Title

An examination of the arguments for and against Marinoan Snowball Earth, 650 Ma, being a solid ball of ice - A Report submitted as the examined component of the Project Module SXG390

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Abstract

This literature review examined evidence for and against a hard or soft Marinoan Snowball Earth, an extreme global glaciation that occurred around 645 Ma thought to have lasted more than 5 Myr. The event was likely followed by a period of extreme warming referred to as a super greenhouse and may have even triggered the evolution of complex life. Reliable material was carefully sourced and methodically considered during this investigation which includes geological and geochemical evidence, and the use of climate models. The first comprehensive Snowball Earth Hypothesis developed in the 1990's, contained some challenging concepts and may require revision in light of more recent studies, many of which support a softer Snowball Earth. Geological evidence that ice existed at low latitudes is wide ranging and plentiful but often suggests that an active water cycle was also present. This is contradictory to the anoxic oceans that form part of a hard Snowball Earth. Geochemical evidence considered was inconsistent but may prove useful if combined with other forms of data. Studies involving climate models showed preferential support for a soft Snowball Earth and could prove to be a promising research area as climate models will increase in complexity as computing capabilities improve. Life's survival of Marinoan Snowball Earth is an exciting topic and surprisingly, research considered led to the conclusion that eukaryotic life could have survived even a hard Snowball Earth. Comparisons with present day Antarctica showed that some lifeforms can live in ice-covered environments and has the potential to acquire adaptations far beyond our current understanding. Future research on Snowball Earth could prove vital to the survival of humanity via enabling better understanding of how Earth's climate responds to increased CO_2 emissions. Investigations could also prove useful in our search for life and habitable planets beyond our solar system.

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Chapter 1 – Introduction

1.1 The Snowball Earth Hypothesis

The Snowball Earth Hypothesis was originally proposed in 1837 by Louis Agassiz (Allen & Etienne, 2008), and describes an event where Earth was completely covered in ice up to 1 km thick (as imagined in **Figure 1**). Scientists, Kirschvink and Hoffman, used geological evidence to develop the idea in the 1990s when the topic appeared to gain some traction. The most recent Snowball Earth is referred to as Marinoan Snowball Earth and occurred around 640 Ma. The event is marked on **Figure 2** which provides some context regarding where this sits within the geological timeline.

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Figure 1. 'When Earth was a frozen snowball' taken from Ravilious, K, (2015).

Several triggers were likely responsible for Marinoan Snowball Earth and are still a matter of debate. Neoproterozoic Earth (1000 Ma – 541 Ma), received 6% less sunlight, featured land masses predominantly at mid to low latitudes, and featured a climate dependent on greenhouse gases (Hoffman & Schrag, 2002). This dependency followed enhanced silicate weathering, exacerbated by continental fragmentation, creating more margins (prime sites for erosion) and ultimately removing large quantities of CO_2 from the atmosphere (Hoffman et al., 1998, Hoffman & Schrag, 2002). A reduction in greenhouse gases and increased albedo (due to continental landmasses), would both cause Earth's temperature to fall, resulting in ice beginning to spread from the poles (Hoffman & Schrag, 2002). When ice

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Figure 2. Labelled snapshot of the geological timescale (original from Cohen et al., 2020)

cover reaches around 50%, runaway feedback occurs, and Snowball Earth is in effect unstoppable (Hoffman et al., Hoffman & Schrag, 2002). Other potential triggers include low CO_2 degassing rates prior to glaciation (Hartman, 2017) and increased oxygen production by cyanobacteria (Casado, 2020).

An important question currently being asked is whether Snowball Earth was hard (fully glaciated with thick ice) or soft (glaciated with thinner ice and/or with ice free zones). This literature review aimed to consider this question whilst specifically addressing the below objectives.

