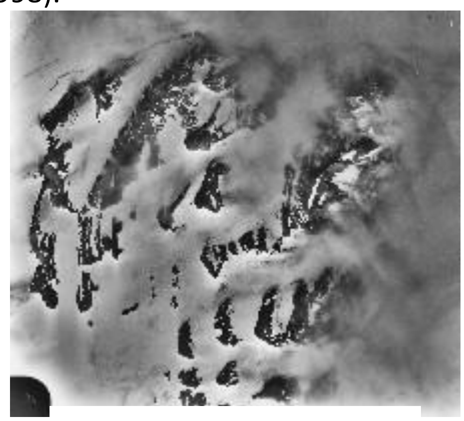
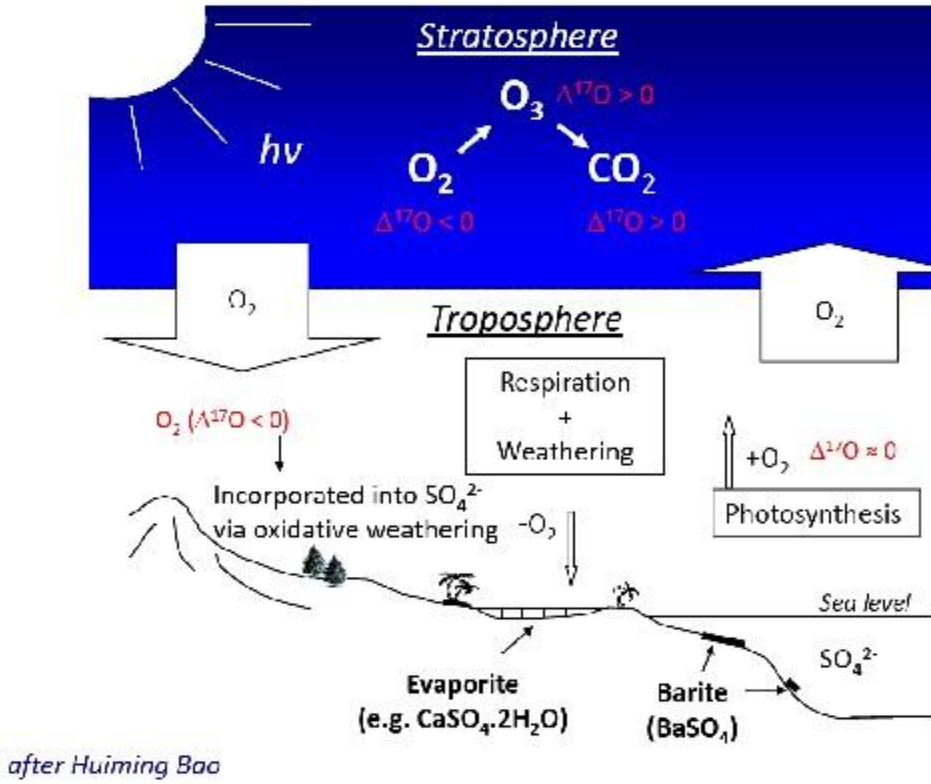
What's hot on Snowball Earth?

A paper published by [***Science***] on 2 January 2009 (Bao et al., 2009) is the latest and perhaps most significant development in Ian Fairchild's collaborative research over the past 30 years on Precambrian ice ages and their associated carbonate rocks. The paper comes up with a new line of evidence to support a key, but counter-intuitive prediction of *Snowball Earth* theory: that carbon dioxide levels were high in the Earth's atmosphere during an ancient ice age. During a *Snowball* event you can think of the Earth as being like a baked Alaska pudding – hot on the outside surrounding a cold middle (ice-cream in the case of the pudding). This strange situation arises if the Earth is largely covered in ice and snow in contact with an atmosphere rich in greenhouse gases in which heat is trapped. The covering of ice and snow stops rocks being weathered by carbon dioxide: weathering is the key process that uses up this gas which is continuously released into the atmosphere from volcanoes. So, during an extreme glaciation (probably triggered by low levels of greenhouse gas in the first place), levels of carbon dioxide progressively rose to unusually high levels (Hoffman et al., 1998).

