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Zach Smith, 2000

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Introduction

What are glaciers?

Glaciers are areas of snow and ice that have accumulated over many years and have at some time "flowed". The snow that falls each winter accumulates in **annual layers.** Similar to the rings of trees, these annual snow layers on a glacier represent one year's growth. As each layer is buried by new snow, the previous annual layers stay largely intact. The annual layers are still distinguishable even after the layers have been compressed and transformed into glacial ice. The thickness of glaciers varies but many exceed thousands of meters thick. To reach that thickness, it takes thousands of years of snow accumulation. The ice in a glacier is very dense, reaching 0.9 grams per centimeter cubed (g/cm^3), slightly more than the density of the ice cubes in your home freezer. The smallest glaciers are a few square kilometers in area and are called **mountain or cirque glaciers**. The largest are hundreds of thousands of square kilometers in area called **ice sheets.** Ice sheets are an assemblage of many smaller glaciers such as those found in Greenland and Antarctica.

Where are glaciers found?

Glaciers can be found anywhere that the **average annual temperature** is sufficiently cool enough to allow snow to last from one winter, through the summer and into the next winter, for many continuous years. Imagine, snowball fights in July! Temperatures are colder at higher latitudes and at higher elevations. One thousand feet of change in elevation is equal to three degrees of change in latitude. So, the climate at higher elevations, near the equator, is similar to the climate at higher latitudes (Figure 1: The Elevations at Which Glaciers Form at Latitudes Around the Earth).

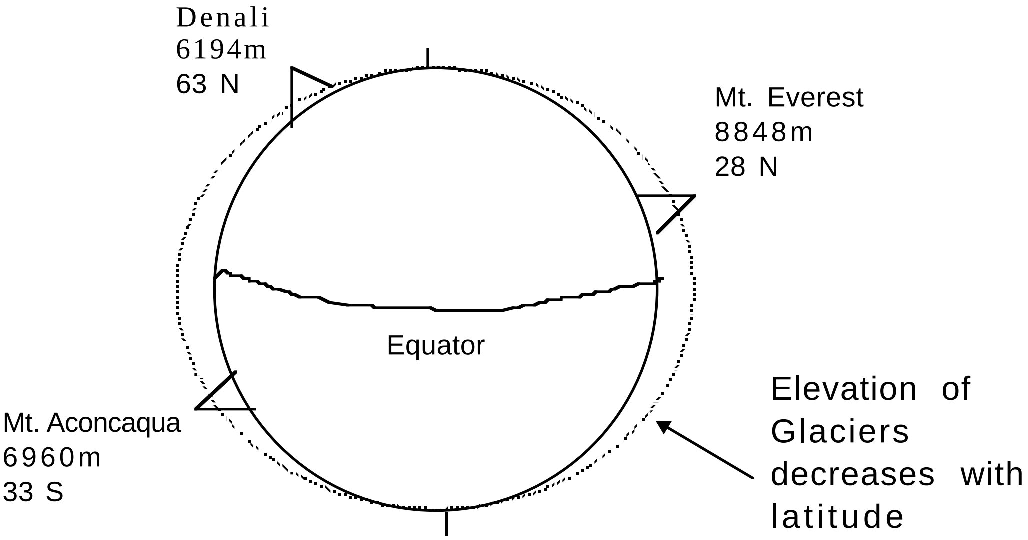


Fig 1: The Elevation at Which Glaciers Form at Latitudes Around the Earth.

Places like the top of Mt. Everest, at 8848 meters and 28 degrees north latitude, have a climate similar to that of the North Pole. The closer you go toward the equator, the higher the mountains must be for glaciers to form. The direction the side of the mountain faces is also important for the formation of glaciers. In the Northern Hemisphere, the sun is always south of the **zenith**, or the point in the sky directly overhead. The directness of the sun's rays to a location on the Earth determines the amount of energy that area receives. The more direct the rays, the more heat energy received. Thus, the northern sides of the mountains receive less solar radiation and heat energy than the southern sides. Glaciers then have a much better chance of forming and surviving on the north, shaded sides of the mountains (Figure 2: Glacier forming on the north side of Donaho Peak, McCarthy, Alaska).

Photo by Z. Smith

Fig 2: Glaciers forming on the north side of Donaho Peak, McCarthy, Alaska.

The prevailing wind direction is another factor important for glacier formation. In the United States, the prevailing winds are the Westerlies, which blow west to east. Remember that winds are named by the direction from which they come. Most or all precipitation is dropped as the clouds push up against the **windward** sides of the mountains. The snow is blown from the windward side to the **leeward** side where it also collects to form small cirque glaciers. Put these two together, shading from the sun and drifting snow, and the north-east sides of high mountains are the best place for glacier formation. Many areas of the world have cirque glaciers such as the Cascade Range in Oregon and Washington State; the Rocky Mountains of Colorado, Wyoming and Montana; the Alps of Europe; and many other parts of Asia. And many icefields can be found in Alaska, Greenland, Russia, and South America.

Who Studies Glaciers?

Glaciers are studied by glaciologists, glacial geologists, meteorologists, geographers, botanists, students, insurance companies, economists, and farmers. Scientists from around the world are doing research on many aspects of glaciers. There are permanent research stations set up on glaciers in Antarctica, Greenland, Alaska, Russia, the Himalayas, and on many other smaller glaciers. (Figure 3: Juneau Icefield Research Program field camp on the Juneau Icefield, Alaska). Research topics at these stations include: the movement of glaciers, thickness of the ice, melt water accumulation, mass balance, and others.

Photo by Z. Smith

Fig 3: Juneau Icefield Research Program field camp on the Juneau Icefield, Alaska.

Why Study Glaciers?

Studying glaciers will not give you the weather forecast for the concert this weekend, but glaciers do contain an excellent historical record of the climate of the Earth. A glacier acts like a “canary in a coal mine” and the glacier’s health serves as an indicator of how the climate of the Earth has changed and is changing. A long time ago, canaries or other birds were carried, by the miners, into the mines as an indicator of the presence of poisonous gas. As long as the birds remained alive, the miners knew that the air did not contain harmful levels of poisonous gas. More knowledge of past climate changes would give scientists a better understanding of how the current climate trends compare to the past. Currently, one of the biggest questions in climate research is how much humans are affecting the climate. Is the Earth getting warmer or colder, and how much of that change is **anthropogenic,** or manmade? And are those changes dangerous to humans? Glaciers help regulate the Earth’s climate, serve as a source of water for farmers, and as a recreation area for outdoor enthusiasts and not only are affected by climate but affect climate change. Glaciers have been identified on other planets and may give us an idea of how the atmosphere and climate on other planets has varied over time. This will be a useful tool in understanding our own planet’s climate.

Glacial History of the Quaternary Period

The Earth’s glacial history goes nearly all the way back to the beginning of the planet. There have been many **glacial periods** (ice ages) in the last 600 million years (Figure 4: Global temperature changes of the Earth’s history).

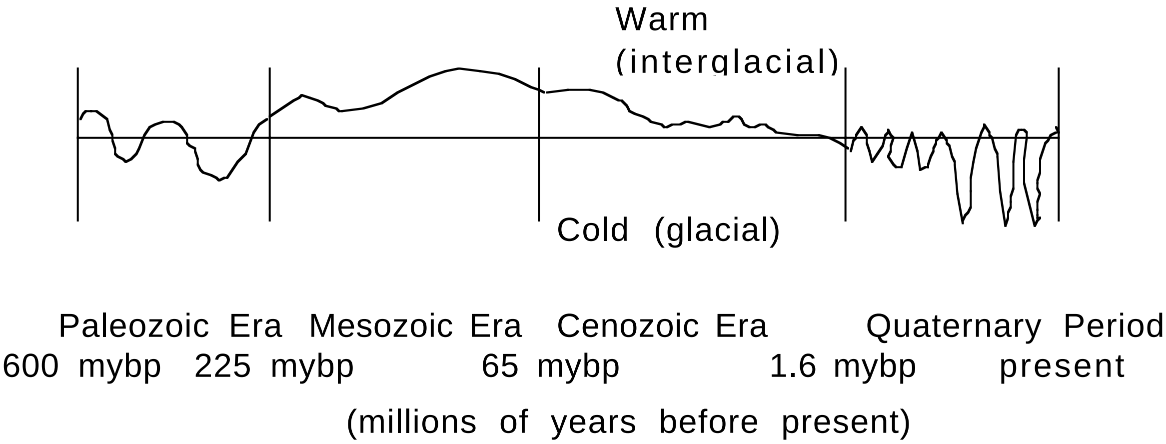


Fig 4: Global Temperature Changes of the Earth’s History.

A glacial period, is a time when glaciers advance from the north and south pole toward the equator. Sea ice also becomes much more abundant, and the average atmospheric temperature of the Earth drops by about 6 degrees Celsius from our present average temperature. Maybe the most important glacial periods, because they are the most recent and we have the most information on them are the glacial periods that have taken place within the last 1.6 million years. That period of time in the geologic lingo is the **Quaternary Period**. Within that time there have been at least seventeen major periods of glaciation (figure 4). The Quaternary period is subdivided into two time periods called **epochs**. One epoch extends from the beginning of the Quaternary to the end of the last glaciation, a period of less than 1.6 million years and is called the **Pleistocene Epoch.** The time after the last glaciation, 10,000 years ago until the present, is known to as the **Holocene Epoch**. It is important to note that geologists talk about time in terms of years from the present back into time, and written as “years before present or ybp”. Since no one was around to “start” the time clock for historical records (even your parents are not that old) we use the present as time zero and count back in time. Thus, 2 million years ago or 2 mybp (million years before present) counts from the present back into time. Before the last glacial period, 110,000 ybp, there was an **interglacial period** (time between glacial periods) with a **climate** similar to the one we have today. That time period was called the **Eemian.** The data from ice cores indicates that interglacial periods have historically lasted about 20,000 years. Scientists are using information from the Eemian to try and understand the Earth's climate in our present Holocene interglacial period, or Holocene epoch. Based on this information, scientists wonder if it suggests that we are less than 10,000 years from our next glacial period?

Throughout time, the climate of the Earth has constantly changed. Sometimes it has changed slowly and sometimes it has changed rapidly. Some rapid changes have taken place during which the Earth has gone from interglacial warm temperatures to glacial cold temperatures, a change of at least 6 degrees Celsius, in as little time as a decade. Evidence suggests that even slower century and millennial scale changes are actually series of stepped rapid change climate events. An example of a cooling event in the recent past, that occurred in less than 70 years, is known as the **Younger Dryas event.** This event started about 12,900 years ago and lasted for approximately 1,400 years. (The Holocene epoch started 11,500 ybp at the end of the Younger Dryas event). The Younger Dryas was a return to glacial conditions around the world. This rapid change in climate seems to have been brought on by many factors. One of those factors may include an ancient glacial lake called **Glacial Lake Agassiz** (Figure 5: Map view sketch of former Glacial Lake Agassiz). Around 13,000 ybp, the water of this glacial lake broke through the ice and debris dams that held it back, and suddenly emptied billions of tons of fresh water, into the St. Lawrence Seaway into the North Atlantic Ocean. The sudden influx of fresh water may have drastically changed the circulation of the ocean currents. As a result, the Earth's climate was changed completely.

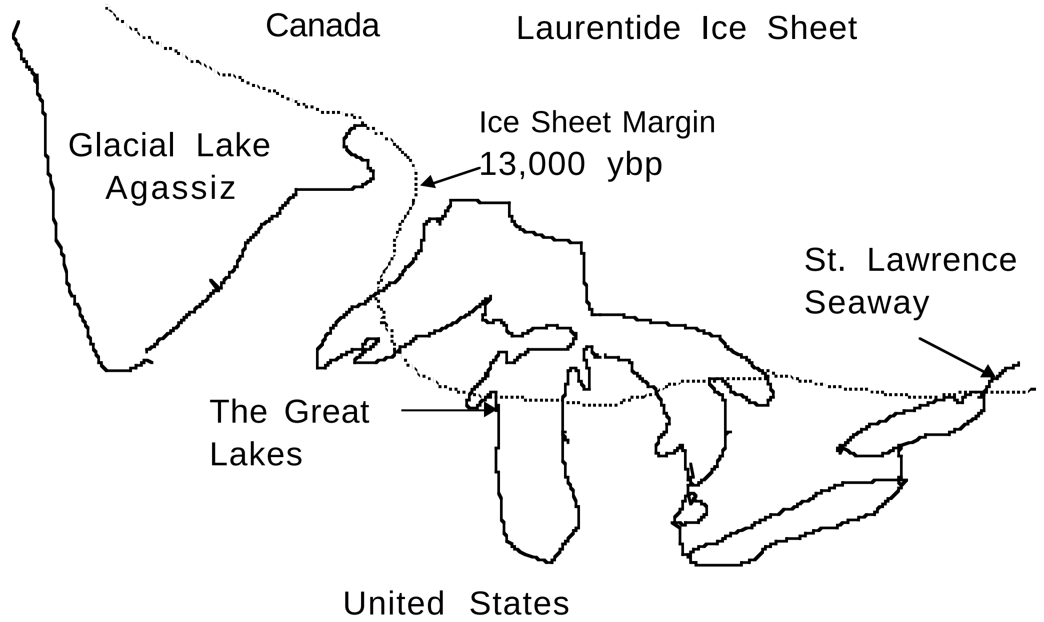


Fig 5: Map view sketch of former Glacial Lake Agassiz.

There have been other times when the climate has changed. During the present warm Holocene period, there were many times with near glacial conditions. The most famous of these took place from the 14th to the 19th centuries when much of the world experienced cooler temperatures and drier conditions. (You might remember from meteorology that it is drier when it is colder. Cold air holds less moisture than warm air). Though not as cold as conditions in the Younger Dryas, the temperature change affected the people of the day. This period is known as the **Little Ice Age**, from 1400 to 1850 AD, and is actually responsible for many new innovations such as tapestry, being used widely in manor houses in Europe to keep out the cold drafts; the installation of chimneys; and the writing of the novel Frankenstein by Mary Shelly while on vacation in the Alps. (Because of the weather, she and her husband were forced to remain indoors and wrote to pass the time). Many periods of time have also experienced warmer than current temperatures such as when climate was at its warmest temperature, called the climate maximum, about 7,000 years ago. At that time, the average world temperature was a few degrees higher than it is today.

It is important to remember that during glacial periods the entire Earth was not covered with ice. Glaciers advanced from the poles as far as 40 degrees north or south latitude and the average climate on Earth was cooler and drier. The drier conditions were due to the cooler temperatures. Temperatures in Greenland may have been as much as 35ºC cooler while temperatures near the equator may have only been 2-3ºC cooler. Large amounts of fresh water on the Earth were also locked up in massive glaciers (about 75% of all the fresh water on Earth is currently locked up in the Antarctic Ice Sheet). During those times, deserts may have been larger, and mid-latitude areas (30 -60 degrees latitude) may have experienced frequent droughts. The reallocation of water from the oceans to the glaciers caused a 300 foot drop in sea levels worldwide which translates into about a 10% increase in the land surface above water just in the United States! From the boardwalk in Atlantic City, New Jersey, you would have to walk almost 300 miles just to get to the ocean for a swim. Surf's out. Kowabunga, Dude!

Glaciology

Formation

Glaciers form when climatic conditions in an area reinforce the existence of ice and snow. Snow falls in many areas of the world when the temperatures are cold enough, but the conditions to form glaciers are more complex. There are six main mechanisms responsible for changing climate and the formation and maintenance of glaciers: solar variability, insolation, dust in the atmosphere, gases in the atmosphere, ocean currents, sea ice, and atmospheric circulation.

Solar Variability

Solar variability is a change in the amount of energy that the sun produces. This solar energy is not constant but varies in regular cycles. Since every physical and chemical process (except plate tectonics) that occurs on

Earth, including the weather, is directly tied into the sun's energy output, any variation in that energy output by the sun affects life here on Earth. A visual example of solar energy output is solar flares. Solar flares are sudden eruptions of hydrogen gas on the sun's surface that are propelled out into space. These flares vary on an 11 year cycle. Solar flares are associated with sunspots because the hydrogen eruptions are actually cooler than the sun's surface and are seen from Earth as dark spots on the sun. Auroras are also associated with solar flares as the erupted energy interferes with the Earth's magnetic field. Solar variability, though important, is responsible for a much smaller change in the amount of energy received at the Earth's surface than is insolation.

