blue ice

AN ILLUSTRATED GUIDE TO A

glacier

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hoh

SOME MEN WERE HUNTING ON HOH MOUNTAINS. They found a hole in the side of the mountain. They said, "This is Thunderbird's home. This is a supernatural place." Whenever they walked close to the hole they were very afraid. Thunderbird smelled the hunters whenever they approached his place. He did not want any person to come near his house. He caused ice to come out of the door of his house. Whenever people came near there, he rolled ice down the mountainside while he made the thunder noise. The ice would roll until it came to the level place where the rocks are. There it broke into a million pieces, and rattled as it rolled farther down the valley. Everyone was afraid of Thunderbird and of the thunder noise. No one would sleep near that place over night.

OVERLEAF: SUNRISE ON MOUNT OLYMPUS PHOTO BY JOEL REID

introduction

MY CLIMBING INSTRUCTOR WAS TRAPPED AT THE BOTTOM of a 30-foot moat just below the summit of Mt. Olympus. As a junior in high school, I knew a little about rope rescue techniques, but hardly anything about glacier moats. Had it been the other way around the entire rescue may have been avoidable, but familiarity with glacial processes is often limited to seasoned mountaineers and geologists. Yet in this age of rapid global warming and increased mountaineering activity, one does not have to be a climber or scientist to interact with glaciers. The dynamic and awesome activity disguised among distant snow-capped peaks is relevant to us all.

Glaciers are inescapable. Farmers throughout the world plow around vehicle-sized stones left behind by retreating glaciers in the middle of perfectly flat fields. In recent geologic time, glaciers have scoured 30% of the Earth's land surface including much of North America. Currently, glaciers hold more than 75% of the planet's fresh water supply; Florida, and other low-lying coastal areas, would be flooded by a rise in sea level if all the world's glaciers were to suddenly melt. Global warming and the potential impact of receding glaciers in the tropics and Antarctica have received much attention from both the scientific and popular press. The current swing toward a warmer climate is a well documented and accepted fact, and a relatively small rise in temperature can dramatically shrink a local glacier at rate noticeable to the casual visitor. Thus a Minnesota soybean farmer, an owner of a coastal cabin, and a hiker passing Mount Rainier on the Pacific Crest Trail are all directly affected by glacial processes.

RIGHT: LEAVING THE GLACIER AT THE END OF A DAY PHOTO BY JOEL REID

For many, kicking crampons into blue glacial ice, looking skyward from the bottom of a crevasse, or mapping past ablation horizons is a geographic and technical impossibility. Hikers often examine glaciers at a cautious distance. For most introductory geology students, the complicated mix of snow, firn, dirt, running water, solid ice, and rock that make up a glacier are explored only through descriptions and photographs in a geology text. However, even in the most thorough book it is often difficult to get a sense of how simple processes like accumulation and ablation interrelate. Often, one may find pictures of features associated with a process, but they may jump from one continent to another or vary in glacier type and climate. This approach often fails to illustrate how separate processes effect one another. A glacier is an integrated and dynamic system, with each detail and process connected to a greater whole. The study of the glacial environment should logically parallel this design.

This book unites the basic concepts of glaciology using the Blue Glacier of the Olympic Mountains as a case study. This glacier has been extensively studied since the 1950's and research data from primary literature is combined with over 60 photographs to provide a complete picture of Blue Glacier as a system. No previous geology experience is assumed; the material should be accessible to an introductory geology student, someone in a beginning mountaineering course, or a coffee table browser. Glacier travel is not an experience that is open to everyone, but I hope to provide geologists and non-geologists alike the next best thing to crampons and an ice axe—a means to explore the glacier environment and glimpse the exciting real-time geologic process at work in our own backyard.

A journey to the Blue Glacier begins with a 27-kilometer walk through the wettest place in North America. The Olympic Peninsula of western Washington is famous for its old-growth firs that reach 90 meters in height, spongy carpets of moss, and incessant rain. The latter is what makes the 266 glaciers hidden among the peaks of the region so active and exciting—Blue Glacier receives more precipitation and is lower in altitude than any other glacier in the country. Ninety percent of North America's glaciers are found here or in the nearby Cascade Range.

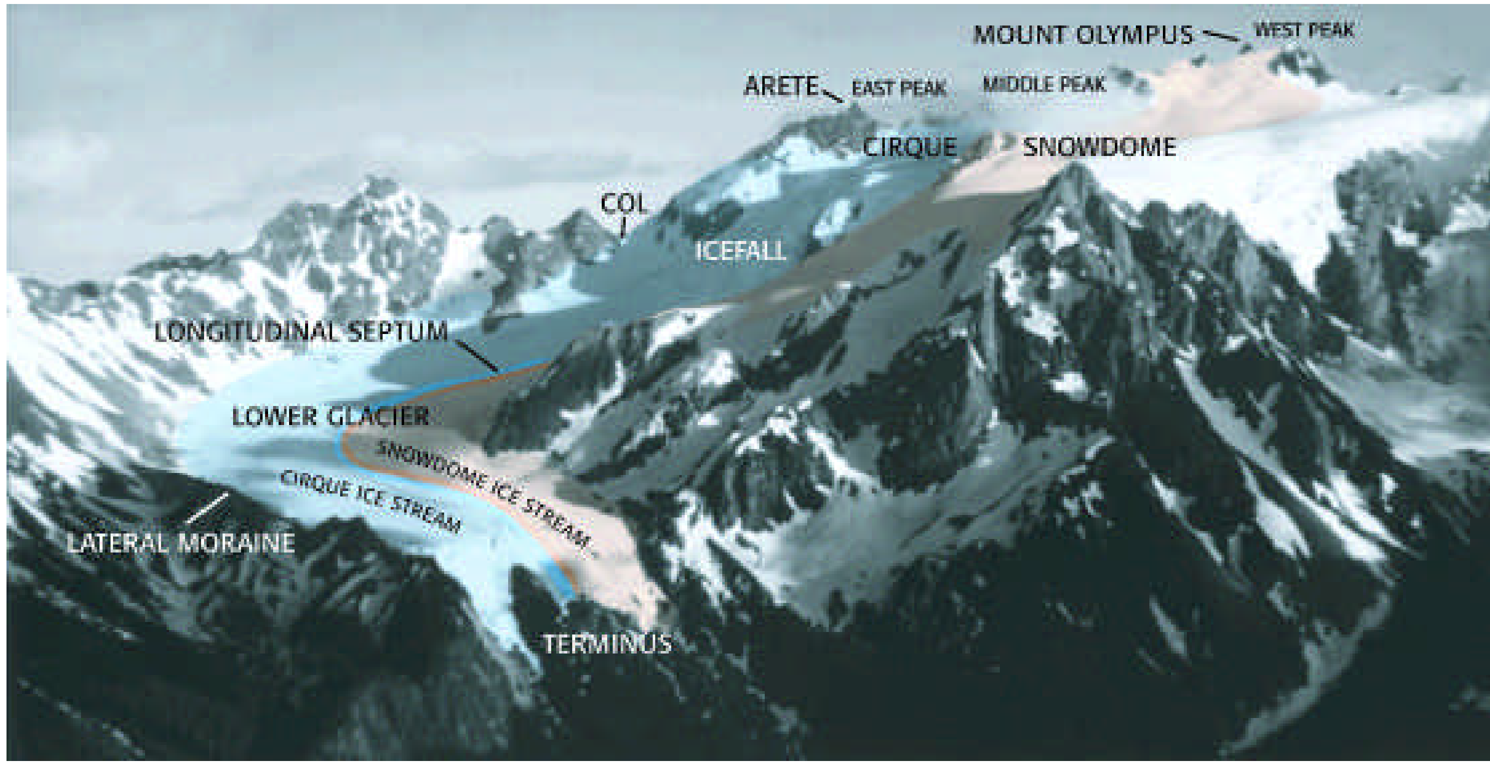
Blue Glacier flows down the north side of Mount Olympus (2428m) in the heart of the Olympic Mountains. The glacier begins at 2377 meters above sea level, takes a left turn, and drops 1143 meters in 4.3 kilometers to a final elevation of 1234 meters. It has a total area of 4.3 square kilometers, and a volume of 0.57 cubic kilometers or 1 trillion one-inch ice cubes. The Blue Glacier is a large contributor to the 25,000 gallons of water per second that flow down the Hoh River to the Pacific Ocean fifty-five kilometers downstream.

All photographs were taken late in the melt season during August of 2001. Many features usually hidden were exposed due to low snow accumulation the previous winter. A chicken was a member of the climbing expedition to provide an object of scale. The rooster is life size but lost both feet to frostbite.

ABOVE: PHOTOGRAPHING THE BLUE GLACIER PHOTO BY JOEL REID

terminology

BLUE GLACIER IS A VALLEY GLACIER—it carries snow and ice that accumulates on Mount Olympus down a valley to a lower elevation where it then melts. This glacier follows a pre-existing stream valley and is confined by slopes on either side. Most valley glaciers are temperate or warm glaciers, meaning that the ice is at or near the melting point. Glaciers can also take the form of an ice sheet or cap such as in Antarctica. Most of the Antarctic ice cap is a cold polar glacier where the temperature is well below the melting point.



WHERE'S THE CHICKEN? The top of a valley glacier is known as the head, the bottom may be referred to as the tip, snout or terminus. Three terms that help identify where something is on a glacier are subglacial—beneath the ice, englacial—within the ice, and supraglacial—on the surface of the ice. Other locations are mapped on the photograph above.

LEFT: THE LOWER BLUE GLACIER | ABOVE: THE GLACIER FROM THE AIR LOOKING SOUTH

AN ICEFALL FORMS WHEN THE GLACIER FLOWS RAPIDLY over a steep or vertical portion of the valley. The chaotic jumble of crevasses and seracs in an icefall creates complex patterns in the structure of the glacier below it.

A SERAC IS A LARGE, ISOLATED, AND OFTEN UNSTABLE BLOCK OF ICE formed where the glacier surface is severely fractured. Seracs are common in the icefall and one of the reasons climbers avoid the area.

ABOVE: THE ICEFALL | RIGHT: SERACS IN THE ICEFALL

A CREVASSE IS AN OPEN FISSURE IN THE GLACIER surface. Crevasses open slowly from the stress of glacier flow and provide a unique window through which one can see the inside structure of a glacier. Crevasses ranging from one to 30 meters deep can be found throughout Blue Glacier.

