Something won, something lost: Exploring emergence and irreversibility through glacier ice

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1 Two curiosities as a means of introduction

I have spent more than twenty years of my life looking at glaciers as a scientist. This is an undeniably cool thing to get to do, but tends to involve rigorously following scientific methods, complying with strict logistics and targets to achieve a predetermined goal. To me, the best part of it is sitting with the glacier and absorbing what is going on around, allowing my mind and curiosity to roam, but there is often not much time left for this reflection in the reality of modern implementation of science. As a result, the starting point for this thesis was my long-held curiosity about two related aspects of material properties of glacier ice that I have not yet understood through my scientific research, which has focused on the behaviour of ice in its aggregated form of 'glacier' rather than on the material itself.

Firstly, when you walk on the exposed ice of a glacier tongue in summer it is usually not the smooth, dense, slippery surface you might expect to encounter, but instead a rough surface made of large, interlocking ice crystals that have such complex shapes that they hang together like a loose 3D jigsaw puzzle, or like large molar teeth wobbling in their sockets. The crystals are sometimes the size of my hand and each time I see this, I realise that I don't know how they grow so big, or how they can achieve such complex interlocking shapes (Figure 1). In growing, do they cannibalise each other through the processes of melt and reformation at the boundaries of individual ice crystals? Can this happen without melting? How is all this movement and growth and change possible in the restrictive environment at depth in a glacier? To what extent is such growth related to the atomic structure and crystal lattice of ice, and how far is it conditioned by the experiences of the glacier as a whole? So far, I have passed over my curiosity about what is really going on, as a cursory look didn't turn up much explanation or discussion of this in the scientific literature, but I ask myself the same questions every summer as I crunch over the glacier surface.

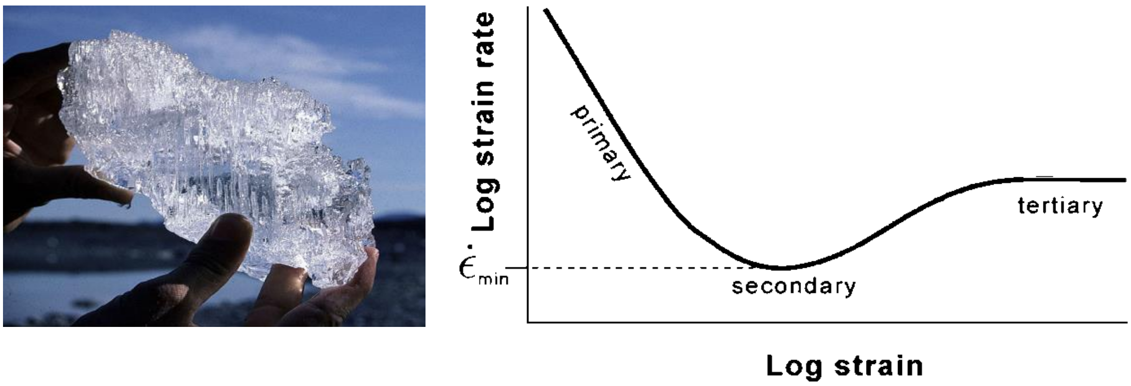

Figure 1: What processes allow glacier ice crystals[1] (left) to grow so large and sculpt themselves into such intricate forms? How does this process of crystal growth and play into the behaviour of polycrystalline ice, which becomes first less and then more malleable as it deforms in response to an applied force[2] (right)?

Secondly, when I was learning about how to code numerical models of glacier flow, we were shown a graph of laboratory experiments of glacier ice deformation rate to a continuous

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[1] Hambrey, M. Glaciers online: https://www.swisseduc.ch/glaciers/glossary/glacier-ice-en.html

[2] Cuffey, K. M., & Paterson, W. S. B. (2010). The physics of glaciers. Academic Press.

applied force (Figure 1). What it shows is that at first the rate of deformation in response to a continuous applied force decreases over time, then recovers a bit and levels off. This was the first time I really thought about the way that bulk properties of polycrystalline glacier ice differ from those of a single ice crystal, which felt interesting in regards to the way that individual ice crystals must, in some way, interact and collaborate to produce the overall motion of glacier ice. It also suggests that the malleability of glacier ice at least partly depends on its past deformation meaning that if you reverse the direction of an applied force, the ice will not deform back in an exactly symmetrical way, as the previous force has fundamentally altered it. This also intrigues me in the way that it seems so like a human life experience; at any moment of time, what I am, and what I can do, is the cumulative product of all my past experiences and the same seems true for glacier ice, and for glaciers themselves.

So, I find my interests drawing me towards looking at glacier ice and its crystals in a closer sense than I have done before. Specifically, my curiosity at the point of departure concerns the questions of how glacier ice crystals sculpt themselves into such large and intricate forms, and how this in turn plays into the emergent behaviour and irreversibility of polycrystalline ice deformation?

Glaciers and glacier ice have a long history of inspiring awe and complex symbolism[3] and have drawn significant previous attention from artists, which caused me pause, as the topic felt kind of 'busy'. Artists, sometimes within activism, have already worked with the long timescales of glaciers[4], the environmental records stored inside them[5], their apparent remoteness[6], melting[7] and its connection to human activities[8], as well as using the medium of ice in symbolic ways[9,10]. I wanted to not work with glacier ice, but it turned out to be unavoidable as I kept coming back to it, so here we are, and this thesis explores some aspects of the medium of polycrystalline glacier ice, examining it from various perspectives, to uncover my more-than-scientific connections to glaciers as entities and to deepen my understanding in new ways. During the research I also wanted to make a concerted effort to 'spend time' with glaciers outside of the scope and conditions of visiting them for scientific reasons. To that end in summer 2022 I spent time on Hintereisferner (Ötztal, Austria) with two artist friends of mine, on Bachfallenferner (Ötztal, Austria) with a group of young people experiencing glaciers for the first time through the Girls on Ice[11] expedition, and in summer 2023 I joined an artistic expedition to Suldenferner/Vedretta di Solda (Ortler group, Italy) and returned to Hinteresferner deliberately during summer storm conditions to be in this environment in

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[3] Carey, M. (2007). The history of ice: how glaciers became an endangered species. *Environmental History*, *12*(3), 497-527.

[4] Weil, P. (2017) 88 cores. Video 4h29: https://pweilstudio.com/project/88-cores/

[5] Chafe, C. (2020) Earth Symphony. Data sonification composition: https://chrischafe.net/earth-symphony/

[6] Paterson, K. (2008) Vatnajokull (the sound of). Performance: https://katiepaterson.org/artwork/vatnajokull-the-sound-of/

[7] Eliasson, O and Rosing, M (2014) Ice Watch. Installation of Greenlandic ice: https://olafureliasson.net/artwork/ice-watch-2014/

[8] Locke, C. (2020) The Terre Ice Chandelier.

[9] Alÿs, F. (1997) Paradox of Praxis I (Sometimes Making Something Leads to Nothing). Performance: https://francisalys.com/sometimes-making-something-leads-to-nothing/

[10] Azevedo, N (2014) Minimum Monument. Installation: https://www.neleazevedo.com.br/monumento-minimo

[11] A non-profit offering no cost expeditions to glaciers for young FLINTA participants: https://www.inspiringgirls.org/goi-austria

conditions when most people stay away. Hintereisferner is a classical Alpine glacier that I have been visiting since 2010, Suldenferner is predominantly covered with a layer of loose stones and rubble from the surroundings – a so called debris-covered glacier – that I have been visiting since 2014 and Bachfallenferner is a small Alpine glacier retreating above a lake of its own meltwater that I have been visiting since 2020, so in some sense all of these glaciers are to greater and lesser degrees old friends.

2 Glacier ice crystals

2.1 The starting points

It started with my finding in 2020 an academic journal article from the late 1940s, in which graphite rubbings of glacier crystals, this 'stuff glaciers are built of', were made vividly visible[12]. But actually, this moment of 'seeing' and my associated excitement, resonated with an earlier experience; my first time inside a glacier cave in the cold air of Svalbard, Norway, in 2013, looking at the way the cold air froze onto the ice roof in a way that was differently aligned for every crystal, so the overall effect is like a seal skin patchwork. Maybe my curiosity about the structures of crystals actually goes much further back; back to the geology labs of Edinburgh University in 1996 as an undergraduate student turning the cross polarizers on the microscope honed on thin sections of rock samples, to make a birefringent kaleidoscope of colours? Something draws me in to this examination of crystals, and continues to do so, in whatever form and context I see it. I decided to try some rubbings for myself.

