Carboniferous Earth Systems: Insights into the Pennsylvanian Planet

Joggins Fossil Cliffs
UNESCO World Heritage Site
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Forward

The Carboniferous Period is unique in the past 540 million years of geologic history because it is the first time that a vegetated Earth experienced multiple transitions from icehouse to hothouse climates. These transitions occurred on our planet as a consequence of the interactions between five physical and chemical systems–Lithosphere, Hydrosphere, Atmosphere, Cryosphere, and Biosphere. A change in one Earth system promotes a response in each other Earth system, the influences of which occur over various scales of space and time. For example, the collision of Earth's tectonic plates builds mountain chains which influence the atmospheric circulation patterns, winds, and rainfall. High latitude continents are affected by the buildup of glacial ice across them resulting in the lowering of global sea level which, in turn, alters the circulation pattern of water on the planet. With ocean levels lowered, marine sediments once submerged under salt water become emergent and colonized by coastal tropical forests. Lower concentrations of atmospheric CO_2 cool the planet and, at the same time, concentrates rainfall around the equator, altering the types of soils formed there. Soil formation promotes an increase in spatial coverage of the forests over hundreds of thousands of square kilometers, which pulls carbon dioxide (CO_2) from the atmosphere, lowering its atmospheric concentration and influencing the planet's carbon cycle. Yet, at the same time, the photosynthetic output attributed to this expansive forest cover increases the output of oxygen (O_2) into the atmosphere which, in turn, affects animal physiology. These are but a very few of the ways in which Earth Systems interact and control our planet. And, evidence of many of these are preserved in the rocks and fossils of the Pennsylvanian Period.

The Pennsylvanian Period, when thick and expansive peat forests formed the basis for many of our coal resources that fueled the Industrial Revolution, began approximately 323 million years ago and lasted for only 24 million years. This interval is similar in duration to our current icehouse climate which began at the end of the Oligocene Epoch, some 23 million years ago. Three icehouse-to-hothouse (glacial to deglacial) transitions occurred during the Pennsylvanian, each of which serves as a model planetary response long before the appearance of man on the planet, some 4 million years ago. Part of that record is conserved in the rocks and fossils found along the Joggins cliffs.

The capstone writing-intensive course for this year's geology majors at Colby College, Maine, focus on Earth Systems that operated during this deep-time analog. Each student has chosen to research one aspect of the Lithosphere, Hydrosphere, Atmosphere, Cryosphere, or Biosphere that operated on our planet during this time interval. The following extended abstracts provide a summary of their investigations and project-research results. Each student will be presenting their ideas as a poster on Saturday, 4 May 2019, where visitors can learn more about our planet's history and what it portends for our current condition.

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One Orogeny, Two Orogeny, Alleghenian Orogeny, Variscan Orogeny

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There were four major orogenies occurring in the Pennsylvanian (approximately 323.2 ma to 298.9 ma) and the Earth's plates were situated in dramatically different positions compared to present geography. An orogeny is a mountain building event where a section of the Earth's crust is compressed and uplifted. These four orogenies were the Cape Fold Belt, the Ancestral Rocky Mountains, the Alleghenian Orogeny and The Variscan Orogeny. While there were older mountain building events in both locations, the Variscan and Alleghenian Orogenies are important because of their essential role in suturing together the supercontinent Pangea. The Variscan Orogeny and the Alleghenian Orogeny, created by Northwest-Southeast convergence of the two major plates: Gondwana and Laurussia, created two, nearly connected mountain belts.

There is a debate about whether these orogenies are the same event or distinct events. The two orogenies are looked at as the same event by some authors because the mountains appear to be one long continuous range and were created by similar processes at similar times. Orogenies can be formed through many processes, but there are three major forms: strike slip (side by side grinding), convergence (head on collision) and subduction (one plate is forced under the other plate, pushing the other plate upwards). Other authors consider them different events because the timing is not simultaneous and the plates acted differently in each location. These mountain building events are not, despite what some claim, the same orogeny.