1.2 Objectives

1. Investigate the possible triggers and feedbacks behind Marinoan Snowball Earth to provide context for this review.
2. Discuss and compare the evidence for and against Marinoan Snowball Earth being hard or soft and form an opinion on the most likely scenario based on the studies reviewed.
3. Consider the impact a hard or soft Marinoan Snowball Earth would have on life and how it could have survived such an event.
4. Establish how research into Snowball Earth could benefit scientists investigating how Earth's systems will respond to future climate change.

1.3 Methodology

Search engines used for this review included Google Scholar, Google and the OU Library, whilst citation searches lead several suitable articles being found. Work on Snowball Earth by Hoffman is extensive and was essential to this project. Key papers included Hoffman and Schrag, (2002), and Allan & Etienne, (2008), as both were a great source of information and provided links to further material. Recent papers such as Lechte et al., (2019), and Liu et al., (2020), were highly relevant to some of the objectives considered during this project.

Chapter 2 – Geological Evidence

Geological evidence formed a large part of the original hard Snowball Earth Hypothesis and the super greenhouse that followed but has also been used to support a soft Snowball Earth. The first confirmed glacial deposit from the Neoproterozoic was found by Reusch in 1891 (**Figure 2a)**, (Hoffman & Schrag, 2002). Snowball Earth studies utilise glacial successions (Allan & Etienne, 2008, Hoffman et al., 1998, Hoffman & Schrag, 2002, Kirschvink, 1992) iron deposits (Kirschvink, 1992, Lechte et al., 2019) and geological features such as giant wave ripples (Lamb et al., 2012). Palaeomagnetism has been used to decipher the Neoproterozoic locations of deposits via magnetic fields which act as a record of past latitude trapped within magnetically aligned grains in rocks.

2.1 Diamictites and Cap Carbonates

Diamictites are poorly sorted glaciogenic sediments set in a fine-grained matrix (debrites are the non-glacial version) and sometimes appear with non-glacial deposits, representing periods of glaciation and non-glaciation, (Allan & Etienne, 2008). **Figure 2a** – **f** provides examples of features found within diamictites, including the Rapitan diamictite in Canada (**Figure 2c** - **d**) and the Ghaub diamictite in Namibia (**Figure 2e** - **f**), (Hoffman & Schrag, 2002). Features highlighted in **Figure 2** provide evidence for massive glaciers active near the equator during Snowball Earth (Hoffman & Schrag, 2002), thus supporting a fully glaciated planet. Glaciogenic sequences topped by cap carbonates, have been found in similar locations (Kirschvink, 1992), implying that both the event and subsequent warming were extreme, which fits into the hard Snowball Earth Hypothesis.

Geological evidence from the Mirbat Group in Oman in **Figure 3,** taken from Allan & Etienne, (2008), provides examples of diamictites and glacial striations (scratches in bedrock caused by glacial abrasion). **Figure 3** presents geology that suggests Snowball Earth was dynamic and involved continual ice advance and retreat, (Allan & Etienne, 2008). **Figure 3** also shows that glacial deposits and features can be difficult to interpret, partly because diamictites (**Figure 3c**) and debrites both contain poorly sorted material. Glacial striations (**Figure 2a, Figure 3d)** require an active hydrological cycle to form undermining the hard Snowball Earth hypothesis, as complete global glaciation must mean that water circulation ceases. A soft Snowball Earth may sit more comfortably with an active water cycle, as open water and/or thinner ice could allow for more active oceans (at least in some regions). Another interpretation for evidence in **Figure 3**, is that formation occurred at the start or end of Snowball Earth, but some diamictites are too thick to support this idea (Allan & Etienne, 2008).

