Contents

1. *Glimpses of an Underworld*

The Swiss Alps

I was twenty, on my first expedition, a somewhat green Geography undergraduate working as a field assistant on a research project that aimed to uncover mysterious details about the flow and plumbing of the Haut Glacier d'Arolla, a small, relatively accessible valley glacier tucked up high in the Swiss Alps. I had pored for hours over the theories of glaciers in geography textbooks, of course, and was familiar with their handiwork from family holidays in the Cairngorms – but it was here that I would meet one for the very first time.

I had come completely unprepared, with a small rucksack full of mostly summer clothes, my brother's old army boots (several sizes too big) and a plastic mac which had served me well in Scotland but boasted the breathability of a crisp packet. Camped at 2,500 metres above sea level in the rocky valley of the Haut Glacier d'Arolla, I had spent my first night sleeping on cardboard in an old sleeping bag I'd used for sleep-overs when I was eleven, with its thin walls of clumpy polyester fibres and all the heat retention of a hessian sack. At this point I'd never heard of Polartec, or Gore-Tex, or even the concept of a Karrimat. Constantly disturbed by the muffled roar of the glacial river not far below and the shotgun-like cracks of rockfalls on the slopes above, not to mention the thin air which laboured my breath and the cold that made my bones throb with pain, I'd barely slept. Suddenly I understood why glaciers had been considered the resting place of ghouls and evil spirits in medieval times.

So this is where it all began – my journey as a glaciologist. Of course, I was following the deeply grooved path of many before me. The European Alps have always been a prime stomping ground for glaciologists, with glaciers of all shapes and sizes mostly accessible by foot – from the elongated, streamlined twenty-kilometre-long ice tongue of the Swiss Aletsch Glacier to tiny, stubby glaciers which are barely noticeable, perched high up in concave rock depressions (cirques) above the wide plains far below. Spanning 1,000 kilometres between Nice in the west and Vienna in the east, the Alps are part of a much greater mountain system, the Alpides, which stretches as far as the western Himalaya. Mountains are always a sign of geological drama, and so it is for the Alps, which formed as the African plate began to creep north into the European plate around 100 million years ago.

During their most intense collision, around thirty million years ago, the two plates squashed old crystalline basement rocks and younger seafloor sediments from a pre-Mediterranean ocean, neatly folding them into a series of vertically stacked 'nappes' – rather like the sail of a boat when hauled in to be stored on the boom, fold overlapping fold. The rock was crumpled most vigorously in the western Alps, where the mountain belt is thinner but higher, and includes such giants as Mont Blanc – at 4,800 metres the pinnacle of western Europe. During the past two million years, the Alps have been reshaped and remoulded by intense phases of glacial erosion as the Earth has plunged in and out of long cold periods (glacials) and short warm periods (interglacials), which reflect natural oscillations of our climate caused by tiny shifts in the Earth's orbit of the sun.

It was Jean-Pierre Perraudin, a mountaineer and hunter from

Lourtier in the Valais region of Switzerland, not far from the Haut Glacier d'Arolla, who posited one of the first modern theories of glaciation.[1] He speculated around 1815 that oddly smoothed rock surfaces were caused by glaciers effectively 'sanding' the rock they flowed over, with any protruding rocks and stones in their basal ice layers gouging deep grooves in the direction of the ice flow. He observed that giant boulders strewn across the valleys near his home were of a foreign rock type, and must have been dumped there by a glacier when ice filled the valleys during the last glacial period. Although Perraudin had an intimate understanding of the mountains, still he had to toil against the prevailing belief of the day, which was that great biblical floods had been the protagonists in forming the alpine landscape. It seemed inconceivable to him that a flood could have dislodged and transported these giant boulders, which would clearly sink like stones. He spoke to the naturalist Jean de Charpentier about his findings, but de Charpentier dismissed them as 'extravagant' and 'not worth considering'.[2]

It took another fourteen years for Perraudin's theories about glaciers to be fully developed, first by Ignace Venetz, a highway and bridge engineer in Val de Bagnes and another native to the Valais region of Switzerland. He had attempted to create channels to drain meltwaters from a large lake which had grown at the edge of a local glacier when its ice advanced and dammed a stream – such glacier advances were common during such times and were a symptom of the final throes of a cold snap during the Middle Ages in Europe, popularly called 'the Little Ice Age'. However, Venetz failed in his attempts, and the lake catastrophically flooded the valley and destroyed many lives and houses.

Venetz had many conversations with Perraudin about the inner workings of glaciers. By 1829 he was finally convinced, and presented his ideas at the annual meeting of the Swiss Society of Natural Sciences, which argued that the glaciers of his time were all that remained of a much larger mass of ice that once covered the Alps. This time, Jean de Charpentier supported him, now also swayed by these theories of massive glaciation. Yet it was Louis Agassiz, a Swiss biologist and geologist who grew up near Fribourg and ended up as a Professor of Natural History at the University of Neuchâtel, who, through a mixture of serendipity and determination, brought the early theories of glaciers to the fore in his famous *Études sur les Glaciers* in 1840. Agassiz is often lauded as the grandfather of glaciology, but in truth there were several, starting with Perraudin. They all applied pressure to the wall of conventional wisdom, until the wall weakened and ultimately collapsed.