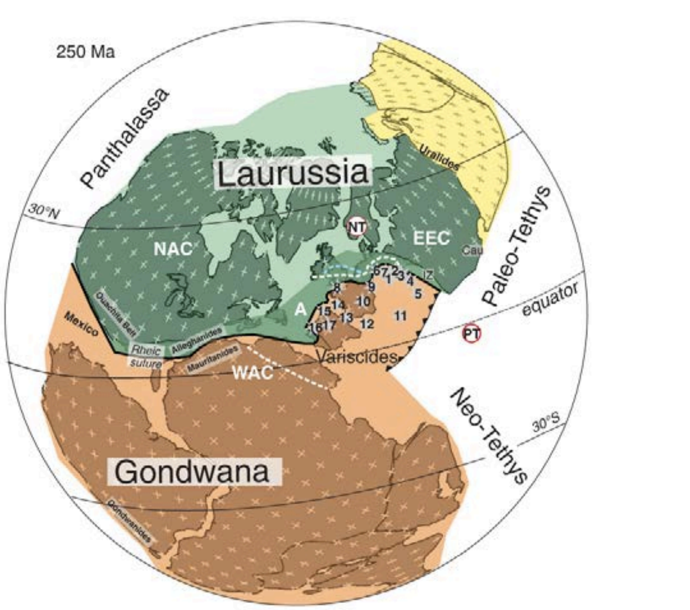

Figure 1: The world at 250 Ma, when the convergence of Gondwana and Laurussia had concluded. The black line shows the seam between Gondwana and Laurussia and in the center is the Alleghenian Orogeny, while the numbers to the right represent the lobed region of the Variscan Orogeny. Image from (Kroner and Romer 2013)

During the Carboniferous, the equatorial region of the planet was undergoing lateral compression as Gondwana and Laurussia collided (Blakey 2003). This lateral compressive stress, however, was not the same in both locations. The onset of Variscan tectonic activity mark the Devonian–Carboniferous boundary (Schulmann et al. 2014). Thanks to radioactive dating, detrital (loose sedimentary) mica deposited in sandstone beds show that boundary at c. 350 ma) and detrital zircons at c. 390–340 ma (Schulmann et al. 2014). Timing of the Alleghenian Orogeny was more recent, and is reflected by detrital zircons at 330-320 Ma (Uddin et al. 2016) and at 335-270 Ma by mica (Hames et al. 2018). In the Variscan case, irregular geometry (Rast 1988) of the plate caused irregular deformation because while the Alleghenian featured the plates grinding past one another, the Variscan caused them to bend, fold and rotate. The theory of escape tectonics is a concept that involves plates reacting to convergence by becoming severely faulted and often rotating away from the impact. The Variscan orogeny is considered a past analogue due to the indirect impact and 'escaping' rotational motion of the central European land (Kroner and Romer 2013), the Iberian Peninsula, and Nova Scotia (Simancas et al. 2005). The Alleghenian Orogeny however, featured a subduction zone non-perpendicular to the direction of plate movement, but was a simpler convergence (Figure 1). The differences in stress and timing are the key differences through which the Variscan and Alleghenian Orogenies remain distinct and should not be considered the same event.

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Effects of Climate Change on the Late Pennsylvanian Midcontinent Sea During the Late Paleozoic Ice Age

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The Late Paleozoic Ice Age was an extended period of icehouse conditions across the globe. During this time warm periods of glacial melting alternated with cold periods of glacial expansion. The resulting sedimentary deposits exhibit a repeated series of stratified layers of varying sediment composition known as cyclothems. These layers follow a cyclic pattern of deposition matching the changes in climate. These cycles of sedimentary deposits include offshore marine shale or limestone, nearshore clay or sandstone, coal produced from swamps and marsh environments, and inland soil or river deposits. These sedimentary deposits are more easily distinguished in equatorial areas where the oscillations of glacial conditions lead to water levels rising and falling, which produced unique sediment deposits depending on the prevailing climate and sea level.

Cyclothems from the Pennsylvanian have been found in the middle and western United States as part of the Late Pennsylvanian Midcontinent Sea (LPMS) (Figure 1). This mostly landlocked ocean basin reached its largest size during the middle to late Pennsylvanian when it was located in the tropical region of western Pangea. Middle to late Pennsylvanian cyclothems show that black-shale deposits, rich with organic carbon, formed during periods of high sea level due to glacial melting (glacioeustatic highstands). These are times when the sea reached its most expansive size (Algeo and Heckel, 2008). Highstand periods are characterized by large scale anoxic (very oxygen depleted) conditions in deep water throughout the basin. The causes of widespread anoxic conditions over the extremely large area are debated. Recently, the mechanism driving bottom water anoxia (oxygen depletion) have been attributed to the formation of a vertically stratified water-column maintained by differences in salinity with depth. This has been referred to as the “superestuarine” model by Algeo and Heckel (2008).

