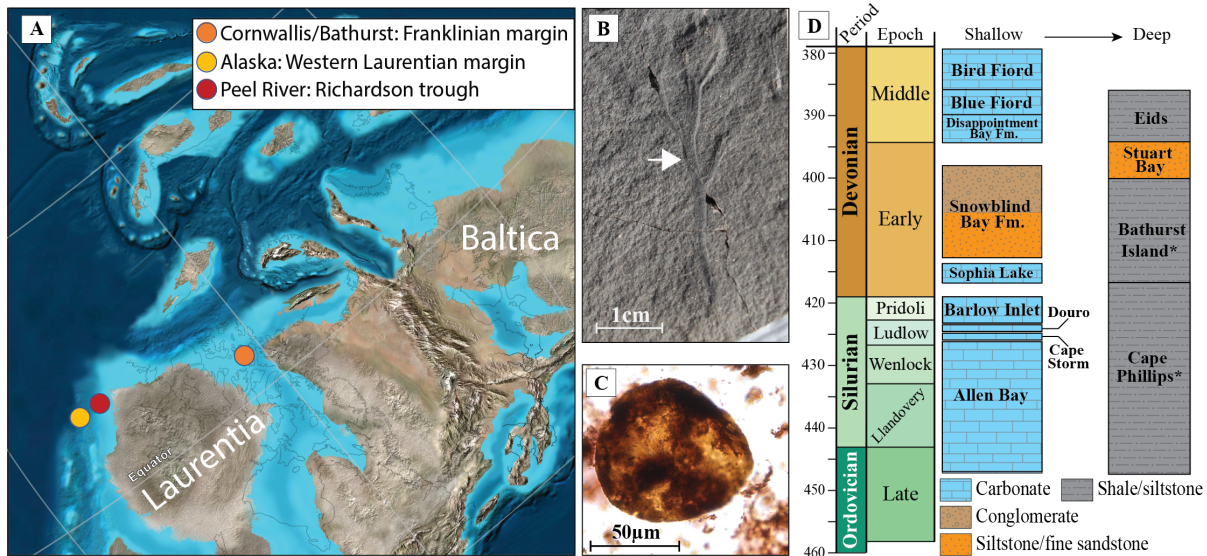


Figure 2. A) Late Silurian paleogeographic map of main fieldwork locality in the Canadian Arctic Archipelago. The Peel River (Yukon) section studied by Sperling et al., 2021 and Strauss et al., 2020 and the open-margin Alaskan sections studied by our research team in 2022 are also shown. B) Plant (euphyllophyte) macrofossil our team recovered from the Bathurst Island Fm, Grant Point section, Bathurst Island. C) Trilete spore recovered from the same sample suite shown in (B). D) Shallow- (carbonate-dominated) and deep-water (shale-dominated) Silurian–Devonian stratigraphy of the Canadian Arctic Archipelago. *Formations studied and sampled in 2023 (see text). All other formations will be studied via the proposed fieldwork.

efforts on the Franklinian paleomargin, primarily exposed on Cornwallis and Bathurst Islands, Nunavut, Canada (Fig. 2 adapted from (Blakey, 2021; Dewing et al., 2019; Freitas et al., 1999; Kerr, 1974; Thorsteinsson, 1958)). Silurian–Devonian strata of the Canadian Arctic Archipelago span a range of marine depositional environments, from proximal carbonate platform to distal deep-water slope settings (Dewing et al., 2019; Freitas et al., 1999), providing an ideal opportunity to both 1) characterize terrestrial records preserved in high-resolution, continuous and stratigraphically expanded marine sinks over long timescales and 2) directly interrogate the ‘downstream’ impacts of any plant-mediated changes in continental weathering on marine redox state, productivity and biodiversity. Although the evolution of the terrestrial biosphere occurred on the continents, coeval marine deposits provide an archive unrivalled in preservational fidelity, biostratigraphic, chemostratigraphic and geochronologic constraints, and stratigraphic continuity.

Critically, these sections are thermally immature. Regional thermal maturity maps demonstrate a suitable $%R_o$ maturity range of 0.5–1.0% (early- to middle-oil window; (Dewing and Obermajer, 2009; Synnott et al., 2018)) (note that this data on thermal maturity comes from decades of

studies on petroleum exploration in the region. These data are highly useful to our questions and inform our choice of field study targets, but our study is explicitly focused on the academic questions posed above regarding land plants and does not relate to petroleum). These data demonstrate that all analyses requiring low-maturity samples (e.g., lipid biomarkers, palynology, phosphorus speciation, $\delta^{17}\text{O}$ analyses of brachiopods) will be feasible. This contrasts with many other sections (including those studied by our research team in Yukon (e.g., Sperling et al., 2021; Strauss et al., 2020)) that are at much higher thermal maturity and where we cannot conduct such geochemical analyses.