The first time you wake up somewhere new in the mountains is always the most explosive for the senses. Dragging myself out from beneath my humble canvas on that first alpine morning, I was greeted by a panorama that remains one of the most memorable of my life. Directly across the valley an imposing mass of ice tumbled over a col (the saddle between two peaks) and down the seemingly vertical rock wall about five hundred metres in height – not a waterfall but an icefall, where the glacier meets the end of its hanging valley and must venture over the precipice below.

Here the glacier in question, the Bas Glacier d'Arolla, flows quickly down over the steep rock face, stretching until its tiny crystals can no longer deform fast enough to permit flow as a single mass, and the ice fractures in a million planes to form a chaotic field of crevasses and sharp ice towers, known as seracs. Icefalls are death traps to the mountaineer. Perhaps the most notorious example of an icefall can be found in the upper reaches of the Khumbu Glacier, the highest glacier on Earth, which moves at about a metre per day. This is one of the most treacherous parts of the ascent from base camp to Mount Everest's summit in the Himalaya. Climbers can take as long as a day to pick their way through the glacier's tortuous path, and it has caused several dozen deaths over the last fifty years – simply because ice flows, and the faster it flows the more difficult it becomes for it to move as a single body, leading to crevasse fields and icefalls.

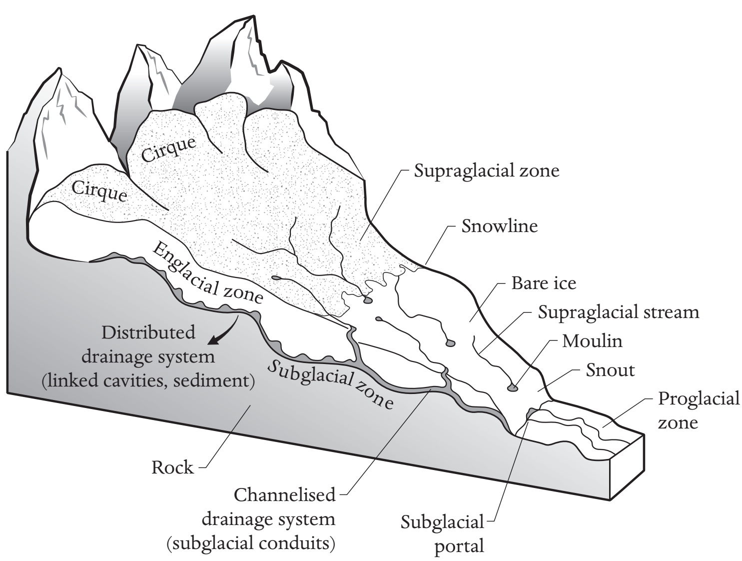
A rather incredible feature of glaciers is that they have been found to flow in three possible ways, the slowest of which is through the deformation of glacier ice crystals. Ice behaves more like a liquid than a solid; technically speaking, ice is a 'viscous fluid', or a 'non-Newtonian fluid', which means that its viscosity (or gloopiness) depends on its temperature and how much pressure it is under; the greater the pressure and the warmer the ice, the gloopier it becomes, and the more its crystals squash or 'deform'. Glaciers grow ever-deeper over time as snow accumulates, and compression plus a little melting and refreezing turn it to ice, after which the crystals start to deform under pressure. By this means, a typical alpine mountain glacier like the Haut Glacier d'Arolla might move just a few metres per year.

All glaciers flow by means of the imperceptible deformation of ice crystals, but they have much quicker ways of moving too. A second means by which glaciers flow involves the glacier sliding over a wet, slippery rock surface. Imagine taking an ice cube from the freezer, placing it on a flat plate, then tilting the plate – the ice cube slides off, right? Now consider the same ice cube on the same tilted surface, but still in the freezer – it's going nowhere, because the cube is frozen to the plate and there's no liquid water to lubricate its flow. Small glaciers in the Arctic, where the air is very cold, behave like the frozen ice cube – they don't slip and slide. They can only move by their ice crystals deforming. But in warmer climes, like the Alps, where the bottoms of glaciers have a thin layer of water, they can slip over their beds – these are called 'temperate glaciers'.

Even in perishingly cold places like Antarctica, very thick glaciers can curiously still have liquid water at their beds. Imagine blowing up our ice cube to monstrous proportions, the size of a skyscraper hundreds of metres in height, but still keeping it in a freezer. (It's a very large freezer!) Will it move if you tilt the surface? Actually, it might. Remember that old physics experiment where you hold a cheese wire across a block of ice, then apply pressure to the ice through the wire? The pressure lowers the melting point of the ice, and the wire slices down through it. Thus, our gigantic ice cube – a bit like the Antarctic Ice Sheet – will probably melt at its base due to the huge pressure of the overlying ice. Then, if by some superhuman feat you manage to tilt the surface upon which it rests, it will start to slide – in the wonderful world of glaciology, this is called basal sliding.