The idea of a carbon dioxide-rich atmosphere during an ice age is fine in theory, but lacked independent evidence. To make our breakthrough, we studied some strange limestones that were deposited probably around 630 million years ago, in salt lakes next to an ice sheet. Such lakes are found today in Antarctica where they become very salty by evaporation in a cold, dry climate. The limestones and associated sedimentary rocks (called member W2) were collected on an expedition to the glaciers of Spitsbergen (Svalbard) where they are exposed in nunataks - jagged rocks sticking out of the modern ice.

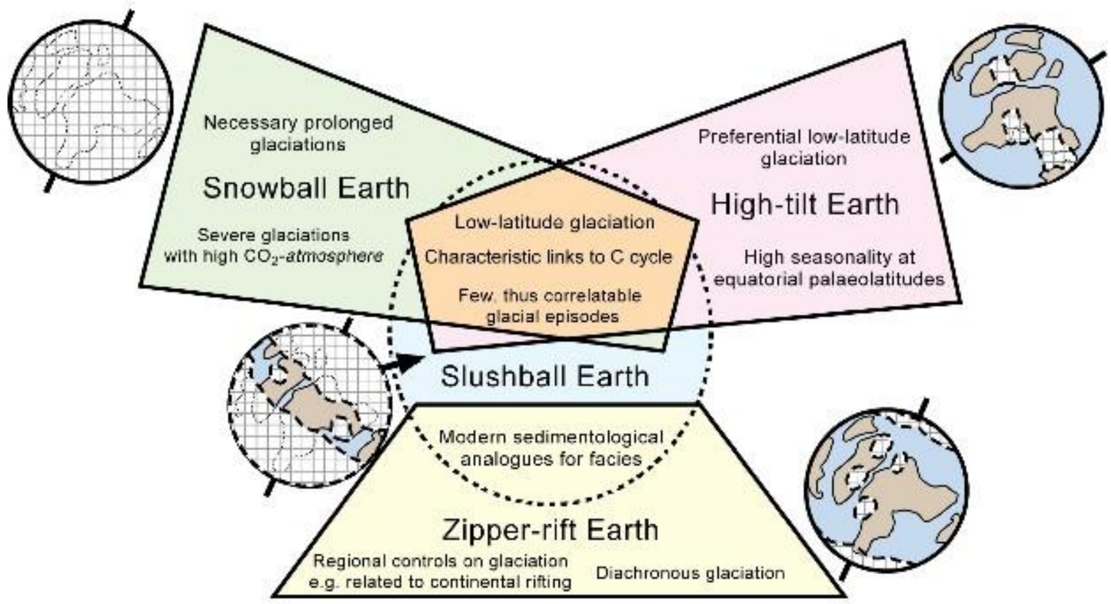

Nunataks in aerial photograph

We found several aspects of the chemistry of the rocks that broke world records. Some limestones showed a strange chemical signal: they have less of a particular isotope of oxygen (^{17}O) than expected. Such a signal can only be created by chemical reactions stimulated by cosmic rays in the top of the atmosphere (the stratosphere). In the modern world this gives rise to ozone and carbon dioxide with excess ^{17}O and much larger amounts of oxygen with a small deficiency in ^{17}O. Our co-author Huiming Bao has recently shown (Bao et al. 2008) that if carbon dioxide in the atmosphere is much more abundant than at the present day, it causes oxygen in the atmosphere as a whole to carry a strong signal of depletion in ^{17}O. In the latest work we have found this signal much more strongly developed than in the examples found by Bao et al. (2008). The signal found its way into our rocks by the oxidation of reduced sulphur (iron sulphides) on the land surface by oxygen resulting in sulphate which got washed into lakes where it was precipitated within limestone.



The second and third world records were found in the lakes that become more salty and formed dolomite - $CaMg(CO_3)_2$ instead of limestone - $CaCO_3$. Here microbes reduced and re-oxidized the sulphate (SO_4), replacing the oxygen atoms with new ones with an excess of ^{18}O (and the dolomite also shows the same signal), but in doing so the unusual ^{17}O signature is lost. These dolomites have the heaviest oxygen yet found at the Earth's surface in the geological record, attesting to a hyper-arid glacial environment.