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Figure 3. Examples of glacial features from the Neoproterozoic used by Hoffman & Schrag (2002) to support a hard Snowball Earth. **a** - Diamictite above striated pavement, Bigganjargga, Varangerfjord, Norway. **b** - Faceted multistriated stone from Jbe'liat diamictite, Adrar, Mauritani. **c** - Sharp boundary between Rapitan diamictite and bycarbonate strata, Stone Knife River, Mackenzie Mountains, Canada. **d** - Dropstone (dolomite) in banded iron formation within Rapitan diamictite, Snake River, Mackenzie Mountains, Canada. **e** - Ice-rafted dropstone in slope-facies carbonates, Ghaub Formation, Fransfontein, Namibia. **f** - Abrupt contact between dropstone unit and cap carbonates (dolostone), Fransfontein, Namibia. (Modified images from Hoffman & Schrag, 2002).

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Figure 4. Evidence of a glacial – interglacial epoch from Dhofar, Oman. **a** – Shallow marine deposits alternating with 200 m thick diamictites. **b** – Evidence of delta progradation into proglacial lakes/seas provided by clinoforms (C). **c** – Evidence of rain-out from floating ice provided by clast poor diamictites with a dyke deposited at a later point (D). **d** – Evidence of ice contact via glacial striations on a subglacial sedimentary substrate (Modified images from Allan & Etienne, 2008).

A hard Snowball Earth involves rapid deglaciation due to atmospheric CO_2 build-up, followed by oceanic carbonate precipitation, (Hoffman et al., 1998, Hoffman & Schrag, 2002). Rapidly deposited cap carbonates (**Figure 2f**) are therefore an expected result of post glacial warming that followed Snowball Earth, (Hoffman et al., 1998, Hoffman & Schrag, 2002). Snowball Earth had to be complete to allow enough CO_2 to accumulate for rapid warming, (Allen & Etienne, 2008). However, multiple magnetic reversals, carbon isotopic profiles and geochemical evidence found in some cap carbonates, imply that carbonate deposition may not have been as rapid as first thought, (Allen & Etienne, 2008). This data supports a softer Snowball Earth scenario where less CO_2 built up pre deglaciation, meltback was slower and warming less extreme than that representative of a hard Snowball Earth. Varying deposition of cap carbonates across the globe may also support a slower and somewhat irregular deglaciation, conforming to a soft Snowball Earth, but Hoffman et al., (1998), suggest that this is due to carbonate precipitation being localised on reefs (platforms of warm shallow water) as sea level rises post glaciation.

2.2 Dropstones

Dropstones are sand to cobble sized clasts (isolated rock fragments), draped by overlying laminations of a finer grained sedimentary rock, (Allan & Etienne, 2008). Neoproterozoic dropstones, like those in The Ghaub Formation, Namibia, (**Figure 2f**), always provide evidence for ice as there was no other way for them to form during the period, (Hoffman et al., 1998, Hoffman & Schrag, 2002). The Ghaub Formation is also home to a trough supposedly carved by an ice stream during extreme glaciation with thick deposits directly above, most likely formed during deglaciation, (Allan & Etienne, 2008). Dropstone units like those in Namibia have been used as evidence for rapid meltback of a hard Snowball Earth, but speedy deposition does not necessarily mean ice was present immediately prior to formation. Therefore, rapid deglaciation cannot be used as an explanation for all Neoproterozoic glacial and non-glacial deposits, (Allan & Etienne, 2008).

2.3 Giant Wave Ripples

Giant wave ripples are thought to form during extreme weather events such as storms and hurricanes, providing evidence for the climatic instability linked to intense warming in the aftermath of Snowball Earth, (Hoffman et al., 1998, Hoffman & Schrag 2002, Lamb et al., 2012). However, Lamb et al., (2012), used a new bedform stability diagram to prove that giant wave ripples do not require extreme weather for deposition and formation may occur over long time periods, under normal wave conditions. Lamb et al., (2012), concluded that two key conditions are required for giant wave ripple formation: the production of large sediment grains, and high cementation rates allowing aggradation and preservation. Therefore, giant wave ripples may not support th super greenhouse that follows a hard Snowball Earth. Interestingly, wave generated ripple marks from the Neoproterozoic, like those in the Elatina Formation, Australia, require a large body of ice-free open water to form, suggesting ice free oceans during Snowball Earth, offering further support for a softer scenario, (Allan & Etienne, 2008).