A glacier has a third ingenious way to flow if it rests on top of wet mud (or sediment, as a glaciologist would probably call it). Imagine that we now slid a tray of very wet soil collected from the garden just after a heavy rainstorm beneath our vast ice cube in the outsize freezer. What happens next? Well, the pressure of all that ice pressing down on the wet soil causes the water in its tiny pore spaces to become pressurized, which lowers the friction between the soil grains. This makes the soil weak and easy to deform, so if you tilt the tray, the soil will move like a mudslide downhill. The ice cube rides majestically on top of this moving platform of wet, deforming mud. This mechanism of ice flow is known as sediment deformation.

So, ice deforms, ice slides, sediments beneath the glacier deform – that's three ways glaciers can flow. Putting it in human terms, some glaciers crawl (ice deformation only), other glaciers walk (ice deformation and basal sliding), and a few virtually sprint as ice deforms and the glacier slides, perhaps also hitching a ride on top of deforming sediments. Small glaciers in the European Alps can be considered walking glaciers. In an average year the Haut Glacier d'Arolla moves at most ten or so metres in its centre, where the ice is not slowed down by dragging against the rock sidewalls.[3] However, the speed of the ice can more than double for brief periods in summer when meltwater crashes to the base of the glacier, pumping at such high pressure that it pushes up against the ice and raises it slightly off its bed, a process called 'hydraulic jacking'.[4] What's common to all glaciers with water at their beds is that the processes controlling much of the glacier's flow mostly happen in this inhospitable abyss known as the subglacial zone.



The grand purpose of the expedition I was part of was literally to get to the bottom of the Haut Glacier d'Arolla. This compact valley glacier – so described because it neatly inhabits its valley without overflowing it – formed the focus of the Cambridge University-led 'Arolla Project', headed up by one of my all-time glaciology heroes, Professor Martin Sharp, with the audacious goal of discovering what lies beneath glaciers by simply *going there*. In the case of Arolla, this meant somehow passing through one hundred metres of solid, moving ice.

For me, one of the most enthralling things about glaciers is the fact that the place where all the action happens you can neither see nor touch. You are left to imagine the point where the ice ends and the rock begins, and ponder what life could survive such grinding hostility as the glacier moves, picks up and regurgitates boulders, stones and sand. Only when the ice retreats is the evidence revealed, an ornate assemblage of ice-etched, polished rock surfaces, carved melt channels, moulded sediments – traces of a past dark, violent underworld.

You sense a glacier long before you set foot on it – it makes itself known in the sharpness of the air. But first, reaching the front of any glacier (commonly known as its snout or terminus) normally involves a monotonous hike through what is known as the 'proglacial zone'. Here, a mass of boulders, pebbles, sands and silt present a chaotic scene, parading sediments and rocks regorged by the glacier during cycles of advance and then retreat, like a person who has upped sticks in a hurry, leaving their house in a mess. Only the ribbons of milky rivers and jewels of emerald lakes trapped between moraines offer signs of life in this barren, uneven moonscape. You barely notice much beyond your feet, while dodging holes and other unsavoury features such as sinking mud, which is commonly found in the vicinity of river channels – fine glacially eroded sediments masquerading as waterlogged leg-sucking death traps. If you prod the surface with a pole, it wobbles like a blubbery belly – 'porker mud', we called it, a term you won't find in the glossary of any textbook.

Meanwhile an icy wind increasingly penetrates your lungs; if anything can be both exhilarating and foreboding, this is it. That first tantalizing smell of the ice, that sense of being stroked by its soft, frigid fingers, is a welcome and a warning. This 'katabatic' wind (from the Greek word *katabasis*, meaning 'descending') often builds through the day; it results from heavier, ice-cooled air flowing down the glacier to its snout. Such winds are often seen by mountain communities as the spirit of the glacier.[5] For me, they are a sign to prepare, to put on an extra layer and get ready for a laborious climb up the steep front of the glacier.

If I'm honest, my first sighting of the Haut Glacier d'Arolla was something of an anticlimax. In fact, I wasn't even sure that it was a glacier, for it was barely distinguishable from its rocky surrounds. Glacier snouts are grubby things, 'snout' being an appropriate word here, given that it essentially has its nose buried in mud, rather like a foraging pig. As glaciers move, they pick up sediments and stones from their rocky beds and receive rockfall from their surrounding valley walls, transporting all this debris, then releasing it upon melting in their lower reaches. Since melt is always highest at the snout of a glacier simply because it's warmer at lower altitude, the release of this grey debris from its icy shroud is fastest here, and consequently mounds of dirt accumulate chaotically at the margins and fronts of glaciers in ridges known as moraines. Glacier snouts might seem motionless and silent, almost dead, but still the ice continues to flow, albeit slowly, only advancing if the glacier as a whole receives more snowfall in a year than it loses through icemelt.

