Glaciation and the Ice Ages

Water: So familiar in both states, yet the strangest substance of all! All due to the electrical polarity of the molecule, which enables it to link weakly to its neighbours – randomly in liquid, but open network in solid ice.

The very unusual properties of water are the result of this weak hydrogen bonding between the water molecules, leading to high melting and boiling points, high density – and solid less dense than liquid!

So ice is more compressible than water, and will melt under high pressure. Ice can exhibit **plastic flow** as well as **brittle fracture.**

The start of glaciation:

- It's winter – snow falls; the next summer, it doesn't all melt.
- The next winter new snow falls on old snow (firn), which has partly melted and re-crystallised into larger clusters.
- If this is repeated over many years, the packed snow turns to ice, and an ice sheet forms.
- Ice sheets can grow to cover a mountain range, and several can unite to cover even a continent over thousands of years.
- Around the edges of the ice sheet, ice flows down slope to form glaciers
- In polar regions, the ice is frozen right through, and its base in direct contact with solid rock below.
- In temperate regions, glaciers tend to have more meltwater within and below them, and flow more readily.

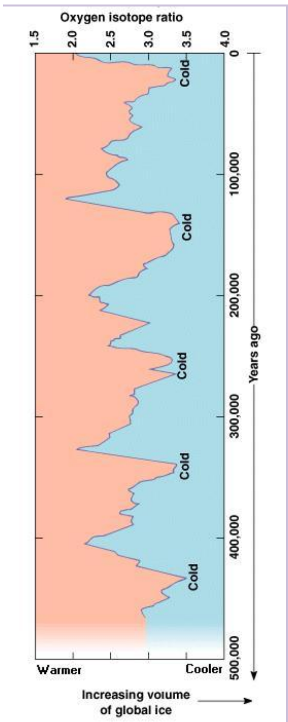
Scientists involved in early work: Louis Agassiz, James Croll

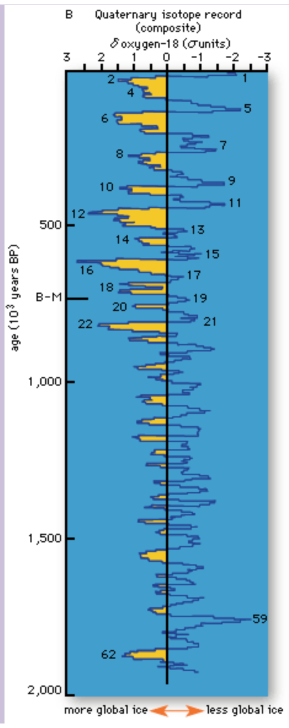
Climate & Oxygen Isotopes:

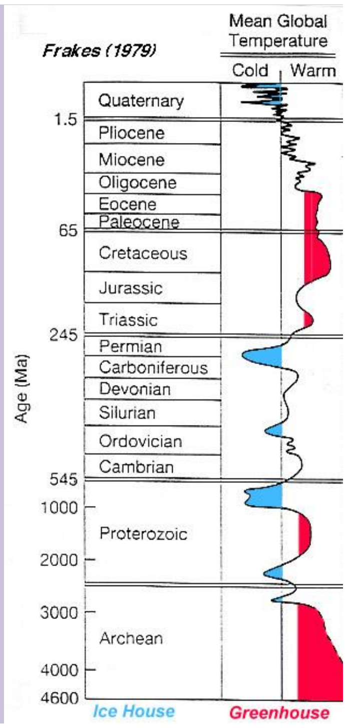
- Some marine organisms hold a record of climatic temperature changes in their shell composition.
- In life oxygen is taken from the water to build the shell of calcium carbonate, $CaCO_3$.
- Oxygen atoms exist as 3 stable isotopes O-16 (99.7%) O-17 (0.04%)and O-18 (0.2%).
- The proportion of O-16:O-18 in water taken up by marine organisms is sensitive to temperature, so can be used to measure past temperatures.
- Laborious work on zooplankton fossils in deep sea sediment cores has built up past temperature records for millions of years!
- $H_2{}^{16}O$ evaporates from the ocean more readily than $H_2{}^{18}O$, so rainwater is enriched in O-16.
- When snow falls on land in a glacial period, O-16 is trapped, enriching the oceans in O-18.
- When the climate warms again, ice on land melts and flows to sea, re-supplying the O-16 to the oceans again.
- So past O-16:O-18 ratios provide a record of temperature changes in the oceans.
- More information can be gained from oxygen isotope ratios in ice cores.