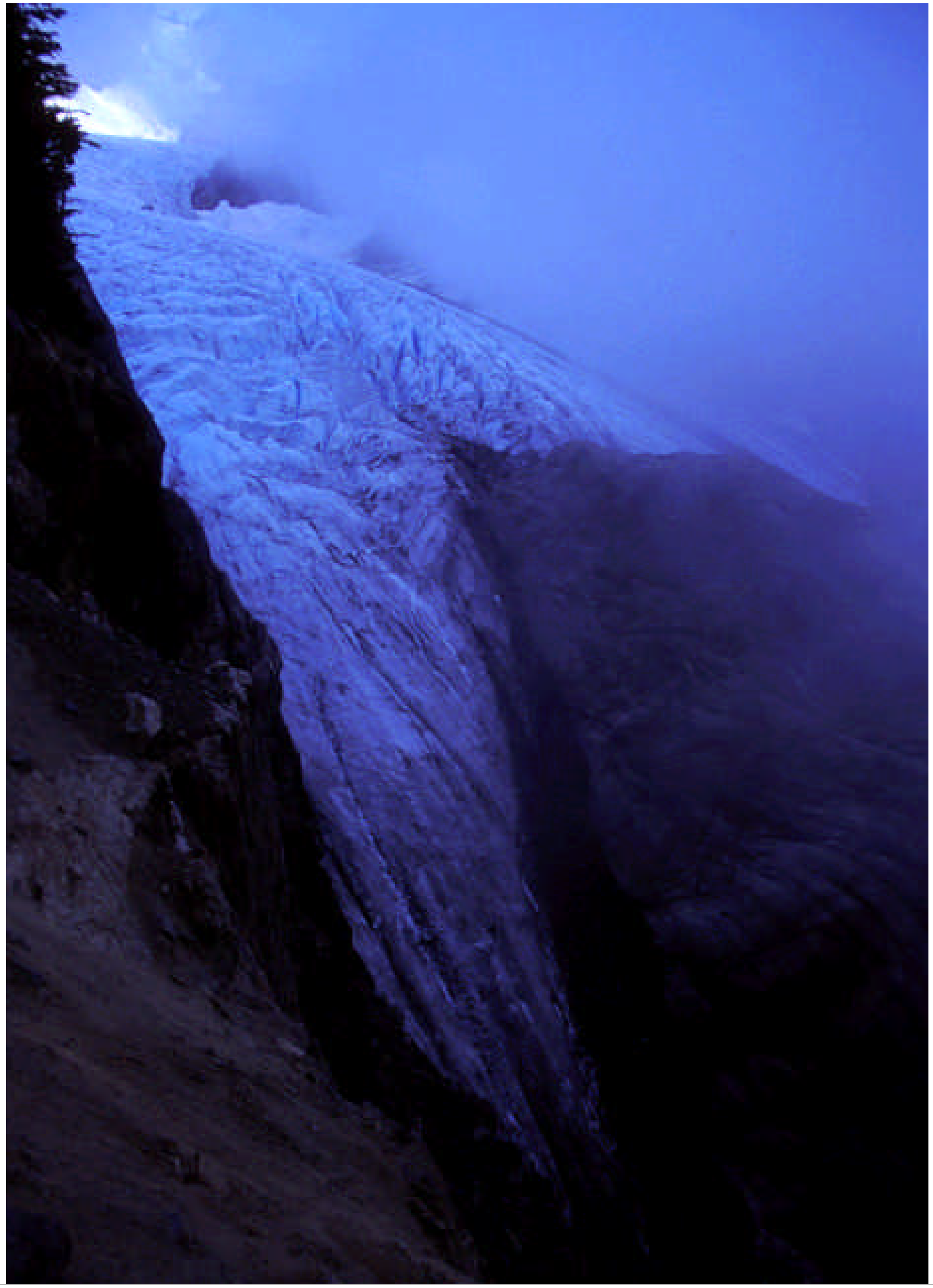
THE BERGSCHRUND IS A CREVASSE that separates the stagnant ice attached to the rock at the head of a glacier from the flowing ice. Though often disguised by snow, the feature is usually permanent. This bergschrund at the head of Blue Glacier is visible as a series of parallel crevasses below the summit arete. If all the snow was removed and the ice exposed, the crevasses would form a single gaping crack. The bergschrund often creates a challenge for late season mountaineers, as they have to cross it to reach summit rock.

A CIRQUE IS A SEMI-CIRCULAR GLACIER CARVED BASIN near the head of the glacier. The three summit peaks of Mount Olympus ring a cirque carved out by the Blue Glacier.

LEFT: A CREVASSE | ABOVE: THE BERGSCHRUND IN THE CIRQUE BASIN

A SHARP NARROW RIDGE ERODED FROM BOTH SIDES IS KNOWN AS AN ARETE. The three summits of Mt Olympus, West, Middle, and East are on an arete that separates the Blue from the Hoh Glacier.

THE BLUE GLACIER'S TERMINUS is currently divided 100 meters above the tip. A large rocky buttress has split the flow of ice into two smaller termini since the early 1900's; previously the ice was deep enough to flow over it. Glacier Creek begins at the snout of the glacier and joins the larger Hoh River that eventually flows into the Pacific Ocean 55 kilometers downstream.



AN OPEN U-SHAPED PASS IN A RIDGE IS KNOWN AS A COL. Formed by glacial erosion working on both sides, the col links the Blue with the Hoh Glacier. Climbers pass through this saddle in the arete to reach Mount Olympus' East Peak.

ABOVE: THE COL AND THE LOWER SHOULDER OF AN ARETE | RIGHT: THE EAST TONGUE OF THE TERMINUS

It takes both cold conditions and wet weather to create a glacier. The Olympic Mountains, Alaska, New Zealand, and Patagonia, among other places, all have highly active glaciers. About 4.5 meters of precipitation falls on Blue Glacier every year. Much of this comes during the winter and accumulates as snow. More rain and snow land on Blue Glacier than on any other glacier, or even any other place, in the continental United States.

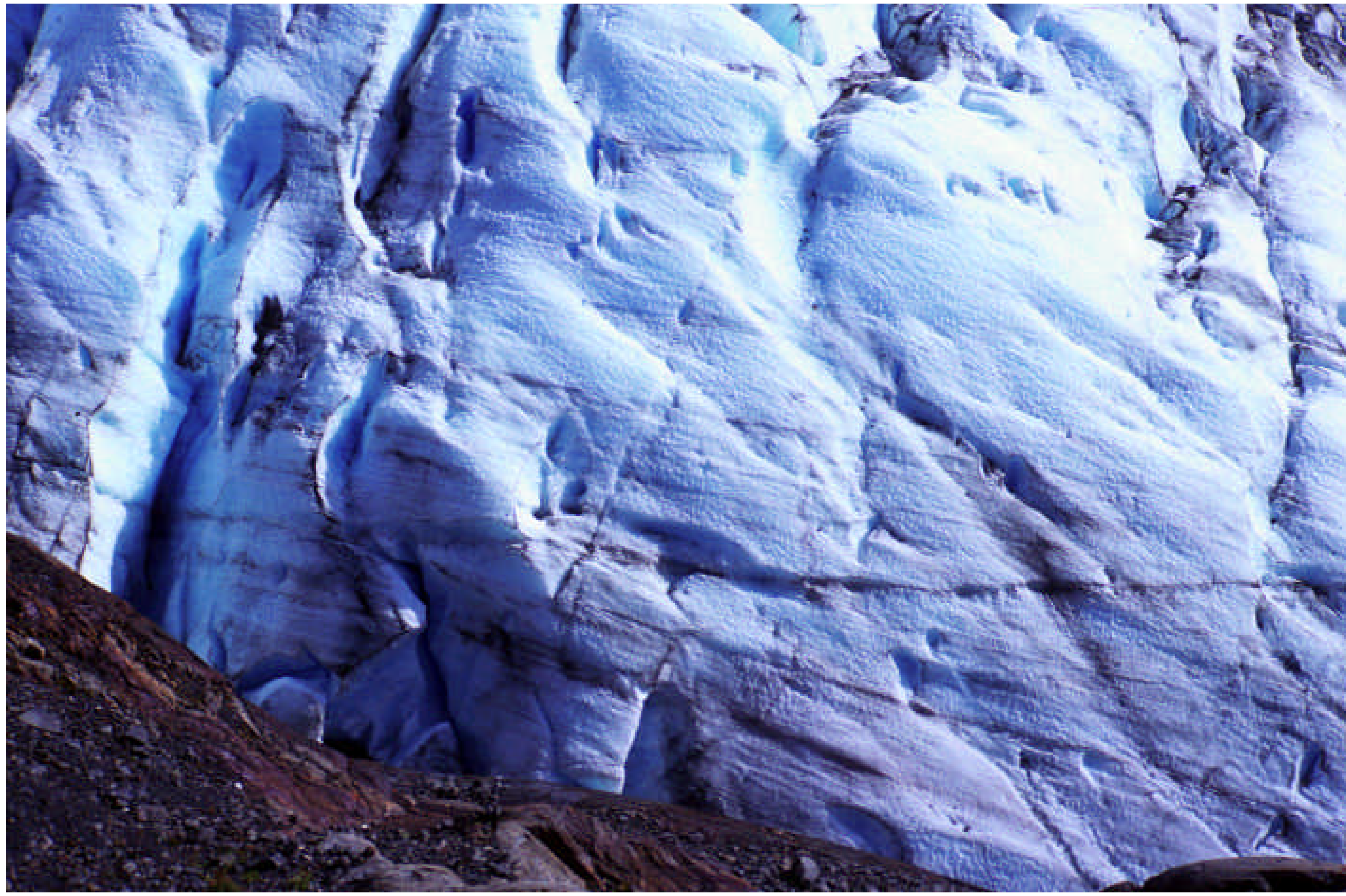
Snow falls on all areas of Blue Glacier from roughly October to May; but if you were to measure the snowfall after a large storm you would find varying depths at different locations. Winter winds frequently exceed 145 kilometers per hour on the glacier causing the snow to drift and redistribute. Fifty percent more snow, for example, accumulates in the relatively sheltered cirque above the icefall than at the adjacent but exposed snowdome—even though the elevations are similar.

Not all of Blue Glacier's precipitation is snow and counts as accumulation—throughout the year it also rains on the glacier. Two-thirds of this rain remains liquid and helps to melt the snow base while the remaining third freezes directly to the glacier. A big storm in the autumn is more likely to be snow and add to the accumulation amount while spring precipitation is often in the form of rain and can increase melting. Thus the yearly depth of new snow accumulation depends on not only how much precipitation the glacier receives, but also on what time of year it falls.

accumulation

LEFT: THE CIRQUE ACCUMULATION ZONE | ABOVE: THE SNOWDOME

firn



With roughly 4.5 meters of snow falling on Blue Glacier annually, one would expect to see snow everywhere. But there is hardly any snow visible in most of the photographs in this book—the white stuff is almost exclusively firn.

Firn is old snow. More specifically, it is snow that has survived one or more summer melt seasons. The aging process is a little more complicated, however. Snow lands on a glacier in the beautiful and delicate shapes we mimic with paper and scissors. Gradually the individual crystals lose their pointed shape and become blunted, round grains of ice. The sharp points of a flake are dulled by the bumps and bruises it receives during landing, the subsequent redistribution by wind, and the compaction from an increasing blanket of snow. Water molecules also evaporate easily from the sharp ends of the flake and then condense back to ice in the center leading to a more spherical and granular shape.