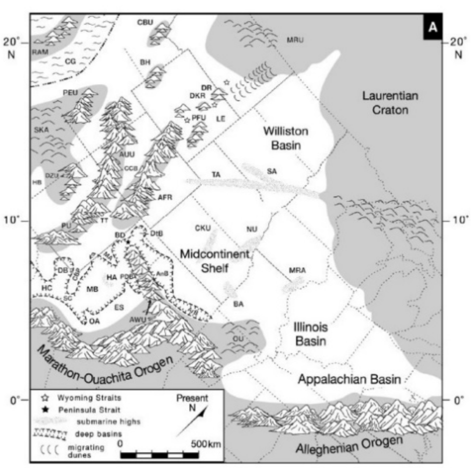

Figure 1: Geography of the Late Paleozoic Midcontinent Sea of North America. Oriented relative to paleogeographic North with the United States overlain to show the present-day of the deposits. From Algeo and Heckel (2008).

The superestuarine model explains the anoxic environment of deep water in the LPMS through the development of pronounced vertical salinity gradients. These gradients are driven by high quantities of freshwater runoff creating a low salinity surface layer across most of the sea, while higher salinity waters are trapped at depth. This stratification prevents oxygenation of the bottom waters, resulting in highly anoxic waters near the seafloor. According to the model, several conditions are necessary for the formation of such a widespread anoxic layer. These include: a humid tropical climate with ample rainfall to continually replenish the fresh or brackish surface layer, a landlocked location, a shallow seafloor, a long and winding ocean connection, and sourcing of sea water from an oxygen-deficient water supply from the ocean (Algeo and

Heckel, 2008). The maintenance of these oceanic conditions is expected to result in a stratified water-column. This is due to the formation and persistence of a halocline (a separation of layers of water based on salinity) separating anoxic highly saline deep waters from the fresh or brackish surface water layer. However, the strict requirements of the superestuarine model make seriously limit the climatic conditions it may occur under.

Data continues to support the formation of an anoxic deep-water layer throughout the LPMS (Turner et al., 2018). However, climate proxies indicate that the region of the LPMS steadily shifted to a more arid and seasonal environment during the late Pennsylvanian (Tabor, 2007). Oxygen isotope data collected from conodont apatite indicates a weakening of salinity gradients during seasonal and drier periods (Joachimski and Lambert, 2015). This has been attributed to a decrease in terrestrial freshwater runoff. Interestingly, deep-water anoxic conditions remain present during these seasonal and drier periods which seemingly negate the necessity of the humid, high-precipitation conditions described in the superestuarine model (Algeo and Heckel, 2008). Hence other forces in addition to fresh water runoff probably play a significant role in the ongoing water-column stratification. In addition, the lack of a present-day analog makes it difficult to verify the model's plausibility.

Computer modeling conducted on the Baltic Sea could provide a modern analog explaining water-column stratification. Recent models have shown that the stratification of the Baltic Sea is controlled by freshwater runoff during the early spring (Hordoir and Meier, 2011). However, the stratification switches to a primarily thermal driver in summer and shows increased stratification during the remainder of the warm season. Computer models also tested future changes in seasonality with increased and decreased freshwater runoff, indicating a more significant stratification of the water-column during times of decreased freshwater runoff (Hordoir and Meier, 2011). Decreased freshwater runoff allows warming of the surface water to occur rapidly, because less additional water needs to be heated. As a result, the surface water becomes hotter, producing a density difference with the colder layers.

Processes operating in the Baltic Sea provide a possible explanation for the sustained anoxic environment in the LPMS during glacioeustatic highstands with decreased runoff. Although salinity may have played a role, based on the data, it is most plausible that thermal heating provided an equally important driving mechanism behind ocean stratification. Stratification produced a distinct thermocline, dividing the upper lower density layers from the colder and denser deep layers which impeded oxygenation of these deeper waters. This set of conditions promoted the accumulation of organic matter in the black-shale seafloor sediments within the shallow LPMS.