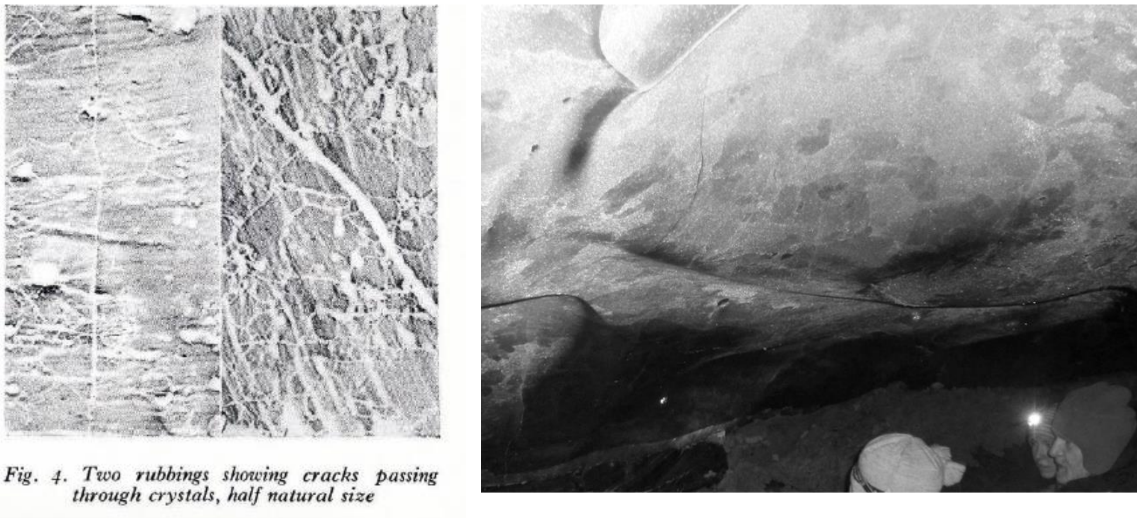

Figure 2: Examples of ice rubbings from mid-20th century scientific studies and what I call seal skin texture revealing something of the ice crystal outlines and internal structures in a cave beneath a glacier in Svalbard, Norway in 2013. I assume that the texture in the right arises from vapour from the air freezing on to each crystal slightly differently depending on the crystal orientation, though I have not found any mention of these textures reported in scientific studies.

2.2 Practice and result

The process of obtaining the glacier crystal rubbings used in the late 1940s and 1950s, involved finding a surface of interest, melting the surface smooth and flat with something like a portable hot iron and then drying it with blotting paper and taking a rubbing. Lacking the logistics for this approach, I decided to work with the glacier, so instead of modifying its surfaces to get a rubbing, I'd seek those already suitable for rubbings.

12 Seligman, G. (1950). The Growth of the Glacier Crystal Some Further Notes. *Journal of Glaciology*, *1*(7), 378-381.

Where the glacier is ablating under the sun the surface is rough, and makes this so-called ‘weathering crust’ of interlocking loose crystals caught on the complex surface forms of the neighbouring crystals, that so fascinates me when waling on glaciers. I could not find much written about this weathering crust in the scientific literature, but discussion with glaciological colleagues revealed that they, like me, take it that the crystal shapes are inherited from processes within the glacier and the looseness is a result of preferential melting at the crystal boundaries affected by sunlight penetrating the near surface. What I know from years of poking about on, in, and under glaciers is that I can expect to find smooth, albeit curved, surfaces where the ice surface has been ablating under the flow of air or water and in the absence of sunlight. So, my first attempts to find a suitable surface for a rubbing were to crawl into and under the edges of glaciers, taking simple paper and pencil, and a graphite stick. The first attempts on Hintereisferner in summer 2022 were disappointing; the paper got too wet, despite using blotting paper, and tore. The fat graphite stick I expected to help me so much was cumbersome, could not capture the curved surface well, and didn’t produce good results. Things quickly got wet, graphite smeared everywhere and despite trying several different locations I went home having learned something but with only pockets full of smudged and chewed up paper.

The second attempt at Bachfallenferner later in summer 2022 was a delightful surprise. I had the idea to try using stone paper as it remains so strong when wet. Crawling into a cave at the margin of the glacier late one evening I could see the floor and ceiling were made of crystals of all sizes. The boundaries between the crystals were visible as recessed lines creating texture even in the dim lighting conditions.

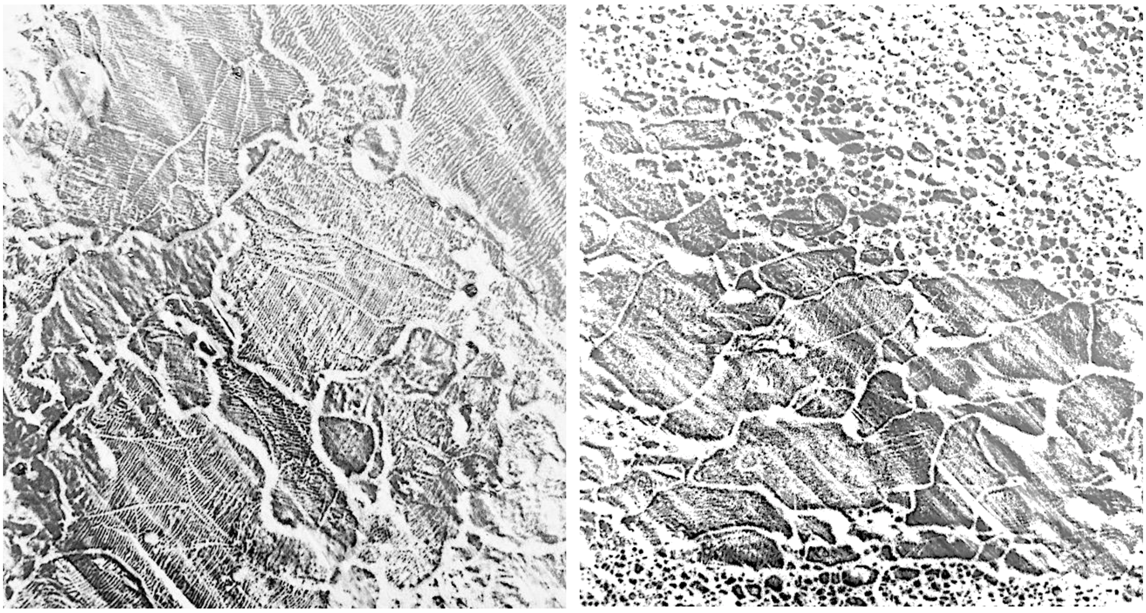

Figure 3: Ice rubbings from Bachfallenferner showing individual ice crystals boundaries as white where they are recessed into the surface. On the left the ‘fingerprint’ texture of some of the large crystals can be seen and on the right the juxtaposition of large glacier ice crystals with smaller crystals that have been reformed by shear deformation inside the glacier.

The boundaries are recessed as in all the formation and reformation of the ice crystals any non-H_2O molecules are progressively excluded from the crystal lattice and are consequently concentrated in the liminal zones between the crystals, lowering the specific melting temperature relative to the purer centre of the ice crystal lattice. In the simplest of sampling procedures, I went back early in the morning when there was no meltwater was around and just with stone paper and a normal 4B pencil got some great rubbings showing big crystals and smaller reformed ones, and also amazing 'fingerprint' features that I'd not seen before (Figure 3).

Following this success, I also took several other samples of ice crystal rubbings from Hintereisferner and Suldenferner in summer 2023. Originally, I planned to some quasi-scientific structured sampling, trying to follow a meltwater stream down glacier and sample the possible changes in structures as ice moves through the body of the glacier, but actually no opportunity to do so arose, as the meltwater stream channel walls in warm summer conditions were very wet even through the nights, and access to caves beneath the glacier is limited. Nevertheless, the crystal structures I revealed in these rubbings were endlessly fascinating, beautiful in of themselves and showed complex masses of cracked interlocking crystals and bubbles. Like the mid-20th century scientists I could see annealed cracks in the ice, cutting across crystals, and banding of smaller crystals where the ice had been torn and sheared as it moved.