And so I tentatively set foot upon my very first glacier. The front of a glacier is treacherous terrain, often full of holes and cracks caused by the collapse of the roofs of channels which convey meltwater beneath the thinning terminal ice. As far as snouts go, that of the Haut Glacier d'Arolla was not particularly steep – high rates of melting and relatively slow ice flow maintained a gently sloping profile. But for someone whose exercise regime involved gentle pedalling around the flats of Cambridgeshire, it still came as something of a shock. I began to climb slowly, following the steady footfall of my more experienced companions up the eastern middle ('medial') moraine, which guaranteed me safe passage onto the bare ice. Such moraines are common on alpine glaciers, formed by rockfall off the head and side walls of glacier valleys onto the ice. The fallen rock becomes buried by successive winter snowfalls in the upper reaches of the glacier; the fragments are transported along with the ice until they re-emerge on the glacier's lower flanks, where melting brings them once more to the surface to pile up in elevated ridges, protecting the ice below from melt. When seeking to walk up onto a glacier, you're well advised to find yourself a moraine.

Eventually the steepness of the snout abated, my breathing slowed, and my jellified legs regained their equilibrium. Gingerly, I stepped off the moraine and onto the ice. The first steps on ice signify an important moment of union for me. Regardless of how many glaciers I have set foot on, the feeling is always reliably vivid. The repetitive crunch as the brittle surface crust shatters beneath your feet, combined with the mesmerizing sensation of walking upon a block of shifting ice some hundreds of metres thick – the sense of mystery and danger never dulls.

The meandering, ice-walled streams on the glacier surface, which beam cool turquoise in the sun, might seem benign enough – until they end abruptly and flush their watery load into deep vertical shafts, moulins, which lead straight to the bed. Staring into the abyss of a moulin always gives me vertigo – I try to stop myself, but it's almost impossible not to imagine 'what if' scenarios. What if I just slipped and plummeted head first down this vertical hole? What if, what if, what if . . . *stop*! The key thing about moulins, though, is that by passing vast volumes of water to the dark depths, they provide the only teleconnection between the glacier surface and the bed.

After an hour or so of trudge and crunch, a curious spectacle appeared on the horizon – a collection of silhouetted figures, beetling about around a humming machine which, on closer inspection, was itself framed by an untamed, writhing umbilical mass of black hose, giant water tanks and assorted tools. One figure carried a vertical lance-like pole, a jet of water and steam spewing explosively from its end. This was the famous drill site – where a bunch of resourceful scientists from the University of Cambridge had solved the challenge of accessing the icy depths of the Arolla Glacier using an extremely long hosepipe. The hot water was emitted as a high-pressure jet from a metal drill nozzle directed down vertically on to the ice, stuttering to life with the vigour of a car-wash powerhose. Gradually, over some hours, it bored a hole about as wide as a tea plate through hundreds of metres of glacier ice to its deep, murky underbelly.

Until the early 1990s, there had been scant attempts to reach glacier beds. The pioneering Arolla Project aimed to perforate a small rectangle of the glacier surface (a few hundred metres by fifty metres) with holes that stretched from surface to bed, and then to drop pressure and temperature sensors down these holes to gauge how water flowed beneath the ice. A typical borehole was almost invisible when walking over the ice surface, its location only revealed by the jumble of wires protruding out of it, tethered to various devices at the glacier bed. I would gaze down these holes, mesmerized by the swirl of cool blue and white glassy ice walls getting darker and darker until they disappeared to black nothingness. The thirty or so boreholes that were drilled to the bed of the Haut Glacier every year told us so much about how glaciers worked. Over time, the continual sliding and deformation of the ice around the boreholes caused them to stretch from vertical to more of a banana shape, since the ice at the top of the column was flowing faster than the layers below it. This is due to the cumulative effect of all the different glacier flow types, which add up as you move from the glacier's bottom to its surface.

But I was always most fascinated by the story that boreholes told me about water. Most boreholes when you peered down them appeared strangely dry; yet, while being drilled, they could be brimming with water. As soon as the drill nozzle hit the glacier bed, though, the water would often mysteriously vanish, sometimes slowly, sometimes rapidly as though someone had pulled out the plug. This disappearance of water indicated that the hole had intercepted some form of active drainage system at the glacier bed, such as a river channel (or 'subglacial conduit', as a glaciologist might call it), with ice walls and a rocky base.

The faster the water drained and the lower the water level in the borehole plummeted post-drilling, the more likely it was that the drill had intersected a channel that could rapidly transport the water down-glacier. These channels were capable of gulping more and more meltwater; they were able to grow by simply melting back their ice walls, which meant they could keep their meltwaters flowing at low pressures, leading to low borehole water levels. That said, sometimes things happened too quickly for conduits to do this. Vast fluctuations in surface melting and water flow to the glacier bed between day and night caused the water levels of the boreholes that pierced these channels to swing wildly by as much as one hundred metres (almost as thick as the ice) over just one day.[6] Bordering these super-efficient channels at the glacier bed were swamp-like zones of tiny interconnected waterways, which only allowed the sluggish flow of meltwater, on a mission to eventually arrive at a fast-flowing channel. Technically called a 'distributed drainage system' (see figure, p. 9), they coped well with a small, constant drip feed of meltwater, but tended to over-pressurize, then melt out when flooded with meltwater. When this happened, super-efficient fast-flowing rivers or channels formed in their place.