Though it takes only a season for firn to form, the complete transition to ice may take many more. The physical blunting and melting processes continue, making the grains denser and larger until they freeze together along with small air bubbles. The whole process can take as long as a thousand years or as short as a single season. A plentiful supply of melt water, rain, and freezing temperatures contribute to rapid densification of snow on Blue Glacier.

LEFT: CHICKEN IN FIRN | ABOVE: CONSOLIDATED FIRN IN THE LOWER GLACIER

why is ice blue?

Almost all glacier travelers have stared with awe into the brilliant blue depths of an open crevasse. The bright white snow of the surface is a marked contrast to the deep rich blue inside a glacier. But why is ice blue?

Snow is white because full spectrum, or white, light is scattered and reflected at the boundary between ice and air. The white color of bubbles at the top of a dark beer work the same way—small pockets of air reflect and scatter visible light. Ice only appears blue when it is sufficiently consolidated that bubbles do not interfere with the passage of light. Without the scattering effect of air bubbles, light can penetrate ice undisturbed. In ice, the absorption of light at the red end of the spectrum is six times greater than at the blue end. Thus the deeper light energy travels, the more photons from the red end of the spectrum it loses along the way. Two meters into the glacier, most of the reds are dead. A lack of reflected red wavelengths produces the color blue in the human eye.

RIGHT: LIGHT ATTENUATION IN A DEEP CREVASSE

ablation

Blue Glacier set an ablation record on a summer day when it was cooler than normal at 8°C with low thin clouds and fog, occasional showers, and a strong west wind. Glaciologists use the term ablation to describe the loss of material from a glacier through processes such as melting, evaporation, or calving. Sunshine is a highly effective means of melting snow and ice, but warm, wet, and windy weather can also quickly melt a glacier.

Both intensifying and reducing forces are always involved with solar radiation. For example, a dense cloud cover will reduce the amount of radiation reaching the snow but a thin layer of fog or clouds will actually increase melting. The incoming solar radiation bounces off the snow due to its high albedo, or reflectivity, and then is reflected again off the cloud layer. Solar radiation does not necessarily change snow to water, however. Often snow and ice evaporate directly into water vapor through a process called sublimation.

Water, through rain, condensation, or a supraglacial stream, is also an active means of ablation due to its high specific heat. A drop of rain just above freezing, or vapor condensing to the liquid state, contains enough heat energy to melt a significant amount of snow.

A thin layer of cold air, at or below freezing, insulates the glacier. Wind can disturb this layer so that it mixes with warmer air from above. The new air molecules on the glacier surface must lose their water vapor—condense—and in so doing cause melting. A glacier often creates its own wind. A katabatic wind forms when air cools over the ice surface and becomes heavier than the surrounding air. This cold mass sinks, flowing down slope or following a valley.

In order of importance, solar radiation, surface water, and vapor condensation cause ablation on Blue Glacier. Annually, the average melt is equal to a layer of water three to four meters thick over the entire glacier surface—roughly 4.5 billion gallons.

ABOVE: THE SUMMIT OF MOUNT OLYMPUS | RIGHT: SURFACE MELT WATER AND SLUSH

If you were thirsty or wanted to take a quick swim, the best spot on the glacier is at the transition between firn and ice. On Blue Glacier this is below the icefall about halfway down the lower glacier. As snow melts, water percolates through the permeable firn grains down into the glacier until it reaches the impermeable surface of the ice. This horizontal seal forces the melt water to flow sideways, down slope, until it surfaces where there is no firn to conceal it. If you were walking down from the col onto the lower glacier late in the afternoon you would witness a progression from dry snow, to slush, to a snow swamp, and then finally a network of supraglacial streams in the ice.

In the snow swamp, little streamlets combine to form large smooth-walled surface streams. These cut narrow sinuous channels down into the ice often incorporating existing crevasses or melt holes. Some stream channels on Blue Glacier are two or three meters deep yet only half a meter wide while others are broad and shallow. Though their length is short—streams usually disappear into a crack or moulin within 100 meters of becoming established—they are often relatively permanent features and remain in the same place during multiple ablation seasons.

water

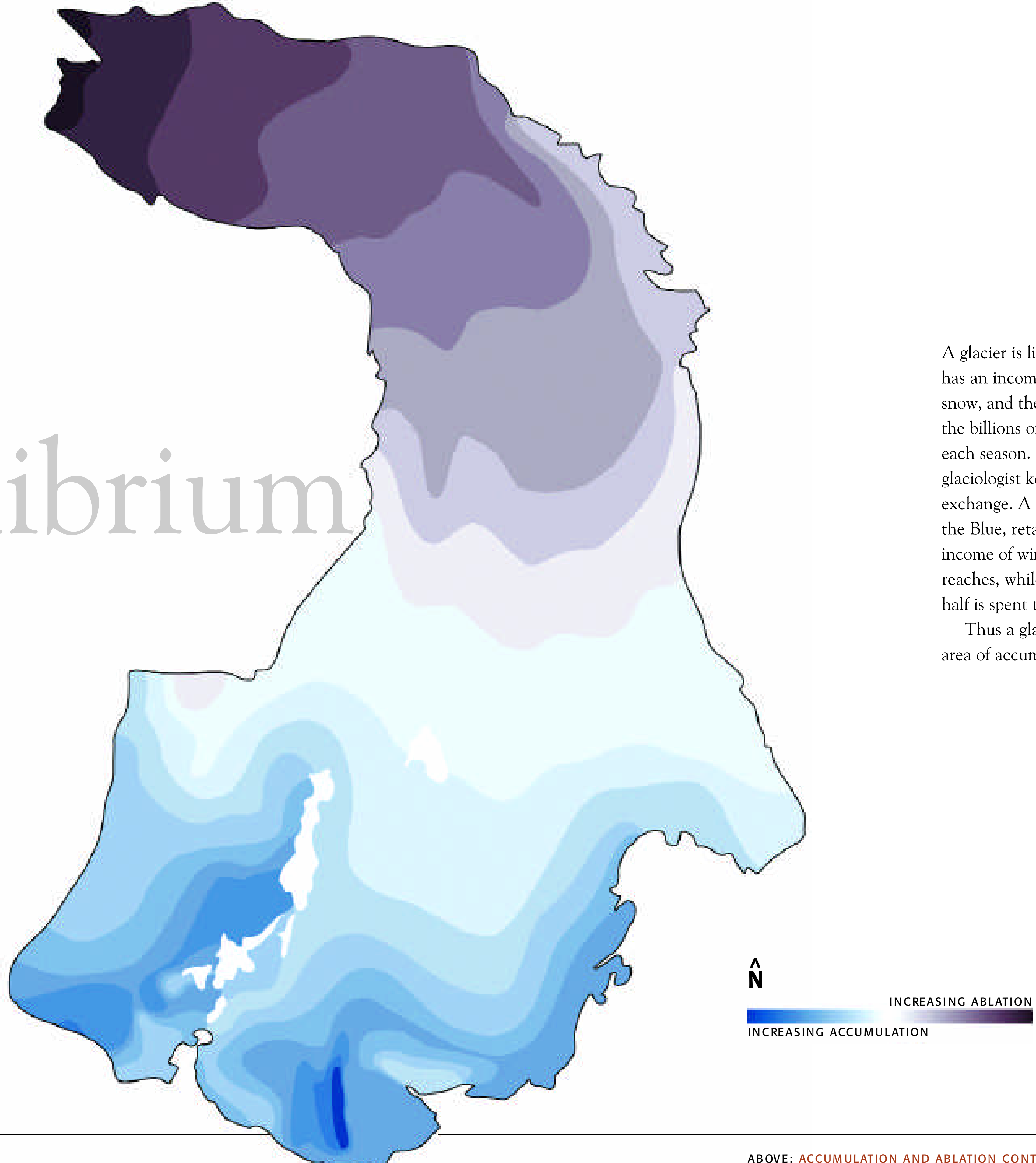
LEFT: SURFACE STREAM

moulin

One can usually hear the deep rumble of a moulin before seeing it. The surface water disappearing into the black abyss of a moulin may drop vertically for 10 to 20 meters before connecting to a complex internal plumbing system. Englacial channels are largest where the glacier is thinnest, such as the sides or near the terminus. Streams may flow directly towards the terminus, or pond up in underground lakes where water may be stored for a few hours or a thousand years. Movement of the glacier, and the ability of a fast flowing stream to cut through the ice, causes the glacier's plumbing system to be constantly rerouted. Most of the moulins on Blue Glacier are relatively small with a maximum diameter of three meters. Nevertheless, falling into one would likely be a permanent affair.