Insolation

Insolation (not insulation) is a measure of the amount of energy, radiating from the sun, that strikes the Earth's surface as a result of the astronomical position of the Earth to the sun. Insolation varies by changing the distance from the sun to the Earth and/or by changing where the most direct rays of the sun fall on the Earth. Remember that the directness of the rays that strike the Earth is more important than the distance between the Earth and the sun. We know that this is true because, in the northern hemisphere, the Earth is closest to the sun during winter. At the same time, the Earth's axis is tilted away from the sun. Currently, the Earth's axis is inclined at 23.5 degrees relative to the ecliptic, or plane of the Earth's orbit around the sun. The opposite is true in summer, in the northern hemisphere, when the Earth is further away from the sun but is tilted toward the sun. The distance from any point on the Earth to the sun varies naturally in three main ways. They are the eccentricity of the orbital path; the amount of inclination of the Earth's axis; and the wobble of the Earth's axis.

Eccentricity

The first way that insolation varies is in the actual path that the Earth takes in its orbit around the sun. In the 16th century it was shown by Johannes Kepler that the orbit around the sun is not a circle but an **ellipse**. Ellipses are characterized by their **eccentricity** or deviation from circularity (Figure 6: Eccentricity of the Earth's revolution around the sun).

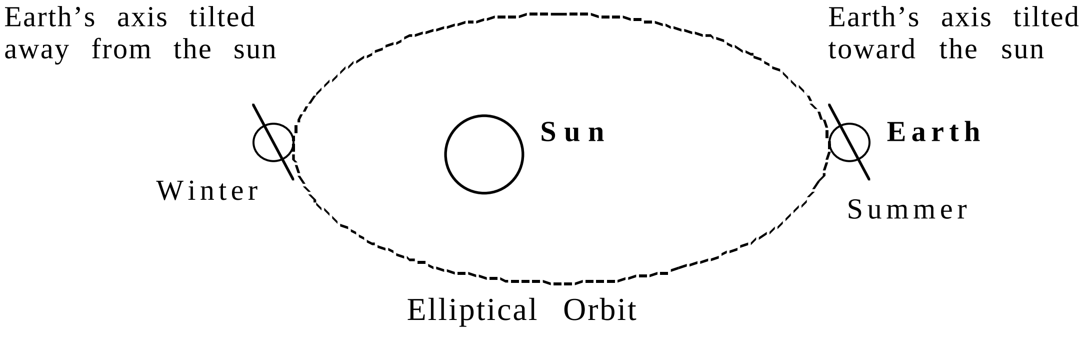


Fig 6: Eccentricity of the Earth's revolution around the sun.

Certainly, you must know a few eccentric people that vary just a little bit "away from center" or act a little different. The eccentricity of the Earth is very slight, 1.7%. So slight that it was unnoticed by scientists until the 16th century. The amount of eccentricity also varies on a 100,000 year cycle, moving slightly (<10% of orbit) closer or further from the sun. It would be very difficult in fact to actually draw a circle, on a piece of paper, that only has a 1.7% eccentricity. Though slight, that eccentricity is enough to change the distance from the sun to the Earth by almost a million miles and changes the amount of heat that reaches the Earth's surface. Since the average distance is only 94 million miles, a 1 million mile change is important. We need to also remember that the distance from the sun to the Earth also changes from winter to summer every year. The average distance between the Earth and the sun, when the axis is titled away from the sun, is 92.5 million miles (winter in the northern hemisphere) and the average distance when the axis is tilted toward the sun is 94.2 million miles (summer in the northern hemisphere). Remembering that it is colder in the northern hemisphere winter, though closer to the sun, note that the angle that the sun's rays hit the Earth are more important than is the distance.

Obliquity

The second way the insolation changes is by the **obliquity** of the Earth. Obliquity is the variation in the tilt of the axis over a 41,000 year cycle. Throughout this 41,000 year cycle, the angle of the axis will vary from its current 23.5 degrees to between 24.4 and 21.8 degrees. This further changes the angle at which the sun's radiation strikes the Earth's surface. A lower angle translates into more direct rays at the equator (Figure 8: Obliquity of the Earth's axis).

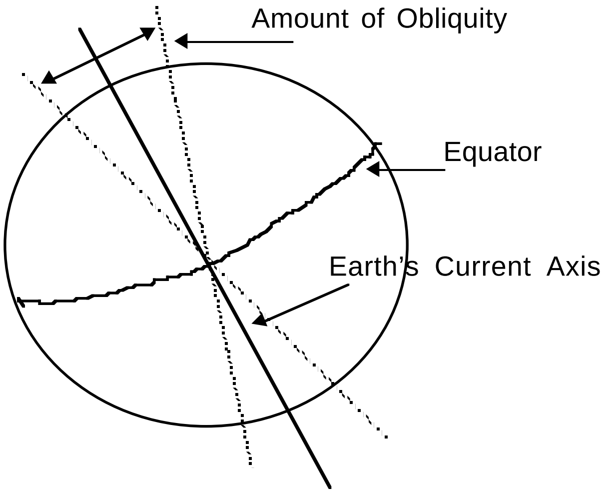


Fig 7: Obliquity of the Earth's axis.

Precession of the axis

This brings us to the third way that insolation can vary called **Precession of the axis.** Precession of the axis actually enhances the first two mechanisms, eccentricity and obliquity. Simply put, as the Earth spins on its axis, it wobbles (Figure 7: Precession of the Earth's axis).

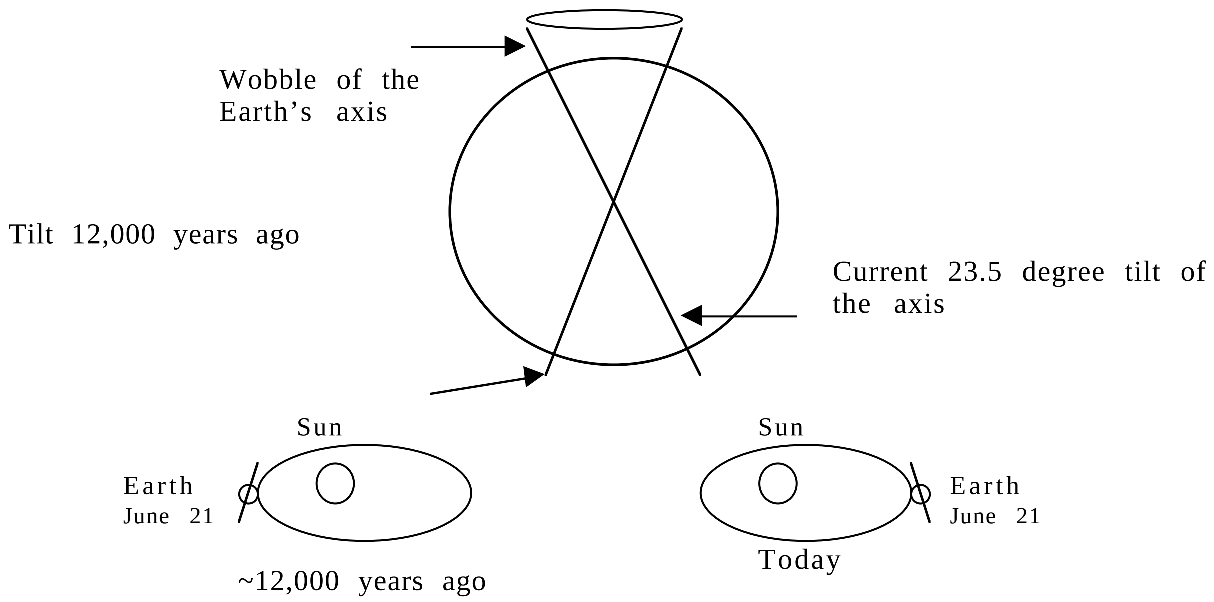


Fig 8: Precession of the Earth's axis.

Think of a top that is running out of energy and starts to wobble. This wobble varies on a 24,000 year cycle. It means that the spot in space that the Earth's axis points towards, currently Polaris the north star, does not remain constant. The path drawn by the pointing of the axis moves in a circle over a 24,000 year period until it returns to the same point. The "north star" that the Greeks knew was not Polaris but in the constellation Draco! Precession of the equinox changes the position of the Earth such that in 12,000 years it will be inclined toward the sun during its closest distance from the sun (summer in the Northern Hemisphere will be warmer) and inclined away from the sun, six months later, when it is farther away (winter in the Northern Hemisphere will be cooler).

Alone, each of these changes in insolation may account for very little change in the energy that the Earth receives from the sun but, when each reach their maximum or minimum at the same time, the change in the amount of energy absorbed can be substantial. Thus, Earth/sun positioning is the mechanism that creates the opportunity for glacial periods to occur reinforcing the existence of ice and snow.

Dust

Dust is considered to be any particle from the Earth's surface that has been carried into the atmosphere. The accumulation of dust in the atmosphere is important because the dust particles reflect incoming solar ultraviolet rays causing cooling of the Earth's surface. These particles may result from wind erosion, volcanic eruptions, or forest fires. Dust particles are carried aloft to the **troposphere**, which is the lowest level of the atmosphere, and may travel two or three times around the Earth before settling out.

Wind-eroded dust

The actual mineral composition of dust can vary just as there are many types of elements in the Earth, but the most common are Aluminum (Al), Calcium (Ca), Sodium (Na), and Silica (Si). Calcium is derived from limestone or calcium carbonate ($CaCO_3$). Limestone is a rock type, formed under the ocean and exposed on the continental shelves during times when sea level is lower (typical during glacial periods). When these areas are exposed and have not acquired a vegetation cover, they are subject to rapid and massive erosion by the wind. Sodium is derived from sodium chloride (NaCl) or sea salt. Winds blow across the ocean, pickup sea water, evaporate the water, and carry the salt into the atmosphere. Silica is typical quartz, as in the quartz sand at the beach. Winds can erode silica dust from most land surfaces, especially deserts and glaciated valleys. Silica and calcium dust are both more plentiful during cold, dry, glacial periods.

Volcanic particles

Two types of particles result from volcanic eruptions. The first type are dust particles that, like wind-eroded dust, are carried into the stratosphere and reflect incoming solar ultraviolet radiation. The second type originates as sulfur dioxide (SO_2) gas. The gas is carried higher into the stratosphere. There the particles are oxidized and become sulfate particles (SO_4). Though physically smaller in size than other types of particles, the sulfate interacts with larger quantities of incoming radiation because it both absorbs and reflects incoming radiation.

Forest fires

Forest fires also add particles to the atmosphere, in the form of ammonium (NH_4), potassium (K) and nitrate (NO_3). These particles also reflect incoming ultraviolet rays but tend to settle out more quickly because they are not carried as high into the atmosphere.

Dust in the atmosphere enhances the formation of glaciers. As the sun's rays enter the atmosphere, dust reflects the ultraviolet radiation. The more dust particles (also SO_4) in the atmosphere the less heat energy that is received at the Earth's surface. The dust layer actually shields the Earth, lowering surface temperatures. Volcanic dust events have been shown to directly precede decreases in global temperatures. For wind-eroded dust, the quantity of dust in the atmosphere is one big feedback loop. The more dust in the atmosphere, the less solar radiation the Earth's surface receives and the colder it gets, the more dust is then made available by lower sea levels. Many large wind-eroded dust events have been identified that correlate directly with global cooling events in a type of chick and egg relationship. But which actually came first, the cooling event or the dust event? What is certain is that once one event starts it is enhanced by the formation of the other.

Gas

Another mechanism responsible for changing climate and glacier growth is the gases in the atmosphere. Some atmospheric gases actually absorb heat and raise the temperature of the atmosphere. Those that raise the temperature are called the Greenhouse Gases. The most significant of these in order of importance for raising temperature are: water vapor (H_2O), carbon dioxide (CO_2), and methane (CH). The more water vapor, the more heat is absorbed. This is also a feedback loop because more heat evaporates more water, and so on and so on. Carbon dioxide has many natural sources in the Earth including respiration of organisms and volcanic explosions. Methane is created by the decomposition of organic material. Methane is largely swamp gas from decomposing vegetation; millions of tons of which are currently held underground. It would seem then, that the warmer the temperature is, the more vegetation there is, and therefore the more rotting vegetation there is, which increases temperature and so on and so on. The addition of methane to the atmosphere is one big positive feed back loop.

Ocean Current Circulation

The entire Earth is affected by the circulation of one long continuous ocean current. This current runs as a deep ocean current from the North Atlantic Ocean to Antarctica and then around Africa and Asia north through the Pacific Ocean. Then the deep ocean current surfaces in the North Pacific and flows as a surface current back down around Africa and Asia north to the North Atlantic Ocean. Here the surface water sinks and connects to the deep ocean current. One complete circulation takes approximately one thousand years. The water sinks in the North Atlantic, known as the **North Atlantic Deep Water (NADW),** because of increased density. The density increases due to a temperature decrease and its high salinity. The decreased temperature occurs because of the lack of solar energy available to continually heat the water at higher latitudes. The temperature of the surface water averages about 10 degrees Celsius. As the warm water from the equator flows north it begins to lose heat to the atmosphere cooling the water. The water in the NADW averages around 3 degrees Celsius. The salinity increase in the North Atlantic occurs because winds blowing across the water evaporate fresh water and leave behind excess salts. This raises the salinity from approximately 34 parts per thousand in the surface water to approximately 35 parts per thousand. This circulation of the deep ocean current is a process known as **Thermohaline Circulation** (Figure 9: Thermohaline circulation pattern). This entire circulation is driven by sinking water in the North Atlantic (NADW). Though the actual circulation pattern is very complicated, the diagram below has been greatly simplified for ease of understanding. This gigantic ocean circulation helps control the climate of the entire Earth. It has been shown that any disruption to this circulation disrupts climate. One theory suggests that about 12,000 years ago glacial Lake Agassiz emptied into the North Atlantic Ocean it added fresh water to the sea water decreasing its salinity and therefore density. Because of this change in density, the sea water in the north Atlantic may have stopped sinking. When the density changed and the sinking stopped, the Earth was thrown back into a glacial age in less than a few decades. Any other modification to sea water circulation by density changes due to evaporation, adding sudden mass quantities of fresh water, or through sea ice blocking the flow of surface waters can sometimes result in extreme changes in worldwide temperatures. The thermohaline circulation may also be responsible for spreading any climate changes throughout the entire planet. Insolation changes that have taken place in the past have largely affected the Northern Hemisphere, though evidence shows that climate changes in the Southern Hemisphere, as evidenced from glacier activity, have occurred at roughly the same time. If insolation is the engine that drives dramatic global climate changes, then thermohaline circulation may be the mechanism that distributes temperature changes throughout the entire Earth.

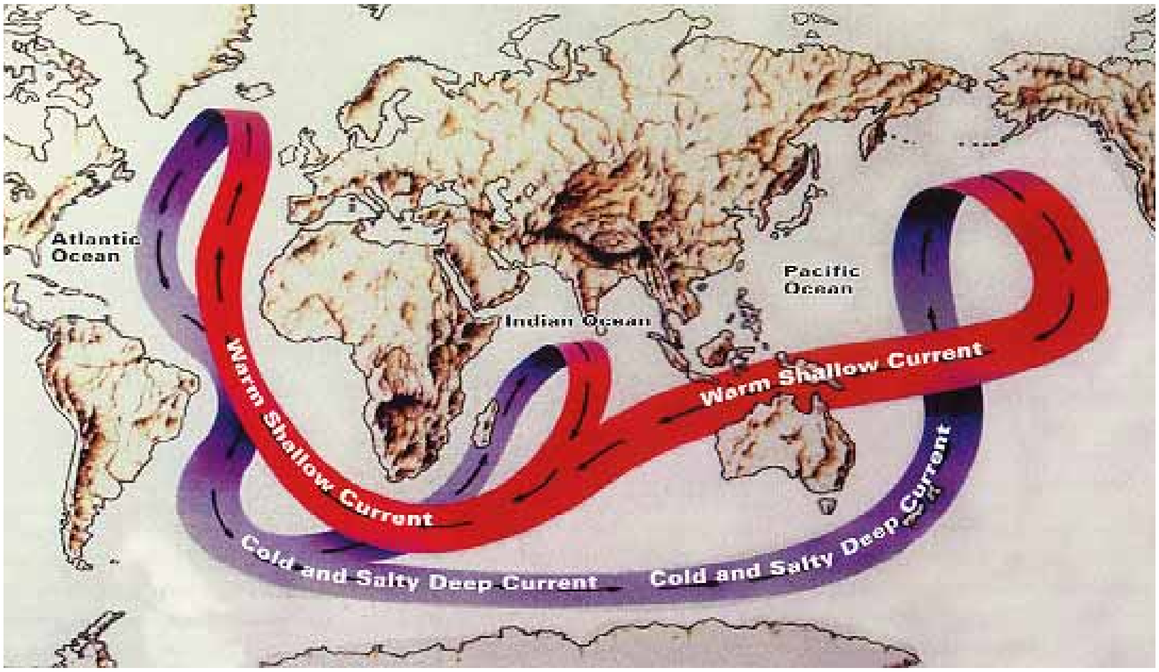


Figure from NOAA publication, OCEANS: Into the next Millennium of Oceanographic Research.