Boreholes had the pitfall of only supplying information about what was going on at a single point, rather than the entire glacier bed – which, in the case of the Haut Glacier d'Arolla, covered several square kilometres. But there were other techniques which provided a more 'zoomed out' picture of what was happening beneath all that ice. Dye tracing was one of them. Early on in my Arolla days I crossed paths with Pete Nienow, a tall, lanky Cambridge PhD student who was legendary for his ability to jog up and down the steep mountain path between the Arolla village and our camp in under forty minutes, in espadrilles, barely breaking a sweat. Pete's job was to build this 'big picture' view of the glacier plumbing system, which he did using a harmless bright pink tracer dye called rhodamine.

Each day Pete would beetle up the glacier, a tiny bag of the powdered dye stashed in his rucksack, until he sighted a moulin. He would then swiftly sprinkle the pink stuff into the water gushing down the moulin, before sprinting back down the glacier to eagerly await the dye's arrival in the main river bubbling out from the glacier's snout – by which point the dye had been so diluted that it no longer turned the water pink, but could still be detected by a fluorometer. This instrument, by shining a small beam of light into the water, then measuring the amount of light that was absorbed and re-emitted by any pink particles, could compute how much dye there was in the river. The faster the dye appeared and then disappeared in the river at the glacier front, the quicker and more efficient a flow path it must have taken to get there. Pete did this all summer for several years, identifying some thirty moulins dotted over the glacier surface.

These dye-tracing experiments revealed that, over the course of a summer, as the snowline retreated up the glacier and melt rates soared, the slow, rambling passage of melt through sluggish passageways at the glacier bed was soon replaced by rapid flow through efficient channels[7] – in effect the glacier bed's network of rural tracks collapsed and was traded for giant motorways. Pete's results from across the entire glacier complemented the experiments with 'single-point' boreholes, which taught us via their water levels how the speedy and sluggish parts of the glacier plumbing system interacted on a daily basis. During the day, ice on the glacier surface melted, supplying water to super-efficient conduits at the bed, which overflowed, forcing water into the channel margins and the inefficient drainage networks beyond; at night the flow reversed, returning water to the channels.[8]

It was an ingenious plumbing system, but by no means perfect. In spring, when the first pulse of fresh snowmelt gushed to the bed via moulins and crevasses, the internal pipework couldn't accommodate this sudden influx of water, and the force of all the pressurized water literally jacked the glacier off its bed. Imagine the curious spectacle (if only we could see it with the naked eye) of the entire glacier surface lifting, rising on a pillow of meltwater, and, as it lifted, suddenly the glacier loosening its contact with its rocky bed, removing the friction that kept it from racing downhill, and surging forward.[9] These 'spring events' happen on glaciers the world over, but are soon curtailed by the formation of channels at the glacier bed which whisk away the ponded meltwater, allowing the glacier to nestle back onto its rocky base and slow down.

In the evenings, after long days working on the Haut Glacier d'Arolla, during the slow plod down over the ice and through the glacier forefield, I always felt a sense of deep connection with the barren mountainscape, as the fatigue softened my senses. As I descended, to the east, turning a soft pink in the sunset, stood the jagged Dents de Bouquetins – a classic arête, or knife-edged ridge, towering as much as one thousand metres above the glacier below, its sharp features derived from powerful erosion when much of the valley was occupied by the glacier at the height of the last 'cold' period, about 20,000 years ago.

The ridge is named after the bouquetin, the enigmatic alpine ibex (*Capra ibex*), which looks like a deer but is more closely related to a goat. Bouquetins are native to much of the European Alps and traverse dizzying heights, usually close to the snowline, their split hooves enabling them to clamp tenaciously onto the underlying rock. Occasionally, at dusk, I'd glimpse the distinct horned profile of one poised on the cliffs above. These graceful mountain goats display what is called sexual dimorphism – a fancy way of saying that the males and females look different. The males can have spectacular horns which curve backwards, continuing to grow throughout their lives,[10] sometimes up to a metre in length. The size of a male bouquetin's horn determines its place in the hierarchy. The females are smaller, with less dramatic horns. The sexes mostly live apart, reuniting during the mating season in late autumn. The horned goat features in the star sign Capricorn, which happens to coincide with the main breeding period for the bouquetin in December, straddling the winter solstice. Could people in ancient times have associated their mid-winter celebration of fertility and rebirth with the breeding cycles of this sure-footed mountain dweller?[11]

These elusive animals have long beguiled alpine communities; their body parts were believed in medieval times to boast magic, medicinal powers, and they were also once prized for their meat. Indeed, the stomach remains of the 5,000-year-old iceman 'Ötzi', who was found preserved within a glacier high in the Ötztal Alps in Austria in 1991, contained remnants of cooked ibex meat.[12] The goats also feature in prehistoric cave paintings in France, such as the Chauvet-Pont-d'Arc cave in the Ardèche from 30,000 years ago. However, following the invention of firearms in the fifteenth century, the tale of the bouquetins was a sad one – they were hunted to close to extinction. They only thrive today due to conservation measures and campaigns to re-introduce them.