ABOVE AND LEFT: WATER CASCADING INTO A MOULIN

equilibrium

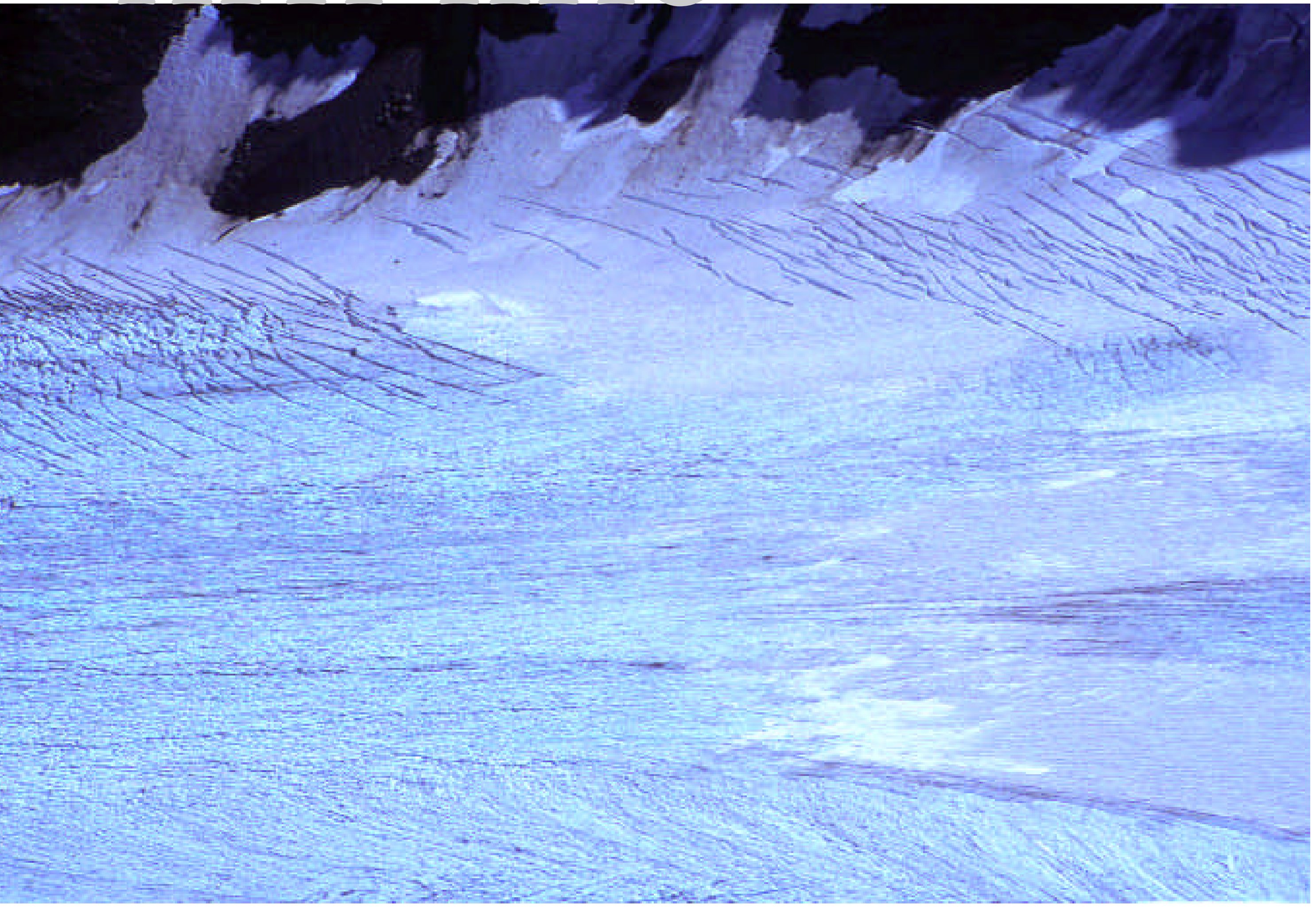


A glacier is like a checking account. It has an income in the form of new snow, and there are expenditures in the billions of gallons of water it loses each season. Like a good accountant, a glaciologist keeps track of this exchange. A healthy glacier, such as the Blue, retains a large fraction of its income of winter snow on the upper reaches, while the snow on the lower half is spent through yearly melting.

Thus a glacier has two zones: the area of accumulation where snow is retained, and the ablation area where more ice melts than accumulates. The boundary between these two zones is called the equilibrium line and is usually measured in altitude. Glaciologists can quantify the health of a glacier by calculating the ratio between the area of accumulation and the entire glacier surface. The higher the ratio, or the more accumulation, the healthier the glacier. Unfortunately, you cannot see the equilibrium line on a glacier—its is something that must be computed.

ABOVE: ACCUMULATION AND ABLATION CONTOURS; INTERVALS REPRESENT A HALF-METER OF WATER. ADAPTED FROM LACHAPELLE 1960.

firn line



Late in the summer a climber can see at least two distinct lines on the glacier: the snow line, and also, a few meters down slope and a little darker in color, the previous year's snow line known as the firn line. The brighter blue below the firn line is bare ice. On Blue Glacier the snow line is usually around 1675 meters, just below the base of the icefall. At the end of the summer, the snow line may lie above or below the firn line depending on the severity of the current ablation season. If the snow line is below and obscuring the firn line, the glacier is growing, because accumulation is greater than ablation. On Blue Glacier the firn limit is exposed indicating that either expenses exceed income or the glacier is in equilibrium.

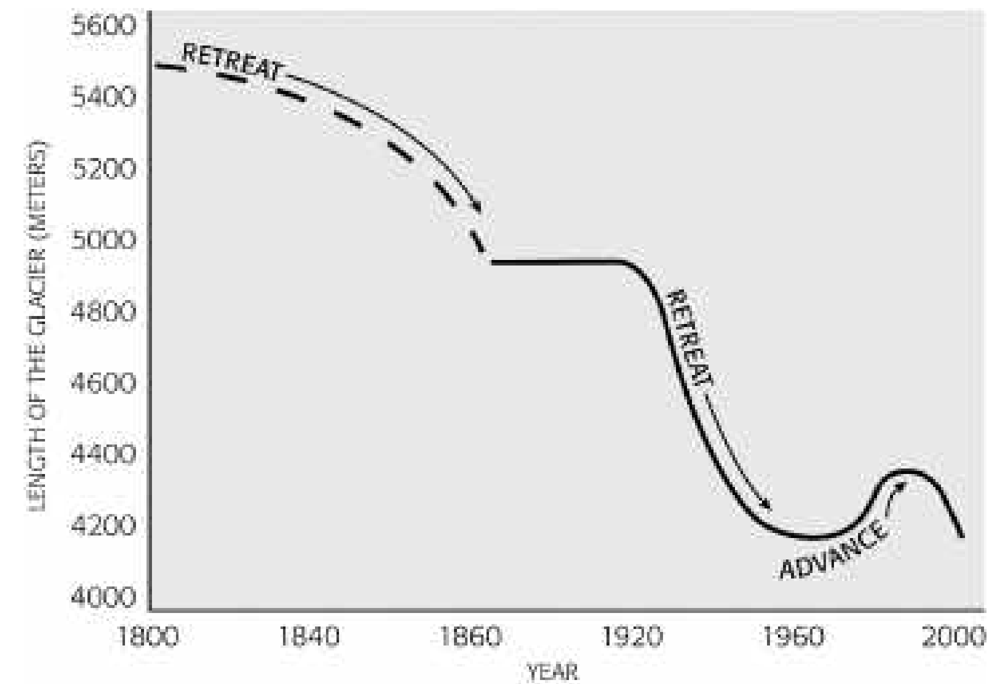
Because a new firn line is created annually and the glacier is flowing, a succession of firn lines—usually darkening in color—are visible in the ablation zone. These layers look like topographic lines on a map and are made more visible by the dust and debris that collect on the surface. When viewed in cross-section, on the wall of a crevasse for example, each firn line becomes a horizontal band known as an ablation horizon. Each band represents one year's accumulation similar to the growth rings in a tree. If a summer season is extremely hot, multiple ablation horizons may melt away. A break in the record occurs as new snow lands on a much older ablation horizon and takes the place of the missing layers. This gap in deposition is known as an unconformity.

ABOVE: THE FIRN LIMIT | RIGHT: ABLATION HORIZONS

mass balance

Glaciers have a story to tell. The accumulation and ablation a glacier experiences describe the mass balance, or the yearly growth or shrinkage, of the glacier. Glaciologists spend weeks tromping around the ice each summer and examining aerial photographs to keep track of the final yearly firn line and the equilibrium line altitude. By recording the yearly mass balance of a glacier, scientists can actually trace changes in climate. If a glacier has a positive mass balance it is growing and the weather is cold and wet. The balance is negative when the climate is dry and warm. Thus the health of a glacier is highly sensitive to local and global changes in climate.

Keeping track of glacial movement was not always so sophisticated. In the early 1900's, park rangers used red paint to mark the location of Blue



Glacier's terminus on a rock wall. Until covered by the advancing ice, this crude measurement technique did record variations in the glacier, but scientists now know that advance or retreat does not necessarily reflect the mass balance of a glacier. Movement of the terminus usually accompanies prolonged changes in mass balance, but a short succession of dry years, for example, may not cause the glacier terminus to recede.

The last 50 years of the mass balance story for Blue Glacier is remarkably boring when compared to earlier times. The glacier reached its farthest and lowest position known around 1650. A second maximum occurred 165 years later in 1815. Both early explorers in the area and local Hoh legend recount hearing large explosions coming from a second, and now extinct, icefall. Though now only a rock cliff below the snout, the glacier cascaded down a nearly vertical 500-meter high icefall before reaching a terminus. Between 1815 and 1960, the glacier retreated an estimated 1650 meters up this slope and then remained near this point for about 40 years. Since 1976, however, the mass balance has become increasingly negative and the glacier is now considered to be out of equilibrium with the warming climate.

Tracking the recession of a glacier is more significant when human-induced global warming is causing the retreat. National Weather Service data indicate that average winter temperatures in the Olympic Mountains have increased by 3.3°C since 1948—a rate about five times higher than the global average. Paint is unnecessary when you can almost watch a glacier disappear.

ABOVE: THE GLACIER'S RECEEDING TERMINUS | RIGHT: THE VARIATION IN BLUE GLACIER'S LENGTH PLOTTED AGAINST TIME, ADAPTED FROM SPICER 1989

Though not particularly exciting to watch, Blue Glacier is always flowing. The snow a glacier receives in the accumulation zone constantly adds mass at the head. Because a glacier is a single sheet of ice, gravity forces this weight to flow down slope until it melts from the relatively warmer conditions at a lower elevation. Ablation at the bottom also allows more ice to flow down to replace what melted. The more accumulation a glacier receives at its head, the faster it flows and the more melting occurs.

Blue Glacier is about 100 meters thick on average and moves quickly. In the accumulation zone and near the terminus the glacier moves about 20 meters a year. Within the icefall the speed is much greater and can reach 300 meters per year, or three centimeters in an hour at full throttle. This speed is unrelated to whether the glacier is advancing or retreating—even when the terminus appears to move back up the valley the ice still flows downstream to remain in equilibrium.

The general movement of ice down the valley can be divided into two types of flow: extending and compressing flow. Extending flow occurs at the top of an icefall when the ice pours down a steep slope without resistance. Compressing flow occurs at the base of the icefall where the speed of the ice decreases and the glacier flattens out. To stay in equilibrium, the ice from above must push the lower ice down the valley, compressing it like a bulldozer. In general, extending flow is found in the accumulation zone, compressing flow in the ablation zone.