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Carbon Cycling in the Carboniferous: Pennsylvanian glacial and interglacial intervals reflected by a changing atmosphere

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The Late Paleozoic Ice Age (LPIA) included multiple phases of glaciation, in which the Earth dynamically changed between an ice-dominated to a green planet. Spanning from 360 to 260 million years ago, it is considered to be one of the most profound ice ages in Earth's history. Several decades' worth of research has thus been conducted to investigate the global processes responsible for the LPIA. Rearranging tectonics and changing of ocean circulation patterns are contributors to global glaciation patterns; however, atmospheric carbon dioxide has been cited as the main driver of the LPIA. The Pennsylvanian (299 to 232Ma) period of the LPIA is marked by glaciation followed by a warm interval of deglaciation in which temperature records, preserved in stable oxygen isotope proxies, match records of atmospheric carbon dioxide (Frank et al., 2008). This fluctuation of global climate states can furthermore be measured through cycling of atmospheric carbon dioxide. The feedback loop between pyrite sulfur and carbonate rock erosion (releasing of CO_2) and formation of these rocks (consumption of CO_2) best defined this carbon cycle prior to the period. The evolution and rapid spread of large terrestrial plants was crucial to the development of the Pennsylvanian carbon cycle, and has remain relatively unchanged to the modern carbon cycle. A comprehensive view of atmospheric carbon dioxide and oxygen cycling, driven by photosynthesis and coupled with lithospheric processes are presented to best describe the components of the Pennsylvanian carbon cycle.

Carbon dioxide is known as a greenhouse gas for its ability to trap heat within Earth's atmosphere. The Pennsylvanian is characterized by relatively low atmospheric carbon dioxide (Montañez & Poulsen, 2013), recorded in carbon isotopes in brachiopod calcite (Frank et al., 2008) and modeled by computer-generated estimates based off of proxy records. Carbon dioxide cycling related to the lithosphere, the solid rock component of the Earth's systems, occurs mainly in relation to tectonic processes. During the LPIA, large-scale tectonic rearrangement of Earth occurred, resulting in significant volcanism, uplift, and erosion of lithospheric plates. All of these processes contributed to increased atmospheric CO_2 by releasing greenhouse gases trapped in the upper mantle or exposing carbonate and pyrite sulfur rocks to weathering (Krause et al., 2018). The reverse of these same processes caused the release of carbon dioxide into the atmosphere. A greater impact of tectonics on the carbon cycle of the Pennsylvanian the effect of sea-level changes on photosynthesis and organic carbon burial.

The rapid spread of large terrestrial plants during the Pennsylvanian greatly contributed to atmospheric CO_2 drawdown from photosynthesis and subsequent organic carbon burial. Photosynthesis sucks carbon dioxide from the atmosphere and releases oxygen as a byproduct. When sea-level rises, due to melting ice or tectonic subsidence, these plants and their carbon reserves become locked away in coal bodies (Chen et al., 2016; Grossman et al., 2008). This process is referred to as organic carbon burial. While the Pennsylvanian processes that suck carbon dioxide from the atmosphere and release it back into the atmosphere are similar to the modern carbon cycle, examining the balance between these processes is important for recognizing how anthropogenic burning of Pennsylvanian-aged organic carbon stores rereleases carbon dioxide back into the atmosphere. Widespread photosynthesis of the Pennsylvanian increased atmospheric oxygen which may have had additional impacts on global climate changes.

Atmospheric oxygen, coupled with carbon dioxide drawdown, is hypothesized to have affected global cooling. The Pennsylvanian is indicated to have relatively high oxygen levels, recorded in charcoal inertinite records (Glasspool,

2015) and modeled by GEOCARBSULFOR (Krause et al., 2018). Atmospheric oxygen is not typically discussed as a factor in global climate change for the current earth system or the paleo-climate of the Carboniferous. Elevated atmospheric oxygen, however, contributes to the thickening of the atmosphere and, thus, the increased reflectivity of solar radiation, but as a gas does not exhibit properties that would trap water vapor or heat. In simpler terms, coupled with the loss of insulating atmospheric CO_2., increased oxygen, due to widespread photosynthesis, would have a cooling effect on the global climate. Oxygen's impact on climate over the Phanerozoic has been explored and hypothesized to have an effect on global climate trends (Poulsen et al., 2015); while these trends may be applied to the Pennsylvanian, higher resolution data, beyond general models, are needed.