Fig 9: Thermohaline circulation pattern.

Sea Ice

Sea ice is another important factor in changing climate and enhancing the growth of glaciers. Sea ice is formed when the ocean surface water expels sea salt and freezes. The salts lower the freezing point of the water. This requires the temperature of the water to be below zero (0 degrees) Celsius before freezing. These ice masses always accompany glaciers flowing into the ocean. Ice affects atmospheric temperature in a number of ways. The ice reflects large amounts of incoming solar radiation back into space, cooling the Earth’s surface. Large amounts of sea ice also block ocean water from sinking in the North Atlantic and prevents the thermohaline circulation of the ocean currents important for modulating atmospheric temperatures. When the thermohaline circulation are not operating efficiently, the temperature of the surface waters in the North Atlantic averages about 5 degrees Celsius colder. Sea ice, through the reflection of solar energy and the blocking of the NADW, can easily cause a 5 to 8 degree Celsius change in the temperature of the air over Greenland and Northern Europe. Sea ice is very temperamental. It is the last ice to form in glacial periods and the first ice to melt when global warming occurs. Though sea ice may not be a cause of glacier formation, it does enhance the building of more massive glaciers on land.

Atmospheric Circulation

The circulation of the atmosphere is also responsible for climate and the growth of glaciers. In the atmosphere there are six distinct circulation belts, three in the Northern Hemisphere and three in the Southern Hemisphere. They roughly occupy the latitudes from 90 degrees north to 60 degrees north, 60 degrees north to 30 degrees north, and 30 degrees north to 0 degrees north (equator). The three circulation belts in the southern hemisphere are a mirror image of those in the northern hemisphere. The circulation of air in each belt resembles a giant **convection cell.** Warm air rises at the equator, cools, and sinks at about 30 degrees latitude, north and south. The air then circulates back to the equator where it again warms, rises, then cools and sinks at 30 degrees latitude. This same pattern of convection circulation occurs as warm air rises at 60 degrees latitude, cools, and this time sinking at 30 degrees latitude and also at 90 degrees latitude (Figure 10: Atmospheric convection cells). The exact position of the rising and sinking of air is determined by surface temperatures across the Earth. During glacial periods, ice sheets advanced south, in the Northern Hemisphere, and the position of the northern most cell was expanded further south. This helped to exaggerate glacial conditions already present in the north.

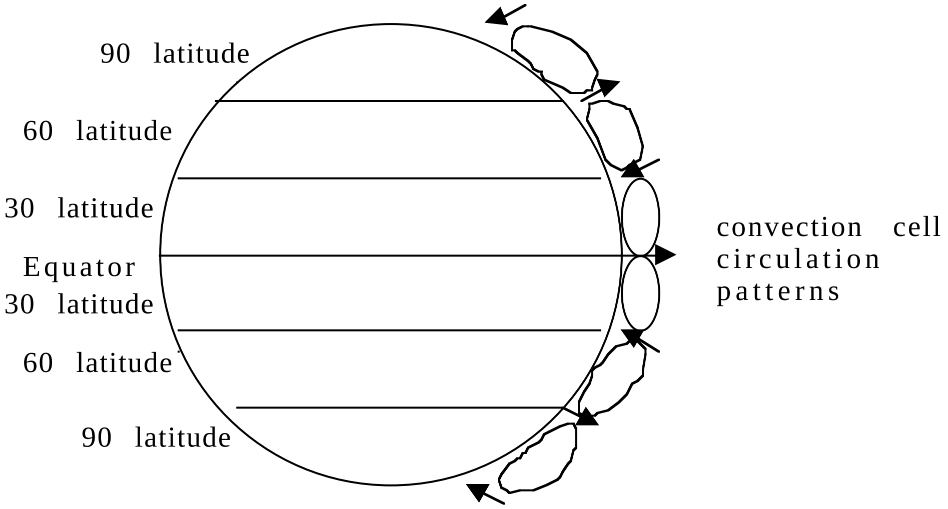


Fig 10: Atmospheric convection cells.

Atmospheric circulation is also responsible for carrying the dust into the upper atmosphere, forming strong winds, and changing the position of the jet stream and the storm tracks. During glacial periods, the polar atmospheric circulation patterns were more global in their extent. This further enhanced the growth of polar ice sheets. During interglacial, or warm periods, such as the present, the extent of atmospheric circulation patterns were limited and regionally organized.

In recent years, the connection between ocean and atmospheric circulation, and daily weather has become better understood. The connection between

El Niño events, which are the upwelling of ocean water in the eastern pacific off the coast of Chile, and weather conditions in North America have become much more clearly understood by scientists. El Niño events seem to occur in regular 7-year cycles. There is also a similar system in the Atlantic Ocean, called the **North Atlantic Oscillation (NAO).** The NAO which is less understood, operates in the Atlantic ocean and affects the atmospheric convection pattern between 30 degrees north latitude (Azore high pressure) and 60 degrees north latitude (Icelandic low pressure).

The astronomical positioning of the Earth and the Earth/sun system, thermohaline circulation, ice sheet dynamics, and solar variability account for changing the climate of the Earth. Atmospheric dust, gases, and circulation are also capable of enhancing climate changes. All of these mechanisms have the potential to effect the climate of the Earth, and all of these things occur naturally. Each also increases and decreases in constant cycles. Though the time period for each cycle is different, they often reach their maximum or minimums at the same time. When that occurs, subsequent warming or cooling events occur. The other way to create warming is to artificially increase the quantity of one of these variables. The only variables that can be manipulated by humans are the greenhouse gases!

Crystal Structure of Ice

Along with an understanding of factors that lead to changing climate and glacier formation the study of glaciers requires a knowledge of the crystal structure of ice. Once the conditions are right for snow to fall and persist on the ground year after year, the snow can be transformed into glacial ice. Ice is a mineral. It satisfies the requirements for being a mineral: it has a definite crystal structure; a definite chemical composition; it is naturally occurring; and it is inorganic. The crystal structure of a snowflake is a **hexagonal molecule** with each oxygen atom bonded to a hydrogen atom in a ring (Figure 11: Structure of a snowflake crystal).

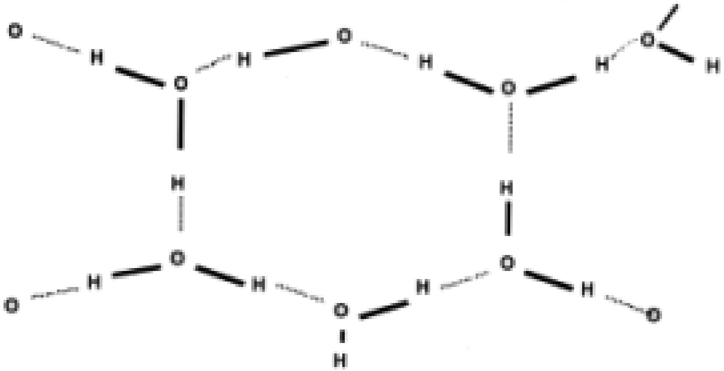
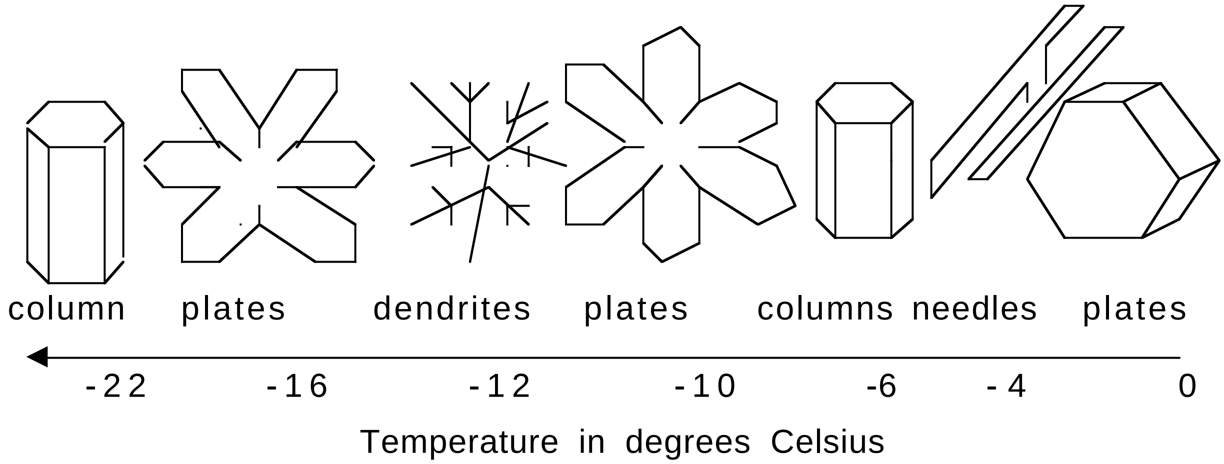


Fig 11: Structure of a snowflake crystal.

Attached to each branch of the snowflake are additional H_2O molecules bonded to hydrogen atoms on the ring. It is interesting to note that at different temperatures, all below approximately 0 degrees Celsius (C), the shape of snowflakes differs. The colder the temperature, the less delicate and more blocky the snowflakes become before they hit the ground (Figure 12: Snowflake shape relative to temperature change).



Adapted from The Weather Book

Fig 12: Snowflake shape change relative to temperature.

As snow accumulates, the shape of each crystal begins to change as it is compressed, melted, and crystallized. In Alaska, snow may accumulate at the rate of a few meters of snow a year and in Antarctica it may accumulate at the rate of only centimeters per year. At each level in the already existing snow pile, the shape of each crystal becomes more "lumpy" and the density of each snow crystal increases. This yearly accumulation compresses and compacts the snow crystals together, still further increasing the density of the already existing snow pile. The density (Density = mass per volume) of fresh newly fallen snow is very light, about 0.1 g/cm^3. Snow that persists for an entire year is called **Firn**, German for "last year's snow." Firn reaches a density of 0.6 g/cm^3. Deeper in the snow pile, the density increases until ice is formed at a depth of about 50 meters (m) deep. Glacial ice has a density of about 0.9 g/cm^3, slightly more than that of the ice in your refrigerator. It is interesting to note that the density of fresh water is 1.0 g/cm^3. This is why ice floats in water, it is less dense than water (Figure 13: Density of snow /ice). In this manner, through the continual accumulation of snow and compaction of the layers over hundreds and thousands of years, glaciers form.

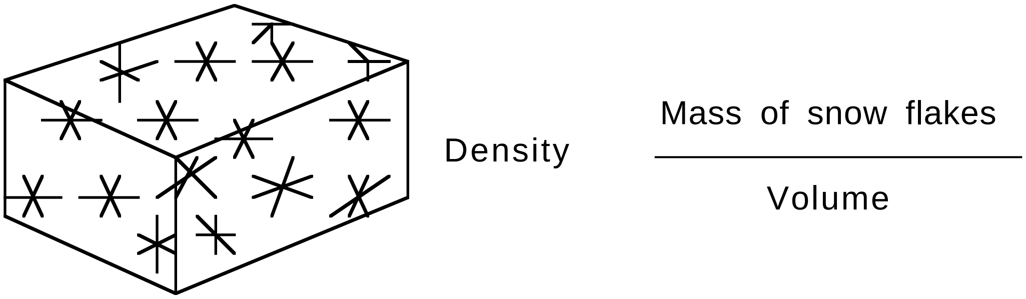


Fig 13: The density of snow/ice.

Movement

Movement is another important factor in the study of glaciers. Once the snow has been converted to glacial ice, the glaciers begin to flow. Glaciers "flow" due to three different mechanisms which operate simultaneously. They are the **slope of the bedrock surface**, the **internal deformation** of the ice within the glacier, and the **basal meltwater** at the base of the glacier. Bedrock slope is a measure of how steep the land surface is and as it increases toward the vertical, glaciers can actually fall down a mountain. As the thickness of the glacier exceeds 60 meters (m), glacier surface slope, internal deformation, and basal water allow a glacier to flow across level plains or even uphill to some extent. Some glaciers are actually frozen to the bedrock surface and then only internal deformation controls movement. Internally, the ice crystals in a glacier are flattened by the overlying pressure and lie parallel to the base of the glacier. Similar to what happens with a deck of playing cards, when laid flat and pressed down and forward, ice crystals slide along the platy flat surface of each successive ice crystal below them. This movement, similar to **plastic flow**, is known as internal deformation (Figure 14: Diagram of internal deformation).

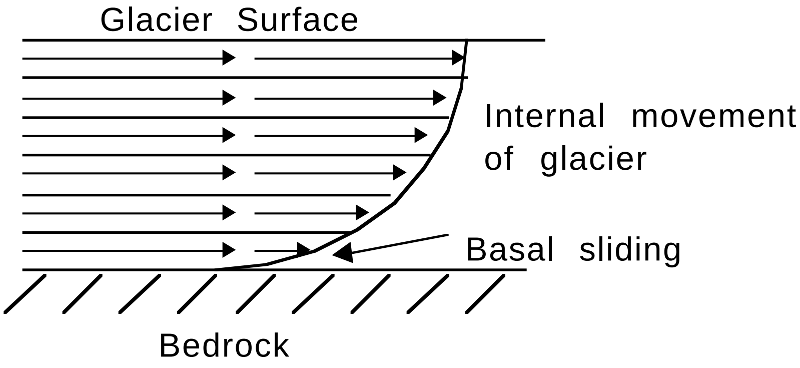


Fig 14: Diagram of Internal Deformation.

In internal deformation, the ice crystals literally slide one on another and the glacier “flows.” The speed at which a glacier can flow depends on many physical aspects of the land surface: such as the thickness of the ice (> 60m), the climate of the area, Earth movements such as Earthquakes or volcanic eruptions, the season, a change in the slope angle, and the amount and rate of accumulating basal water. The surface of the glaciers is subjected to melting during the summer months. Most of the melt water percolates downward through the snow layers when snow is **ablated** or melted. Due to the **pressure melting effect**, glaciers also create a little water at their bases. This happens in the same way that a skater is able to glide across the ice when a thin layer of water is formed at the contact between his skate blades and the ice surface. The water created at the base of the glacier, along with any water percolating downward from the surface, form a lubricating water layer beneath the glacier. Most glaciers move slowly, about 0.5 m per day. Glaciers can **surge**, due to a build up of basal water and move up to 10’s or 100’s of meters per day. Flow can only take place moving forward. Glaciers never retreat, or move backwards. If the proper conditions for flow are not met, a glacier may stall. This only happens at the end of a glacier’s life when there is little mass left. The amount of melting may exceed the amount of forward movement and may give the impression of backward movement. When melting exceeds forward flow, not a happy condition for a glacier to be in, it is referred to as **downwasting** (Figure 15: Sketch of a downwasting glacier).

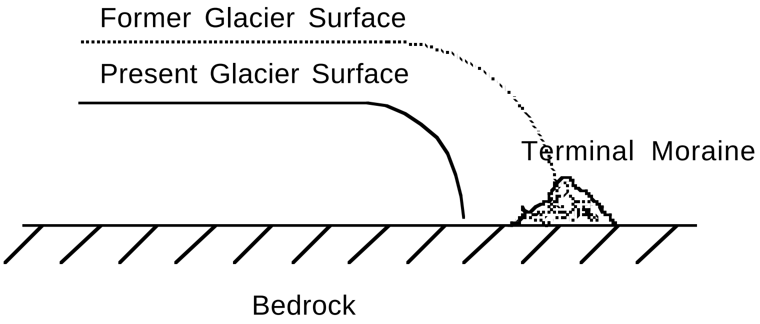


Fig 15: Sketch of a downwasting glacier.

Morphology

Scientists study the morphology, or the shape and structure of the glaciers, in order to better understand them. The snow that lingers on some mountaintops, or at the local ski area, into the summer is not considered to be a glacier because it is not ice and it does not move under its own weight. There are many sizes of glaciers. The smallest are cirque glaciers, glaciers that fill bowl-shaped depressions that may be a few square kilometers (Figure 16: Cirque, Tuckerman’s Ravine, Mt Washington, New Hampshire).

Photo by Z. Smith

Fig 16: Cirque, Tuckerman's Ravine, Mt. Washington, New Hampshire.

The next largest glaciers flow through valleys and may be enlarged by cirque glaciers which flow out of the mountains. These are called **valley glaciers** or even **piedmont glaciers** if the glacier flows out of the valley onto the adjacent plain (Figure 17: Piedmont glacier, Mont Blanc Region, France).

Photo by Z. Smith

Fig 17: Piedmont glacier, Mont Blanc Region, France.