flow

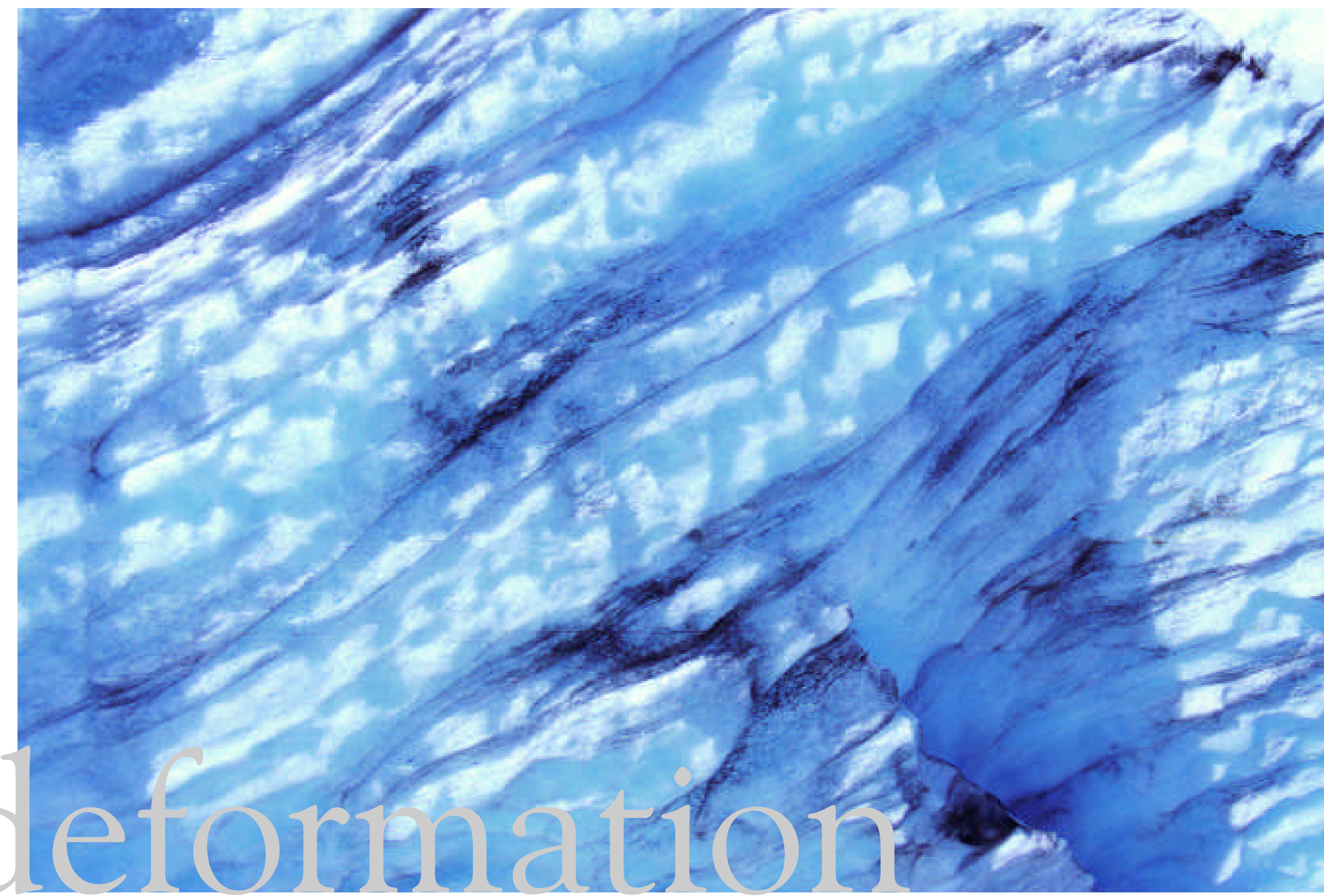
LEFT: EXTENDING FLOW IN THE ICEFALL | RIGHT: COMPRESSING FLOW IN THE LOWER GLACIER

basal slip

On Blue Glacier the physical movement of flow occurs by internal deformation and basal slip. Imagine an aluminum pipe inserted into a hole drilled from the surface to the rock in the middle of the lower Blue. In only a year's time, the pipe would be both curved and a few meters farther down the glacier. The transport of the pipe is caused by basal slip, the curve by internal flow. In fact, one can find the remains of such pipe experiments scattered around the lower glacier.

Basal slip, the simple process of ice sliding across rock, accounts for over half of the glacier's movement. Due to the intense pressure at the base of the glacier, a layer of ice a few centimeters thick melts. To slide over the rough and uneven rock surface, this thin layer melts from the high pressure on the up-stream side of an obstacle and then refreezes when the pressure decreases on the down stream side. The rest of the glacier moves as a flexible solid atop this conveyor belt. Less-intense pressure—not enough to cause the ice to melt—creates internal flow as ice deforms under its own weight due to gravity. Deformation is actually the net result of millions of tiny movements in the crystal structure of the ice and is most prolific in thick warm ice under high pressure.

If we were to follow a grain of firn along its travels down glacier, we would notice a distinct path. If our grain fell as snow just above the firn line, it would be in the area of fastest flow, it would stay near the surface, and it would quickly melt as it entered the ablation zone. On the other hand, if our grain landed at the top of the accumulation zone, in the cirque for example, it would be buried by subsequent snowfalls and eventually reach the base of the glacier. The firn grain would travel slowly along the bottom and emerge after a long and difficult trip at the terminus. On Blue Glacier the icefall complicates this flow path, but the principle remains.



deformation

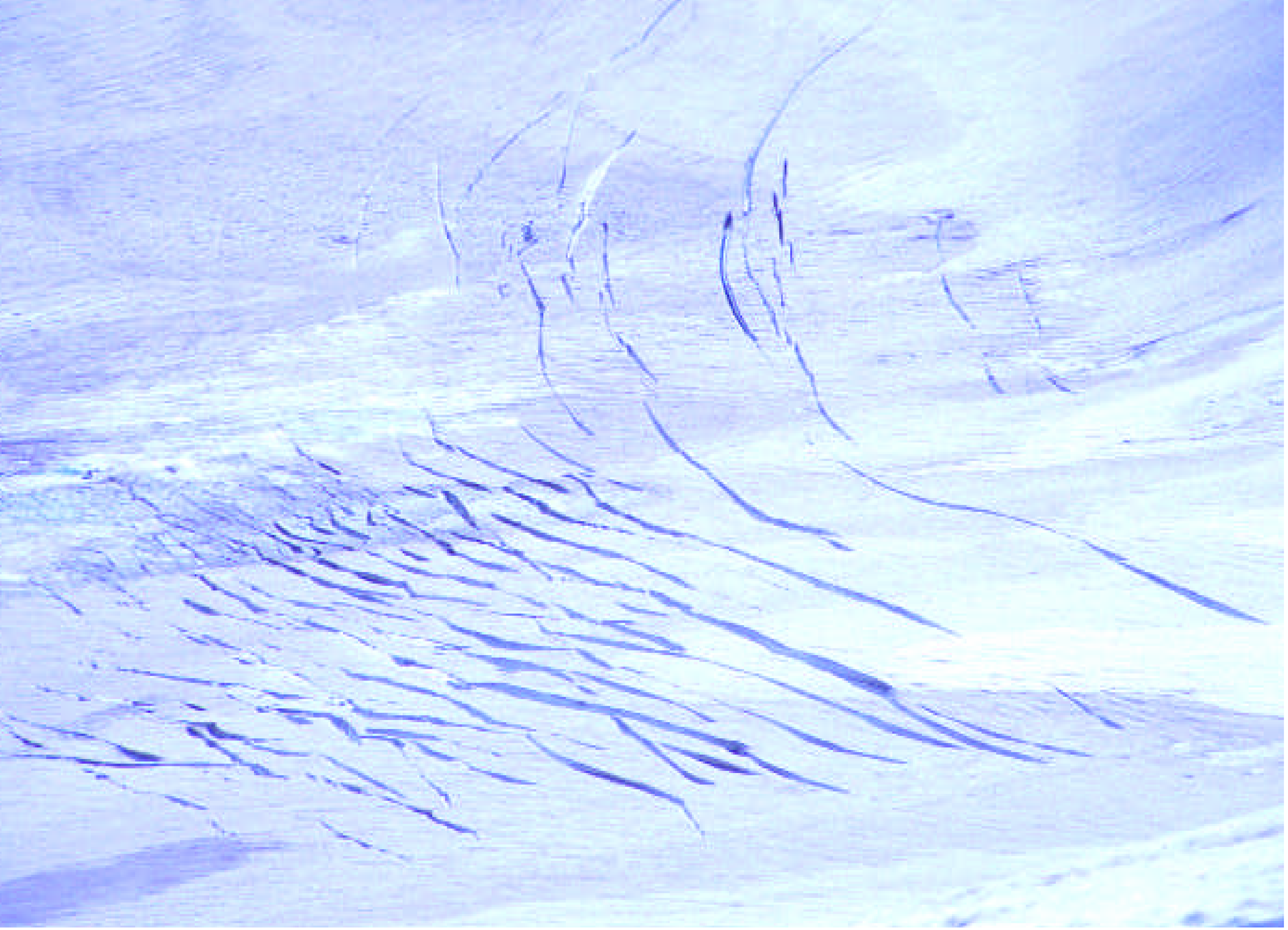
ABOVE: THE SNOW-ROCK CONTACT IN A MOAT | RIGHT: DEFORMED FIRN LAYERS

crevasse

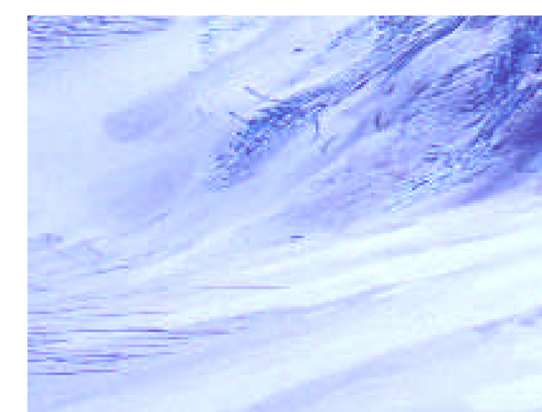
For most mountaineers, the primary goal of glacier travel is not to reach the summit, but rather to not fall in along the way. Crevasses are notorious for swallowing even highly skilled travelers. Yet looking into the abyss of a deep crevasse is also one of the great thrills of glacier travel. A little knowledge in rope rescue techniques and in how crevasses form can help make glacier travel safe.

Crevasses form because the glacier is flowing over a rough uneven surface. Frozen water, as you know, does not easily pour. Thus as the thick sheet of ice moves down the mountain cracks open up in the brittle ice sheet. The depth of these cracks on a glacier like the Blue can reach 30 meters or more while the width can vary from a few centimeters to tens of meters. The main reason crevasses present such a hazard to climbers is that snow bridges often obscure them. Winter snow accumulation regularly covers the openings. As ablation increases, these bridges become thinner and thinner. The most common mountaineering accident occurs when a climber pops through a thin snow bridge into a hidden crevasse. Climbing parties rope up in three or four person teams so that others can stop someone from falling to the bottom.