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REGIONAL VARIABILITY OF GONDWANAN ICE SHEET BEHAVIOR AND DEVELOPMENT DURING THE LATE PALEOZOIC ICE AGE

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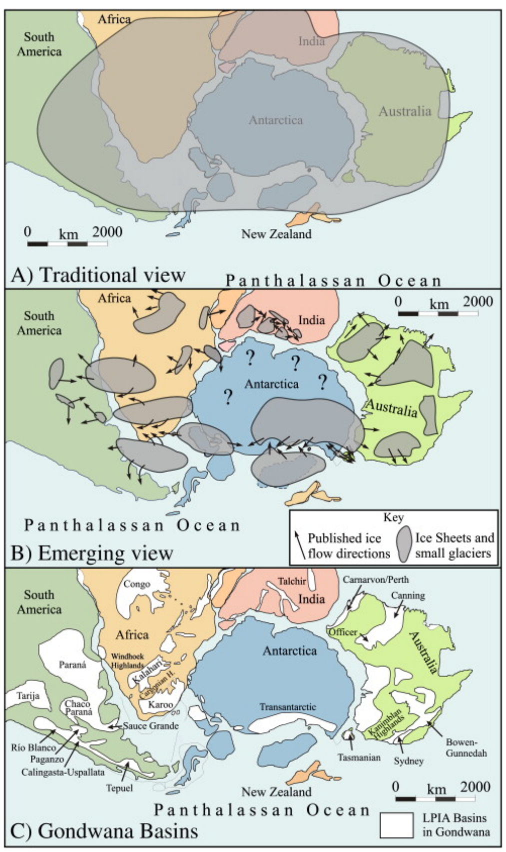
In the year 2019, global climate change is a hot topic that is almost ever-present in politics and mass media. While current climate change is unique in its causes and rate of change, this is not the first time that the planet has transitioned to warmer conditions. 350 million years ago, before the continents had formed into their current configuration, the landforms of South America, Africa, India, Australia, and Antarctica all made up Gondwana. This was the southern half of the supercontinent Pangaea. During this time, icehouse conditions prevailed on planet Earth: the South Pole was for the most part glaciated, much like it is now. Due to various effects, such as the sequestration of CO_2 into land plants similar to trees rather than being present in the atmosphere, atmospheric CO_2 levels were low; plate convergence and the weathering of silicate rocks also drew down CO_2 levels (Rolland et al. 2019). As a result of this weakened greenhouse effect, glaciers were able to grow and spread, reaching their zenith approximately 300 million years ago in the Pennsylvanian. This period of icehouse conditions is known as the Late Paleozoic Ice Age (LPIA), named for the time in which it took place, and is widely acknowledged.



Early interpretations of the LPIA have favored that of a singular, ever-present ice sheet growing out of high-elevation regions of Antarctica to lower-elevation, lower-latitude regions (Isbell et al. 2012). The extent of this ice waxed and waned over time, and was broadly defined by the outline of all glacially related Late-Paleozoic debris and deposits found on Gondwana. However, in the past decade a shift has taken place away from that of a singular ice sheet and towards that of a series of glacial events that took place across Gondwana, separated by both space and time (Figure 1). These glaciations generally took place in high-latitude, high-elevation regions and flowed down to lower latitudes and elevations. Researchers have identified approximately four main pulses of glaciation across Gondwana. Several of these involved large ice sheets covering large swaths of land across several modern-day continents, and some involved consolidated alpine glaciers in high-latitude regions. Scientists disagree about the exact timing of these glaciations. Glacial onset is hard to date, and detrital zircon analysis (decay of uranium into lead, which takes place over billions of years) can only provide minimum ages of glacial deposits, since it provides information about the age of samples when they were weathered; thus, samples can be no younger than the ages provided by analysis. Information about the locations of ice centers and the direction of glacial flow can be determined primarily from physical evidence left behind by glaciers. These include striations in the rock and deformation of the landscape as the immense weight of the glaciers scraped icebound rock over softer bedrocks, leaving lineations marking the direction of ice flow and retreat.