The rubbings allowed me to really look more deeply at the structures and wonder further about how this crystal (re-)organisation actually happens? How much of the past experiences of the ice is written and stored in this crystal structure? How do these crystal structures alter the properties of the ice? What is the source of the 'fingerprinting' features? Why were these fingerprints not seen, or not mentioned, in the historical studies? Is the fingerprinting structure related to the internal molecular structure playing out at a macroscale, and does it relate to the seal skin patterns I saw in Svalbard? It was time to tap into some material science literature and expertise to seek answers.

2.3 Glacier crystal growth

Glacier ice forms from compression of snow from the overburden of successive snowfall layers accumulation at the surface. This metamorphosis of snow into ice first involves breaking the fragile branching snowflake forms into sub-rounded grains, which then fuse together due to snow grain deformation, sublimation, vapour migration and re-nucleation within the snowpack, gradually infilling most of the air pockets trapped within the snowpack until each air bubble is locked in by surrounding ice, at which point the medium it is finally deemed to be ice. If melt and refreeze can happen the transition from snow to ice is much faster. But even after this ice has been formed the component crystals continue to evolve in shape and form. This can be seen, not only in rubbings such as I collected, but also in thin sections of ice cores taken from glaciers, which, when viewed through cross polarised light reveal the crystal boundaries and internal crystal lattice orientation as different colours, thus revealing the texture (grain sizes and degree of interlocking) and fabric (grain orientation) of the ice (Figure 4).

As glacier ice is often relatively near the melting point, the molecules within the crystal lattice are relatively mobile and can move within the crystal and cross crystal boundaries[13]. Molecules will move to minimise the free energy, which is achieved by reducing the surface area and convexities, resulting in larger, smoother crystals.

[13] Cuffey, K. M., & Paterson, W. S. B. (2010). The physics of glaciers. Academic Press.

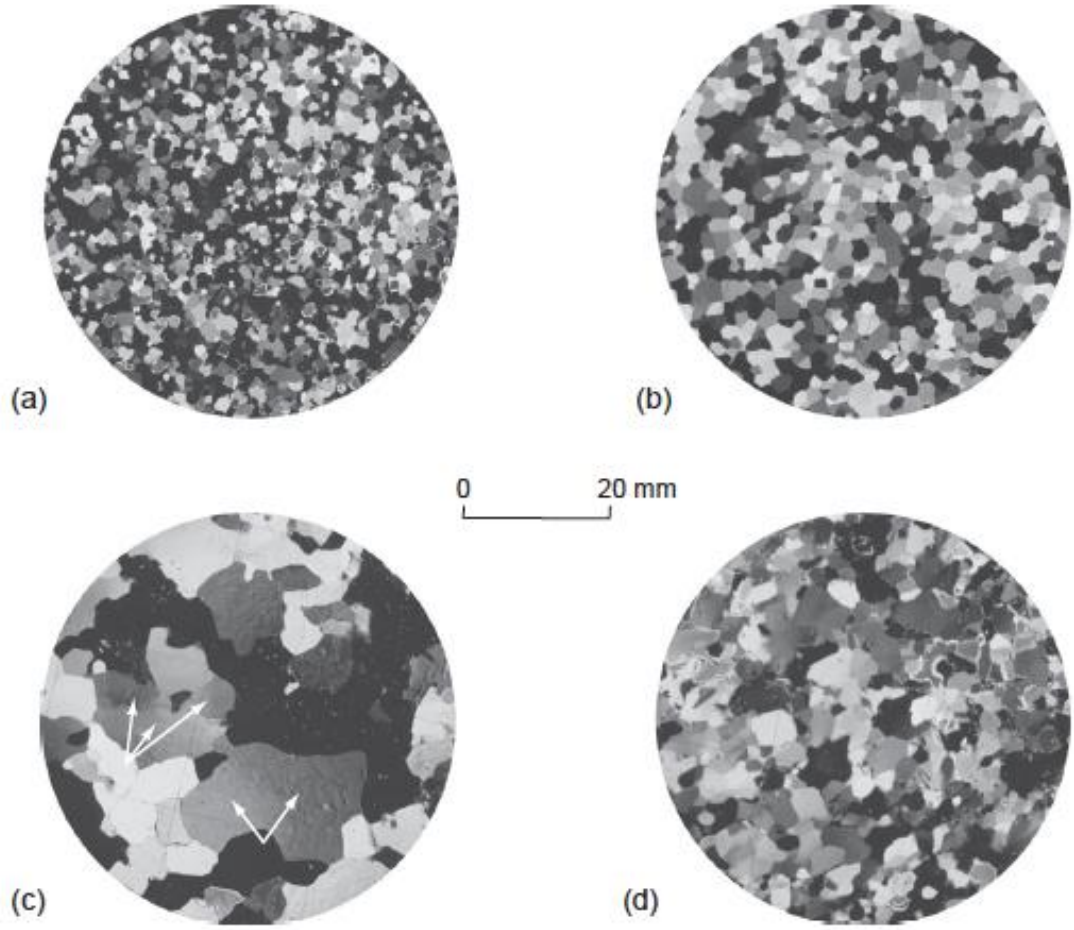

Figure 4: Photographs of thin sections of ice from the Greenland ice sheet taken under crossed polarizers[14]: "The different grayscale tones of the grains reflect different orientations of the crystal c-axes. (a) Initial texture formed by compaction of snow with addition of small amounts of melt water. (b) Texture resulting from grain growth with little or no deformation. (c) Texture resulting from recrystallization. Adjacent grains with nearly the same grayscale tone (arrows) have c-axes that are nearly parallel to one another. The grain in the lower centre is bent; in the one to the left of centre, distinct boundaries have formed between parts with slightly different orientations. (d) Texture following significant deformation. Grains are interlocked, and c-axes have a strong preferred orientation."

This type of grain growth may be what is seen in the transition from (a) to (b) in Figure 4. However, in (c) and (d) the crystal shapes are both larger but also more complex than the initial forms in (a). This arises from deformation of the ice under gravity, which, after the initial period of compression, tends to dominate the changes of crystal structures at depth within the glacier. So, what exactly happens when glacier ice is deforming?

2.4 Polycrystalline glacier ice motion

[14] Hooke, R. L. (2009). Principles of glacier mechanics. 2nd Edition. Cambridge University Press.

In an ice crystal, water molecules are arranged in layers of hexagonal rings (Figure 5). This structure is governed by the particular angles of the bond positions in H_2O and the behaviour of hydrogen bonds operating between water molecules. The layers are called the basal planes of the crystal, and the direction at right angles to the basal plane is called the C-axis or the optical axis of the crystal. The bonds between molecules situated in the same basal plane are much stronger than the bonds between molecules located in different basal planes. An individual ice crystal deforms easily in the direction of the layers, which can slide over each other like a deck of cards, but is three to four times more resistant to deformation along the C-axis, perpendicular to the layers. In the snow pack the crystals tend to not have a preferred orientation so the ice is built of crystals that, while anisotropic within themselves, are initially distributed with quasi-isotropic orientation within the ice body.

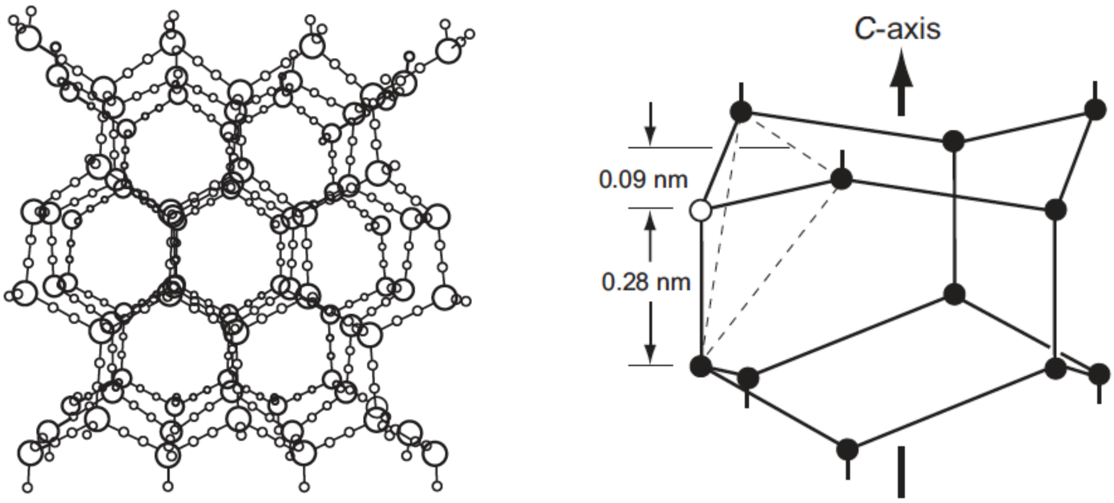

Figure 5: Impressions of the crystal lattice of ice[15]: (left) looking at right angles to the stacked layers, with large circles representing oxygen atoms and the small circles representing the possible sites of hydrogen atoms (with only half of those possible sites being filled); (right) looking along the stacked layers showing the structure forced by the molecular bond angles. The C-axis depicted in the right panel refers to axis perpendicular to the layers (i.e. the view angle of the left panel).