Bouquetins can be confused with their smaller cousins, the chamois, which have much smaller, curved tipped horns and partially white faces. Chamois haunt the lower mountain flanks – I often spotted them during my numerous hikes up the path from the Arolla village to camp. I would always hear them before I saw them. First, there was a clatter of rock fall, and looking up, if I was lucky, I would catch a glimpse of one of these bold, nimble creatures athletically leaping across some near-vertical precipice, seemingly defying gravity.

That first summer at Arolla was a heady time of my life.

I remember practising ice-axe arrests by throwing myself down a practically vertical slope; learning how to rope up to cross crevasses; and, most essentially, teaching myself how to imbibe throat-scorching *eau de vie* at altitude while still commanding control of my legs. These were high-octane experiences. The communal mirth of field-camp life was infectious, I had never laughed as much before – in short, I was hooked.

Even so, it was demanding. Day after day, we followed the same drill. Get up, thaw out over a brew, trough down a bowl of gritty muesli (the sand produced by glaciers defies all barriers, literally penetrating everything), toil through the moraines, then clamber up onto the ice. Often the build-up of heat during sunny days was so intense that electric storms rumbled through the night – shocks of lightning and thunder reverberating around the cavernous valley, echoing off the steep rock walls, booming and repeating as if on an interminable loop. I recall these epic storms as black and white negatives etched in my mind; the glimpse for a millisecond of the tumbling icefall illuminated by flashing light, like a sinister beast caught prowling in the darkness. The next day, I'd wake and it was as though nothing had happened – just a bad dream and ghosts of memories in monochrome.

Our small camp consisted of a humble collection of sun-bleached canvas tents, nestled in a hollow in the mountainside overlooking the Bas Glacier d'Arolla icefall. It was encircled by barren rocky slopes, adorned with clumps of rough grass that were grazed by herds of scruffy sheep which wandered in and out without warning. Often in the middle of the night you would wake startled by their scuffling and snuffling beneath your tent fly in search of tasty morsels. The camp was situated just above the glacial river, its raging torrent always audible as white noise. Its flow was lowest first thing in the morning, after a cold night of low melt on the glacier, reaching a climax in late afternoon – but day or night, it continued to whoosh its fine milky suspension of sediments downstream, eventually feeding into the Rhône, then Lake Geneva and onwards, finally discharging its load into the Mediterranean in the south of France near Arles.

Many of our great rivers originate as tiny trickles of snow and icemelt in the high mountains – which begs the question, what will happen once the ice that feeds them has all melted? It's a question of special importance in regions where glaciers are melting and human communities are numerous and vulnerable, such as the Himalaya and the Andes, for the pulverized rock in these rivers, known as 'glacial flour', has been shown to be a fertile source of nutrients. The farmers of the Swiss valleys give credence to this notion by habitually spraying the glacial meltwater onto their croplands to ensure a bountiful harvest. But the one thing you must never do is drink the milky liquid. The very fine rock powder which gives glacial rivers their cloudiness can in some glaciers contain harmful levels of heavy metals like arsenic, mercury and lead, and some of its minerals can easily irritate the stomach lining.

The sheer power of the river emerging from the Haut Glacier d'Arolla became apparent to me early on during that first summer. I was standing on the bank one day, preparing to cross from one side to the other, holding a prism on a stick as a colleague surveyed its position from the river terraces above. (A survey prism reflects beams of light sent out by a surveying instrument – in this case a geodimeter – back to the meter, which is normally sited somewhere high up and with a wide view of what you want to survey. The time taken for the signal to arrive back is used to measure the distance.) I started to shuffle across, moving ever so slowly so as not to lose my footing, cautiously placing the prism in position lest I dropped it, and finally reaching the central main flow. The force of the wall of water pushing against my spindly rubber-coated legs was immense. Suddenly I lost my footing and found myself bouncing downstream over the cobbled riverbed, tossed by the turbulence of the ice-cold water, heading directly for the intake point for the hydro-electric power station. I could barely think, let alone panic. I tried rolling into an upright position, but this was challenging in the chaotic flow. Eventually I was lucky enough to be fished out by another team member, a tall, ginger-haired chap called Mark, who spotted my blue and white dry suit bobbing down the river. Thus my first glacier fieldwork romance was sparked.

Bidding farewell to the Haut Glacier d'Arolla at the end of that first summer expedition was, for various reasons, an emotional experience – I keenly felt the loss of the close companions who, only weeks earlier, had been complete strangers. A few years after my departure, an astounding discovery emerged from the Arolla Project. Martin Sharp (now based in Canada), working with UK microbiologists and chemists, had found life at the bottom of boreholes drilled to the bed of the glacier, stunning the global research community.[13] There are sometimes discoveries that you simply don't anticipate, but when you look back, you can't comprehend why not. It's obvious – why wouldn't you expect life beneath glaciers? There's plenty of water, which is a prerequisite for life. But still, it came as a bolt from the blue, because the mindset of the glaciologists (mostly physicists and geographers) had been shattered through collaborating with a bunch of biologists. Such revelations demonstrate the value of working together across the traditional boundaries between disciplines, because it's at these boundaries that ideas are catalysed.