2.4 Banded Iron Formations (BIFs)

An Earth covered by thick icesheets, results in an ocean effectively being cut off from the atmosphere. At some point during a hard Snowball Earth, the water cycle and oxygen circulation, could have ceased completely causing anoxic bottom ocean waters, (Hoffman et al., 1998, Hoffman & Schrag, 2002). The level of iron, released from mid ocean ridges, built up as there was no oxygen available to allow the normal reactions to take place, (Kirschvink, 1992, Hoffman et al., 1998). Oxygen would be available again when the hydrological cycle becomes re-established towards the end of Snowball Earth, at which point the iron oxidises leaving a layer of iron rich deposits known as BIFs (banded iron formations) (**Figure 2d**), (Kirschvink, 1992, Hoffman & Schrag, 2002).

BIFs were common, until they disappeared around 1.85 Ga, long before Marinoan Snowball Earth. Banded iron formations re-appeared during the late Neoproterozoic and are found in multiple locations, including Canada, Brazil, Australia, and South Africa (Kirschvink, 1992, Hoffman et al., 1998, Hoffman & Schrag, 2002). Neoproterozoic BIFs are thought to represent sudden, post Snowball Earth oxidation and the preceding oceanic anoxia associated with a hard Snowball Earth. However, a period of oceanic anoxia could also form part of a soft Snowball Earth, allowing for periods with and locations that have an active water cycle. Lechte et al., (2019), studied multiple BIFs looking for evidence of a glacially derived oxygen source and oxygen oases supported by subglacial meltwater. This alternative interpretation may support a softer Snowball Earth where anoxia was present in certain ice-covered locations, but oxidation increased towards ice shelf grounding lines, (Lechte et al., 2019). Ocean circulation may exist in some regions in this scenario, resulting in oxygenated water being available via an oxygen pump, (Lechte et al., 2019).

Chapter 3 – Geochemical Evidence & the use of Climate Models

3.1 Geochemical Evidence

Negative carbon isotope anomalies in Neoproterozoic glacial deposits found in Namibia, show that CO_2 increased to around 350 times that seen today, during Snowball Earth, which ties into cap carbonates at the same location, (Hoffman et al., 1998). This supports a hard Snowball Earth, but confusingly, rapid deglaciation has also been disputed via carbon isotopic profiles, (Allan & Etienne, 2008), leaning towards slower meltback and a soft Snowball Earth. Hartmann et al., (2017), investigated oxygen stable isotope composition in zircons to learn about weathering in Earth's geological history. The minimum coupled ^{18}O-Hf-U/Pb isotope value obtained in the study, coincided with Neoproterozoic glacial events, verifying a lack of silicate weathering during hard Snowball Earths, (Hartmann et al., 2017). Hartmann et al., (2017), believe various feedbacks and fluxes within the carbon cycle would have balanced Earth's climate within less than 1 Myr of extreme glaciation. Marinoan Snowball Earth is expected to have lasted around 5 Myr, so it is unclear why Earth's climate took so long to self-regulate if assumptions made by Hartmann et al., (2017), are correct.

3.2 Climate Models

Climate models are used to simulate scenarios such as Snowball Earth and involve various climatic factors and feedbacks. Climate model components include the atmosphere, oceans, ice, and the carbon cycle.