Each crystal responds to an applied directional force (such as gravity) dependent on its orientation, and this creates strong local variation in internal stress, and to maintain the continuity of the material all crystals need to find a way to accommodate the local stresses invoked by deformation of its near and far away neighbour crystals. Furthermore, in nature few crystals are perfect and they more commonly contain flaws in the crystal lattice called dislocations. Under applied forces, crystals can deform, rotate, be bent and broken, and recrystallize. Movements are focussed at crystal boundaries or internal dislocations in the crystal lattice. Revisiting the graph in Figure 1, the initial 'hardening' of the ice (labelled primary creep) is thought to involve a combination of various dislocations in different plans of the lattice becoming entangled with each other to actually inhibit the tearing of the lattice, and from internal stresses being transferred through the polycrystalline medium onto crystals oriented unfavourably for deformation, which also block the motion. At its 'stiffest'

[15] Hooke, R. L. (2009). Principles of glacier mechanics. 2nd Edition. Cambridge University Press.

(corresponding to secondary creep in Figure 1), the polycrystalline deformation rate is slower than a single crystal under the same conditions by a factor of a hundred. Thereafter, continued application of the force results in 'softening' (tertiary creep), which is due to migration recrystallization and nucleation beginning to build new crystals with a preferred orientation that facilitates bulk ice deformation. The multiplicity of processes at work feels a bit overwhelming, but in short: the molecules are moving around the crystal structure, the crystal boundaries can 'migrate', and, if the ice is being deformed, these options are supplemented by several types of dynamic recrystallization in which crystals can cannibalise each other by boundary migration to try and reduce their internal lattice stress, and this, along with new crystal nucleation builds the interlocking jigsaw puzzle of glacier ice.

2.5 Conversation with Dr Ilke Weikusat

To check my understanding about these processes of grain growth and to find out how I should best think of ice texture and fabric in relation to the overall glacier history and behaviour, I spoke with Dr Ilke Weikusat[16], who is an ice core scientist working at the Alfred Wegener Institute who is highly esteemed for her work on glacier ice fabric.

Ilke explained to me that dislocations within the crystal lattice are additional ½ lattice planes and when the tips of these planes intersect then they form an 'entanglement' by creating a problematic tube of elastic energy that squeezes the lattice around it. She also confirmed by understanding that growth by crystal grain boundary migration progresses when the zone of disordered molecules at the boundary re-orientate themselves to align with the lattice of an adjacent crystal, forcing the zone of disorder to migrate through the medium, which is indeed like this cannibalization of neighbouring crystals that I initially considered. She told me that crystals at the base of a glacier may be many meters across, although as this cannot be observed from the narrow columns sampled in ice cores it cannot be confirmed, which reminds me of the limitations of the various observations possible in the laboratory or in the wild. This conversation was pivotal to me determining how best to think about these (to me) complex ice crystal processes and I'm grateful for her sharing her time and enthusiasm with me. Ilke also pointed me to two key publications[17] [18], which I subsequently read to deepen understanding both of the processes as outlined above and also of the historical developments of the tools used to study glacier ice and what consequently can and cannot be observed.

2.6 Encapsulated experience in glacier ice

The very material constituting the ice crystals is built of snowfalls from a particular time, providing a solid deposit of past atmospheric conditions, and from appreciating all the internal processes of crystal growth and change, it becomes clear that the very structure of glacier ice encodes a record of past experiences, that can be uncovered at certain access points through, for example, the rubbings of surface ice or microscopy of thin sections of ice.

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[16] https://www.awi.de/ueber-uns/organisation/mitarbeiter/detailseite/ilka-weikusat.html

[17] Faria, S. H., Weikusat, I., & Azuma, N. (2014). The microstructure of polar ice. Part I: Highlights from ice core research. Journal of Structural Geology, 61, 2-20.

[18] Faria, S. H., Weikusat, I., & Azuma, N. (2014). The microstructure of polar ice. Part II: State of the art. Journal of Structural Geology, 61, 21-49.

Considering these encoded properties, that in some way feel like they are hiding in plain sight, I began to produce etches of my crystal rubbings and some others from the historical published literature on acrylic in order to experiment with ways of revealing the internal structures either with illumination of the composite layers or by cast shadows (Figure 6). Presenting slices of the crystal structure of a block of glacier ice on acrylic, illuminated from the side with a directional light has the effect to light up the etching on each slice in turn, producing an analogue effect similar to a CAT scan of a human body. By sliding the light along the layers, it is possible to visually travel through the ice block structure following individual centimetre scale grains through their tortuous entanglement in 3D space. In this way the powerful internal properties and accumulated experiences are brought forth from their otherwise subtle presence in the medium. Likewise, the cast shadow can be used to reveal and enlarge the elusive internalised shape of the glacier ice, while also alluding to the ways that past experience cast themselves into present experience and possibilities.

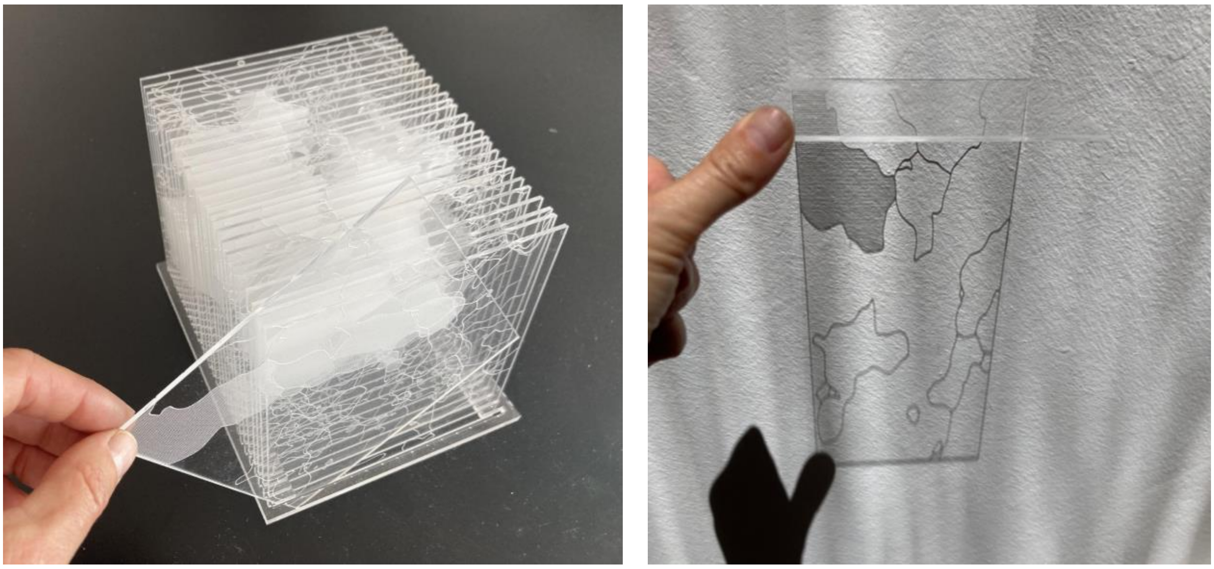

Figure 6: Examples of glacier ice crystal boundary patterns etched onto acrylic for experimentation of progressive illumination of 3D crystal arrangement or casting shadows of individual slices through the glacier ice.