ABOVE: A FRAGILE SNOW BRIDGE OVER A CREVASSE | RIGHT: A COLLAPSED BRIDGE



The patterns crevasses make on the glacier surface reveal much about the glacier's flow. On Blue Glacier two types of crevasses—transverse and marginal—are easy to recognize. The rows of parallel crevasses pointing up glacier along the edges of the glacier are marginal crevasses. This pattern develops when friction from valley walls actually slows or stops the flow along the edges of the glacier. The ice is also relatively thin in these areas. Transverse crevasses span the width of the glacier and are found anywhere there is active movement. Their concave up glacier shape is due again to the faster center flow. Transverse crevasses are often of great assistance to mountaineers following the standard climbing route on Mount Olympus. In a whiteout they simply travel parallel to the cracks across the glacier towards home. Blue Glacier also features a unique patch of tic-tac-toe crevasses at the base of the icefall. This small spot where sets of parallel cracks run perpendicular to one another is formed by a high spot in the bedrock that the ice must flow over.



patterns

ABOVE: TRANSVERSE AND MARGINAL CREVASSES | RIGHT: THE TIC-TAC-TOE PATTERN

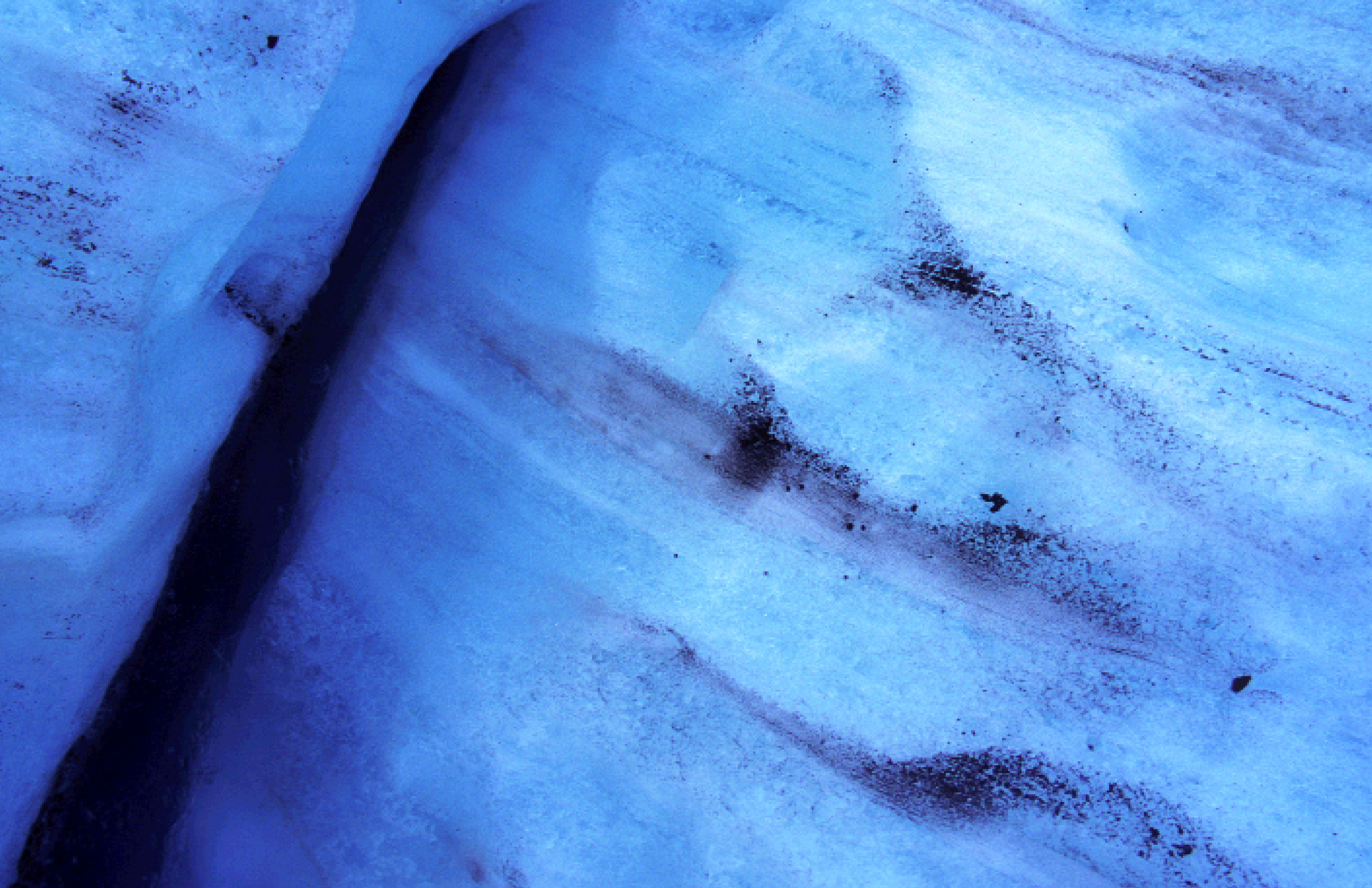
ice streams

Though it is the shortest line to the summit, the 300 meter-high icefall pouring onto the lower Blue Glacier is avoided by even the most seasoned mountaineers. An icefall's movement is not as rapid as the name implies—it is not an avalanche—though by extending flow it does move about 15 times more quickly than the rest of the glacier.

The icefall on Blue Glacier results from the steep gradient of the slope and the confining rock features. A sheet of ice cannot deform quickly enough to smoothly cover such an extreme elevation change and so breaks into crevasses and seracs. It is these towering and unstable blocks of ice that convince climbers to find an alternative route; often large explosive sounds can be heard as house-size chunks of ice break off and collapse. The Khumbu Icefall on Mount Everest is a classic zone of treachery that climbers are forced to traverse.

Blue Glacier has two accumulation zones, the cirque and the snowdome. Each of these feeds the lower glacier and extends all the way to the terminus as a distinct stream. Before forming the lower reaches of the glacier, the two ice streams merge as they pass through the icefall. Consequently this area plays a significant role in shaping the structure of the rest of the glacier.

ABOVE: THE ICEFALL IN THE CIRQUE ICE STREAM | RIGHT: THE SNOWDOME ICE STREAM

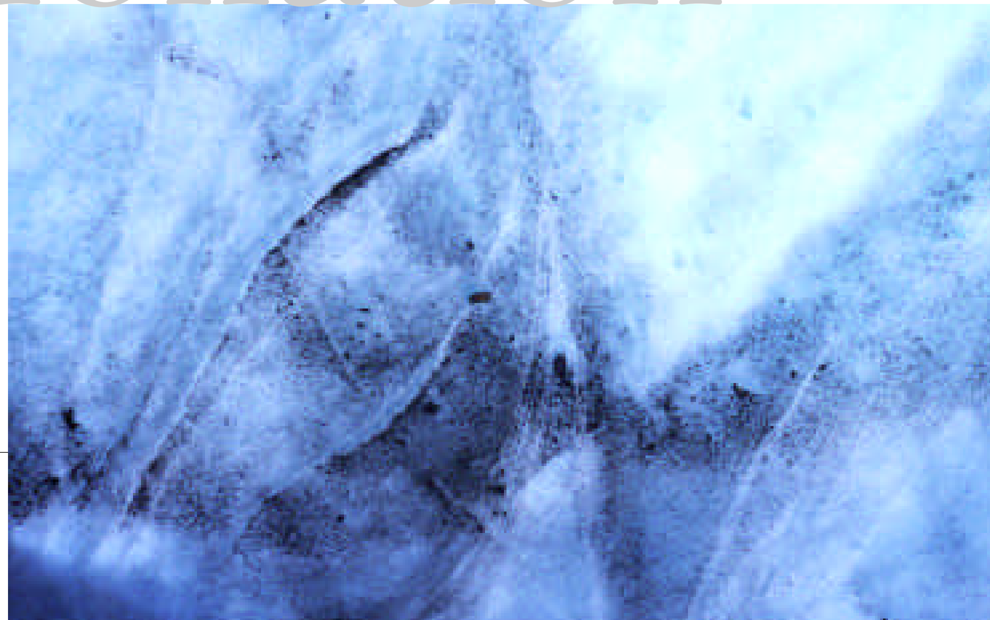


The ice below a fall is under high compressive force. As firn consolidates to ice, the resulting crystal size is determined by factors such as temperature and pressure. Glacier ice on the Blue is classified into three distinct types based on the size of the crystals and the presence of bubbles. Coarse-clear ice is usually bright blue and has large crystals. Coarse-bubbly ice is white and the most common as it makes up 90 to 95% of the lower glacier. Fine ice has small crystals and can be found along the margins and down the center. These ice types can be seen as variations in color in the preceding photograph.

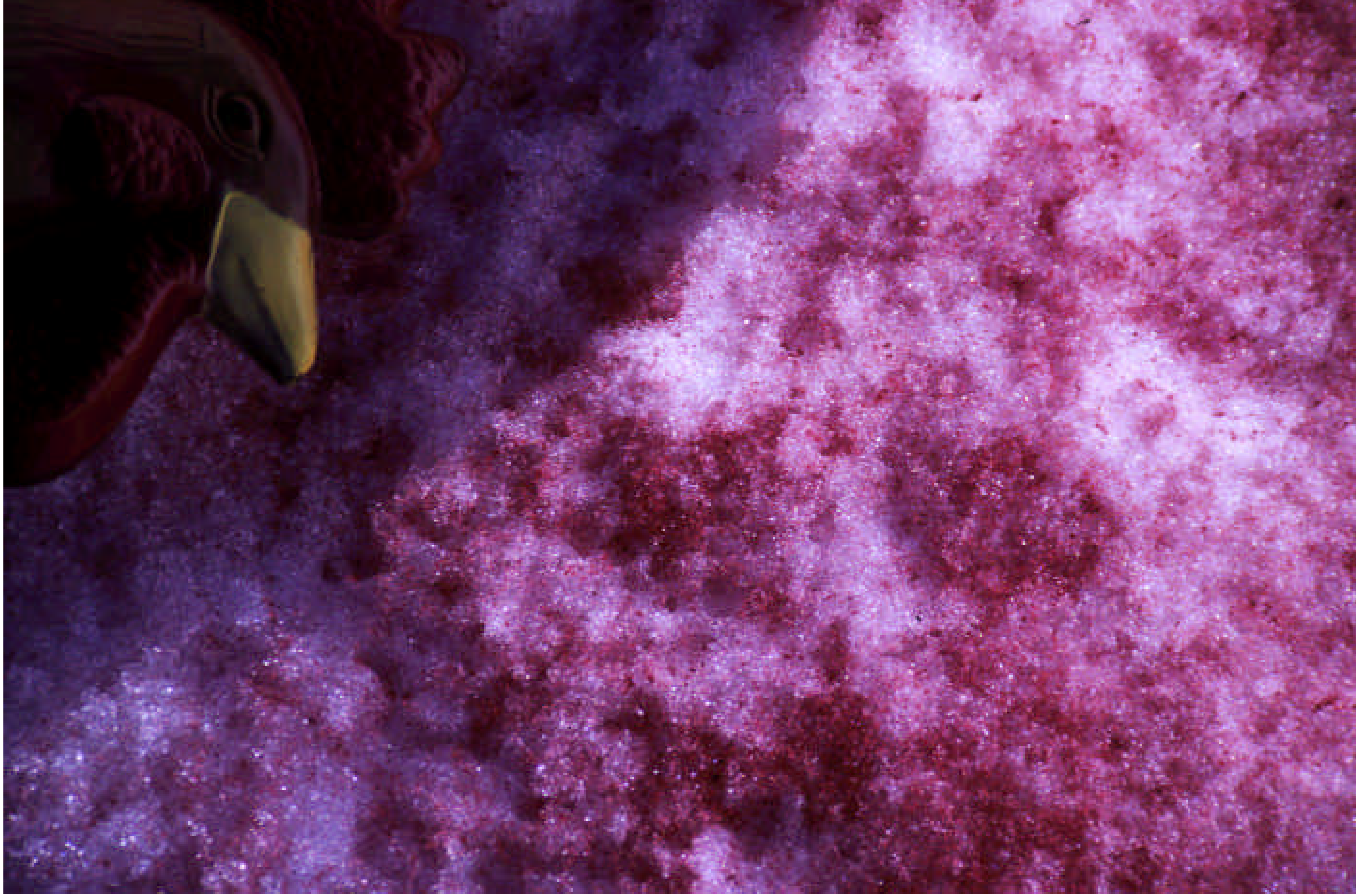
In the icefall the chaos of snow, ice blocks, and rock dust are consolidated and re-crystallized. During this process the three ice types form distinct layers known as foliation bands. (The ability of ice to undergo deformation and re-crystallization causes geologists to consider ice a metamorphic rock because they both behave similarly.) The predominant foliation bands on Blue Glacier are transverse and in the shape of nested spoons cupping up glacier. The two ice streams each have a separate set. Large-scale repetitive foliation patterns that form topographical swells are known as ogives and can be faintly seen below the snowdome.