Okay, so in the case of the Arolla glacier, we are not talking about the discovery of anything greater than can be spotted down the lens of a microscope – but still, here were microorganisms, the most adaptable and resilient life on Earth. As much as the published article was lauded across the world, those of us who knew the glacier recalled that the borehole site wasn't far down from the pipe responsible for evacuating human waste from the Refuge des Bouquetins on the precipice above. However, my expeditions since have shown that, actually, wherever you look in glaciers, you do in fact find life – surviving against the odds, and using every clever biological trick in the book to do so. How does this life survive and function, and what impact does it have beyond the glacier? These are mysteries that I have spent the last twenty years trying to solve.

In 2018, twenty-six years after my first encounter as an enthusiastic but somewhat green undergraduate, I revisited the Haut Glacier d'Arolla. I trudged the steep path from the Arolla village at 2,000 metres above sea level to the spot where our camp had once stood, eagerly anticipating the sight of my beloved glacier. The climb was easier than I remembered, probably reflecting my higher level of fitness, having long since traded the flats of Cambridgeshire for the rolling hills of the West Country. Returning to the place where my passion for ice had first taken hold was both exhilarating and moving. The memories flooded back – of life amid our tiny cluster of sun-scorched tents, the daily toil up the glacier, even the position of particular boulders – but one thing truly stunned me. The icefall, which I recalled as a colossal flowing mass spanning the mountain from top to bottom, was barely recognizable. Its tongue, which once tumbled as a single crevassed torso down the steep rockface, was now drastically severed in the middle, such that its upper part was no longer connected to the lower tongue of the Bas Glacier d'Arolla in the valley below. Thus, the Bas Glacier d'Arolla, which the icefall had previously nourished, was about one kilometre shorter. I had witnessed the death of a glacier.

Up and over the lip of the hanging valley, in the main valley once carved by the Haut Glacier d'Arolla, I was again dumbfounded – where was the glacier? The landscape was painted in drab greys and browns, as if in mourning, apart from high white splotches where seasonal snowfall had yet to melt. Squinting, I could just make out the tiny brown snout of the Haut Glacier. Compared with twenty-five years ago, it was a kilometre further up the valley, and it sat motionless like a dark ghost, the steep, rocky sidewalls forming a shroud around its lower flanks. I was aghast – it was as if I'd returned home, only to find it had been ransacked. My stomach was in knots, and tears of disbelief welled up in my eyes.

Climate change might at times feel like an abstract concept, but when you experience a spectacle like this, and can compare your own before-and-after photos, the conclusion is undeniable. Such observations are echoed in the scientific literature, for satellite images reveal more than 20 per cent loss of glacier area in the Swiss Alps between the early 1970s and 2010.[14] But how do we know this to be the fault of humans? Couldn't it just be caused by natural cycles? Certainly, the planet has seen dramatic swings in temperatures, which have caused glaciers to both grow and shrink. During the Cenozoic Era, spanning the past sixty-five million years, over which our continents drifted to roughly their present positions, the climate (bar a few blips) has cooled, causing the gradual growth of glaciers. A key player in these shifts has been the concentration of carbon dioxide in the atmosphere, and changes in what we call 'the greenhouse effect'. This effect describes the fact that when the sun's rays hit the land surface they warm it up; some of that energy is radiated back to space, only not all of it makes it back, and instead is absorbed by clouds and greenhouse gases (one of which is carbon dioxide). This energy, or heat, is effectively trapped, as in a greenhouse.

The amount of carbon dioxide in the atmosphere over very long time periods such as the Cenozoic – before humans got to work, that is – has been a tug of war between several countervailing forces.[15] Volcanos add carbon dioxide to the atmosphere, erupting as the Earth's tectonic plates shift around. The breakdown of carbon-rich rocks at the Earth's surface also adds a little. Meanwhile, carbon dioxide is removed from the atmosphere by the weathering of other rocks and the growth of plants. Plants on land and plant-like creatures in the ocean are direct consumers of carbon dioxide during photosynthesis, and if their dead remains become buried below ground or in the depths of oceans – in the form of carbonate rocks such as limestone or perhaps as undecayed organic matter in peatlands and permafrost – this burial removes the gas from the atmosphere for a long period of time.

These different push-pull forces are thought to interact – for example, if volcanos spew out more carbon dioxide, this stimulates more weathering and plant growth which consume the gas and helps stop the planet getting too warm. It's a bit like a thermostat. Over the last four hundred million years, as life moved out of the oceans and on to land, the expansion of land plants and the associated weathering of rocks are thought to have gradually taken more and more carbon dioxide out of the air, helping prevent the Earth from heating up too much as a result of volcanic carbon dioxide.

During the Cenozoic a melting pot of different forces and their impacts on atmospheric carbon dioxide have slowly nudged Earth into the most recent of its so-called great 'Ice Ages' – times with significant ice at the poles. At its beginning, around sixty-five million years ago, continents were in their final phase of wandering away from their mother super-continent, Pangaea, hitching a ride on top of tectonic plates. India at this time was detached from Eurasia, and the Indian plate dived down beneath the European plate by a process called subduction. High volcanic activity at the point where the plates met heated up carbon-rich rocks, producing carbon dioxide that flooded the atmosphere – more than a thousand molecules per million of carbon dioxide,[16] compared to just over four hundred per million today.[17] Earth's climate was hot – too hot for the build-up of ice.