"Ice is a recording medium and a storage medium. It collects and keeps data for millennia. Unlike our hard disks and terabyte blocks, which are quickly updated or become outdated, ice has been consistent in its technology over millions of years. Once you know how to read its archive, it is legible almost as far back – as far down – as the ice goes. Trapped air bubbles preserve details of atmospheric composition. The isotopic content of water molecules in the snow records temperature. Impurities in the snow – sulphur acid, hydrogen peroxide – indicate past volcanic eruptions, pollution levels, biomass burning, or the extent of sea ice and its proximity. Hydrogen peroxide levels show how much sunlight fell upon the snow. To imagine ice as a "medium" in this sense might also be to imagine it as a "medium" in the supernatural sense: a presence permitting communication with the dead and the buried, across gulfs of deep time, through which one might hear distant messages from the Pleistocene."

– Robert MacFarlane[19]

[19] MacFarlane, R. (2020). *Underland*. Les Arènes.

3 Something won: Emergence

Everywhere you look, including into glacier ice, forces are pulled together to create behaviours and beings that are more than the sum of their parts and capable of shaping their own futures; it is a property of physics, ecology, societies and artificial intelligence, and so much more, regardless of whether you consider all these elements a part of nature or apart from nature. This property is known as emergence:

"In philosophy, systems theory, science, and art, emergence occurs when a complex entity has properties or behaviours that its parts do not have on their own, and emerge only when they interact in a wider whole."

- Wikipedia entry on emergence

3.1 Weak and strong emergence

Weak and strong emergence are two contrasting concepts in the philosophy of science and metaphysics that describe the relationship between different levels of organisation or complexity in a system[20]. Weak emergence suggests that the properties or behaviours of a higher-level system are entirely dependent on, and can be explained by, the interactions and properties of its lower-level components, even though they may exhibit novel or unexpected characteristics at the higher level. An example could be a murmuration of starlings. In general, weak emergence is amenable to computer simulation[21] as the interacting sub-components retain their independence, or put another way, the emergent behaviour is predictable from the known or prescribed interactions of the individual behaviours[22]. However, if either the behaviours or interactions are not well known, then the emergent behaviour is more challenging to predict as is the case in understanding the multiple (scale bridging) interactions between components of the climate system to make up the whole.

In contrast, strong emergence posits that the properties or behaviours of a higher-level system cannot be fully reduced to, or predicted from, the properties and interactions of its lower-level components. In strong emergence, new and irreducible phenomena emerge at higher levels, and these phenomena cannot be explained solely by examining the lower-level constituents. Consciousness is often given as a potential example of strong emergence.

"Although strong emergence is logically possible, it is uncomfortably like magic."

- Mark Bedau

The distinction between weak and strong emergence has significant implications for our understanding of complex systems and their predictability, with strong emergence challenging the idea of reductionism in science and suggesting the presence of genuinely novel and emergent phenomena.

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[20] Bedau, M. A. (1997). Weak emergence. *Philosophical perspectives*, *11*, 375-399.

[21] https://wyss.harvard.edu/media-post/kilobots-a-thousand-robot-swarm/

[22] Flicker, F. (2022). *The Magick of Matter: Crystals, Chaos and the Wizardry of Physics*. Profile Books.

3.2 Snowflakes and emergent design

Snowflakes, the building blocks of glacier ice, are often given as an example of emergent design in physical systems, and their hexagonal symmetry has long piqued curiosity. The first recorded observations come from 135 B.C., but by the 17th century, Johannes Kepler presented a small treatise entitled *The Six-Cornered Snowflake* realising there must be an underlying structure to the symmetry, and René Descartes recorded the first detailed account of snow-crystal structure. Observations of snow crystals were revolutionised by the invention of photography and specifically when in the late 19th century Wilson Bentley developed a technique to image fresh snowflakes before their delicate structures could melt away. Bentley's book[23] was key in spreading the idea that no two snowflakes were the same, and it remains the leading source of snowflake images and a true wonder (Figure 7).

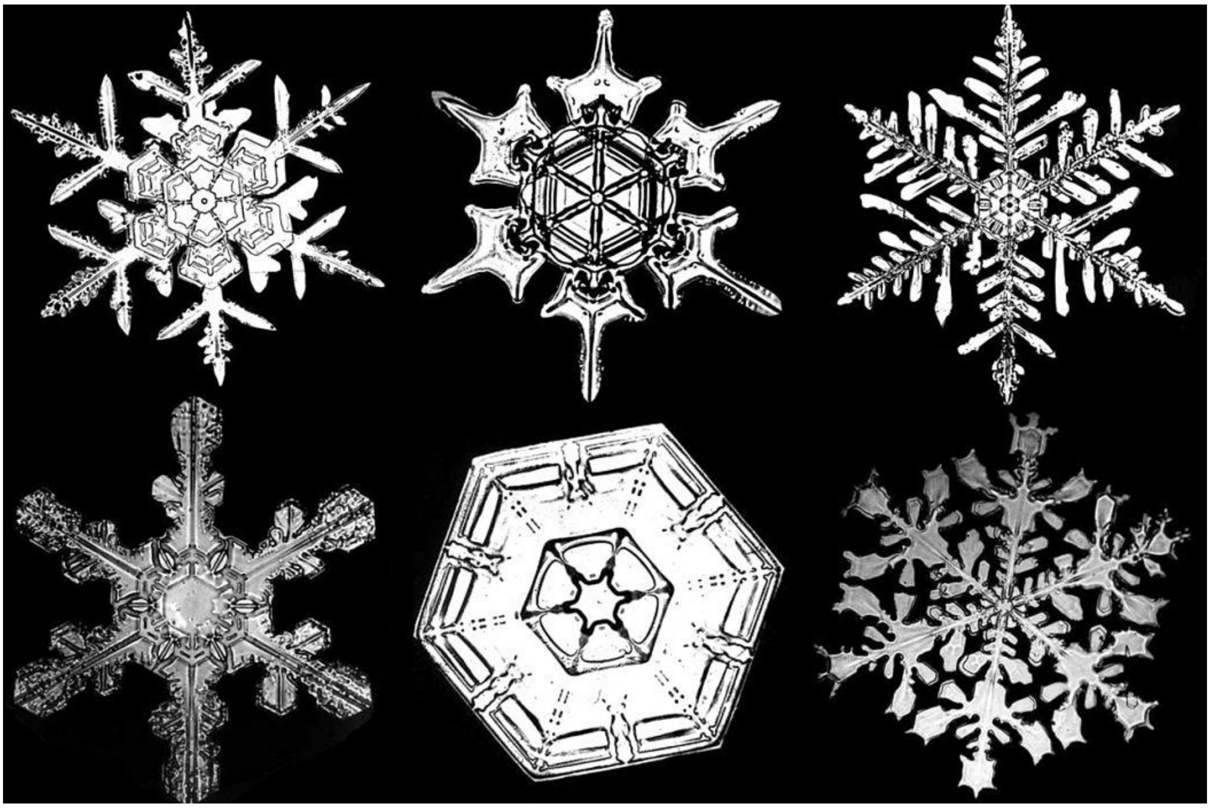

Figure 7: Images of snowflakes from Bentley's collection demonstrate the variety of emergent structured designs resulting from the properties of water molecules.

In the 1930s Ukichiro Nakaya started trying to grow snow crystals in the laboratory, and on the basis of this research could identify specific conditions of temperature and humidity that control whether snowflakes take on hexagonal rod-like or plate-like forms. Nowadays Kenneth Libbrecht has taken this even further and is the leading expert in laboratory produced snow crystals[24], having developed a system to precisely control the temperature and humidity conditions so that crystals of specific forms can be generated, thereby demonstrating that the emergent design of snowflake structures is not only explainable by the behaviour of its

[23] Bentley, W. A., & Humphreys, W. J. (1962). *Snow crystals*. Courier Corporation.

[24] http://www.snowcrystals.com/science/science.html

component parts, but also dependent on the ambient conditions in a predictable manner. Bentley's crystal book is focused on showcasing the diversity of crystal forms showing strong symmetry but it also contains a section of the 'misfits', where atmospheric chemical species, dust or other interferences have been incorporated into the crystal. The imperfections are almost as fascinating to look at as the symmetry; it feels a bit affronting to see the crystal design interrupted, but this emergent design has no specific attachment to achieving perfection – it is only doing what it cannot help but do.