In other parts of the glacier the foliation patterns are aligned down glacier, or longitudinally. Where the two accumulation zone ice streams are united at the base of a rocky rib in the icefall, intense horizontal compression between the two flows forms what is called a longitudinal septum (See page 11). About 80 meters wide and extending vertically throughout the ice, this band of longitudinal foliation forms a foliation divide or center spine in the lower glacier. The predominantly fine ice found here is slightly dirtied as it contacts the rock in the fall, leaving a faint dark line marking the septum all the way to the terminus. Longitudinal foliation also occurs along the glacier margin from the intense pressure difference between stationary valley walls and flowing ice.

foliation



OVERLEAF: FOLIATION MARKED BY VARYING ICE TYPE | ABOVE: LONG FOLIATION BANDS | RIGHT: COMPRESSED AND DEFORMED FIRN



Nicknamed watermelon snow by many climbers, the red patches in spring snow are actually one step in the life-cycle of green algae. *Chlamydomonas nivalis* has a red pigment in its cyst stage to protect it from harsh sunlight. Each year the cysts are buried under new snow. When the snow starts to melt in the spring, the cysts burst and release single cells with whip like tails. The cells must swim upwards through the melt water and reach sunlight where they photosynthesize and reproduce. Every spring huge colonies of these algae thrive in the ablation melt waters on Blue Glacier. Different species of algae are responsible for red, green, and orange tinting in snow. Yellow snow is from something else.

algae

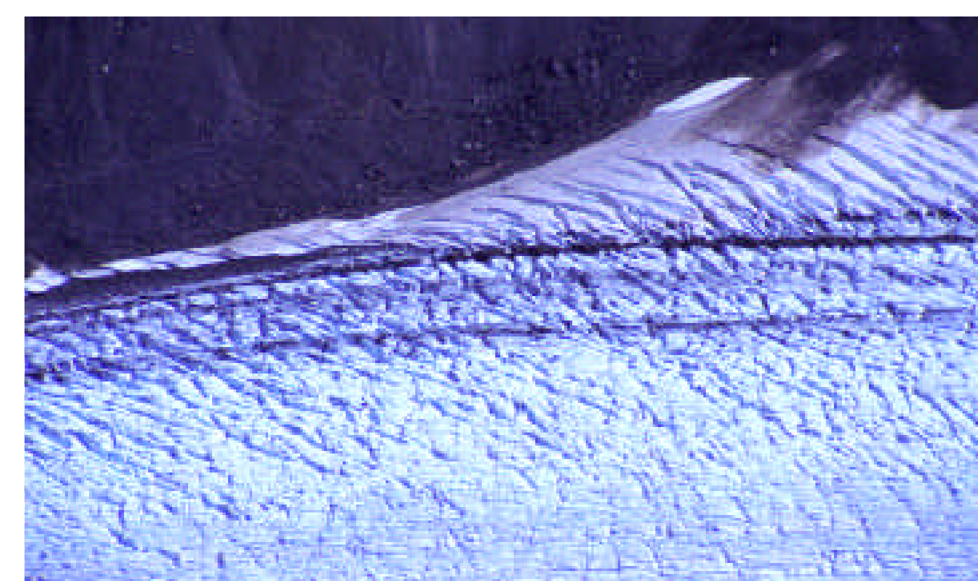
ABOVE: WATERMELON SNOW ON THE SNOWDOME

moraines

Glaciers have a garbage problem. Bits of rock, ranging in size from powdery glacier flour to large boulders, are carved from the valley floor and walls by the flowing ice and deposited as moraines along the edges and on top of the glacier. Glacial till is the name for this unsorted mix of clay, silt, sand, gravel, and boulders.

Moraines are named after their location; a collection of debris at the snout of a glacier is called a terminal moraine. Blue Glacier has deposited most of the debris collected up glacier in a 50-meter high lateral moraine that follows nearly 900 meters of the right flank. This monstrosity was likely deposited over a number of separate glacial advances when the thickness of the ice was much greater.

A second type of moraine found on the Blue is a medial moraine. Here, debris is deposited on top of the glacier's surface. Medial moraines originate when an ice stream picks up rock from an outcrop and carries it into the body of the glacier. Some years a medial moraine marks the longitudinal septum. Two medial moraine ribbons run parallel to the glacier's right margin.



LEFT: DEBRIS ACCUMULATING ALONG THE EDGE OF THE GLACIER | ABOVE: THE OLD LATERAL MORAINE | RIGHT: MEDIAL MORAINES

dirt

Glacial till has a lower albedo than the surrounding white snow and thus absorbs more solar radiation. Debris on the ice can both insulate and melt. A thick blanket of sand and rock will prevent any sunlight from contacting the ice, keeping the glacier surface in the dark and frozen. On the other hand, any exposed snow next to a rock face or surrounding a small pebble will melt from the warmth given off by the absorbing body. A large rock face, for example, will melt the nearby snow creating a large and undercut moat. The transition from snow to a rock outcrop may not look hazardous but moats have a reputation for swallowing climbers just like crevasses.

LEFT: AN UNDERCUT MOAT | ABOVE: AN INSULATING BLANKET OF DEBRIS

The solar radiation absorbed by a small pebble or grain of sand will have a much different effect. A small pebble will melt the snow around its perimeter and this water will eventually wash it and other fine dust particles, or cryoconite, into small clots. These larger aggregations of rock debris absorb more solar energy and gradually bore holes into the ice known as cryoconite holes or dust wells that can reach bathtub proportions.

If you were to kick these dirt ridges with your boot you would find that you could not scatter them like piles of dirt. Rather, your toes would come in contact with a much more painful debris covered cone of ice. A dirt cone, as they are called, is actually an inverted crevasse, puddle or moulin. These ones are from an old crevasse—notice their linear alignment. They form when debris accumulates in a dust well or cryoconite hole in a zone of high ablation. Gradually, as more and more material accumulates and the surrounding ice melts away, the two to three centimeter thick coating of dirt insulates the ice underneath. The top of the cone marks the bottom of the original depression. Dirt cones demonstrate the astounding ability of debris to both insulate and melt ice.

dirt cones

LEFT: A CRYOCONITE POOL | ABOVE: DIRT CONES | RIGHT: THE ICE CORE OF A CONE

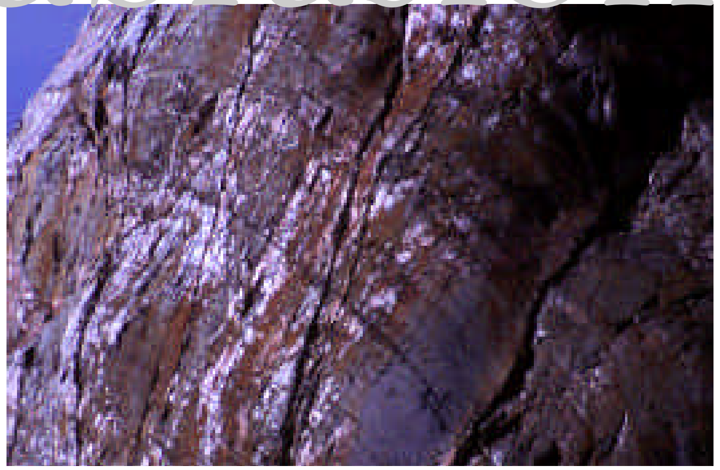
Glacier tables are formed when large chunks of rock become perched on the ice surface. As it slowly rides down the valley with the ice, the rock protects the snow beneath it from solar radiation. Gradually the surrounding snow melts away leaving the rock perched on a pillar of snow. In the northern latitudes the tables tilt towards the south where ablation is the highest. Eventually the table will slide off its base and begin the process again.

Some rock bits are ground so extremely fine that they can remain suspended in water. These particles are nicknamed glacial milk as it colors the water a milky gray. The Hoh River that transports the Blue Glacier's melt water is chalky gray from all the ground rock.

glacier table

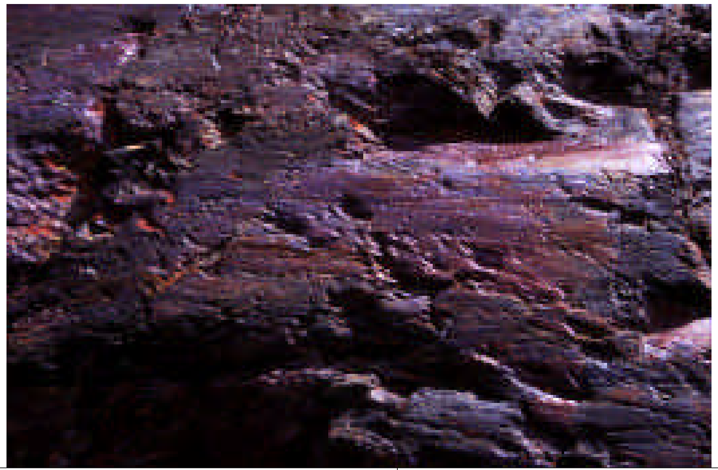
ABOVE: A SOUTHWARD-TIPPING GLACIER TABLE

abrasion



Glaciers are famous stone carvers. Around eight percent of the world's surface has experienced some aspect of glacial erosion. The three most common types of evidence of past glacial activity are smooth U-shaped valleys, deposits of till and outwash, and glacial grooves cut into a rock.

Along the edges of Blue Glacier one can find evidence of an older and bigger glacial past. Deep striations parallel to the direction of glacier flow cover the valley walls. At one time these surfaces were beneath the glacier and heavily abraded. Similar to coarse sandpaper, the rocks caught in the flowing ice sheet ground down the bedrock surface. The type of mark left depends on the rock and mineral particles at the ice-rock interface. Large angular fragments of a hard mineral such as quartz will carve a deep and continuous groove. Smaller particles, on the other hand, will polish the rock smooth rather than striate it. Most often, such as in the marks shown here, a random assortment of materials leave a complex variety of striations. Though the rate of erosion is slow, the process of abrasion is continual and over hundreds of years can profoundly alter the landscape.