This discovery is of general interest for two reasons. Firstly, there is a fascination with extreme events in the history of our planet. It is proposed that a small number of *Snowball Earth* events of near-global or total glaciation of the planet occurred: if so they certainly represent one of the major challenges to survival of life on the planet. This was the reason that Channel 4 chose this topic for one of the programmes in their recent series called *Catastrophe.* The concepts behind *Snowball Earth* are accessibly described at the website of Paul Hoffman, who has been a major advocate for it: http://www.snowballearth.org/. A key part of the theory is that once snow and ice cover all the higher latitudes, the glaciation would go out of control because of a runaway positive feedback between the growth of a reflective white surface of ice and snow (i.e. high albedo) and cooling of the surface. Modelling shows that a stable state would be reached with the Earth close to -45°C (compared with +15°C) today. A weak hydrological cycle (with a little melting and evaporation in summer) would eventually create moving glaciers kilometres thick. However, many geologists think that although the Earth may have been significantly covered with ice, it did not freeze-up completely - they find open marine deposits sandwiched between glacial deposits (reviewed by Allen and Etienne, 2008). Some modellers find that a stable climate state could exist with a mean Earth temperature around zero and significant open water in the tropics: this has been termed *Slushball Earth*: still an extremely inhospitable place from a human perspective! A carbon dioxide atmosphere would also have built up in this case since weathering would still have been inhibited.



Theories of Precambrian glaciation

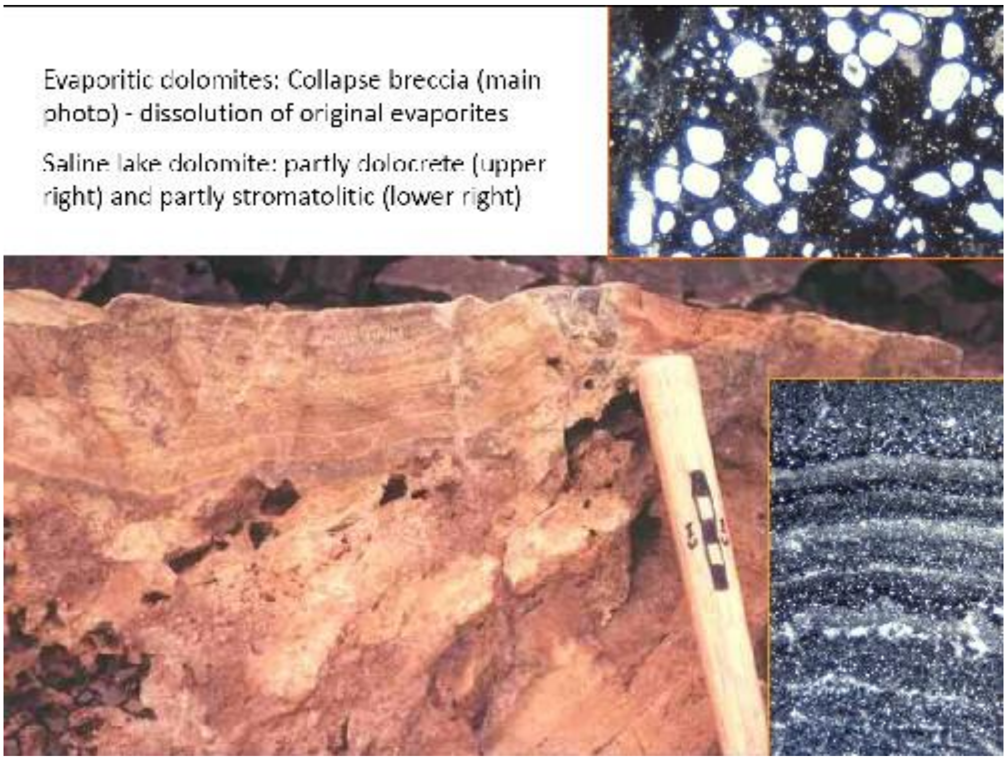
The second reason why the discovery is of general interest is that it brings home how catastrophically the conditions on Earth could change. The initial modelling for the *Snowball* theory was done to find out what could happen in a *nuclear winter* if the atmosphere became dusty as a result of a nuclear war.   The distinguished chemist Paul Crutzen has revived an older idea that we could inject sulphate aerosols into the atmosphere to counteract global warming (Crutzen, 2006). However, if we overdid it, the consequences are likely to be a *Snowball Earth*.