3.3 Fabric, flow and emergent behaviour in glacier ice

The motion and deformation of glacier ice seems also to conform perfectly to the definitions of emergence, but here we see, rather than an emergent design, an emergent behaviour. The reshaping and flow of polycrystalline glacier ice is a result of the ways individual crystals can deform as well the ways all these individual crystals interact. As in the case with impurities in snowflakes, flaws in the crystal lattice of glacier ice introduce crystal dislocations that are critical in controlling the malleability of glacier ice. Dislocations facilitate breaking of lattice bonds by a process of unzipping the bonds, which is much more energetically efficient than breaking all bonds in a particular plane simultaneously. In nature, the fact that glacier ice moves only under the influence of the low force of gravity is partially attributed to the abundance of crystal dislocations in natural ice.

Furthermore, over time the polycrystalline deformation reforms itself to alter the individual crystals and by shifting their alignment, rotation and size, necessarily also alters the interactions. By rebuilding, rotating, breaking and nucleating new crystals, the texture (grain size and interconnectedness) and fabric (orientation) of the individual crystals is continually changing. It is like an emergent behaviour that keeps on evolving through its own material remodification.

3.4 More than the sum of its parts?

Artistic works on emergence are often heavily embedded in generative algorithmic art, producing images and music and more on the basis of the activation of a coded set of rules combined with randomness. Generative art has been explored since the mid-20th century, and involves a collaboration of the artist and coded behaviour. Artificial intelligence is also used in studying emergence of systems and testing theories of emergent behaviour with programmable micro-robots provides conclusive evidence that the complex behaviours or, say a murmuration of starlings, emerges from the basis of simple rules acted out by the individual birds.

The simplest of generative art tools applied to information I collected about glacier ice show some of the ways that these can be reinterpreted by AI, drawing out possible unseen structures in potentially interesting ways (Figure 8). However, my interest is not in the emergent design of generative art, but more in the emergent behaviour of glacier ice. Also, I do not see the parameters controlling the emergent behaviour as entirely random, rather as embedded in past experience.

To me, something more appealing than these numerically controlled experiments is the idea of performing the emergent behaviours of ice itself in some sort of interaction between the artist and ice that bridges the scales of the emergence from the single to the poly crystalline behaviour. These multiple interactions are what makes the product more than the sum of its parts. I have experimented with this through drawing outlines of projected glacier crystal textures and layering different structures, representing different states of the polycrystalline ice, over each other. Eventually a composite drawing emerges from the outlines of individual crystals interacting with each other and my own interventions in choosing the type and positioning of the projected crystals.

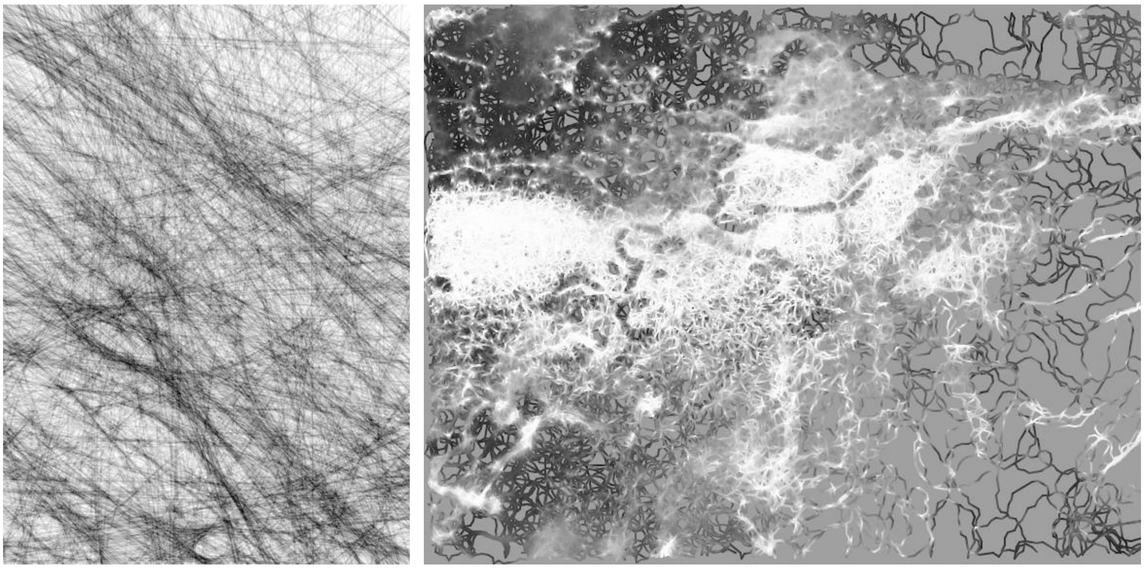

Figure 8: Examples of generative art applying a pattern-controlled linear algorithm to a glacier ice surface rubbing (left) and a turning algorithm applied to a photo from inside a glacier cave (right).

4 Something lost: Irreversibility

Irreversibility in systems refers to a characteristic where a process or change within the system cannot be undone or returned to its original state, even if the same initial conditions are restored[25].

4.1 Irreversibility and notions of time

This concept is closely tied to the second law of thermodynamics, which states that in natural processes, the overall entropy, or disorder, of a closed system tends to increase over time, making many changes irreversible. Irreversible processes are often associated with energy dissipation and the directionality of time, highlighting the idea that certain transformations are inherently one-way and cannot be reversed without external intervention or energy expenditure. However, at the quantum scale, the concept of reversibility takes on a unique character as quantum systems are governed by unitary time evolution, which implies that the evolution of quantum states is, in principle, reversible. In a closed quantum system, if you know the initial state and all the relevant physical laws, you can, in theory, precisely predict and reverse the quantum evolution to return to the original state. Although practical limitations, such as measurement and entanglement, and the quantum no-cloning theorem can introduce a degree of irreversibility in quantum systems, the concept of reversibility at the quantum scale is more nuanced than at classical scales.

Thus, as is the case when considering emergent design or behaviours, the directionality of time and related concepts of irreversibility become evident only at specific scales of observation. At scales humans are designed to observe, different fluxes and changes arise as the delicate balance of energy transfer; physical fluxes and motions, reversible equilibrium chemistry transformations, gradual growth, and at longer timescales evolution and planetary scale cycles of circulating water and magma play out. These arrow of time changes can be linear, non-linear, oscillating or cyclical change or comprise complete changes of state. Early debates about geological time were bound up in debates between so-called uniformitarianism and catastrophism[26], which respectively explain geological change to occur by the cumulative effects of very gradual and continuous processes or by rapid change in large-scale events. We would now accept that these two are not mutually exclusive, but they remain impactful as uniformitarianism is the source of the idea that the present is the key to understanding the past, and vice versa, while catastrophism is a part of the narrative of changing states and tipping points. While these two opposing sides were competing, James Hutton introduced the proposition of endless cycling of Earth's elements and structures over geological deep time[27], which continues to have relevance for our modern day understanding of Earth's planetary boundaries.

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[25] Notes from Mapping the Irreverse, Graz, 16-18 January 2023: https://www.the-irreverse.zone/

[26] Gould, S. J. (1988). *Time's arrow, time's cycle: Myth and metaphor in the discovery of geological time*. Harvard University Press.

[27] Hutton, J. (1788). X. Theory of the Earth; or an Investigation of the Laws observable in the Composition, Dissolution, and Restoration of Land upon the Globe. *Earth and Environmental Science Transactions of The Royal Society of Edinburgh*, *1*(2), 209-304.

"… we find no vestige of a beginning and no prospect of an end."

- James Hutton

Reflecting on glacier ice it seems to be that at both the small and the large scale it is a medium that has both reversible and irreversible characteristics, highlighting different ways in which the scale of observation and the rules you wish to apply influence the notion of irreversibility.

4.2 Tangible loss in reversible change

The embodied experiences of glacier ice are lost in melting, even if the same water molecules are refrozen. It is wholly possible to reverse the melting by refreezing the very same water, but it produces ice that no longer holds the crystal structures inherited from the compression of snowflakes over time, nor the same time sequence of atmospheric chemistry laid down over time in the successive snowfalls that form the glacier ice. Once melted, refreezing it cannot reconstruct the environmental history it held before and the memory of the past events forming the ice is irrevocably lost in the process of reversal.