These sections also contain ‘gold standards’ for lower Paleozoic biostratigraphy, with deeper-marine strata containing abundant and well-studied graptolites (Lenz and Kozłowska-Dawidziuk, 2004; Lenz and Melchin, 1990; Lenz, 2013; Melchin, 1989), while shallow-marine strata contain conodonts (Fortier, 1963; Kerr, 1974; Thorsteinsson, 1958; Thorsteinsson and Uyeno, 1980). Interfingering facies allow direct correlation of regional graptolite and conodont data (Zhang et al., 2017, 2016). Shallow marine carbonates contain abundant and well-preserved brachiopods and stromatoporoids, which will be targeted for lithium isotope and $\Delta^{17}\text{O}$ work (refer to Johnson, 1975; Jones, 2011; Kerr, 1974; Lenz, 1974; Li and Jones, 2003; Thorsteinsson, 1958). Additionally, the deeper marine strata also contain some of the best evidence of life on land during this interval in the form of early plant body fossils with preserved rooting structures (Kotyk et al., 2002). Our field work in 2023 indicates that these sections have near-continuous exposure and minimal weathering. ***To our knowledge, no other Silurian-Devonian field area in the world meets these criteria of low thermal maturity, lithofacies control, stratigraphic continuity, exposure, and shallow- and deep-water records hosting both marine and terrestrial fossils.***

Locations and dates: Our primary research camp for this work will be near Read Bay on Cornwallis Island. This represents the type section for the Barlow Inlet, Sophia Lake, and Snowblind Bay formations (Thorsteinsson and Uyeno, 1980). It also represents good exposures of the Allen Bay, Cape Storm, and Douro formations (Sodero and Hobson, 1979; Thorsteinsson, 1958). The strata are low maturity (as described above) and a relatively short helicopter flight from the PCSP base in Resolute Bay. Finally, team member Dr. Martin Brazeau has previously worked in this area and is personally familiar with the stratigraphy. We are also planning a research camp at Twilight Creek, Bathurst Island, under a separate Parks Canada application.

This work will be carried out between 7/15/2026 and 8/15/2026. Our primary camps will be for ten days (Read Bay) and six days (Twilight Creek), exact dates determined based on aircraft availability.

We are requesting permission to work in three additional areas (that may or may not be studied depending on logistics and permissions). First, we request to study the Cape Storm Formation exposed on Signal Hill and Cape Martyr near Resolute Bay. This would overlap with the study in Read Bay and would only be completed if we have extra days at the Polar Continental Shelf

Project (PCSP) research base in Resolute Bay due to aircraft or weather delays. Second, we hope to travel down to the Aston Bay Holdings/American West Metals mineral exploration camp on Somerset Island to study previously collected drill core through the Cape Storm and Allen Bay formations. Permission to visit this exploration camp and sample their drillcore is currently being negotiated with these companies and may or may not happen, but the scientific value of fresh drill core material would add greatly to our study. Finally, we have listed Truro Island as a possible backup site for our work in Qausuittuq National Park. The PCSP staff have been unable to confirm the landing strip near our site at Twilight Creek. In the event that we cannot land there, on the way home we would be flying back over the established strip on Truro Island. Truro Island hosts nice exposures of the Cape Phillips, Disappointment Bay, and Blue Fiord formations, and so we request permission to work there so that we do not waste researcher time, PCSP logistics, research budgets, and carbon dioxide costs of travel. We scouted the Twilight Creek strip from the air in 2023 and are confident we will be able to land and work in Qausuittuq National Park, and primarily list Truro Island as a backup out of an abundance of caution.

Research methodology: In each field area, we will measure, on a decimeter scale, stratigraphic sections in which detailed sedimentological and paleontological data will be recorded (leading to detailed paleoenvironmental and biostratigraphic characterization of the section). We will implement a tiered sampling system, taking samples for laboratory analysis every 2-5 meters of stratigraphic section (~100 grams; the size of a small egg) for routine analyses (e.g., TOC, carbonate carbon isotopes, trace elements) and sampling every 10-20 meters for larger samples (fist sized) that will be subdivided for more sophisticated and time-consuming analyses (e.g., metal isotopes, $\delta^{18}\text{O}$ phosphate, biomarkers). Seven types of macrofossils and microfossils will be collected, specifically plant and vertebrate body fossils, brachiopods and stromatoporoids (as geochemical archives), graptolites (for biostratigraphy), and palynological (spore) and conodont microfossils (for biostratigraphy; prepared from bulk rock samples).

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