Recent analyses of the sources of evidence mentioned above have revealed that glaciation occurred in a gradual manner across Gondwana, first occurring in mountainous regions of western Gondwana (South America and southern Africa) in the Mississippian (Isbell et al. 2012; Andrews et al. 2019). The next glacial pulse occurred in the Late Mississippian – Early Pennsylvanian as ice flowed from highlands of southern Africa and South America to lower latitudes and elevations, filling basins and occupying uplands of Eastern Australia before once again retreating. Beginning in the latest Pennsylvanian and continuing into the Permian, the most extensive glaciation of Gondwana occurred during the LPIA, with ice flowing from upland centers in Antarctica to South America, southern Africa, and Australia (Isbell et al 2012; Mottin et al. 2018). This was the only interval for which evidence has been found showing glaciation within the lower-latitude regions of India and the Arabian Peninsula. Following this glaciation, ice retreated almost entirely, leaving even the South Pole deglaciated. However, ice remained in high-latitude parts of Australia; evidence shows that parts of Australia underwent three pulses of glacial growth and deglaciation during the Permian following the deglaciation of the South Pole. Exact reasons for this are still unclear. It has been hypothesized that these anomalous periods of glacial growth occured due to favorable conditions resulting from regional cooling by ocean water and high elevation (Isbell et al. 2012). It has also been hypothesized that tectonic activity during the Late Permian shifted western Gondwana to lower latitudes over time, making the conditions of many upland regions unfavorable for glaciation despite high elevations (Cagliari et al. 2016). In this scenario, Australia, which remained relatively fixed in its latitude during this shift, would have been affected less, allowing glaciers to form and grow.

While exact causes and timing of Gondwana glaciation during the LPIA remain murky, it is surmisable that tectonic activity played a large role in influencing both the conditions that allowed for glaciation to occur and the locations of glacial growth as silicate weathering drew down atmospheric CO_2, regions were elevated due to convergence, and regions were shifted to and from high-latitude locations. This project seeks to identify and build on the conclusions related to an E-W trend in glacial growth regarding the regional glaciation of Gondwana during the LPIA.

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PENNSYLVANIAN EVOLUTION OF GIGANTISM IN THE TERRESTRIAL AND MARINE REALMS, AN INVESTIGATION OF THE HYPEROXIA MODEL

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Three hundred million years ago Earth's forests were ruled by a very different type of top predator. Instead of tigers and wolves, imagine dragonflies the size of seagulls, scorpions taller than a man, or salamanders that could swallow a dog. These are not creatures of one's imagination, but the animals of the Carboniferous period. This period is unique in that species across different phyla increased in size. Gigantism does not just appear in one species. It is observed in many, such as arthropods, tetrapods, and marine invertebrates. Since the early 1990's a hyperoxia model has been used to explain gigantism. This model hypothesizes that increased oxygen levels allowed organisms to grow larger than ever before (Verberk and Bilton, 2011). However, recent papers have put this hypothesis into question. This study examines the resilience of the hyperoxia model when applied to various taxa in the Pennsylvania (peak oxygen levels) with respect to terrestrial and marine gigantism.

Atmospheric oxygen has been modeled by a number of researchers over the last three decades. Paleo-Oxygen levels peaked in the Pennsylvanian, significantly higher than our present day atmosphere of 21% oxygen. The Berner model, referred to as the GEOCARBSULF, is most often cited. The model gets this name because the oxygen estimates are derived from both the carbon and sulfur cycles. The carbon cycle represents the complex movement of carbon through the atmosphere, oceans, and lithosphere. The sulfur cycle is linked to the carbon cycle through weathering processes, such as the dissolution of carbonate rocks by sulfuric rain (H_2SO_4). Both of the models are related to atmospheric oxygen and together can be used to reconstruct of the paleo-atmophere. The Berner model was most recently revised in 2009 and illustrates pO_2 peaking at around 33% in the late Pennsylvanian (Fig. 1). This is lower than previous estimates of around 35%. Determining how living in