It is obvious, but nevertheless appealing, to experiment artistically with the melting of ice to elaborate my thinking about irreversibility and ice. I started this at a small scale with ice cubes from a household freezer, and also with blocks of natural glacier ice hacked out of a glacier. There is not much to see without the interaction of some marker or colour, and so in the studio I used simple watercolour paint, and in the glacier environment I used carbon ink and fluorescein, which is a fluorescent dye used in low concentrations as a tracer in studies of glacier hydrology. In the studio I was interested in taking time lapses of the melting process either of coloured ice, or highlighted with colour added during the melting process, as well as recording the traces left behind as a mark of this irreversible process (Figure 9).

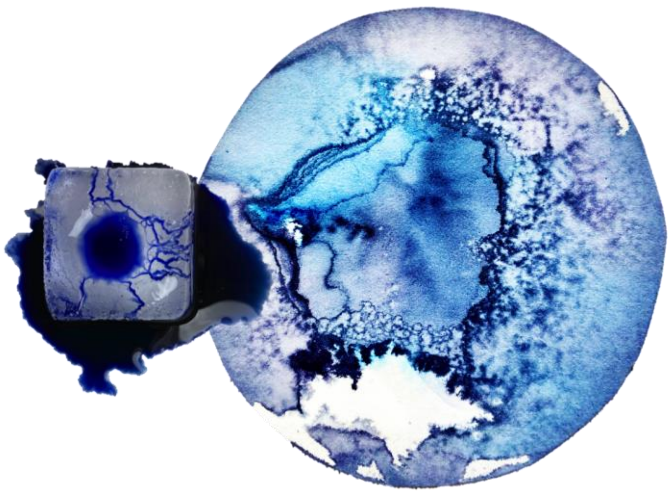

Figure 9: A melting ice cube interacting with ink, and the result of its melting overnight captured on watercolour paper – a print of an irreversible loss.

In the glacier environment I simply used an ice axe to hack out a chunk of ice from overhangs at the glacier margins, and by applying dye could highlight the surface and internal structure, trying to capture its nature and decay photographically (Figure 10).

Figure 10: Chunks of natural glacier ice interacting with ink and dye as they melt in situ on Suldenferner. The colouration is at first sucked into the crystal boundaries, highlighting their internal arrangement, and then as melting continues it drains out of the block with the meltwater from the crystal boundaries.

4.3 Moving forward by coming back round

At the larger scale it is also clear that glacier ice is somewhat reversible and somewhat not. During the Pleistocene (spanning 2.58 million years ago to 11.7 thousand years ago) multiple cycles of continental-scale glacial growth and recession occurred, forced by variations in Earth's orbit around the sun and related fluctuations in energy receipts. While this feels like reversibility, geological records show that the (slow) growth and (rapid) decay are asymmetric, showing hysteresis, meaning that as the pathway between these states is not the same and uncovering a form of irreversibility hidden within the apparently reversible expanded/contracted states. This is thought to be related to non-linear feedbacks in the glacier system behaviour and it illustrates that, depending on your perspective, question of interest, and how strictly you wish to apply the concept of reversibility, these past glaciations can be seen, as either reversible or part of an irreversible progression. Hysteresis is defined as the dependence of the state of a system on its history, which also bears some similarities to the encoded experiences and evolving emergent behaviours highlighted before.

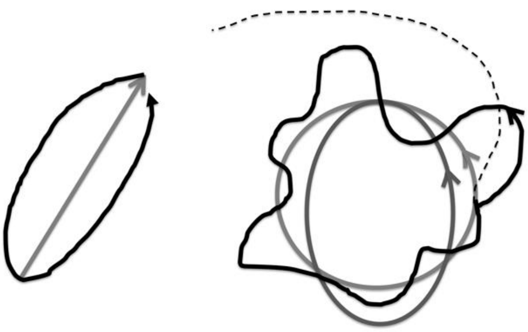

Figure 11: Earth systems rarely follow a perfectly reversible linear path or cycle (grey lines), but instead oscillates in hysteresis loops or sometimes wildly meandering cycles (black lines), or even shoots off towards a different state (dashed line).

In the debris cover of Suldenferner you can find rocks broken apart by frost (Figure 12). As long as I can remember I have been collected these from different glacier environments to play with back at the camp, as they make wonderful 3D jigsaw puzzles, but in the context of thinking about imperfect reversibility and cycles around ice I see these broken rock crystals as more than a game but a tool to experiment with. I can freeze them together again with ice, the very medium that split them apart, and then I can allow them to break apart again. Neither the rebuilding, nor the second disintegration is exactly the same as the first but it recreates this imperfect reversibility made possible by the phase changes of ice, but where something is always changed along the way.

Figure 12: A simple 3 piece rock jigsaw found on the surface of Suldenferner. More commonly they have many more parts and some are possibly even missing. Playing the game of reconstructing one requires close observation of the crystal cleavage and internal patterns and colouring of the rock.

4.4 Tipping points and irreversibility

On timescales of human relevance however, it is clear that the melting and loss of glacier ice from the climate system is irreversible. Numerical models of future climate and the global glacier response to that climate[28], predict that mountain glaciers (i.e. excluding the ice sheets) are projected to lose 26 ± 6% (+1.5°C) to 41 ± 11% (+4°C) of their mass by 2100, relative to 2015, for future global temperature change scenarios. Closer to home, those observing the glaciers in Austria suggest that the Austrian Alps might be deglaciated completely as early as 2050.

This represents some form of new world, into which new systems and ways of being must emerge. In climate science these threshold-crossing events are referred to as tipping points which have a clear connection to irreversible change as expressed in IPCC definitions of tipping points:

[28] Rounce, D.R., Hock, R., Maussion, F., Hugonnet, R., Kochtitzky, W., Huss, M., Berthier, E., Brinkerhoff, D., Compagno, L., Copland, L. and Farinotti, D., 2023. Global glacier change in the 21st century: Every increase in temperature matters. Science, 379(6627), pp.78-83.

"critical threshold beyond which a system reorganizes, often abruptly and/or irreversibly".

- *IPCC Sixth Assessment Report*[29]

"A level of change in system properties beyond which a system reorganises, often in a non-linear manner, and does not return to the initial state even if the drivers of the change are abated. For the climate system, the term refers to a critical threshold at which global or regional climate changes from one stable state to another stable state."

- *IPCC Special Report on the Ocean and Cryosphere in a Changing Climate*[30]

These differing definitions refer to irreversibility but do not require it. One reason is because within these reports the goal is to make statements that are relevant for decision-making in human society. An irreversible change within that framework may not be essentially so over the longest of geological timescales. The Greenland ice sheet today is a remnant of the large-scale northern hemisphere Pleistocene ice sheets. It formed in a very different climate and survives in the present climate due to a self-sustaining feedback related to its sheer size. However, if we were to magic it away, it could not regrow in the current climate. As continued global warming above pre-industrial temperatures causes progressive loss of the Greenland ice sheet, there are thresholds beyond which any more loss of ice locks in the loss of parts or all of the ice sheet[31]. The IPCC reports that we could be very close to such a threshold, or tipping point, and, while the actual loss of the ice sheet would still progress slowly over centuries or more, what is critical to understand is that it would be inevitable, even if we could return global temperature to its pre-industrial level. Thus, the current scientific understanding indicates that over timescales relevant to planning human societies crossing this ice sheet size threshold or tipping point would be essentially irreversible, and the consequences of several metres of sea level rise would have to be dealt with by generations to come.

5 Scaling and transforming ideas of self-sculpture, emergence and irreversibility

The issue of scale, both in space and time, is entangled throughout the themes of self-sculpture, emergence and irreversibility. The question of scale for example in the glacier case we can see the self-similar behaviour of sediment blocks at the metre scale and tributary hanging glaciers at the hundred metre scale on and around Suldenferner (Figure 13), but it is something many have recognized in comparing the deltas in satellite images with the deltas in puddles.

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[29] IPCC, 2021: Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change, Cambridge University Press, Cambridge, United Kingdom and New York, USA

[30] Masson-Delmotte, V., Zhai, P., Pörtner, H.O., Roberts, D., Skea, J. and Shukla, P.R., 2022. Global Warming of 1.5° C: IPCC Special Report on Impacts of Global Warming of 1.5° C above Pre-industrial Levels in Context of Strengthening Response to Climate Change, Sustainable Development, and Efforts to Eradicate Poverty. Cambridge University Press.

