Ice age to snowball Earth: geology as scientific rebel

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The importance of geology within the natural and social sciences as a whole is historical and continuing. Historically, geology was the first science to appreciate the "deepness" of time and also that their object of study (the Earth) had a history inadequately described by the "timeless" laws of Newtonian mechanics. In the early 1800's, geology paved the way for other sciences that study systems that change over time in ways contingent on their histories—astronomy, cosmology, biology, and even history itself. Its continuing importance is in revealing important phenomena that could scarcely be imagined if investigations were limited to the present world.

The discovery of the "greenhouse" effect by the Irish-born physicist John Tyndall (better known for explaining why the sky is blue) in 1863 was explicitly motivated by the controversial hypothesis that North America and Europe were mostly covered by glacial ice sheets in the geologically recent past. Physicists had previously assumed that the Earth's climate was steadily cooling because the Sun (they thought) must be growing dimmer over time. Tyndall's experiments showed that small variations in the concentrations of trace constituents in the atmosphere, notably carbon dioxide, could "account for all the mutations of climate that the researches of geology have revealed". Today, the sufficient reason for concern over climate change in coming decades is the non-controversial measured increase in anthropogenic carbon dioxide.

The interest stirred up by the ice age controversy of 1837-1862 led to the discovery of more ancient (300 million-year-old) glacial deposits (tills, erratic boulders, sculpted landforms) in India, South Africa, Australia and South America. Their geographical distribution and patterns of former glacial flowage was so nonsensical that the young German meteorologist Alfred Wegener proposed in 1912 that the continents had "drifted" separately across the face of the Earth, and were still doing so. Acceptance of this theory was delayed until the 1960's, when it reemerged in the form of "plate tectonics", the conceptual basis for all modern studies of the Earth's internal dynamics, geochemical cycles and evolution of terrestrial ecosystems.

C.E.P. Brooks first recognized in 1926 that the Earth's has experienced two discrete climate states since the Cambrian (541 million years ago): "glacial-interglacial" states (like today or the Pleistocene) in which 1-4 continents bore ice sheets, and "non-glacial" states (like the Mesozoic) when no large ice sheets existed. Mathematical models of climate subsequently showed that this schizoid behavior results from positive feedback loops, causing the climate system to "jump" suddenly between states. These same models exposed an ominous third ("pan-glacial") state in which all continents are covered by ice sheets. Climate physicists assumed this state had never actually existed because an ice-covered Earth would reflect >50% of incoming Solar radiation (seawater reflects only 10%) and could never (they thought) have warmed up again to the melting point even at the equator.

Geochemists eventually realized, however, that a frozen surface would not allow the carbon dioxide that is continuously emitted into the atmosphere by volcanoes (even through an ice sheet, as on Iceland) to be removed. Its concentration would rise for millions of years until the "greenhouse" effect reached the threshold where the ice sheets begin to recede. Total meltdown follows catastrophically due to the same positive feedbacks as before, but now working in reverse (melting creates water which absorbs more sunlight causing increased melting). With ice sheets gone, the "greenhouse" overload and the darkened surface conspire to create a hot and acidic "dawn" following the multi-million-year pan-glacial "night". Carbon dioxide rains out of the atmosphere, reacts chemically with glacially-powdered rock, dissolves in river water and eventually exits the ocean as carbonate sediment (limestone and dolomite). These deposits are called "cap" carbonates by geologists.

Based on geological evidence that had been accumulating for 100 years, Joe Kirschvink at Caltech proposed in 1992 that such "freeze-fry" climatic cycles actually did occur, more than once, 600-700 million years ago. He named the pan-glacial state "snowball" Earth, and intimated that these climate switches somehow sparked the evolution of complex animal life around that time. The furore that soon developed and which continues today is highly reminiscent of the controversy 150 years ago over the Pleistocene ice ages and their biological response. The difference in age between the last "snowball" Earth meltdown (635 million years ago) and the oldest eumetazoan (sponge-grade animal) fossils—diapause eggs and embryos found in Hubei, China—is currently less than 3 million years. This is a very close association given 1.5 billion years of eukaryotic evolution. How did the most extreme climate switches imagineable spawn the crown of life as we know it?

Reference: Hoffman, P.F. & Schrag, D.P., *Terra Nova* **14**, 129-155 (2002). Or go to <www.snowballearth.org>.