Penman & Rooney, (2019), used pre–Cambrian carbon and silica cycles within the PreCOSCIOUS model (PreCambrian Ocean Silicate-Carbonate Inorganic Ocean Underwater Sediment), and parts of previous climate models, to simulate climatic and geochemical processes over several Myr. The reservoirs and fluxes used in PreCOSCIOUS are shown in **Figure 4** which provides an example of the typical components and fluxes used in climate models. Hard and soft Snowball Earths (including deglaciation) were simulated by Penman & Rooney, (2019), over a 15 Myr timeframe, taking several hours to run. Atmosphere to sea gas exchange was completely removed from hard scenarios, while CO_2 was allowed to mix with the surface and deep ocean in soft scenarios, (Penman & Rooney, 2019). Thresholds required for deglaciation were reached in an average of 4.5 Myr for a soft snowball and 6.7

Myr for a hard snowball, showing a quicker path to deglaciation for a soft Snowball Earth, (Penman & Rooney, 2019). This contradicts earlier work by Liu & Peltier, (2009), which used the Carbon Cycle Climate Model of Neoproterozoic Glaciation to suggest that a hard Snowball Earth would last for 10s Myr. Liu et al., (2020), modelled sand wedge formation during a Snowball Earth, to consider conditions required for their development. Deep sand wedges are thought to require cold annual temperatures, a large seasonal cycle, and an exposed land surface for formation and only a hard Snowball Earth would involve the necessary extremes, (Liu et al., 2020). Liu et al., (2020), concluded that the conditions required for sand wedge formation have been exaggerated, meaning they could also have formed during a soft Snowball Earth. The results of studies by Liu et al., (2020), and Penman & Rooney, (2019), neither support or refute a hard or soft Snowball Earth but imply that either scenario could have taken place.

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Figure 5. Systems diagram of the reservoirs and fluxes that make up the PreCOSCIOUS model discussed in the text. **Blue arrows** = carbon, yellow arrows = alkalinity, **green arrows** = silicate, **black arrows** = combination of more than one tracer, (figure taken from Penman & Rooney, 2019).

Many papers that involve climate modelling support a soft Snowball Earth, (Hyde et al., 2000, Liu & Peltier, 2009, Micheels & Montenari, 2008, Yang et al., 2011), partly because a hard glaciation would have involved temperatures so low that CO_2 would have turned into dry ice, nullifying any greenhouse effect. Multiple articles also state that escape from a hard Snowball Earth would require untenable levels of CO_2, (Hyde et al., 2000, Micheels & Montenari, 2008, Pierrehumbert, 2005). Micheels & Montenari, (2008), concluded that a soft Snowball Earth is more realistic than a hard Snowball Earth because global climate appeared to react less sensitively to reduced levels of CO_2 in hard scenarios. Results from Micheels & Montenari, (2008), were cross referenced against fossil records and other studies. Yang et al., (2011), agreed that a soft snowball is more stable and realistic due to the dramatic forcings required to induce the hard snowball state. The CCSM3 (community climate model) used by Yang et al., (2011), resulted in a soft Snowball Earth that maintained open water, continental ice, and low latitude glaciers, all coexisting in a stable state. A 13 – 14% reduction in solar radiation was required to create a stable hard Snowball Earth using CCSM3, yet the Neoproterozoic era likely experienced only a 6 – 7% reduction in solar radiation, (Yang et al., 2011). Evidence that rapid deglaciation may not only have been a feature of a hard Snowball Earth is provided by Hyde et al., (2000), who concluded that rapidly retreating ice would be possible during a softer scenario at certain levels of CO_2. Lewis et al., (2007), explained that a softer snowball with a dynamic atmosphere could have remained stable, but that model stability was only achieved with complete ice cover, providing support for a hard Marinoan Snowball Earth. A waterbelt earth has been rejected by some scientists, (Lewis et al., 2007, Liu et al., 2020) due to issues modelling the scenario as areas of open water (Including melt ponds) may decrease albedo, preventing runaway feedback. This combined with sea ice dynamics would make it harder for Earth to enter a Snowball state, (Yang et al., 2011).