[31] Höning, D., Willeit, M., Calov, R., Klemann, V., Bagge, M. and Ganopolski, A., 2023. Multistability and transient response of the Greenland ice sheet to anthropogenic CO2 emissions. Geophysical Research Letters, 50(6), 2022GL101827

Figure 13: Sand in the meltwater stream on Suldenferner resembles miniature versions of the hanging glaciers perched on the slopes above, that periodically send blocks of ice crashing downslope, just as parts of the sand block collapse and are carried away in the water.

The issue of scale is tightly linked not only to a physical reality but to the scale of observation. What space or time scale is relevant for our interest or for the overall outcome? What can and can't be observed at each scale. How can we define things as reversible or not if these distinctions can be understood to change at different scales? I still need to think more about how emergence and irreversibility and their respective scales of operation all tie together, but I don't expect a universal answer. Reductionism either up or down a scale can only reveal part of the story, and all the definitions and meanings are somewhat slippery across these scales. I think I've learned to sit more comfortably in this multi-perspective space and better accept the multifaceted nature of things, as well as giving myself space to connect with glacier ice in new ways.

5.1 Recharacterizing glacier ice

The properties of glacier ice that I have explored in this thesis are:

- Its existence as a medium of self-sculpture that builds and reconstitutes itself in ways that encapsulate its past experiences in terms of its composition but also its structurally-dependent emergent behaviour; its character if you will.
- The way that though it has cycled through earth history, it has done so imperfectly reversibly; once melted, refreezing cannot reconstitute it in a way that rebuilds its past experiences and if we continue to lose ice from the system as we currently are, we potentially enter new states within the climate system.

I find it unavoidable to draw parallels between the path of my own lived experience and that of a glacier. It stores its memories and changes its competences over time as a result of internal change in response to external forcing. It can go back, but it recalls the past nevertheless and so in going back, it is not unchanged. I'm also drawn to the self-sculpting abilities of ice crystals, in some many ways they become themselves and their way of becoming dictates their character. Drawing this parallel could be seen as anthropomorphism, but I see anthropomorphism and ecocentrism as a two way street; in seeing ourselves as an integral part of the wider world it is perhaps helpful to see our own experiences in its structures and behaviours in order to achieve the goals of deep ecology to identify with all of nature, fostering empathy and responsibility towards the environment, and to restate our position as co-participants in the complex web of living and non-living entities and processes.

It is evident from the examination of glacier ice that reductive approaches to try and consider each component part individually will at best necessarily not reveal the whole truth and at worst be misleading. In the case of glacier ice, the laws that are applied in models of glacier flow are based on a few observations of the rate of deformation of glacier ice, and while its behaviour can be understood from an understanding of individual ice crystals, once in the polycrystalline body the interactions become too complex to calculate explicitly. Thus, the flow laws for glaciers are empirical and based on a few laboratory observations in which the scales of space, time and force found in the wild cannot be directly duplicated, and from observations in the wild for which many of the important parameters are unknown and uncontrollable. A model that can really reproduce the emergent behaviour of ice from its constituent parts remains a long way off, but we can at least think flexibly across these scales to understand the processes and tools that we are working with.

I’ve explored the encoded experiences in glacier ice, that give rise to its emergent behaviours, and the irreversible elements of its melting away. At a larger scale, I’m also interested in how such behaviours in the physical world might be analogous to and relevant for, transformation, emergent behaviours and points of irreversibility in human societies, particularly in the light of the ongoing climate crisis, which so fundamentally affects the glacier ice of the world.

5.2 Climate change narratives

In the Anthropocene[32] we find ourselves in the midst of a climate crisis of our own making, by which I mean, continuing as we are now will make our planet increasingly inhospitable to our own peaceful survival[33]. We are not the first life form to radically change Earth's climate but we are perhaps the only species that is doing so knowingly, with access to some intellectual understanding of the process and its impacts on the human and more than human parts of this planet[34].

Whether we choose to adapt to or mitigate future potentially negative impacts of anthropogenic climate change, both require navigating a complex landscape of ecology, economy, politics and human behaviour. Emergent behaviours stemming from both individual properties and complex interactions point us to the way that individual actions have the potential to collectively trigger a completely different behaviour, and that collaboration can lead to surprising outcomes. While the way it forces us to examine things on multiple scales engenders flexible thinking and consideration of changes that can act both locally and on the level of the global societal structures that bind local communities together.

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[32] Lewis, S. L., & Maslin, M. A. (2015). Defining the anthropocene. *Nature*, *519*(7542), 171-180.

[33] Djalante, R. (2019). Key assessments from the IPCC special report on global warming of 1.5 C and the implications for the Sendai framework for disaster risk reduction. *Progress in Disaster Science*, *1*, 100001.

[34] Pörtner, H. O., Roberts, D. C., Poloczanska, E. S., Mintenbeck, K., Tignor, M., Alegría, A., ... & Okem, A. (2022). IPCC, 2022: Summary for policymakers.

As greenhouse gases are a primary control on the global temperature the IPCC reports highlight that by reversing the anthropogenic greenhouse gas emissions, by means of negative emissions technologies, we can have meaningful agency over future climate evolution. Nevertheless, the abundant embedded non-linear processes and connections within the climate system pose the threat of tipping-points being crossed. I wonder how this coexistence of both reversible and irreversible aspects of anthropogenic climate change plays out in societal confusion about what can be won through climate change mitigation. A binary seems to exist in the narratives of those who resist any form of action: Those who say we should do nothing either (1) believe climate change is reversible and therefore no problem or (2) believe climate change is irreversible and therefore there is nothing to be done.

The language around irreversibility, tipping-points and climate catastrophe has been shown simultaneously to have an ambiguous and inter-related effect on individual motivation to act to mitigate human caused climate change; some dose of fear appears to be required to incite action, yet too much is paralysing[35]. Given the need for coordinated global action it will become increasingly important to have clarity on our responsibility, and the degree of control we have within the climate system. Understanding the degree of our agency, while appreciating the emergent and irreversible parts that might remain out of our control is important in managing expectations around adaptation and mitigation in a new climate world. For example, it could be seen as disappointing to realise that even if we were to halt all greenhouse gas emissions tomorrow, glaciers would continue to recede as they continue to respond to past anthropogenic climate forcing, and their recovery, if possible, would take tens of thousands of years. Alternatively, it could be seen as positive that rapidly divesting from fossil fuels and the associated emissions, will enable a larger percentage of glaciers to be retained compared to doing nothing.

Unrealised emergent behaviours and feedback processes could work for or against climate restabilisation, but I find hope and even some fun in the fact that even within all the complexity, global temperature scales linearly with greenhouse gases, which implies that every action taken to mitigate climate change does count. To me this means that even when it might seem that we are losing if we fail to reach a specific threshold to prevent a tipping point, we are still winning compared to doing nothing at all. That gives me courage to go forward doing whatever I can to live better as a tiny but integral part of this world, while remaining curious about how we will continue to co-create a new world in the future.

[35] Sangervo, J., Jylhä, K. M. and Pihkala, P. (2022) Climate anxiety: Conceptual considerations, and connections with climate hope and action," Global Environmental Change, vol. 76, p. 102569.

6 Biography

Lindsey Nicholson (*1978, UK) is an Assistant Professor in Atmospheric and Cryospheric Science at the University of Innsbruck and a practising artist and member of ParTerre6 studio in Innsbruck. Her work is rooted in environmental philosophy and explores the boundaries of scientific and artistic inquiry/understanding and how they can generate meaning in society. She regularly participates in excursions, workshops and panel discussions exploring the interfaces of science and art.

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Education

2000 BSc in Geography, Edinburgh, UK
2005 PhD in Glaciology. St Andrews, UK
2020 Habilitation in Atmospheric and Cryospheric Science, Innsbruck, AT

Exhibited works

2022 All our in betweens – mixed media sculpture
Part of the group exhibition From there through here at Künstlerhaus, Vienna

2021 The seekers – video loop (3 min)
Weeds and words – installations with Lena Violetta Leitner
Part of Hospitable Utopia group shows at Galerija Reflektor, Uzice, and at Improper Walls, Vienna

2021 Glacier Nex Us – digital performance (35 min) with Ida Marie Corell
Part of ClimArtLab, an Austrian StartClim funded project

2020 Intension – video loop (2 min)
Part of group show ….white reflects Sunlight. Fuck you, Albedo! at Improper Walls, Vienna

2020 Hack the World – video (4 min)
Shown at The Angewandte Festival and Vienna Art Week 2020, Vienna