As glaciers accumulate more and more snow, and many glaciers begin to collect together, they can begin to cover hundreds of square miles. These massive collections of glaciers are called **icefields**. The largest accumulations of glaciers are called **ice sheets,** and are thousands of square miles in area. Most icefields and ice sheets do not entirely cover all of the highest mountain peaks. Those exposed peaks are called **nunataks**, the Innuit word for rock islands (Figure 18: Nunataks on the Taku Glacier, Alaska).

Photo by Z. Smith

Fig 18: Nunataks on the Taku Glacier, Alaska

Glaciers have a number of important parts. This top (map) view of a glacier (Figure 19: Map view sketch of a glacier) identifies the head, or uphill top end, and the **terminus** or downhill end. The terminal moraine marks the furthest forward movement of the glacier (Figure 20: Terminus of the Mendenhall Glacier, Alaska). Between the ablation area, where most melting occurs in the summer and the **accumulation** area, where snow lasts from one winter to the next winter, is the **Snow Line**. **Firn** is year old snow found in the accumulation area. This line marks an important boundary between how much of the last year's snow has melted away during the summer ablation season and how much of it has been retained through the summer. The firn line moves up glacier as the summer ablation season continues. The average position of the firn line is called the **Equilibrium Line Altitude or ELA**. During the winter the snow line may be at or near the terminus and in the summer it is found further up in the glacier.

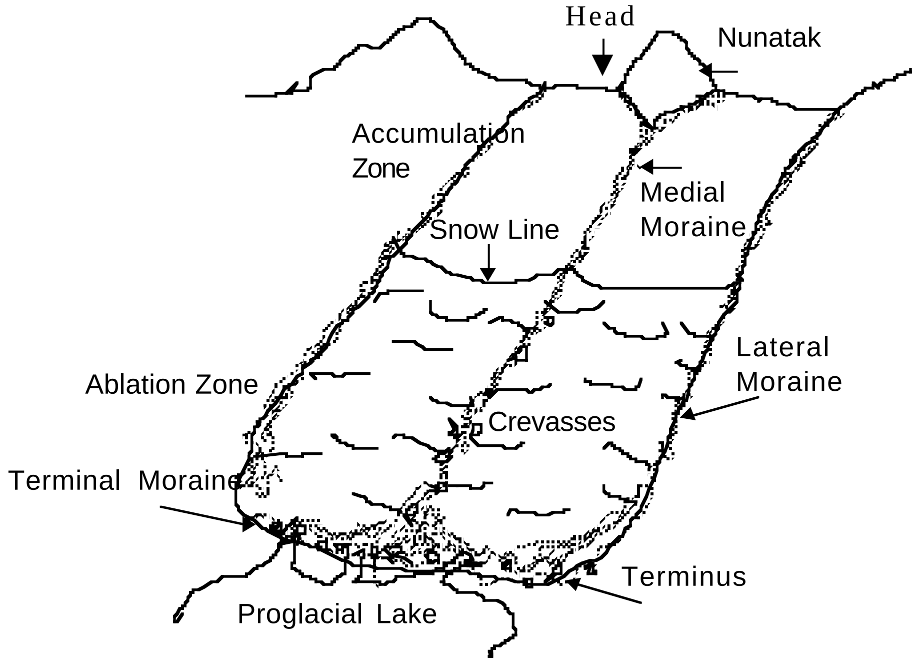


Fig 19: Map view sketch of a glacier.

Photo by Z. Smith

Fig 20: Terminus of the Mendenhall Glacier, Alaska.

You will notice that glaciers are not generally very white but are blackened and dirty looking. This is because they contain millions of tons of material eroded from surrounding mountains (Figure 21: Rock accumulation of the surface of the Van Lewis Glacier, Alaska). On the surface of the glacier, in the ablation area, there are **superglacial** streams which carry surface melt water.

Photo by Z. Smith

Fig 21: Rock Accumulation on the Surface of the Van Lewis Glacier, Alaska.

Also associated with the glacier are the piles of rock material that have eroded from the valley walls and pushed to the front and sides of a glacier. These are called moraines: **terminal moraines** at the front, and **lateral moraines** at the sides. And when two glaciers meet they form **medial moraines** (Figure 22: Medial and Lateral Moraines on the Van Lewis Glacier, Alaska).

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Photo by Z. Smith

Fig 22: Medial and Lateral Moraines on the Van Lewis Glacier, Alaska.

A glacier flows as it is pushed downhill by the accumulating snow uphill. Areas where the glacier is constantly pushed from behind are **compressional flow areas**. The bedrock surface, over which glaciers flow, is not smooth but is very irregular and varies greatly. As soon as a glacier flows over a topographic high, the ice on the downhill side of the topographic high flows even more quickly due to the increased slope and the ice is stretched. Ice responds slowly to change and it can not flow fast enough to continually stay compressed. These areas are called **extensional flow areas** (Figure 23: Extentional Flow on the Van Lewis Icefall, Juneau, Alaska).

Photo by Z. Smith

Fig 23: Extensional flow on the Van Lewis Ice Fall, Alaska.

Here the ice starts to pull apart forming **crevasses**. Crevasses are cracks or breaks in the surface down to a depth of usually less than 50m (Figure 24: Skiing across a crevasse, Lemon Glacier, Alaska)(Figure 25: View inside a crevasse). Crevasses are formed because the surface ice can not deform and therefore crack to accommodate the plastic flow of deeper ice. Imagine pulling a piece of taffy candy of Silly Putty. If you pull slowly you will stretch and lengthen the material but if you pull too fast the material can not respond quickly enough and it snaps. Though the forming of crevasses in ice is not directly related to velocity but Silly Putty creates a good visual image.

Photo by Z. Smith

Fig 24: Skiing across a crevasse, Lemon Glacier, Alaska.

Photo by Z. Smith

Fig 25: View inside a crevasse.
Photo was taken 10 m deep in the crevasse.

A closer inspection of the glacier surface reveals many features in the ablation zone that result from the melting of the ice. As previously mentioned there is a large amount of dust and rocky material scattered over the surface of the glacier. That material is called **superglacial** debris. The uneven reflection of sunlight by ice and rock determines how much melting occurs. **Albedo** is the percent of sunlight that a surface reflects. For ice and snow it is approximately 95%. (Figure 26: Albedo of three different surfaces).

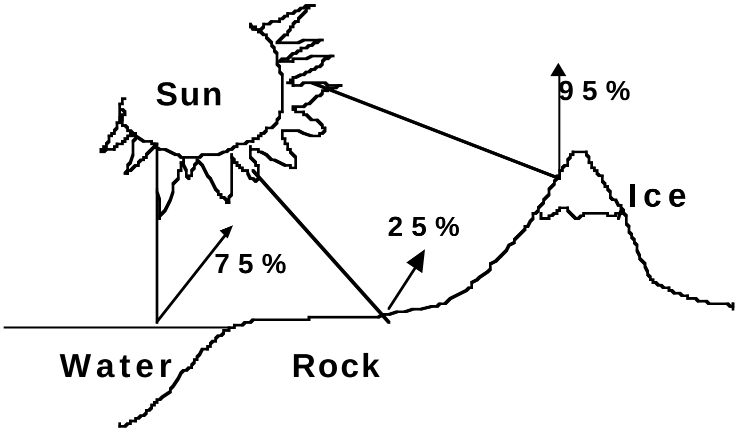

Fig 26: Albedo of three different surfaces.

For rock and dust the albedo is around 50%. Sunlight that is not reflected is absorbed. That means that rock and dust absorb 50% of the sunlight and convert it to heat energy. The heat absorbing ability of dust, the angle that the sun's rays strike the glacier's surface, and the already uneven surface of the glacier combine to form **sun cups, diagenic ice mounds, cryoconites, and rock pedestals.**

Sun cups are small rounded depressions, from 1 cm to 30 cms in diameter and equally deep, in the surface of the glacier. Sun cups cover the entire accumulation area during the summer. They can make travel, on skis or on foot, especially difficult (Figure 27: Sun cups).

Photo by Z. Smith

Fig 27: Sun cups.
Chickadee in foreground for scale.

The formation of sun cups is due to this uneven heating of the snow surface in the accumulation area. Sun cups grow larger and deeper depending on the conditions. On low latitude, high altitude glaciers they may even grow to a depth of a few meters and are know as penitents for their shape resembling that of people bent in prayer, repenting their sins.

Depending on the thickness of any rocky material, heat is either conducted to the ice beneath the rocky material or the rocky material insulates the ice from the incoming sun's energy. The **critical thickness** between insulation and conduction to the ice surface is around 3 mm. The result is that the ice surface that is not covered by rocky material then melts faster than the ice surface that is covered by rocky material. That leaves the large pieces of rock and thicker accumulation of rocky material as "highs" on the glacier surface. These are the diagenic ice mounds and pedestals. (Figure 28: Diagenic Ice).

Photo by Z. Smith

Fig 28: Diagenic Ice Mounds.
70 centimeter ice axe for scale.

If the rocky material is dust-sized, it absorbs the sun's energy, conducts it to the ice surface in the ablation area, and literally melts its way into the ice forming small holes. (Figure 29: Cryoconites). The cryoconite holes are not perfectly vertical because the sun is not directly overhead (it is only between the Tropic of Cancer and Tropic of Capricorn at different times of the year). The orientation depends on the sun's angle and the pull of gravity on the dust. It has been observed that the cryoconite holes do angle slightly towards the sun and a small stick placed in a hole would slightly change its orientation to point toward the sun throughout the day.

Photo by Z. Smith

Fig 29: Cryoconites.
Author's feet for scale.

From a side view you can see the material on surface called **superglacial** material which may be rocks from dust size to as big as a house. (Figure 30: Sketch of the side view of a glacier). The material that is carried internally in the glacier is called **englacial** material. Layers of ice and snow accumulate in **annual layers** and are visible in crevasses, in test pits, or at the terminus of many glaciers. The base of the glacier moves against the bedrock land surface where **subglacial** material, or the rock material at the base of a glacier, is eroded from the bedrock and pushed along under the glacier.

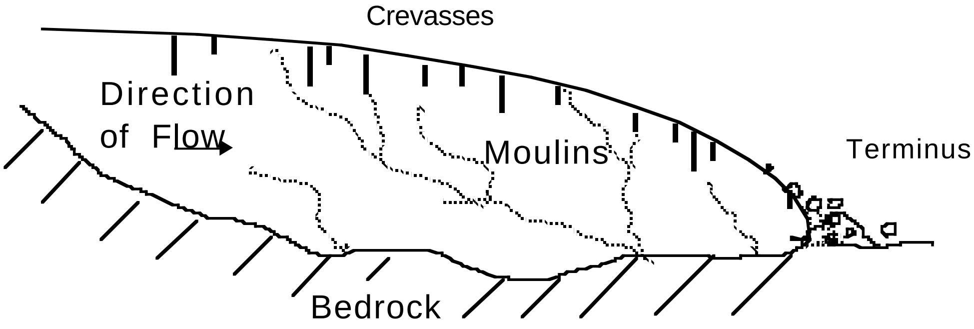

Fig 30: Sketch of the Side view of a glacier.

During the summer melting season the Firn Line migrates up glacier, and millions of metric tons of meltwater from the glacier. Small surface streams and ponds are formed on the glacier surface. Much of that water also flows into the interior of the glacier through conduits such as crevasses and **moulins** (Figure 31: Moulins, Llewelyn Glacier, BC).

Photo by Z. Smith

Fig 31: Moulin, Llewelyn Glacier, BC.

A glacier has a very intricate internal plumbing system through which melt water flows. Some of these “pipes” can be up to 10 meters in diameter.

Moulins are the portion of the pipes that are exposed on the glacier's surface. The "pipes" are also often exposed along the margins of the glaciers and when free of water form ice caves. (Figure 32: Ice Caves, Llewelyn Glacier, BC).

Photo by Z. Smith

Fig 32: Ice Caves, Llewelyn Glacier, BC.

Much of the water that melts from the glaciers makes it way off and out of the glacier and forms rivers and/or **glacial lakes** downstream from the glacier terminus. (Figure 33: Proglacial lake, Mendenhall Glacier, Alaska).

Photo by Z. Smith

Fig 33: Proglacial Lake, Mendenhall Glacier, Alaska.

Since more water melts during the day than at night, these rivers are shallower in the early morning when melting is at a minimum. The downstream ponds in front of cirque glaciers are called **tarns** and formed most of the beautiful mountain ponds that we see in the higher latitudes today. Melt water from a glacier can be torrential in the spring and more gentle as the melting season progresses. This water is essential for agriculture in many areas of the world (Figure 34: Tarn, Cascade Range, BC).

Photo by Z. Smith

Fig 34: Tarn, Cascade Range, BC.

Glacial Geology

Glacial geology is the study of the effect of glaciation of the landscape. There are two types of Earth features that form as the result of glaciers, they are erosional and depositional. Erosional features are those features that are formed by the erosive action of ice, snow or glacial melt water. Depositional features are those features which are formed as a result of material that are deposited by the glaciers.

Erosion

Ice is a mineral. As with all minerals, it has a hardness, a luster, a cleavage, a fracture, and other specific properties. The hardness of ice is relatively low compared to other Earth materials, around 2 on Moh's mineral hardness scale. The obvious question is then how does a mineral with a hardness of 2, scratch and erode minerals like **quartz** (hardness of 7) and **feldspar** (hardness of 6)? These and other Earth minerals form the composition of the rocks on the Earth's surface and have a hardness far greater than that of ice. The answer is that by itself, ice does not erode the Earth's surface. You may think that ice is hard and rough. Remember being hit by a snowball when you were younger? Anyway, it is not the ice, glacial or otherwise that erodes the land surface, but the rocks that are carried along in the bed of the glacier, a Ha! These rocks called **subglacial** debris, grind against the **bedrock,** or solid rock surface, beneath the glacier and abrade or erode bits of rock. These bits of rock in turn erode more rock. All of the erosion occurs under the glacier. The erosional features that glaciers produce are only visible after the glacier has been melted out of the area. The subglacial material erodes **striations** or grooves up to a few centimeters deep and up to 10's of meters long. (Figure 35: Striations on bedrock surface). The subglacial material may also polish the bedrock leaving smooth polished surfaces, known as **glacial polish**.

Photo by Z. Smith

Fig 35: Striations on bedrock surface.

In some cases the glacial rocks are ground into "flour" and carried in the streams, called **rock flour** (that is some tough tasting bread!). The glacial flour can often be scraped off of the bedrock surface with your fingers after a glacier has downwasted. (Figure 36: Glacial rock flour).

Photo by Z. Smith

Fig 46: Glacial rock flour.

Rock grinding against rock is only one way in which glaciers erode the Earth's surface.

Another way that erosion occurs as a result of glaciation is through **frost wedging**. Frost wedging occurs anywhere that temperatures vary above and below freezing. This occurs when a rock fragment is separated from the bedrock's surface because it is heaved, lifted, or pushed by expanding ice. Water need only be a micron thick to expand as it freezes (remember the other science classes you've had?) and to push rock pieces. The strength of expanding ice is incredibly great. Expanding ice lifts sidewalks, highways, and boulders the size of your house. The more liquid water that gets into a crack, the greater the amount of movement that can take place from the expansion of the ice. When ice pushes up from the ground it is called frost heaving. In New England, "Frost Heave" signs are common sights along the highways in the winter and early spring. When ice pushes from the sides and breaks off pieces of rock it is called frost wedging. Expanding ice can literally bring down a mountain, one piece at a time. Many of those mountains being eroded away line the sides of the glaciers. As rock material is eroded off of the mountains and carried down to the glaciers, the surface of a glacier becomes dirtier and dirtier. Some of that rock also becomes incorporated into the glacial ice. The name for this rock material is **superglacial** debris (on top of) and **englacial** debris (within), respectively (Figure 37:Frost wedging).

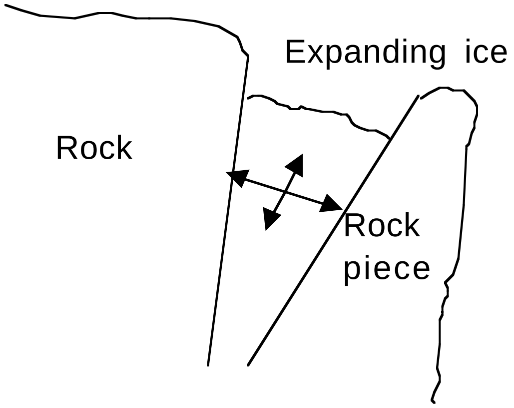

Figure 37: Frost wedging.