Chapter 4 – How Life Survived Marinoan Snowball Earth

Snowball Earth most likely had a severe impact on all life, leading to a dramatic reduction in aerobic eukaryotes. Interestingly, no evidence for a mass extinction has been found in the geological record, (Lechte et al., 2019, Micheels & Montenari, 2008). Incredibly, life survived Marinoan Snowball Earth and some lifeforms, such as Metozoans, may have even diversified during or immediately after the event, (Lechte et al., 2019). Strong selective pressures provided by icehouses, and greenhouses, might have acted as an environmental filter, terminating certain species whilst allowing others to radiate. An example of this turnover is the Edicarian fauna that appeared a relatively short time after Marinoan Snowball Earth termination, (Hoffman et al., 1998).

A hard Snowball Earth would have involved temperatures of around -45°C at the equator and -70°C at the poles, whereas a soft Snowball Earth likely maintained temperatures of around 0°C in low latitudes and -50°C at the poles, (Micheels & Montenari, 2008). These temperature differences offer support for a soft Snowball Earth because life is expected to require temperatures closer to 0°C. Light and nutrients are both essential to life so it can be assumed that light reached some organisms during the event. Microbial communities at the ocean's surface required an active hydrological cycle to obtain nutrients, (Hyde et al., 2000, Micheels & Montenari, 2008). This is at odds with the hard Snowball Earth Hypothesis, where oceans stagnated under thick ice, but Hoffman & Schrag, (2002), believe that a hard snowball could still have harboured life via various refugia. Potential oases include brine channels, tidal cracks, polynyas (a stretch of water surrounded by ice), and shallow hot springs around volcanoes, (Hoffman & Schrag, 2002).

4.1 Antarctica – Modern Day Comparisons to Marinoan Snowball Earth

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Figure 6. Microbial communities living on the Markham Ice Shelf, Antarctica. **A-B** – Overviews of the Markham ice shelf. **C-D** – Exposed microbial mat communities. **E** – Micrograph (x1000) of green algae from the surface layer of a microbial mat. **F** – Micrograph (x1000) of the colonial cyanobacterium (Gloeocapsa sp.) from the mat under-layer (Images taken directly from Vincent et al., 2004).

Current prokaryote and eukaryote communities in ice dominated parts of the world may help explain how life survived Snowball Earth, (Vincent et al., 2004). Lechte et al., (2019) stated that subglacial meltwater could have supported aerobic marine habitats by providing eukaryotes with oxygen lacking in mostly anoxic, ice-covered oceans. Oxygen rich meltwater mixed with iron rich seawater via an oxygen pump, would provide energy for chemosynthetic organisms, which in turn provides Earth's early animals with oxygen and carbon during a hard Snowball Earth, (Lechte et al., 2019). Vincent et al., (2004), studied microbial mats on the Markham Ice Shelf, Antarctica, and concluded that the ability of such communities to thrive in glacial habitats (snow, sea ice and permafrost) has been proven. **Figure 5** provides three kinds of images of these microbial communities – overviews (**Figure 5A-B**), images of microbial mats (**Figure 5C-D**) and micrographs (x1000 magnification) of microbial mat communities (**Figure 5E-F**). These species have evolved multiple adaptations, including freeze-thaw tolerance and the ability to maintain a large biomass in winter dormancy, ready to begin photosynthesis when sunlight increases, (Vincent et al., 2004). Heterotrophs, including eukaryotes and sponges, live hundreds of metres below the ice on the Antarctic subice shelf, (Lechte et al., 2019) and the Neoproterozoic tropics received 4 times the light available to dry valley lakes in modern-day Antarctica, even allowing for a 6% reduction in the solar constant, (McKay, 2000). Therefore, if life can survive in Antarctica, it may have survived in equatorial regions of Marinoan Snowball Earth. Comparisons with glaciomarine environments made by Lechte et al., (2019), and Vincent et al., (2004), provide compelling arguments on how eukaryotic life survived a hard Snowball Earth, even in severely restricted habitats. However, melt ponds and lakes on Snowball Earth were probably larger, deeper, and less transitory, than those seen in the Arctic today, (Yang et al., 2011).