But starting from around fifty million years ago, India ran into Europe, pushing up the Himalaya mountain belt and the Tibetan Plateau – there was no more plunging of one plate beneath the other, and the carbon dioxide emitted by volcanos gradually fell. There's some debate as to whether the weathering 'sink' for carbon dioxide grew or not. It's possible it was boosted by the expansion of plants and some large-scale movement of plates; possibly the uplift of the Himalaya caused high rates of erosion, as the mountains were worn down by the elements and glaciers, and attacked by carbon dioxide in rain and meltwater.[18] Whatever the cause, carbon dioxide concentrations have fallen since about fifty million years ago and Earth has shifted from a 'greenhouse' climate to an 'icehouse' one.

Around thirty million years ago, the climate was cool enough to form a large ice sheet in Antarctica.[19] This was aided by the creep of Australia, South America and Africa away from the Antarctic continent, creating a sea way and a powerful ocean current which swirled anti-clockwise (the Circum-Antarctic

Current) around its land mass, keeping Antarctica cool. Two to three million years ago, following further cooling and carbon dioxide decline, ice sheets grew in the northern hemisphere, starting with the Greenland Ice Sheet that still remains today. Once ice sheets grow to a large size, their white, twinkling surfaces help keep the climate cool by reflecting as much as 90 per cent of the sun's rays back into space.

The last two million years of the Cenozoic are known as the Quaternary Period. During this time carbon dioxide in the atmosphere was at an all-time low in the Cenozoic and conditions were already cool. Our records show that a new factor became important in the climate's tug of war at this time, producing a fresh suite of climate variations on top of long-term Cenozoic cooling. Tiny, regular shifts in the shape of the Earth's orbit of the sun began to influence Earth's glaciers, by affecting the amount of heat reaching the surface of the planet, and acting as the pacemaker for regular cycles of warming and cooling.[20] These orbital variations were not new, but started to have more impact once the ice sheets were large and the climate was cool. There is also some evidence that they became more pronounced around three million years ago, causing cooler northern hemisphere summers which allowed ice to build up.[21] Thereafter, they led to a pattern of swapping between short warm 'interglacial periods' of tens of thousands of years to longer cold 'glacial periods' of up to 100,000 years. Glaciers and ice sheets grew during glacial periods – including ice sheets across North America and Europe – and then melted again during interglacial periods, in cycles called 'glacial-interglacial cycles'.

We are currently sitting in an interglacial of the Quaternary period called the Holocene, and have been for roughly the past 10,000 years. There have been naturally occurring climate variations during this period – we know, for example, that during 'the Little Ice Age' of the Middle Ages, temperatures were as much as two degrees Celsius lower than those found today. Many glaciers grew during this time, continuing to do so until the mid-nineteenth century. Countless paintings depict glaciers advancing down their valleys, engulfing entire alpine villages; bishops were even summoned to exorcise the evil spirits from these ice monsters.[22]

So climate change has clearly occurred naturally in the past, both warming and cooling. However, the alarming truth is that atmospheric levels of carbon dioxide and other greenhouse gases such as methane have soared over the last century. We know this from the tiny air bubbles trapped in ancient ice laid down in the middle of Antarctica and Greenland, sampled by drilling deep cores down to layers that go back almost a million years, covering as many as eight glacial-interglacial cycles.[23] This is largely due to human activity – burning fossil fuels, cultivating rice paddies, felling forests, rearing livestock, to name but a few. Some people have argued that we can't call the current period the Holocene anymore, since humans have created their own climatically distinct epoch – the Anthropocene.

The present-day concentrations of carbon dioxide in the atmosphere are now as high as during the mid-Pliocene, three million years ago;[24] global mean air temperatures were up to three degrees warmer than today and sea levels twenty metres higher – as if the Greenland and West Antarctic Ice Sheets largely disappeared, plus some ice from around East Antarctica.[25] Which begs the question, where are we headed?

As we pump more and more greenhouse gases into the atmosphere, we have to delve ever further back in time to find a period where similarly greenhouse gas-charged conditions were present on Earth – only then it was due to the rising influence of volcanos. By the mid-twenty-first century, if emissions continue unabated, carbon dioxide concentrations are likely to be at the level of fifty million years ago – that's before ice sheets were able to form over Antarctica and Greenland, because the Earth was too warm. After another two hundred years, they could hit the level of four hundred million years ago[26] – an apocalyptic place to have arrived in just a few centuries.

When you look at forecasts compiled by computer models, the future for our Swiss alpine glaciers is bleak. Irrespective of our success in cutting carbon dioxide emissions over the coming century, the glacier loss will be very high. It is estimated that more than 80 per cent of their ice will be lost by the end of the twenty-first century[27] – so there'll be no more Haut Glacier d'Arolla, or certainly not as I once knew it. The landscape that I experienced and which inspired me as a twenty-year-old student will be irrevocably changed, and the loss will be incalculable.