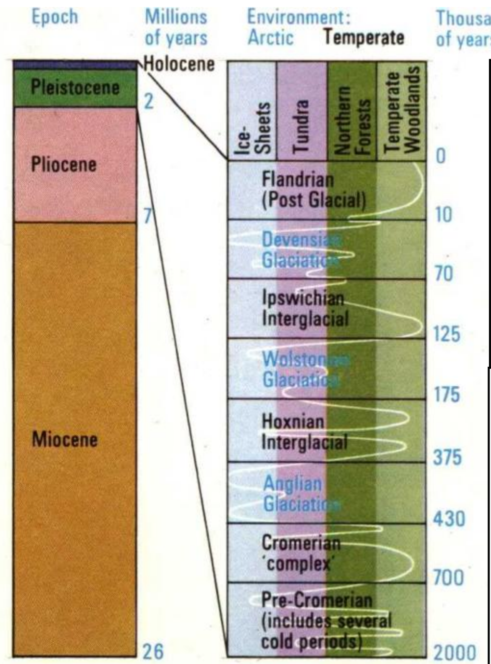
Sea Level and the Ice Ages

- At the peak of the last glacial period, 18,000 yrs ago, the sea level fell by about 100 metres (330 ft) and 5% of all the ocean water was trapped as ice.
- Satellite images at the end of a northern winter still show ½ land and ¼ sea is snow covered, but melts during summer.
- If it did not, but accumulated year on year, next cold period on the way?









100 Subdivisions of Neogene and Quaternary time

Permo-Carboniferous:
No record in British Isles, which were then in their various pieces in equatorial latitudes.
Glacial deposits of that period found in North Africa, which was then in polar latitudes!

Late Pre-Cambrian:
Deposits found in Islay, Jura, Scarba and the Garvellachs!
Also found in northern Ontario

Glacial and Interglacial Periods

- Note the cycles within an Ice Age, as climate cools and warms repeatedly, giving glacial and interglacial episodes.
- We are at present in an interglacial period within the present Ice Age!
- The previous interglacial was 120,000 years ago.
- Even today ¾ freshwater on Earth is locked up as ice
- In the 1970's, research suggested that Antarctica was the key to tipping Earth back into the next glacial, in a short time frame of under 100 years!
- Maximum Ice – 18000 years ago!

Several inter-related causes of Ice Ages

- Throughout time, average temperature on Earth has fluctuated but remained within a narrow band. Last 3 Ma: particularly cold, but for past 10,000 yrs in a warm patch.
- Difference between mean annual temperature in a glacial and an interglacial period is only 10 °C! A fall of 5 °C will tip back to glacial.
- 1867: James Croll, Scottish geologist, argued that climate is influenced by the distribution of oceans and continents and circulation of ocean currents.
- Early Mesozoic (Triassic-Jurassic) super-continent of Pangaea.
- Ocean currents could circulate freely, mixing hot and cold waters effectively.
- So minimal temperature differences and no ice caps at all.
- Last ice age began 2Ma ago, when distribution of continents and oceans was as now.

- Opening of Drake's Passage between South America and Antarctica was crucial.
- Circular current now all round the Antarctic, cutting off supply of warm water and air from north
- Clustering of large continents around North Pole, with high mountains and plateaux.
- The Arctic thus became an inland sea, with land all round it cutting off warm currents.
- James Croll recognized that accumulated snow would reflect back solar radiation, speeding up the onset of an ice age. We'll return to this….
- But meanwhile remember that many other factors may be involved, and we do not have time to cover them all – e.g. inter-planetary dust particles entering the atmosphere.
- 1920: Milutin Milankovitch, a Yugoslav meteorologist measured the solar radiation reaching Earth.
- Linked temperature changes on Earth to three factors occurring in cycles.
- Variations in:
  - the Earth's elliptical orbit around the Sun (2 cycles, 95,000 years and 400,000 years)
  - the tilt of the Earth's axis with a cycle of 41,000 years
  - 'wobble' cycle of 27,000 yrs in Earth's axis due to gravitational interactions with Sun and Moon.
- These 3 cycles occur simultaneously; when they coincide, their effects are very significant!
- Milankovitch calculated interactions of the cycles > solar radiation curves for the past 650,000 yr.
- He compared these with observed climatic cycles and found close agreement.
- Oxygen isotopes ratios match these cycles too.
- So Milankovitch cycles are crucial in causing ice ages to start
- James Croll recognized that accumulating snow would reflect back the solar radiation, speeding up the onset of an ice age. The increased albedo means that 90% of solar radiation is reflected back to space by white surfaces rather than melting the ice/snow.
- So at latitudes above 60°N winter snow will survive the summer.
- This is a positive feedback system, accelerating the deterioration of the climate.
- Just 20 cold summers can lead to a marked build up of snow, and trigger a glacial period!

Cooling the Climate

- Surface and deep water oceanic currents are important in controlling temperatures.
- The temperature of surface waters influences the temperature of winds that blow over them.
- The Polar Front between warm & cold water and thus warm & cold air now located along a line between Newfoundland and Iceland.
- In glacial times the Polar Front was further south between Newfoundland & Portugal.
- Ice formed as far south as the Bay of Biscay.
- Small changes can have big effects in a delicately balanced mechanism!