4.2 The Thin Ice Solution

Scientists such as McKay, (2000), do not believe that life could have survived a hard Snowball Earth because the ice would simply be too thick to allow for photosynthesis. McKay, (2000), explained how thin tropical ice cover (10 metres or less), during a soft Snowball Earth could have allowed enough light to reach photosynthesising organisms such as eukaryotic algae. Photosynthesis can occur in clear ice to depths of almost 30 m if sunlight penetration is balanced by heat released via freezing, underneath the sea ice, (McKay, 2000). Ice clarity could be the key to life's survival of global glaciations, as low ablation would result in clearer ice, improving light availability further, (McKay, 2000). Hyde et al., (2000), discounted McKay's thin ice solution suggesting there is no evidence that life could exist underneath any kind of ice (thick or thin), hence ice-free areas must have remained. McKay, (2000), and Hyde et al, (2000), may offer different theories, but both supported a soft Snowball Earth. The thin ice solution may need to be revisited, especially if the only requirement for ice thin enough to allow for photosynthesis in equatorial zones, is global temperatures of -40°C or above, (McKay, 2000). This temperature would be fully achievable in a soft scenario, (Micheels & Montenari, 2008).

Chapter 5 – Discussion - Hard versus soft Snowball Earth

The geological evidence considered during this literature review revealed many contradictions surrounding Snowball Earth. Stratigraphic and sedimentological evidence found in multiple locations, confirms that ice existed in equatorial zones and has therefore been used by supporters of a hard Snowball Earth, (Hoffman et al., 1998, Hoffman & Schrag, 2002, Kirschvink, 1992). These scientists logically assume that if ice reached low latitudes, it must have covered the entire planet. However, glaciers involved in Marinoan Snowball Earth must have been on the move at some point to result in much of the evidence seen. A hard Snowball Earth could not co-exist with an active water cycle, (Allan & Etienne, 2008), yet the evidence suggests that the environment was dynamic. Diamictites discussed in papers by Hoffman et al., (1998), and Hoffman & Schrag, (2002), may have been formed during the first phase or deglaciation of Snowball Earth, but Allen & Etienne, (2008), stated that thick diamictites could not have been deposited in such a short time frame. Evidence for anoxic oceans provided by BIFs has been cited to support a hard Snowball Earth, (Hoffman et al., 1998, Hoffman & Schrag, 2002 and Kirschvink, 1992), but has been used more recently provide evidence for an oxygen pump that supported meltwater oases, (Lechte et al., 2019).

Snowball Earth deglaciation poses problems for both hard and soft scenarios and was mentioned in multiple papers. A soft Snowball Earth required a relatively modest increase in atmospheric CO_2 to trigger deglaciation, whereas the amount of CO_2 required to escape a hard Snowball Earth, is significantly higher. Supporters of the hard snowball insist that complete glaciation is necessary to allow enough CO_2 to build up and launch the 'super greenhouse' required for termination of the event, (Hoffman et al., 1998, Allen & Etienne, 2008). This area requires further work as the levels of CO_2 required to reverse a hard Snowball Earth, pose a significant challenge to the current understanding of climate dynamics (Hyde et al., 2000, Micheels & Montenari, 2008, Pierrehumbert, 2005).

Studies that utilised climate models may be difficult to interpret as the models used and results obtained are so varied, with many studies providing contradictions within their own outcomes. When dynamic sea ice was included in the model used by Lewis et al., (2007), only a hard snowball remained stable, something difficult to resolve as one defining feature of a hard Snowball Earth, is thick slow moving or stationary ice. Climate models have different requirements for Snowball Earth and multiple factors and feedbacks affect the results, (Yang et al., 2011). A waterbelt Earth may seem implausible to many as geological evidence for ice at low latitudes is out of step with a wide band of open ocean, maintained throughout Marinoan Snowball Earth.