Depending on the thickness of a glacier, it flows over most topographic highs, mountains, and hills as it moves down valley. Ice in a glacier responds slowly to change as it flows and deforms. When a glacier overrides a topographic high it pushes against the up glacier side of the hill and creates a small void on the down glacier side of the hill. In this void, through the process of mechanical weathering, pieces of rock along joints or other features in the bedrock are wedged by the frost and lifted or plucked from the surface. This process is called **plucking**. In this way, steep cliff faces may form. Often hills in glaciated areas have smooth, gentle up-valley sides and abrupt, sharp, cliffs on the down valley sides. This makes for some spectacular scenery and some great rock climbing. These features are called **roche moutonnees**, after the French for "sheep backs" (Figure 38: Sketch of roche moutonnee formation).

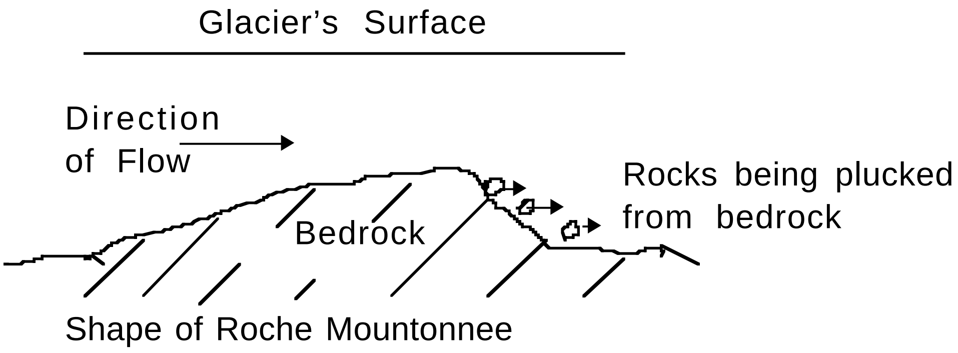

Fig 38: Sketch of Roche Moutonnee formation.

Even small cirque glaciers erode the tops of mountains and form **horns**, such as the classic Matterhorn, get it horn? Shaped like an animal's horn. Between the horns, steep ridges called **aretes** and narrow gullies called **couloirs** are formed (Figure 39: Glaciated Mountain Tops, Mont Blanc Region, France).

Photo by Z. Smith

Fig 39: Glaciated Mountain Tops, Mont Blanc Region, France.

These processes together are responsible for creating the classic **"U" shaped valleys** seen in many places in Northern New England, Yosemite California, the Cascade Mountains of the northwestern United States and numerous other places in the world. (Figure 40: "U" shaped valley, outside Coumayeur, Italy).

Photo by Z. Smith

Fig 40: "U" shaped valley outside Courmayeur, Italy.

Deposition

All of the material that is eroded by glaciers must go somewhere and it is probably not with all those single socks and keys that you have lost. Eroded material is carried away by the ice and by the meltwater. Rock material from the size of dust to the size of a house can be carried by the ice over water and is called **ice rafted debris** (Remember the term superglacial?). The term ice rafted debris is also used to describe debris carried by icebergs. The bedrock surface of the Earth is made up of many different rock compositions. As the glaciers flow across the bedrock they erode rocks of many of these different types. After the ice melts away, the glacial debris is deposited. If this material has been carried over land to a place where rocks of that composition are not present, it is called a glacial **erratic**. Some erractics have been carried hundreds of miles. Remember that erratic does not describe a rock's mannerisms only its transport and placement into an area of differing rock type. (Figure 41: Erratics at the terminus of the Ptarmigan Glacier, Alaska). The deposits are not well sorted and large debris particles are in place with smaller debris particles.

Photo by Z. Smith

Figure 41: Erratics. Terminus of the Ptarmigan Glacier, Alaska.

As opposed to glacial debris, the material that is carried by water is better sorted (**fluvial sorting**) and more rounded. Think back to the power of water and those holes you dug in your mother's garden as a kid with the hose. The higher the water velocity the bigger the size of the materials that you could erode out of the ground. Geraniums, ornamental stones, small critters, etc. So, the lower the water pressure the smaller the debris particles you can erode and/or carry. Bigger debris material is carried or transported only as long as the water pressure remains high. Then it is deposited. Smaller debris material that is suspended in the water is carried, often further, even if the water velocity is low. The sorting of the debris material depends on the water velocity. This happens in all flowing water situations, your mother's garden and the local river (Figure 42: Examples of the sorting of deposited materials).

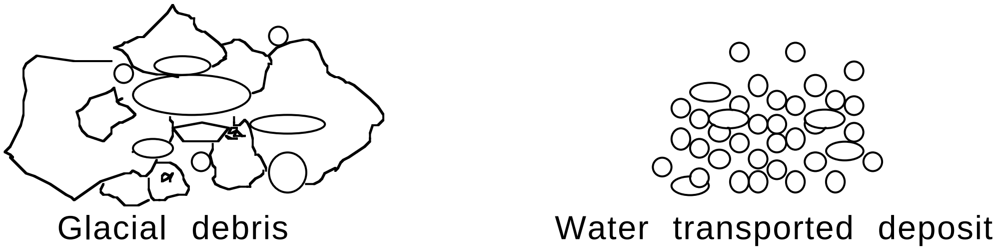

Fig 42: Examples of the sorting of deposited materials.

As a glacier downwastes, or melts down faster than it flows forward, it can not fill the valley that it once filled. (Remember glaciers can not flow back uphill but recede by melting downward). The margins between the glacier and the valley walls begin to fill with sediments carried by the meltwater. The sediment originates as superglacial and englacial material but are mostly eroded by meltwater at the base of the glacier. The conical, hilly deposits, of well-sorted material stratified material are called **Kames** and the features they produce along the valley walls are called **Kame Terraces**.

These sand and gravel deposits are very common in glaciated valleys and in many locations are excavated for their value as building materials for roads and in making concrete (Figure 43: Kame Terraces).

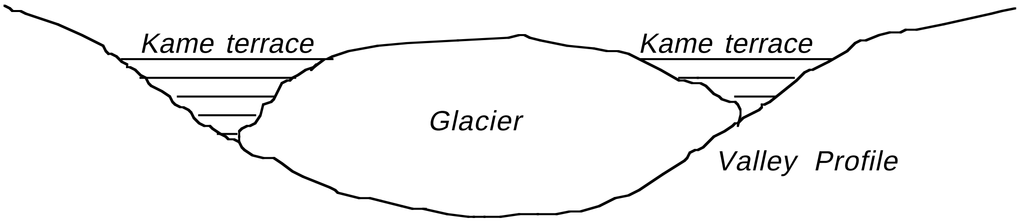

Fig 43: Cut away view of Kame Terraces.

The depth of the material that is deposited, through these various forms of deposition, may reach a depth of a 100 meters or more. The terminal moraines or other former features may be buried as a result of these new deposits. **Deltas** may also be formed when the melt water streams reach lakes or perhaps the ocean.

Within the debris material that is deposited are often huge blocks of ice. These ice blocks, often 10's of meters across, have **calved** or fallen off of the terminus of the glacier. These blocks may become partially buried with the continual deposition of material being carried by the melt water streams. As the blocks melt away, depressions are formed in the sediment. The depressions, then filled with ground water, are called **Kettle Ponds**. (Figure 44: Kettle pond formation). Kettle ponds are very common features in many areas of the country such as southern New England. The most famous of which may be Walden Pond where Thoreau spent two years alone in the wilderness.

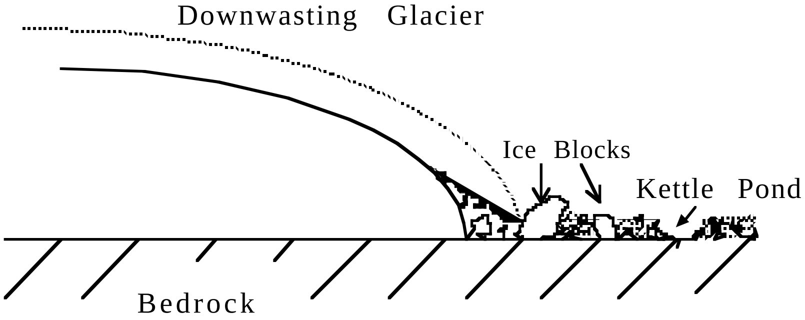

Fig 44: Kettle pond formation.

The blocks of ice and the deposited materials can also form dams, which restrict the flow of meltwater from the glaciers. This causes ponds and lakes to form. The material that is deposited in these lakes shows a seasonal variation. In the summer, with more melt water from the glacier, the material deposited at the bottom of the lakes is silt-sized and larger. In the winter under the ice-covered lakes, there is little to no current. When there is low flow velocity, no eroded material is carried into the lakes and only the clay sized material (in suspension in the water) slowly settles to the bottom. Thus, seasonal layers of clay called **varves** are formed. The summer and winter set of varved clays together are called a couplet. There is usually also a color difference between the summer and winter deposits. The summer deposit is usually lighter and the winter darker due to the difference in mineralogy and grain size of the materials. Some minerals such as quartz sand are clear or white colored and some minerals such as the amphiboles are dark colored. Cores that are extracted from these varved sediments can be counted and dated for the entire length of time for some glacial lakes. (Figure 45: Varved clay sample from Glacial Lake Vermont, Bouquette River Valley, NY).

Photo by J. Ridge

Fig 45: Varved clay sample from former Glacial Lake Vermont, Bouquette River Valley, NY.

Through deposition, sediment accumulates throughout the entire valley floor. Most sediment is transported by the melt water flowing downstream from the glacier's terminus as a result of the summer ablation or the downwasting of the glacier. A few types of deposits are actually formed under the existing glacier. One type, called **till**, is plastered down by the moving ice as it drags debris across the land surface. Till can be deposited in layers ranging from 10's of centimeters (cms) to 10's of meters (m) thick. These deposits are compacted by the weight of the glacier and made up of subangular to slightly rounded, unsorted particles, ranging from dust to pebble-sized. Till is impossible for farmers to plow though and very resistant to erosion and percolating surface water. The material in till may not have been transported by water as far as with Kame deposits or eskers. As a result, the shape of the particles in the till deposit may be very angular. As a pebble is moved along by water it tends to roll or slide and its rough edges are smoothed off. Thus ice carried particles are very angular and water carried particles are, on the other hand, more rounded. The dense compaction, the poor sorting, and the angularity of the individual particles helps distinguish till from other deposits.

If superglacial material, from the surface of a glacier, is carried through a moulin and into the glacier's plumbing system, it may fill the pipes and be deposited as long, snakelike, ridges called **eskers**. (Figure 46: Transparent view of an esker forming under a glacier). The size of eskers may vary greatly. They may be less than a meter or up to approximately 10 meters high. The ridges may extend for a few meters to tens of kilometers. These deposits are well sorted and stratified compared to till owing to the manner in which they formed as rocky material washed through and deposited in the glacial plumbing system. Eskers are very common features in much of the northern United States though they may be very difficult to locate because of their small size or similarity with other hills and ridges.

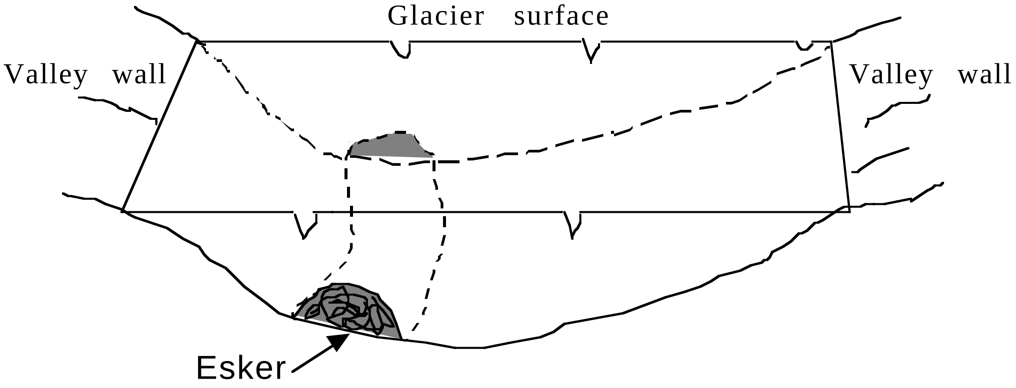

Fig 46: Transparent view of an esker forming under a glacier.

As glaciers move material may accumulate under the glacier. This material is largely clay-rich till but in some cases may be sorted or stratified and overlain by till. This material may be eroded and the entire deposit reshaped in to an elongated ridge. These features are called **drumlins**. They may be steeper on the up valley side and more gently sloping on the down valley side as the deposited material is planed down by the moving glacier or may be exactly the opposite with the steeper end on the down glacier side. Drumlins approximate the shape of an inverted spoon and vary from nearly symmetric on all sides to very elongated narrow forms. Asymmetric elongated drumlins indicate the relative direction of flow of the glaciers at the time that they were formed. As a result, drumlins in the same area always run parallel to each other and roughly parallel to eskers and glaciated valleys. (Figure 47: Side view of a Drumlin).

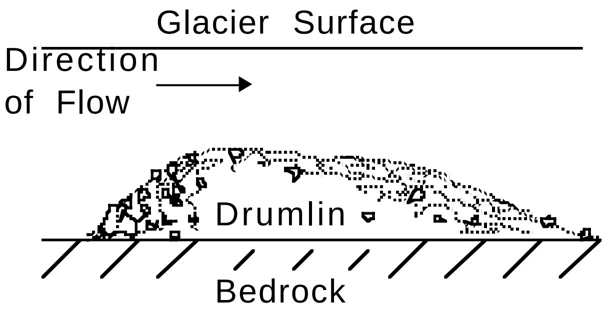

Fig 47: Side view of a Drumlin.

Another type of deposit, that occurs as a result of glaciers, covered many areas in layers of fine sediment. **Eolian deposits** are formed from the removal, transport, and deposition of fine-grained material by the wind. These deposits are very well sorted as a result of the wind's ability to transport only a limited range of particle sizes. During glacial periods, the sea level dropped by as much as 100 meters. This exposed large areas of non-vegetated land to erosion by the wind. The exposed sediments, which were subsequently eroded, were then transported and deposited. Glacial ice and melt water also produce silt and sand deposits on glacial flood plains and in deglaciated valleys which are then subject to erosion by the wind.

Periglacial Features

Other than the features formed directly under or on the margins of glaciers, there are other features formed because of climatic influence in areas where glaciers may also be present. These features form in an area called the periglacial region which may exist from 0 meters to 1000's of meters from the glacier's margins. These include **patterned ground**, **rock rings**, and **tanks** and **tors**. **Frost wedging**, the erosion of rock due to expansion of ice, also occurs near glaciers and/or at extreme latitudes and elevations. Though there may not be any mountains nearby that have been affected by frost wedging, any ground surface can be influenced by **frost heaving**. In areas where the ground is not flat but has small hills and mounds these rocks actually move downhill a little at a time each year. The frost heaving pushes the rocks upward and the pull of gravity along with the slope of the hill pulls the rocks downhill as the frost melts away. The rocks move downhill and eventually form rock rings around the raised areas. These rings may connect together and entire fields will be covered in small, connected rock rings. Often, instead of defined rings, stripes of rocks may be formed depending on the surface topography. Both rings and stripes fit into the category of patterned ground. Together they form an uneven, wavy land surface. In depressions called tanks, rain and melt water may collect and pool. These tanks are often rimmed by topographic highs called tors. The soil in periglacial regions also tends to be water saturated and may freeze to form permafrost up to 10's of meters deep.

Research Techniques

Global Positioning System

Scientists use a number of techniques to research glaciers. For the study of landforms and the physical aspects of the glaciers, scientists use observations, mathematical calculations, physics, and chemistry. In the past, the only way to research a glacier was to work at the glacier. Today, remote sensing techniques, which accurately measure features on the Earth's surface using satellites, have helped scientists do some of their research from their offices. Much of the work on glaciers still involves basic mapping and hands-on measuring. Measuring tapes, and surveying instruments are used to measure the change in size and distance of glacial features. Currently, the use of **Global Positioning System (GPS)** has helped to increase the accuracy and speed at which glaciers can be mapped (Figure 48: GPS system being employed on the Taku Glacier, Alaska).

Photo by Z. Smith

Fig 86: GPS system being employed on the Taku Glacier, Alaska.

GPS utilizes satellites that orbit the Earth to find precise locations on the Earth's surface. Currently, GPS technology has sub-centimeter accuracy and can measure daily changes in glacier movement. That translates into the ability to measure a 1 centimeter (cm) change in the movement of a glacier, either forward through flow, or downward through ablation.

Ablation Triangle

The amount of ablation that occurs on a glacier can be measured using an **ablation triangle**. Three posts are driven into the glacier to a depth of at least 1 meter (m). Between the three posts three horizontal rods are placed. The tops of the posts need not be all at the same elevation and the rods between the posts need not be exactly horizontal. The distance from the snow surface to the center of each rod is the intended measurement (Figure 49: Ablation triangle being employed on the Lemon Glacier, Alaska).