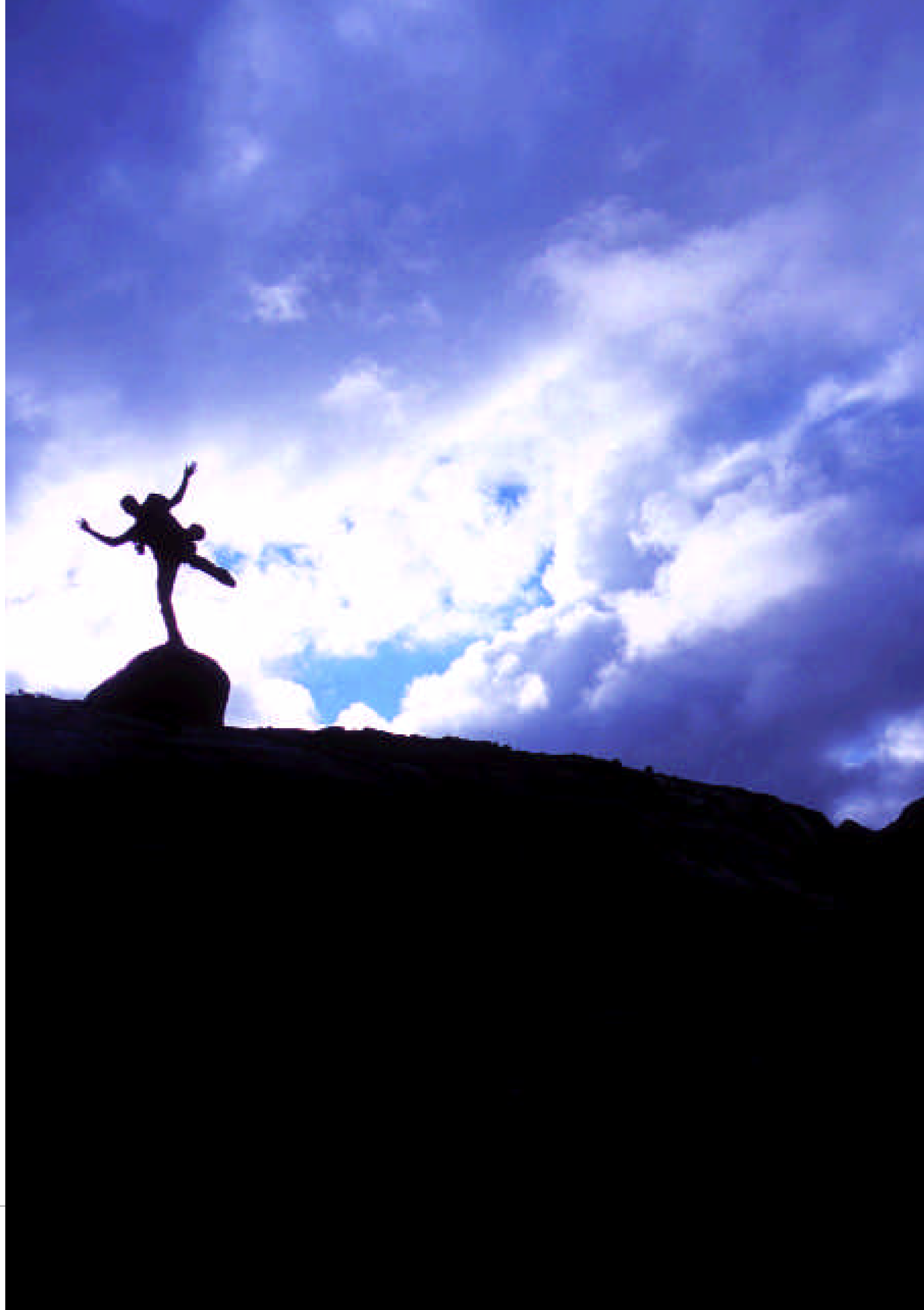


LEFT: ROCK OUTCROP ROUNDED FROM ABRASION | RIGHT: CLOSE-UP OF STRIATIONS AND POLISHING ON ROCK SURFACE

trim line

Another way a glacier will erode material is a process called plucking. Instead of slowly grinding the valley rock down, a glacier will simply break off a large chunk. Melt water can penetrate small cracks or joints in a rock. When the water freezes it expands and breaks the rock free. Small gravel size fragments up to rocks the size of school buses are removed from the glacier floor or valley walls and carried off by the ice.

With such powerful erosional forces, a distinct difference is left between surfaces that have been run over by a glacier and those that were spared. In a valley glacier the horizontal boundary is known as the trim line—everything below having been trimmed by the glacier. On Blue Glacier it's easy to get a sense of the maximum extent of the glacier by the sharp trim line 60 meters above the current surface of the ice.



ABOVE: EDGE OF PAST GLACIAL ACTIVITY | RIGHT: WALKING THE TRIM LINE

ACKNOWLEDGEMENTS
Special thanks to Gay Hunter of Olympic National Park for providing the aerial photograph on page 11. I am grateful for the help of Joel Reid who scrambled around Olympus with me and took the photographs on the title page and pages 6 and 9. Thanks to Tom Drummond for shooting video, tromping 40 miles in plastic boots, and providing fatherly support. Thanks also go to Heather Borkowski for proofing the manuscript and providing four years of geologic sanity. I am grateful to the Carleton Geology Department for funding the photography and Mary Savina, my advisor, for providing free-reign and positive feed back. And finally, a special thanks to Sara Steele for her unwavering support, keen red pen, and bravery on ice.

RIGHT: THE FIFTH MEMBER OF THE CLIMBING TEAM

bibliography

The following list of resources was used in writing *Blue Ice* and is an excellent source of information for the reader who seeks greater depth. Blue Glacier has been the subject of studies by groups from the University of Washington, California Institute of Technology, Ohio State University, United States Geological Survey and the National Park Service. The sources below are a compilation of the primary literature from this research and more general books on glaciology and the Olympic Mountains.

GENERAL GLACIER SOURCES

Glacier Ice by Austin Post and Edward R. LaChapelle, University of Washington Press, Seattle, 1971 and 2000.

The ultimate illustrated guide; this book is valuable to readers of all levels and features gorgeous black and white aerial photographs of glaciers. Recently updated in 2000. This book was a major source of inspiration for the creation of *Blue Ice*.

Living Ice: Understanding Glaciers and Glaciation by Robert Sharp, Cambridge University Press, New York, 1988.

Authoritative and accessible, both glaciology and glacier geology is explained in depth. A good first source.

Exploring the Columbia Icefield by Richard Kucera, High Country Press, Canmore, 1981.

This pamphlet, sold at the visitor center to the Columbia Icefields in Jasper National Park, describes the various geologic processes seen in the park.

Glaciers by Peter Knight, Stanley Thormes Ltd., Cheltenham 1999.

This is the most recent and thorough book on glaciers in this list. A great amount of detail is included, often incorporating mathematics for the advanced reader.

Glacier Glossary by The National Snow and Ice Data Center Glacier and Sue Ferguson, HTTP://NSIDC.ORG/GLACIERS/GLOSSARY/INDEX.HTML

A good easy source for a quick definition of a glacier process. The site is also linked from the *Blue Ice* website.

Glacier Rice University, WWW.GLACIER.RICE.EDU

A general introduction to various glacier and ice topics, this website focuses on Antarctica.

RIGHT: AN EARLY MORNING ICE CUST IN A WATER-FILLED CREVASSE

BLUE GLACIER HUMAN HISTORY

Exploring the Olympic Mountains: Accounts of the Earliest Expeditions by Carsten Lien, The Mountaineers Books, Seattle, 2001.

A comprehensive compilation of journals and newspaper accounts written by and about the early white explorers of the Olympic Mountains.

Tales from the Hoh and Quileute, by A. B. Reagan and L. V. W. Walters, Journal of American Folk-lore, 46 pp 297-346.

Albert Reagan collected the Hoh legend at the beginning of my book between 1905 and 1909 while working as a government agent for the Quileute and Hoh peoples. A number of other legends about the mountain are also in his collection.

RESEARCH AND JOURNAL ARTICLES

A list of the published articles relating to Blue Glacier has been compiled by the Glaciology program at the University of Washington and can be found at HTTP://WWW.GEOPHYS.WASHINGTON.EDU/SURFACE/GLACIOLOGY/PROJECTS/BLUE_GLAC/BIB.HTML. The most general and accessible are listed below.

University of Washington Blue Glacier Project
HTTP://WWW.GEOPHYS.WASHINGTON.EDU/SURFACE/GLACIOLOGY/PROJECTS/BLUE_GLAC/BLUE.HTML

This website provides statistics on Blue Glacier as well as mass balance data. The terminus change graph was adapted from this data.

Allen, C. R., W.B. Kamb, M.F. Meier and R.P. Sharp (1960). "Structure of the lower Blue Glacier, Washington." Journal of Geology 68(68): 601-625.

Detailed description of structural features and patterns in the lower glacier. Excellent aerial photographs and figures of foliation patterns.

Armstrong, R. (1989). "Mass balance history of Blue Glacier, Washington, U.S.A." Oerlemans Journal, Glacier Fluctuations and Climate Change: 183-192.

Good overview of the mass balance changes on Blue Glacier

Heusser, C. (1957). "Variation of Blue, Hoh and White Glaciers during recent centuries." Arctic 10(3): 139-150.

A great source of photos of terminus changes throughout the 1900s.

LaChapelle, E. (1960). The Blue Glacier Project 1959 and 1960. Seattle, Department of Meterology and Climatology, University of Washington.

Now a little outdated, this report chronicles the first two years of monitoring on Blue Glacier. The accumulation figure is adapted from data in this report.

Meier, M. (1974). "Flow of Blue Glacier, Olympic Mountains, Washington, U.S.A." Journal of Glaciology 13(68): 187-212.

A mathematical analyses of flow patterns in the lower glacier. May be difficult for those unfamiliar.

Milius, S. (2000). "Red Snow, Green Snow." Science News 157(21): 328.

Short accessible description of snow algae.

Ramussen, L. A., H. Conway, P.S. Hayes (2000). "The accumulation regime of Blue Glacier, U.S.A. 1914-96." Journal of Glaciology 46(53): 326-334.

This paper attempts to reconstruct the climate on the glacier using precipitation data collected at sea level nearby.

Spicer, R. (1989). "Recent Variations of Blue Glacier, Olympic Mountains, Washington, U.S.A." Arctic and Alpine Research 21(1): 1-21.

Spicer covers the variations of Blue Glacier and the corresponding changes in climate. The article features some of the best aerial photos of the mountain and includes the history of the first explorations. It is both accessible and comprehensive.