One of the most interesting questions surrounding Snowball Earth concerns how life survived the event. Several scientists presented theories that may explain why there is no evidence for a mass extinction during Marinoan Snowball Earth, including two soft snowball ideas - the thin ice model, (McKay, 2000), and a 'Slushball Earth' with ice free zones, (Hyde et al., 2000). Comparisons with modern day Antarctica, (Lechte et al., 2019, Vincent et al., 2004) show the resilience of life in extreme settings, offering more support for a hard snowball. Similarities were considered with caution as Snowball Earth was probably much more extreme than Earth's current ice-covered zones. Papers that backed a hard Snowball Earth have other options for life's survival, including brine channels, tidal cracks, and polynyas, (Hoffman & Schrag, 2002).

Chapter 6 – Conclusions

6.1 Key Conclusions

- Geological evidence proved that ice existed in equatorial zones during Marinoan Snowball Earth, supporting a hard Snowball Earth. However, formation of much of the same geological evidence required an active hydrological cycle, supporting a soft Snowball Earth, (Allan & Etienne, 2008). Geological evidence can be contradictory and open to interpretation.

- Geochemical evidence has been used to support both a hard, (Hoffman et al., 1998), and soft Snowball Earth, (Allan & Etienne, 2008, Hartmann et al., 2017), and may therefore currently be unreliable.

- Climate models generally offered more support for a soft Snowball Earth and may be a promising research area as models are likely to improve as computational power increases over the coming years.

- Several potential theories may explain how life survived Marinoan Snowball Earth, including meltwater oases supported via an oceanic oxygen pump, (Lechte et al, 2019). Ideas studied were varied, suggesting there are potential options for life's survival in either a hard or soft snowball setting.

The research considered during this project leads me to offer more support to a soft or softer Marinoan Snowball Earth than a hard Marinoan Snowball Earth. Nearly 30 years after work by Kirschvink in 1992, much of the current literature has moved away from the original hard Snowball Earth Hypothesis. This is mainly due to some of the limitations involved with the hard scenario, such as the amount of CO_2 required for deglaciation and evidence for an active water cycle. A soft Snowball Earth or a Snowball Earth that sits somewhere between hard and soft, may eventually form part of a well-accepted theory.

There is huge potential for further research into Marinoan Snowball Earth and outcomes could help create a clearer picture of Neoproterozoic Earth. A good starting point might be comparing timescales obtained by Penman & Rooney, (2019), with data from other forms of analysis with the aim of refining the timeframe associated with Snowball Earth. Realistic and more complex climate models are needed to model ice sheet dynamics and clouds to obtain a truer picture of both the hard and soft versions of Snowball Earth, (Yang et al., 2011). Modelling appears to be one of the most promising areas of research into Snowball Earth.

6.2 Looking to the Future – Usefulness of Investigations into Marinoan Snowball Earth

Icehouses and Greenhouses in the geological past offer the chance to better understand the mechanisms that regulate Earth's climate and habitability, but unfortunately no reliable information on Neoproterozoic carbon fluxes, is available at present, (Hartmann et al., 2017). Studies such as Pierrehumbert, (2005), highlight the powerful warming effect of atmospheric CO_2, something highly relevant today considering the role anthropogenic CO_2 emissions are playing in climate change. Proof that a relatively small increase in CO_2 triggered deglaciation of a soft Snowball Earth, could be used as direct evidence of the impact of greenhouses gases.

The continuing investigation into Snowball Earth events in Earth's history may be relevant to both the search for life, and the long-term survival of humanity. Learning about the way a planet recovers from a solid snowball state, especially if it had a frozen start, may prove useful to astrobiologists, (Pierrehumbert, 2005). Determining the minimum levels of CO_2 required for Snowball Earth termination, therefore has implications for future space missions, (Foley, 2019). The relevance of factors related to Snowball Earth, such as solar luminosity, tectonics and outgassing of greenhouse gases, may assist future scientists in their search for suitable Earth-like planets and support targeted missions to find long-lived habitability beyond our solar system, (Foley, 2019).

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