Photo by Z. Smith

Fig 49: Ablation Triangle.

Each day, at the same time of day, the distance from the snow surface to the center of each of the three rods is measured. The average of the three rods is calculated and the amount of change each day is the ablation. Ablation may vary from zero to 10's of centimeters (cm) each day. Depending on many factors, such as the time of year, the elevation, the latitude, the amount of sun shine each day, precipitation, and the daily temperature the amount of ablation may vary. To the casual observer they may not see a change in the elevation of the glacier's surface may not be noticeable because everything has changed equally. Most of the snow that is ablated from the glacier's surface percolates into the glacier as melt water. A small percent of the snow is also lost directly from the solid phase to water vapor through the process know as **sublimation**.

Accumulation Flags

Measurement of the amount of accumulation is done using flags that are placed on the glacier at measured locations at the beginning of the winter accumulation season. The flags are placed in a line from the terminus to the head of the glacier. Each is driven a few meters (m) into the glacier to ensure that it is not flattened by the winter's snow accumulation. At the end of the winter accumulation season, marked intervals on the posts are read. The difference between the snow height at the beginning and the end of the accumulation season is recorded. The height of all the new readings is combined and averaged, then recorded as the accumulation for the winter.

Mass Balance Calculation

The **mass balance** of a glacier is a measure of the difference between the amount of snow that a glacier gains and the amount of snow lost through melting. This calculation gives an idea of the "health" of a glacier. A positive mass balance translates into a glacier that is gaining more snow than is melting away. An accurate measurement, of all of the snow that has fallen and all of the snow and ice that have melted away each year, is difficult to make. Another way to determine the health of a glacier is to calculate the **accumulation area ratio (AAR).** This is done by finding the position of the firn line at the end of the ablation season and using aerial photography to measure the surface areas of the accumulation and ablation zones. The accumulation area "recharges" the glacier and replaces the amount of material lost to ablation. When the accumulation area can no longer replace the amount of snow and ice lost to ablation the glacier downwastes. Most healthy valley glaciers have an AAR of 60%-65%, and 75% for icesheets. That means that the accumulation area is 60% – 65% of the total surface area of the glacier. If the ablation area has a greater surface area than the accumulation area, the glacier will have an AAR of less than 50% and will begin to downwaste (Figure 50: Diagram depicting the calculation of the accumulation area ratio)

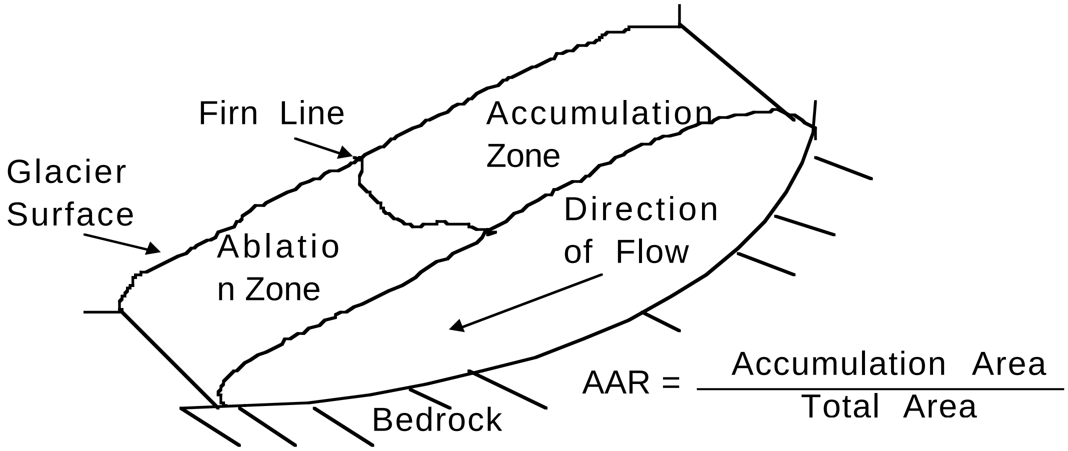

Fig 50: Diagram depicting the calculation of mass balance.

Density Calculation

Measuring the density of the snow on a glacier, allows scientists an opportunity to determine the amount of water that is frozen in a glacier and understand how accumulation rates affect the time it takes to compact snow layers into solid glacial ice. Density measurements are taken by digging pits into the glacier and collecting samples of the snow layers at different intervals in the pit. These samples are measured for their volume and then massed on an equal arm balance. Density is a measure of the relationship between the mass and the volume, measured in grams per centimeter cubed.

The density of new snow is approximately 0.1 g/cm^3 or lower. The density of firn is 0.65 g/cm^3 and increases with depth to approximately 0.9 g/cm^3 for glacial ice.

Movement Flags

The movement of a glacier is measured to determine how fast a glacier is moving. Scientists can use the rate of movement to interpret accumulation rates, ablation rates, and general climate changes. Flags are placed on a straight line across a glacier at measured intervals, perpendicular to the direction of flow. The position of these flags is determined using surveying instruments such as global positioning system (GPS) receivers or **theodolites**. Theodolites are surveying instruments which are used to map an area or determine locations. They are the same instruments which you may have observed workers using as they build new roads or determine where to place new buildings. The position of survey flags on a glacier are recorded as a location defined by their latitude and longitude. The position of these flags is determined again sometime later. The amount of movement of the flags, along with the amount of time it was measured, determines the rate of movement of the glacier, usually measured in meters of movement per day (m/day). The movement of the flags across a glacier is not consistent for all the flags. As the rate of movement changes, the pattern demonstrated by the movement flags, changes. Generally, the center of a glacier moves faster than the sides of the glacier due to thicker ice and friction on the valley walls. Thus flags in the middle of a glacier move down glacier faster than the flags on the sides. The overall shape of the movement flags, under normal conditions for most glaciers, is that of a semi-circle (Figure 51: Flags indicating the surface flow pattern of a glacier).

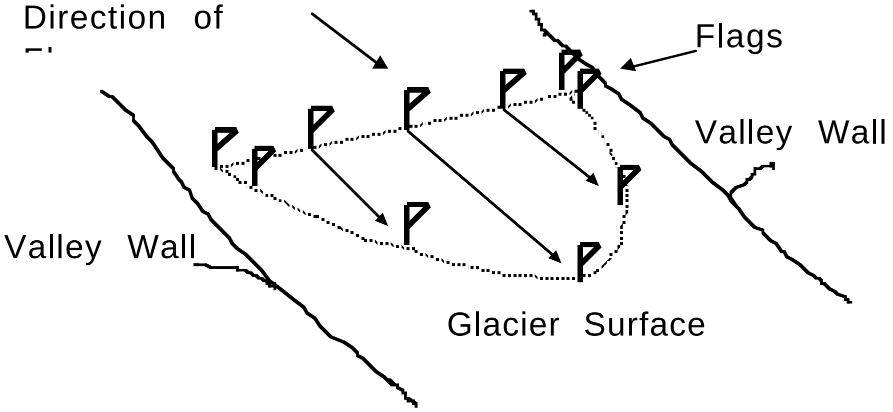

Fig 51: Flags indicating the surface flow pattern of a glacier.

Meteorological Instruments

While in the field, scientists are constantly aware of the weather. Standard meteorological instruments such as thermometers, psychrometers (used to measure relative humidity), barometers (used to measure air pressure), and rain gauges, are still in use today. Though many measurements are still made in person by scientists in the field, much of that is changing and more measurements are being taken with computer-controlled equipment. Field use, computer controlled, meteorology packs are employed in remote unmanned sites or in areas where scientists need to record the weather 24 hours a day. These meteorology packs record high and low temperature, humidity, insolation, barometric pressure, wind speed, and wind direction. Some of the more dramatic measurements are the result of the **Katabatic Winds**. These cold winds flow downhill on glaciers because of gravity and the density of the cold flowing air mass. Katabatic winds can blow up to 100 miles per hour (mph). On ice sheets, the **fetch**, or the distance that the wind blows unimpeded, is so large that the winds erode the snow surface and form **Stratugi**, or snow dunes. These daily and short-term weather parameters are very important to record and use to compile the long-term meteorological data. This long-term data helps scientists to understand climate and its variations (Figure 52: Portable meteorology pack).

Photo by Z. Smith

Fig 52: Portable Meteorology Pack.

Glaciers and Climate

The scientific definition of climate is weather averaged over a thirty year period. And weather is a measure of a number of parameters including temperature, barometric pressure, precipitation, clouds, and wind. As mentioned earlier, solar energy drives the entire meteorological system. This solar energy creates temperature changes on the Earth’s surface and within the atmosphere which creates pressure differences which drives wind and cloud formation. As previously mentioned, as a result of the revolution of the Earth the winds or general Earth circulation systems are organized. If the general wind direction in any area on the Earth were to change the result would be a very different climate in that area. During any given short term storm system, say a Nor’ Easter in New England during the winter, the path that storm takes determines whether Boston receives 2 inches of snow or 20 inches of snow. The path that storm takes is often determined by the location of the jet stream. The location of the jet stream is determined the Arctic cold fronts pushing south into New England, which is again determined by the amount of solar heating in the Northern Hemisphere.

Meteorology

The basic parameters of meteorology are temperature, barometric pressure, humidity, precipitation, and wind. It is a little of a chicken-egg dilemma if we want to know which parameter causes which parameter but suffice to say that if one of the above changes the other three will also change. With that in mind if you can the relative or specific change in one parameter you can interpret the relative or specific change in another. A few things are well know- in the winter when it is cooler it is windier, drier, and barometric pressure changes can be more dramatic. During glacial periods when more of the Earth was covered in ice and snow the climate of the Earth was more global. This means that any meteorological change that occurred on the Earth was felt over a much wider area. During warmer interglacial times any meteorological changes that occur on the Earth are localized. This has a lot to do with wind and circulation. As the Earth continues to warm (ten of the warmest years on record for the last century have occurred in the past 12 years) the circulation patterns on the Earth should change accordingly. But recent ice core evidence demonstrates that the circulation patterns of the earth are still “set” at cold Little Ice Age patterns. The most dramatic changes that will be recognized on the Earth are not temperature but are winds and circulation patterns. We are familiar with the wind direction, intensity, humidity and precipitation that we now receive in our areas but as climate changes the dramatic effects will be in wind intensity, direct, and precipitation.

Climate is defined as, the average weather measured over at least a 30 year period. Climate is very dynamic and changes constantly, sometimes over a very short period of time. The stories that your grandparents tell you about how deep the snow was when they were kids (whether or not they had to walk to school uphill both ways) were largely true. Just in the past fifty years, there has been a large decline in the average amount of snow received at most locations in the United States. Data show that the global average temperature has gone up almost 2˚C in the past two hundred years. The trends of climate are determined based on the average, daily weather data measurements.

Weather data measurements include; precipitation (types and amounts), temperature, temperature highs and lows, relative humidity, barometric pressure, wind speed and direction, dew point, cloud (type and the percent of cover), and insolation. Each of these and other parameters are collected many times each day by professional and amateur **meteorologists.** The data they collect is recorded, placed in a database and used to try to understand weather trends. Though we are most conscientious of the weather at our own area, weather takes place all over the Earth and at every level in the atmosphere, every moment of the day and night. Weather forecasting is difficult because the weather in every location, on the ground and in the air, is connected and helps to determine the weather in every other location. There is a theory, called the Butterfly Effect, which states that a butterfly flapping its wings in Asia will affect the movement of the air, which will affect something, which will affect something, which will affect you, no matter where you are. Nowhere is the Butterfly Effect more obvious than when dealing with the weather. A drought in Africa, a volcanic explosion in Sumatra, or a snowstorm in Colorado, each will have an influence on the weather in your area. The National Oceanographic and Atmospheric Administration (NOAA), which is the government agency in the United States that deals with weather data collection and forecasting, collects and interprets billions and billions of bits of weather information each hour. All this information is fed into huge Cray computers in order to create a worldwide weather forecast. The chance of error is considerable because of the large number of data and the dynamics of that data. That is why meteorologists often can not correctly predict the weather a single day ahead of time. With that in mind, consider the difficulty in predicting future climates?

Climate Records

Daily instrumental weather data has been collected and recorded by people and machines for only the past 200 years. How then is it possible to know the climate of the Earth anytime in the past, even before recorded history? The answer is not in the written word but in the geological word. Though you may not have considered it, the Earth is a giant book just waiting to be read. Though it is not an easy book to "read," and one that requires an education in interpreting geological evidence from the past, it is none-the-less fascinating. As a wise man once said, "Nature often talks in a very soft voice. It talks in a foreign language and frequently with a lisp. We must learn not only to listen but to hear." Geologists and other scientists are involved in interpreting that book. The layers of rock, the ocean sediments, the rings of trees, the structure of ocean coral, and the annual layers in a glacier are the language that need to be understood.

Ocean Coral

Coral, like many animals, are very sensitive to changes in climate. When the climate changes an animal has three choices; to adapt, to move if that is possible and there is anywhere to go, or to die off. Throughout time animals have been doing all three of these things. There are as many adaptive behaviors as there are different organisms. When it gets cold, animals grow thicker coats while others hibernate. Some birds for instance migrate seasonally because of temperature change and food availability. Many organisms have permanently moved to new locations. Because of their method of locomotion and the availability of favorable conditions elsewhere, moving has often been met with different levels of success. Climate change for many organisms has meant death. Many of the mass extinctions throughout time have been attributed to climate change. But even if the organism itself dies, some evidence of the existence may survive through time.

Coral are animals. They may look like plants but the outside structure is their home not the true organism. Coral are small fleshy creatures that build **limestone ($CaCO_3$)** homes that may resemble a branching tree. After the coral dies, the home remains. The limestone homes are in fact very durable and many fossil corals have been found. Throughout the last five hundred million years, coral have existed. The limestone, from which their homes are constructed, comes from the shells of other deceased organisms that live in the ocean known as foramininfera. These are microscopic organisms, some of which are **phytoplankton** (plants), and some of which are **zooplankton** (animals). Most corals build their homes in the ocean, in warm shallow (<20 m) water. As each coral grows it builds a home size appropriate to the amount of available food and appropriate temperatures. During times of cooler temperatures (ocean water) or less abundant food, the coral build smaller homes. During times of warmer ocean temperatures and more abundant food, the coral build larger homes. When each coral dies, its home becomes the building foundation for the next generation of coral. Thus, coral mats can become very thick with the remains of **paleocoral** (ancient coral). A core sample can then be drilled from these coral mats. The core sample can then be interpreted and the data used as an indicator of the paleoclimate record. Since some coral have existed since the **Cambrian Period,** paleocoral dating has a very good long record of paleoclimates.

Dendrochronology

Dendrochronology is the study involved with interpreting the rings of trees. As trees grow, they get taller and each limb gets thicker. The only part of a living tree that is actually alive is the new outside ring, which is added during the summer growing season, called the cambium. The inner part of all non-tropical trees is “dead” and no longer participating in the growth process. The rings that are seen in trees are due to the fact that the trees lie dormant during the winter season. A tree ring represents an annual layer that the tree added during the summer growing season. Since there are no seasons in the tropics, tropical trees do not have tree rings (there are actually a few deciduous tropical trees that lose their leaves). Tree rings are obtained by either cutting a tree down (not the best way) or by using a tool called a Swedish Borer with which you can take a small core sample of a tree. The core sample is from the outside ring into the center of the tree. Remember that only the thin outside ring is “alive” but remember to replace the core when you are finished to prevent insects from entering, and destroying the tree. The easiest observation to make is that the rings are not the same size as each other. Some rings may differ in thickness by a factor of 10 or more. The large, thicker rings indicate prosperous summer growing seasons, and the thin rings represent poor summer growing seasons. In this way, tree rings can indicate paleoclimates. Good seasons are interpreted as warm, wet, years and bad seasons as cold, dry years. Unfortunately, trees do not live very long relative to the geologic record, and only recent paleoclimates can be interpreted. The oldest living trees in the world seem to be the Bristle Cone Pines in California, which date back 6,000 years. Other older trees have been found buried in sediment in Tasmania and have provided climate records from between 10,000 to 16,000 years ago and in Germany back to 10,000 years old.

Rock Layers

As with coral and tree ring dating, the science of using rock layers to interpret paleoclimates is simple in concept. Sedimentary rock is rock that has been deposited horizontally, in air or in water. According to the Law of Superposition, each successive rock layer that is deposited is younger than the rock layer below it. This method only gives relative ages. Given a stack of rock layers you could count down into the rock layers and literally count back into time. Rock layers are often thousands of meters thick and thousands of square kilometers in area so, it is no small task in itself especially since you need a hole deep enough to be able to view many rock layers at one time. In places like the Grand Canyon of Arizona, this type of simple investigation is often done. Another problem with this technique is that the Earth is a dynamic place. Rock layers are constantly being eroded and deposited throughout the Earth’s surface. There is no one place on the Earth where a series of rock layers back in time to the beginning of the Earth still exists. But rather, rock is constantly being recycled. Rock that is deposited under the ocean may find itself on the top of Mount Everest subject to erosion.