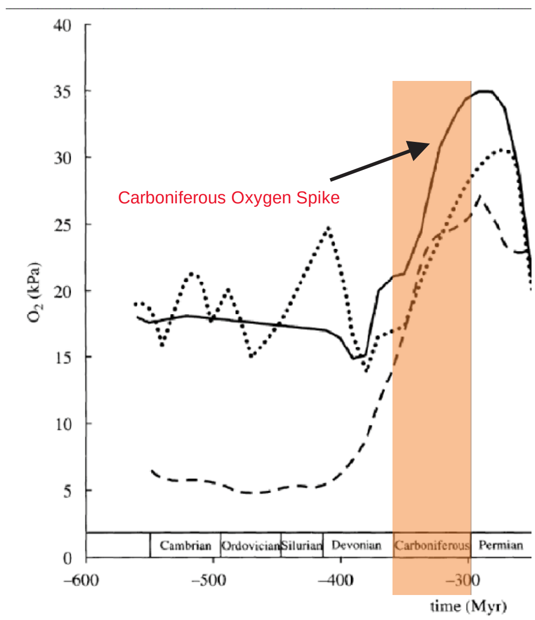

Figure 1: Atmospheric oxygen reconstructions by Berner 1989 (solid line), Berner 2009 (dotted line) and Bergman 2004 (dashed line). Figure adapted from Harrison et al, 2010.

a 33% oxygen atmosphere affects life is a challenging question.

The most well documented Carboniferous gigantism is in some arthropod group. On land griffenflies (*Protodonata*) and dragonflies (*Odonnata*) had wingspans of 70 cm (Butterfield, 2009). A relative of the modern millipede called *Arthropleura,* grew to around 2 m (Harrison *et al*. 2010). The proposed link between arthropod gigantism and a high oxygen atmosphere is tracheal respiration. Arthropods intake oxygen from pores in their exoskeletons. Spiracles are openings that lead to small tubes called trachea, these subdivide into even smaller tubes called tracheols which are distributed through the body delivering oxygen to organs via diffusion (Cannell, 2018). Theoretically, higher oxygen levels make it possible to overcome limitations of the complex and energy demanding tracheal system (Graham et al, 2016). Modern studies on fruit flies indicate that increased atmospheric oxygen results in larger body plans. However, this is not documented in all cases or experimental results (Graham et al. 2016). Also, a tracheal respiration driven gigantism is only applicable to arthropods, because other terrestrial organisms, such as amphibians have a different physiology.

Amphibians, such as *Eryops megacephalus,* and the early proto-reptile *Diadectes maximus* were giants of their day, measuring two and three meters respectively (Steyer, 2012; McGhee, 2018). While these are not giants by the standard of the dinosaurs, these were the largest land vertebrates in the late Paleozoic. Diversification of land vertebrates increased in the Pennsylvanian, from 6-7 families in the lower Pennsylvanian to at least 39 by the middle Permian (Sahney et al, 2010). The development and subsequent collapse of rainforests created new niches for vertebrates. However, the growth of vertebrates is only loosely constrained by atmospheric oxygen levels. There is insufficient evidence to connect vertebrate gigantism with the hyperoxia model. However, it is likely that oxygen is a secondary control helping to improve environmental factors favorable to terrestrial vertebrates such as forage and shelter.

Marine invertebrates display gigantism too, these include brachiopods, such as *Gigantoproductus giganteus*, eurypterids, like *Jaekelopterus rhenaniae* and fusulinoid foraminifera (Payne et al, 2010; Steyer, 2012). While all three of these organisms developed gigantism traits, only one supports the hyperoxia-gigantism hypothesis. Foraminifera are single-celled calcium-carbonate producing animals on the mm or smaller scale. However, Fusulinoid foraminifera grew to an enormous 12 cm in the Pennsylvanian. This growth mirrors the GEOCARBSULF atmospheric reconstruction, Figure 1 (Payne et al, 2010). The reason why increased atmospheric oxygen promoted larger forams is not well understood. However, the correlation is also supported by modern analogs (Payne et al, 2010).

The hyperoxia model for Carboniferous gigantism is testable and, in concept, a valid hypothesis. However, there is insufficient evidence to support this hypothesis as it relates to the entire biosphere. There are a few species of arthropods and foraminifera where the hypothesis can be supported. But even in these cases there is contradictory evidence. For example, griffenflies on the scale of 35 cm were present in the late Permian when atmospheric oxygen was lower than present day levels, today we don't not see anything near this size (Butterfield, 2009). A hyperoxia model for Carboniferous gigantism is too broad in scope. It fails to recognize the timing of major atmospheric oxygen pulses and complicated environmental factors also leading to increased body plans.

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