The *Science* paper has been written with colleagues Huiming Bao of Louisiana State University, Peter Wynn of Lancaster University and Christoph Spötl of the University of Innsbruck.   The work in Svalbard started with adventurous fieldwork in 1982 in a group led by Mike Hambrey, now Professor at Aberystwyth University on an expedition funded by a grant from the Natural Environment Research Council (NERC) to the late Brian Harland of the University of Cambridge. A series of publications in the 1980s in *Nature*, *Precambrian Research*, *Sedimentology* and *Geological Magazine* led by Ian Fairchild explained the sedimentological interpretation of the glacial deposits and their associated carbonate rocks, including the analogy for the glacial lake carbonates with the modern Antarctic salt lakes of the Dry Valleys. A *Slushball*-type model was the working model. The work was summarized in Fairchild (1993).

By the early 2000s, the *Snowball Earth* theory had rejuvenated research in the field by setting up new hypotheses that could potentially be tested. Ian Fairchild realized that the glacial lake carbonates appeared to be unique in the geological record and so embarked on a further round of geochemical studies. Collaboration with Mike Bickle and Hazel Chapman at Cambridge University on Sr isotopes demonstrated that some weathering in the glacial catchment had occurred, so there were at least some rocks exposed at the surface at the time. Our collaborator on stalagmites, Christoph Spötl, carried out many more oxygen and carbon isotope analyses of the samples, which showed that they extended to world-record-breaking values. Studies by Ian Fairchild, funded by the use of NERC ion microprobe and ICPMS facilities, found that the carbonates carried small traces of normal sea salt amongst a wide range of detectable elements, but were unusually rich in sulphate. Ian Fairchild wondered if this sulphate might have accumulated from volcanoes as proposed for carbon dioxide in the *Snowball* theory. Once he was joined at Birmingham by Peter Wynn, funded by a standard NERC grant to work on sulphate in stalagmites, work on the glacial lake carbonates was pursued as a sideline, and was actually helpful in developing the techniques used on the stalagmites (Wynn et al., 2008). Peter extracted S from the rocks and we looked to see if it had a volcanic signature, depleted in the isotope ^{34}S. The result was that a few samples showed some depletion, but the bulk of the S was clearly not volcanic. Ian Fairchild presented results of this work at the Ascona *Snowball Earth* meeting and the Melbourne Goldschmidt meeting in 2006. Ian Fairchild then collaborated with Martin Kennedy of University of California, Riverside, to produce a state-of-the-art review of the significance of Neoproterozoic glaciation for the Earth System, which was published as one of the Geological Society's bicentenary reviews (Fairchild and Kennedy, 2007).

The breakthrough for the *Science* paper came after Ian Fairchild reviewed Huiming Bao's paper submitted to *Nature* in late 2007. Huiming had made a number of novel discoveries using a combination of isotopes in sulphates, with particular emphasis on ^{17}O. In the *Nature* manuscript, the punchline was that there was high carbon dioxide following a glaciation at around 630 million years ago, based on new analyses of barium sulphate crystals in carbonate rocks. However, this could have arisen either if there was plenty of greenhouse gas during glaciation, or if release of methane after glaciation had occurred as proposed by Martin Kennedy (which we know did occur at least to some extent). After reviewing the paper, Ian Fairchild arranged to meet up with Huiming at the American Geophysical Union meeting in San Francisco in December 2007 and proposed collaborative work on the carbonates formed *during* such a glaciation to resolve the issue. Following six months hard and meticulous work in analysis and interpretation, and near-exhaustion of the supply of collected rocks, the results were communicated in papers at the Vancouver Goldschmidt meeting by Huiming Bao and the

Oslo meeting of the International Geological Congress by Ian Fairchild in 2008, followed by rapid writing and revision of the work for publication. It turns out that there is an important signal from the sulphur isotopes measured at Birmingham after all, but only when plotted against the variation in ^{17}O measured at Louisiana State: testament to the power of collaborative endeavour in modern science.



Ian Parkinson and Pierre Bonnand from the Open University are currently adding value to the collaboration by studying rare earth elements, which can give more indications of oxidation state at the time. A more extensive article on the work of the last few years is being planned for publication and the next challenge is to raise funds to re-visit the very remote field area in Svalbard and sample more systematically to discover whether the wonderfully preserved sediments support or challenge Paul Hoffman's idea of deposition of glacial deposits only at the end of a *Snowball* ice age. There is plenty of scope for more field observations: the original field collections on the glacial lake carbonates were made in haste over only two or three field days in total!

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Lone scientist in Svalbard – reminiscent of Snowball Earth