Throughout the Earth there are rocks that are of very different ages. To date rock to their absolute age, not their relative age due to position on top of each other, a technique know as **radiometric dating** is used. The age dates of these rocks have been “reassembled” and a **chronology** of rocks from 3.95 billion ybp to the present has been identified. Each of these rocks, though of very different rock types from igneous, metamorphic, and sedimentary, contains evidence about the conditions under which they were formed. The best evidence for paleoclimates are rock layers that contain **index fossils.** Index fossils include both animal and plant remains. As with corals and tree rings, fossil organisms (now encased as fossils in rocks) developed or did not develop dependent on the climate. That creates an indicator for scientists to identify periods of climate change and the relative temperature change.

Many fossils are excellent indicators of paleoclimate. Recent developments have been made using pollen from paleoplants. **Gymnosperm plants**, such as the modern day pine trees, released large amounts of pollen into the air for the purpose of fertilizing their eggs. Gymnosperm trees are either male or female. For the sperm cells to get to the egg cells (in the pine cones of **coniferous** or evergreen trees) billions and billions of dust like sperm are released into the air, a few of which will hopefully soar to the correct place. Many land on our cars and give us allergic reactions when inhaled but the system obviously works as seen by the number of conifers. This pollen finds its way everywhere including lakes, ponds, and bogs where it settles to the bottom and becomes incorporated into the sediments. The sediment collected, usually in core samples, from any lake bottom will then contain the pollen of all of the plants that inhabit that area. Since different plants grow in different areas depending on their tolerance of temperature, the pollen found in the core sample will indicate what the relative temperature was depending on the types of plants that grow there. Pollen grains are very small and require a trained eye to find, but many other pieces of organisms can be found in the muck at the bottom of any pond (check the bottom of your shoes, or your mom’s carpet). Climate evidence from pollen samples has generated climate data for interpreting back millions of years. The most complete set of data is accurate for the past few hundred thousand years.

Ocean sediments

Deep ocean sediment data is more difficult to collect than many other forms of data. Obviously, the difficulty in collecting a core sample of sediment from under thousands of feet of water presents a few difficulties. The sediments are collected by drilling core samples, using drilling rigs mounted on large floating vessels, offshore in the deep ocean. These sediments are a collection of fine materials from the limestone shells of Foraminifer and/or as

eolian material held in suspension and eventually settled to the bottom, or formed under the ocean during undersea volcanic events.

Deep-sea sediments, since they are largely derived from plants and animals are very good indicators of climate change. Some foraminifer have a particularly odd behavior as a response to climate change. Their shells (foraminifer are zooplankton) are formed with either right hand or left hand twists depending on ocean temperature. The sizes of plankton also demonstrate the relative water temperature, the bigger the plankton the warmer the water. In general though, plankton are useful as climate indicators because of the type of species found as fossils in the sediment cores. Plankton react the same way as terrestrial plants and animals in that certain species are better adapted to the environment and they serve as index fossils for different temperature environments. From deep-sea sediments, a time sequence that runs from 250,000 ybp to the present has been identified.

Ice Cores

Ice cores provide the most detailed climate record available in the paleoclimate archive system. Ice cores have been drilled in Greenland, Antarctica, Asia, South America, Alaska, and just about everywhere that glaciers exist. These cores contain information about the atmospheric concentrations of dust, dissolved isotopes, and gas throughout the 450,000 years. As snow falls on a glacier it traps with it the gases and dust particles that are present in the atmosphere. As the snow is converted into glacial ice, these gases and dust particles are trapped. Though gas can migrate through the upper layers of the ice column, each yearly layer of snow/ice contains the type and concentration of gas and dust present in the atmosphere at the time the snow fell. Thus, scientists literally count their way back through time as they count down through the annual snow layers, the volcanic tephra layers, and the fall-out from the 1950s and 1960s nuclear bomb (“bomb layers”) test to a specific time in the past. Then they can sample that ice and derive from it the types and concentration of any gas or dust that were in the atmosphere when that layer first fell to the glacier as snow. This gives an incredibly accurate and detailed record of the conditions of the atmosphere in the past. Imagine, collecting a sample of ice and dropping that ice sample into your lemonade and taking a drink with air from the time that General Washington or even Neanderthal man were alive and breathing. Try and order that at the corner restaurant!

Ice coring is done from drilling rigs set up on top of a glacier. Scientists drill tens to thousands of meters deep into the glaciers in 0.5 to 5 meter (m) long increments. Depending on the size and location of the drilling project, ice/firn cores are carried to rooms dug into the glacier and partially analyzed on site or shipped back to drilling institution’s home facilities and analyzed there. The purpose of digging rooms into the glacier is to keep the ice cores from melting and maintain the composition of the ice. Some of the dust materials that can be extracted from an ice core and evaluated are sodium (Na) and calcium (Ca) (Figure 53: Greenland Ice Sheet Project 2 calcium record).

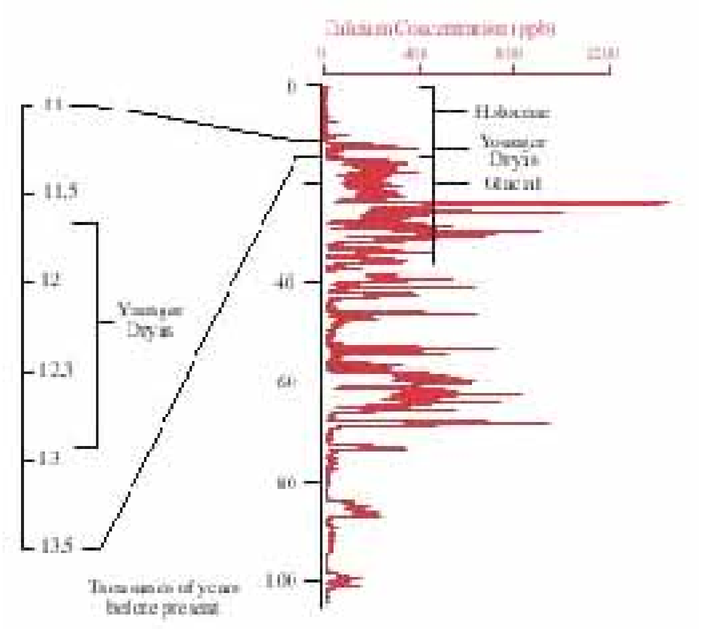

Fig. 53: High resolution from the Greenland Ice Sheet Project 2 ice core indicates the relative amount of dust in the atmosphere over Greenland and thus documents other abrupt, frequent and massive changes in the climate that characterize the glacial portion of the ice core record. Figure modified from Mayewski et al. (1994, 1997).

Gases that are extracted and evaluated from bubbles in the ice are carbon dioxide (CO_2) and methane (CH_4). Some gases that are extracted and analyzed, such as ammonia (NH_4) are soluble in the ice (water). There are also gases that are soluble in air and ice (water) such as the O^{18} and O^{16} isotopes of oxygen. Both types of oxygen O^{16} and O^{18} are always present in the atmosphere, water, and ice. O^{16} accounts for about 95% of the oxygen isotopes present but the ratio of O^{16} to O^{18} varies. The isotope O^{18} has two more neutrons than O^{16} and is therefore a heavier molecule. This makes it easier for O^{18} to condense from water vapor and fall as precipitation than it is for O^{16}. Thus after a rain or snow storm a higher ratio of O^{18} to O^{16} has fallen to the ground. The ratio of O^{16} to O^{18} also varies due to temperature. Using these known changes, the ratio of O^{16} to O^{18} can be used as a proxy for temperature. From the ice cores data, scientists can then determine the relationship between the concentration of a green house gas or a quantity of dust and the temperature of a paleoatmosphere (ancient atmospheres).

There are many recent ice coring expeditions that have revealed startling discoveries about paleoclimate change. The Greenland Ice Sheet Project 2 (GISP2), completed in 1993, drilled to a depth of 3,053 meters at the summit of the Greenland Ice Sheet. This ice core has been annually dated back to 110,000 years ago. From this ice core record scientists have developed numerous theories about the atmospheric chemistry and atmospheric circulation patterns in the Northern Hemisphere. The GISP2 record was complemented by an ice coring project by the European scientific community called the Greenland Research Ice Sheet Program (GRIP) and many other deep ice coring programs in the northern and southern hemispheres. A current ice coring program in Antarctica called the International Trans-Antarctic Scientific Expedition (ITASE) is underway with the cooperation of fifteen nations to drill shallow ice cores (<60 meters) and interpret the past 200 - 500 years of Antarctica's paleoclimate. Antarctica is very large (about one and one-half times the size of the United States) and very little is know about its spatial (across distance) and temporal (through time) climate variability. ITASE hopes to develop a 3-D map of Antarctica's climate. The US component of ITASE will continue drilling ice cores in West Antarctica during the austral summer from 1999 through 2003 (see resource list for information on US ITASE).

From the data collected from coral, trees, rock layers, deep-sea sediments, and ice cores, scientists can interpret the conditions that were present in the Earth's paleoatmosphere. Our present atmosphere contains all of the same gases, soluable ions, and dusts but maybe at different concentrations. From this, we can interpret how their presence indicates and controls temperature, precipitation, and ultimately the Earth's climate.

The data collected so far by scientists indicates that climate is very dynamic and sensitive to change. Global climate has varied greatly over time and at times has even changed by 8 - 10 ^{o} C in less than a few decades. Throughout the past several hundred thousand years there have been many **Rapid Change Climate Events (RCCE)**. The **Younger Dryas Event** is just one such example of a rapid return to glacial conditions. Evidence indicates that sudden, short term, climate changes have been the rule in the past, not the exception. This holds true not only during glacial periods but also though interglacial periods. During the present interglacial warm period, global climate reached its warmest 7,000 – 9,000 years ago. Approximately on a 1,500 year periodicity, the Holocene interglacial period cycles back and forth between warming and cooling. The most recent cooling cycle being the previously mentioned Little Ice Age started around 1400 AD.

Climate has affected human history since there were humans on the face of the planet. Human migrations, industrial innovations, diet, disease, agricultural developments, and work patterns are all dictated by the weather. So, is there really global warming? Has the increased carbon dioxide and methane levels in the atmosphere produced the latest round of warming that the globe has experienced? Actually, most data says yes, anthropogenic global warming does exist but also natural climate is very important as seen from ice core records. The next changes resulting from humans are uncertain.

Sea Level Change

Much of the data for the dating of the advance and the retreat of glaciers stems from evidence of past sea level change. As already mentioned, the hydrologic cycle of the Earth is a closed system. The water that is used for the creation of glaciers comes from lakes and oceans. As glaciers are created sea level drops. This is called **eustatic sea level change** which is the change of the sea level as the position (up and down) of the land is unchanged. The addition of glaciers to the land surface also causes the land to be depressed downward and actually lowers the position of the land. When this happens the relative position of the land to the sea has not noticeably changed because both the sea level and the land level have gone down. The density of continental crust is less than that of oceanic crust (which is why the continents "float" on the oceanic crust) and after the glaciers have melted away the land surface begins to rebound upward. This is called **isostatic change** which is when the land surface changes independent of the sea level. There is another way to change the level of the land surface and that is through tectonics, e.g. mountain building, plate tectonics, faulting, or folding. An interesting case in point is the island of Newfoundland which is experiencing both eustatic and isostatic change. The northern end of Newfoundland is still rising by isostatic rebound since the last glacial period. The southern end of the island is experiencing eustatic sea level change as that portion of Newfoundland is not moving but is displaying the rising sea level that most of the world is displaying.

So, we have both eustatic change when the water level changes independent of the land and isostatic changes that occur when the land level changes independent of the sea level. Both types of changes will give the appearance that the sea level has changed relative to the land surface level. Scientists must be very careful when interpreting sea level changes from their data and distinguish between these two types of changes. In many places around the world scientists are using the position of ancient beaches or coral reefs to interpret sea level change.

Currently the average sea level around the Earth is rising by approximately 2 centimeters per year. The majority of this increase in sea level change though is not from eustatic or isostatic sea level change but actually from **thermal expansion**. In the same way that most materials expand when they are heated the Earth’s oceans are warming up and expanding. Even after all of the world’s glaciers were to melt into the oceans (an increase in sea level of about 60 meters) sea level would continue to rise because of thermal expansion.

Final Thoughts

Hopefully this book has provided you with some insight into how glaciers are both affected by climate and how they affect climate, and has answered the first questions offered in the introduction of this book; What are glaciers?, Where are glaciers found?, Who studies glaciers?, and Why study glaciers? The data that is currently being collected by scientists on glaciers around the Earth will continue to provide valuable insights about the many climate forcing variables and how our life styles must continue to change as we try to adapt to our changing Earth’s climate.

Appendix A: Research Facilities/Teacher Resources

Research/Experience Programs

1. The Juneau Icefield Research Program, http://www.mines.uidaho.edu/glacier
2. Earth Watch, http://earthwatch.org/t/Texpeditions.html
3. Teacher Experience in Antarctica, NSF, http://TEA.rice.edu
   http://www.glacier.rice.edu

Films:

1. Living Glaciers, Films for the Humanities, 1-800-257-5126
2. Glacial Deposits, “
3. Valley Glaciers, “
4. Cracking the Ice Age, NOVA, 1- 800-441-NOVA
5. Warning from the Ice, “
6. El Nino, “
7. A Drft in the Gulf Stream “
8. Vikings in America, “
9. In the Path of a Killer Volcano, “
10. Oceans in Motion, National Geographic Edventures, 1-800-368-2728
11. Glaciers on the Move, “
12. Atmosphere: On the Air, “
13. Investigating Global Warming, “
14. Ozone: Protecting the Invisible Shield, “
15. Technology’s Price, “
16. Greenland Ice Sheet Project 2, University of New Hampshire, 603-862-0322
17. Glaciers, EME Corporation, Danbury, CT, 06810
18. Newton’s Apple: Glaciology video and activities, TBA
19. Escape from Antarctica: Shackelton, National Geographic Explorer
20. Alone on the Ice: Byrd in Antarctica, Kultur International Films Ltd., Inc.,732.229.2343
21. Shackelton: Escape from Antarctica, Kultur Films “ , 732.229.2343
    “

Interactive Antarctic Expeditions

4. International Trans-Antarctic Scientific Expedition (ITASE)
   http://www.secretsoftheice.org
   Includes classroom exercises
5. The Brancroft Arnesen Expedition
   http://www.yourexpedition.com
   Includes classroom exercises

Internet

1. GISP2 Homepage- http://www.gisp2.sr.unh.edu/GISP2
2. GRIP Homepage- http://www.esf.org/lp/lp_013.htm

3. University of Buffalo Science and Engineering library http://ublib.buffalo.edu/libraries/units/sel/sources/climateweather.html#cl
4. National Snow and Ice Data Center- http://www-nsidc.colorado.edu
5. Goddard Institue for Space Studies- http://www.giss.nasa.gov
6. National Climate Data Center- http://www.ncdc.noaa.gov
7. US Global Change Info Center -http://gcrio.ciesin.org/overview.html
8. EPA Global Warming - http://www.epa.gov/globalwarming/climate/index.html
9. http://www.earth.agu.org/revgeophys/firor00/node2.html
10. http://www.atmos.anl.gov/GCEP
11. http://www.nsf.gov/od/lpa/
12. http://gcmd.nasa.gov/pointers/edu.html
13. http://www.giss.nasa.gov
14. http://www.ncdc.noaa.gov
15. http://www.usgs.gov/
16. http://www.esd.ornl.gov/projects/gen/transit.html
17. http://www.esd.ornl.gov/projects/qen
18. Dendrochronology http://www.ltrr.arizonia.edu/people/henri/lorim/lori,htm
19. Dendrochronology http://www.pbs.org/audubon/wildwings/dendro.html
20. Antarctic Meteorology Research Page http://uwamrc.ssec.wisc.edu/amrchome.html
21. ITASE http://www.secretsoftheice.org
22. http://www.clivar.ucar.edu/related.html
23. Danish GRIP project. http://www.glaciology.gfy.ku.dk/Icecores.htm
24. Bancroft/Arnesen Expedition http://www.yourexpedition.com/fleft.html
25. NOAA publications/products (polar slide set) http://www.ngdc.noaa.gov/ngdc.html
26. C-130 aircraft fact sheet http://www.af.mil/news/factsheets/C_130_Hercules.html
27. Antarctica maps/gifts http://www.antarcticconnection.com/
28. Antarctic “Cod” http://www.afprotein.com/noto.htm
29. The Antarctic Circle- resource for historical, cultural, literary, artistic aspects of Antarctica http://www.antarctic-circle.org/
30. Wired Antarctica educational material http://www.geophys.washington.edu/People/Students/ginny/antarctica/people.htm

CDs and Activities

1. Greenland Ice Sheet Project 2, Climate Change Research Center, University of New Hampshire, Durham, 03856, 603-862-0322, mst@unh.edu

2. National Snow and Ice Data Center: Into the Arctic: Information and educational activities for studying climate, nsidc@kryos.colorado.edu
3. Climate Card, Climate Change Research Center, University of New Hampshire, Durham, New Hampshire, 03856, 603-862-0322, mst@unh.edu
4. The Climate Game Climate Change Board Game, TBA
5. National Science Foundation, Polar Connections, National Science and Technology Week, National Science Foundation, 4201 Wilson Boulevard, Room 1245, Arlington, VA, 22230, nstw@nsf.gov, http://www.nsf.gov/od/lpa/nstw/start.htm
6. Forecasting the Future: Exploring Evidence for Global Climate Change, NSTA Publisher, ISBN: 0-8355-139-7
7. Global Warming and the Green house Effect, Lawrence Hall of Science, U. of California, Berkley, 1-510-642-777
8. Global Systems Science, NASA Publication, TBA
9. Glacier,El Nino, Weather Activities – http://sci.lib.uci.edu/SEP/CTS/canyon.html
10. Embracing Earth: Global Change CD-ROM –http://www.in-media.com ARCSS at NSIDC- http://arcss.colorado.edu
11. WDC_A Paleoclimatology Web Site: http://www.ngdc.noaa.gov
12. Maedias-France- http://medias.meteo.fr/paleo/icecore/greenland/summit/index.html

Varve Materials

1. Ulrich's Fossil Gallery, Fossil Station, Kemmerer, WY, 83101, 307-877-6466
2. Burnham Petrographics, 846-1 South Myrtle Ave, Monrovia, CA, 91016, 800-772-3975, burpet@linkline.com
3. The Weather Underground, Weather Reports for current Antarctic conditions http://autobrand.munderground.com/global/AA.html

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Kendall, D.L., 1987, Glaciers and Granite, Down East Books, Camden, ME, 240p.

Kimmel, E. C., 1999, Ice Story: Shackelton's Lost Expedition, Clarion Books (ages 6-12)

Morrison, M.C., 1994, Climate in the Ice, Yearbook of Science and the Future, *Encyclopedia Britannica*, 190-207.

Pielou, E.C. 1991, After the Ice Age: The Return of Life to Glaciated North America, University of Chicago Press, Chicago, IL, 366p.

Shackelton, E., 1988, Aurora Australis, Airlife Publishing Ltd., Shrewsbury, England. ISBN 1 85310 060 9

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Dr. Jack Ridge, Tufts University
D. Zachary Smith, Wright Center for Innovative Science Education, Tufts University
(current- Climate Change Research Center, University of New Hampshire)
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Glossary

Ablation: The combined processes by which a glacier wastes (melts).

Ablation Triangle: Instrument used to measure the amount of ablation that takes place on the glacier’s surface.

Ablation Zone: The area below the Firn Line where the previous winter’s snow has melted away to expose glacier ice.

Accumulation: The adding to of snow.

Accumulation Zone: The area above the Firn Line, at higher elevations, where the most snow is added each winter and some of the last year’s snow (firn) remains and does not melt away during the summer season.

Albedo: The percentage of incoming radiation that is reflected by a natural such as the ground, ice, snow, water, clouds, or particales in the atmosphere.

Anthropogenic: Man made, In this case, anthropogenic greenhouse gases.

Annual Layers: Layers of snow, firn, or ice, that show the accumulation and ablation of one year, from one summer ablation season to the next summer ablation season.

Arete: A sharp ridge, often between two mountain tops.

Average Annual Temperature: The calculated average of the temperature in an area for one full year.

Basal Melt Water: The water that flows between the bottom of the glacier and the bedrock surface.

Bedrock: Any solid rock exposed at the surface of the Earth or overlain by unconsolidated material.

Botanists: A person who studies plants.

Calving: When large blocks of ice, break apart from, and fall off of a glacier.

Cenozoic Era: The period of time between 65 million years ago and today.

Chronology: A sequence of dates and events.

Cirque: A bowl shaped depression on the side of high mountains caused by the erosion of a glacier.

Cirque Glacier: A small glacier on the sides of mountains of mountains occupying a cirque.

Climate: The average weather over a long period of time, usually 30 years.

Compressional Flow Area: Areas where the slope angle allows the glacier to consistently push and compress the ice.

Conifers: Any of various predominantly evergreen, cone-bearing tree.

Convection Current: A circular circulation of air or water where warm air rises up, cools, sinks down and returns up as it is warmed in a continuous cycle.

Couloir: A deep mountain side gorge or gully.

Crevasse: Breaks or fissure in the surface of a glacier formed under stress in extensional flow areas. Generally, only to maximum of 50 m deep.

Critical Thickness: A measure of the thickness of rock needed to prevent the conduction of solar radiation from the top of the rock surface to the bottom of the rock surface, thus insulating the ice beneath the rock.

Cryoconites: Small holes, up to 2 cm across by 10 cm deep, that are melted into the surface of a glacier in the abaltion area by small rock particles.

Delta: Fan shaped (the Greek word delta means triangular) deposits of debris at the mouth of rivers.

Dendrochronology: The study of the rings of trees.

Density: A measure of the mass per unit area of a material (g/cm 3).

Diagenic Ice Mounds: Conical or pyramid shaped mounds, up to 2 m high, of ice covered by a thin coating of rock material. Formed as a coating of rock material insulates the underlying ice from melting as fast as the surrounding ice.

Downwasting: The diminishing of glacier ice in thickness during ablation.

Eccentricity: The deviation from the expected norm, in this case a circular orbit.

Ecliptic: The plane of the Sun’s equator.

Eemian Period: The last interglacial warm period, lasting from 130,000 ybp to 110,000 ybp.

Ellipse: A geometric shape derived from a conic section neither parallel or perpendicular to the base.

El Nino: An ocean/atmosphere circulation pattern that occurs in the eastern Pacific Ocean as a result of upwelling deep seawater.

Englacial: Material contained within the ice of a glacier.

Equilibrium Line Altitude (ELA): The line that marks the average boundary between the accumulation area and the ablation area at the end of the summer.

Erratic: Any rock that has been carried by a glacier or water and is deposited in an area where the rock’s type is different than the surrounding rock type. Some glacial erratics may reach 10 meters in diameter.

Eolian: Carried by the wind.

Epochs: A division of geologic time. A sub-category of geologic periods.

Esker: A long, serpentine hill of gravel and sand, accumulated in internal glacier water tubes and exposed after the glacier has completely ablated.

Eustatic sea level change: An upward or downward change in the position of mean sea level, e.g.

Extentional Flow Areas: Areas where, because of topographic highs over which the glacier flows, the glacier ice is extended and the ice is pulled apart forming crevasses.

Extrapolate: To extend beyond.

Feldspar: A group of abundant rock forming minerals of the general formula MAl (AlSi)3O8, where M can be Na, Ca, K, Ba, Rb, Sr, and Fe.

Fetch: The distance that the wind blows unimpeded by any obsticle.

Firn: A German word meaning last year’s snow. The snow from one winter season that lasts through the ablation season to the following winter accumulation season.

Fluvial: Of or pertaining to water, eg. water deposited sediment.

Frost Heaving: The process by which water freezes, expands, and pushes the surrounding material in the direction which offers the least resistance. Generally refers to locations where the ice has pushed up. Often occurs on roads and sidewalks.

Frost Wedging: See frost heaving. The process of rock material being broken off of cliff faces due expanding ice.

Geographer: A person that studies the Earth and its features.

Glacial Geologists: A person who studies the effects that glaciers have on the land surface.

Glacial Lake: Lakes that form from glacial melt water below the terminus. Often between the terminal moraine and the glacial terminus.

Glacial Lake Agassiz: A lake, that once existed close to present Lake Superior, that formed from the melting of the Laurentide Ice Sheet in Canada, approximately 13,000 years ago.

Glacial Period: A period of time when cold, dry conditions exist that enhance the formation and spread of glaciers.

Glacial Polish: The smoothing of the bedrock surface by the action of glacial erosion.

Glacier: A mass of snow and ice that exists over many years and has the ability to flow.

Glacier Flour: Rock that is ground to a fine powder under a glacier.

Glaciologists: A person who studies glaciers.

Global Positioning System (GPS): A system used to find locations on the Earth's surface using a network of satellites that orbit the Earth.

Gymnosperms: Conifer trees and other plants that do not enclose an egg in an ovary.

Heinrich Events: Cold events within glacial episodes first determined by evidence from ice rafted debris in deep sea sediments.

Hexagonal: A six-sided shape.

Holocene Epoch: The geologic time from 11,500 years ago up to the present.

Horn: A horn or sharply pointed shape of a mountain top formed by the erosion of glaciers.

Ice: A mineral of the composition H2O which forms in crystal shapes that can vary from delicate hexagonal forms to blocky forms.

Ice Cap: Very large, massive glaciers that cover the poles cover, for example the Arctic Ice Cap.

Ice Caves: The entrances to the glacial plumbing system exposed on the margins of a glacier.

Icefield: Large accumulations of a number of connected smaller glaciers that cover 100's of square kilometers, for example the Juneau Icefield, Alaska.

Ice Rafted: Carried on top of the glacier.

Ice Sheet: Large accumulations of a number of connected smaller glaciers that cover 1000's of square kilometers, e.g. the Greenland Ice Sheet.

Igneous Rocks: Rocks that at one time were totally molten. Literally means "from fire".

Index Fossils: Fossils that only lived for a short period of time and are easily identified used to help date rock layers.

Insolation: The energy received from the sun.

Internal Deformation: The movement of individual ice crystals along the flat horizontal planes of other ice crystals.

Interglacial Period: A period of relatively warm climate when glaciers rarely form but tend to rapidly downwaste.

Interstades: Warm events during glacial periods.

Isostatic change: An upwardward or downward change in the position of the land surface.

Kame: Debris deposited by water between the valley walls and a down wasting glacier.

Kame Terraces: Debris that was deposited by flowing water between the margins of a glacier and the valley walls which resembled a level terrace. Often up to a few miles across.

Katabatic Wind: Cold winds that blow down glaciers due to the density of cold air.

Kettle Pond: A pond formed from the melting of a large block of stagnate glacier ice that calved off of a glacier.

Lateral Moraine: Rock debris piled on the side margins of a glacier.

Laurentide Ice Sheet: The ice sheet that formed during the Pleistocene Epoch which covered central and eastern Canada and the United States approximately north of 40 degrees north latitude.

Law of Superposition: States that the rock layers on the bottom are older the rock layers above..

Leeward: The side opposite from the direction that the wind is blowing from.

Limestone: A solid rock material, formed in layers in the ocean from the shells of dead plankton, with the composition Calcium Carbonate ($CaCO3$).

Little Ice Age: The period of time between 1350 AD and 1870 AD when glaciers expanded and the global climate conditions were similar, though not as cold as a glacial period.

Mass Balance: A measurement of the difference between the accumulation and the ablation of a glacier. Either positive (accumulation exceeds ablation) or negative (ablation exceeds accumulation).

Medial Moraine: A moraine formed by the converging of two glaciers. The lateral moraines on the two glaciers combine to form a medial moraine in the middle of the new, larger glacier.

Mesozoic Era: The time period between 225 million years ago and 65 million years ago.

Metamorphic Rocks: Rocks that have undergone chemical change through heat and pressure.

Meteorologist: A person who studies weather and climate.

Moraine: The deposits of rafted and/or eroded debris along the margins of a glacier.

Moulin: A hole or tunnel in a glacier through which melt water flows. Tunnel systems can be very extensive in glaciers and carry melt water from the surface of a glacier to the bottom and terminus of a glacier.

Mountain Glacier: Those glaciers that form at higher elevations in the mountains. Most often forming on the north and east sides of the mountains where abaltion from solar radiation is less.

North Atlantic Oscillation: Ocean/atmosphere circulation pattern that occurs in the Atlantic ocean.

Nunatak: Innuit word for rock island. The exposed peaks surrounded by massive glaciers.

Obliquity: The 44,000 year cycle of the change in the angle of the Earth’s axis.

Paleo: Prefix meaning ancient.

Paleozoic Era: The time period between 650 million years ago and 225 million years ago.

Patterned Ground: The group term for the more or less symmetrical forms such as nets, circles, stripes, polygons, and steps that are characteristic of, but not confined to, mantle subjected to intensive frost action.

Penitents: Very large, deep, sun cups common on high altitude, low latitude glaciers. They resemble people standing and bent over in pray.

Permafrost: Ground that is permanently frozen below the surface all year long.

Piedmont Glacier: Glaciers that are formed as cirque glaciers expand and flow down into the hills and valleys.

Phytoplankton: One celled microscopic plants that form hard limestone shells and live in the water.

Plastic Flow: When a material changes shape slowly without breaking but breaks if the movement is too fast. In contrast to elasticity, plastic material does not automatically return to its original shape once deformed.

Pleistocene Epoch: The geologic time from 2,000,000 ybp to 11,500 ybp.

Plucking: The removal of rock by ice, usually on the down valley sides of a rock outcrop.

PreCambrian Era: The length of geologic time from the beginning of the Earth (4.6 billion ybp) to the beginning of the Paleozoic Period (66 million ybp).

Precession of the Axis: The wobble of the Earth’s rotation on its axis.

Pressure Melting Effect: The effect of ice melting after it is put under pressure..

Quartz: A rock forming mineral of the composition, SiO2.

Quaternary Period: The geologic time period from 2 million ybp to the present. The Quaternary Period includes both the Pleistocene Epoch and the Holocene Epoch.

Radiometric Dating: The dating of rock or organic material using the half-life decay of radioactive isotopes.

Rafted Debris: Any material that is rafted or carried by a glacier and then subsequently dropped as the glacier downwastes

Rapid Change Climate Events: When the average global temperature has risen or fallen by at least 6 degrees Celsius.

Rock Flour: Rock material that has been pulverized by a glacier and ground down into rock dust.

Rock Pedestals: Columns of ice that support rocks. The pedestals and rocks may be small, from a few centimeters in size to many meters in size.

Rock Rings: Rings of rocks that are formed on the ground surface in periglacial areas. Formed when rocks are lifted by frost heaving and are moved slightly downhill each year until rings of rocks form around small rises in the ground surface.

Sedimentary Rock: Rock that has been deposited, horizontally, in air or water.

Slope: A measure of the vertical change in elevation relative to the horizontal change (rise over run, Y over X).

Snow Line: The line between the accumulation area and the ablation area.

Stades: Glacial periods

Stratified: Sediments that are deposited in layers.

Stratugi: Snow dunes formed on ice sheets.

Striations: Long grooves in the bedrock formed by the movement of subglacial material scratched along the bedrock surface. Striations show the direction of past movement of the glacier.

Subglacial: At the bottom of a glacier, as in subglacial rock.

Sublimation: The movement of a solid directly to the gas phase.

Sun cups: Concave depressions, from a few centimeters to 10’s of centimeters in diameter, that form on the surface of the accumulation area of a glacier, due to ablation from solar radiation. Sun cups patterns resemble small waves on a lake.

Superglacial: On the top of a glacier, as in rafted debris, or superglacial streams.

Surging Glaciers: A glacier that moves very rapidly.

Tank: Rises in the ground surface due to frost heaving in periglacial areas.

Tarn: Ponds formed from melt water in ice abandon cirques.

Terminal Moraine: Debris piled at the terminus of a glacier.

Terminus: The down glacier end of the glacier.

Theodolite: A surveying instrument that works like a telescope and compass combined to measure angles.

Transit: An instrument that measures a horizontal and vertical line. Used to survey locations.

Troposphere: The lowest level of the Earth’s atmosphere, from ground level up to 11 kilometers.

Tor: Depressions in the ground surface in periglacial areas.

“U” Shaped Valley: Glaciated valleys that have a cross sectional profile that resembles a “U”. Differs from fluvial valleys that have a characteristic “V” shape.

Varves: Clay sized material deposited in glacial lakes throughout the summer and winter (varved couplets).

Windward: The side the wind is blowing from.

ybp: Years Before Present. Counting from now back into time.

Younger Dryas Event: An intense cooling period and return to glacial conditions between 12,900 ybp and 11,500 ybp.

Zenith: The point in the sky directly overhead.

Zooplakton: One celled, microscopic animals that form limestone shells and live in the water.

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