Ice Ages

- One way to define 'Ice Age' is to consider it as an entire cold period with brief warm interludes.
- Each ice age is a succession of alternating warm and cold times.
- The most recent one in Earth History is known as the 'Ice Age' or the 'Last Ice Age' in the time period known as the 'Pleistocene', and into the present 'Holocene' period up to today.
- During Palaeogene/Tertiary times the Earth had a warm climate.
- Fossils of tropical and sub-tropical plants and animals found as far north as inside the Arctic Circle.
- About 50 to 60 Ma BP, the climate began to cool, temperatures began to fall.
- c.35 Ma BP there was a sharp drop in temperature.
- Glaciers, then ice sheets began to grow on the land of Antarctica, burying it deeply.
- By 3 Ma BP there were permanent glaciers in N. hemisphere.
- Average temperature records show that the past few million years have been much cooler than earlier times on Earth
- In those times, the tropical glaciers of Kilimanjaro and the Andes were mainly absent.
- By contrast the interglacials last only 10,000 to 20,000 years (*we've had 10,000 years so far!)*
- An ice age ends when the alternating cycles stop and the only permanent ice on the Earth is minor, in polar regions and high mountains *(so perhaps we are getting there now after all?).*

The Work of Ice

- Ice is a very effective agent of all of weathering, erosion, transport and deposition!
- The landscape of a glaciated area will have recognizable landforms produced by the ice of the previous ice age.
- But the landscapes of earlier ice ages have been largely obliterated by later erosion.
- So we only see the glaciated landscapes of the Last Ice Age.
- First, consider what the landscape was like before the ice.
- Then see how it has been modified by the ice.
- The highlands of N and W Britain are very different from the lowlands of S and E.
- In terms of bedrock and topography, this was true at the end of the Palaeogene/Tertiary and is still the case after glaciation.

The Palaeogene/Tertiary

- A time of intensive weathering, much of it tropical to sub-tropical in character.
- Removed much of the evidence of previous landscapes in Britain as the products of weathering and erosion were carried out to sea.
- Imposed its own characteristic landscape features which were then subject to glaciation.
- Erosion surfaces in the landscape – so-called 'platforms' at roughly 1000 m (3000ft) and 600 m (2000 ft) above present sea level.
- Produced by uplift, then tilting, finally erosion
- Other such erosion surfaces have been suggested (e.g. 4000 ft level around Ben Nevis and in Cairngorms).

The Imprint of Ice

- The movement of ice has over-printed this Tertiary landscape, leaving both sets of features visible in an entangled present-day landscape.
- But the last glacial period removed most of the evidence of the previous glacial periods!
- In the last glacial period, the weather was drier than in the previous interglacial but still with the most precipitation in the west.
- Ice built up gradually over the high ground as ice caps.
- Valleys were filled with ice, and a tremendous thickness of ice blanketed all.
- This formed an ice dome around 2 kilometres deep, centred on Rannoch Moor.
- Only a few mountain tops poked above the ice, called 'nunataks'.

The Extent of the Last Major Ice Advance

- Boundaries:
  - Orkneys and St Kilda outside the ice.
  - Shetland had its own ice cap.
  - Reached as far south as Birmingham.
- Present landforms are from the very last glacial episode - 22,000 to 13,000 years ago.
- Thicker ice in the west of Scotland, insulating the rocks below, with some meltwater at the bases.
- Thinner ice in the east, colder and frozen at the bases.
- Water at the base caused the ice to move much faster, up to 10 times as fast as over a cold base!
- Some of the water was generated by friction.
- The end result is that the glacial processes were much more severe in the west, with 90% Scottish cirques and 90% over-deepened rock basins.
- Last glacial period peaked about 18,000 years ago and ice caps melted by about 13,000 years ago.
- Finally brief but rapid Loch Lomond Re-advance; mountains tops re-covered, icecap from Torridon to Loch Lomond.

	EROSION	TRANSPORT	DEPOSITION
Glacial Processes	**Abrasion**: Rocks frozen into ice wear down the surface of the bedrock by grinding down, polishing, and smoothing it. **Plucking**: Rocks frozen onto ice are torn out as ice moves on. They now abrade other rocks as they move away.	Ice carries boulders and fragments in its 'sole' (base) downhill. The rock fragments have been plucked away or ground down by other rocks. Rocks weathered, mainly by freeze-thaw, fall down slopes and onto the ice surface. Rock flour is carried by meltwater and turns the water cloudy blue-grey.	When the ice melts, it drops all the rocks it has been carrying above, within or below it. Some material may travel on further in meltwater streams to give fluvio-glacial deposits of sand and gravels.

	EROSION	DEPOSITION
Highland Landscapes	Severe erosion. Bedrock exposed & scoured out.	Material found mostly in the troughs and valleys of the landscape.
Highland Landforms	'Knock and lochan' topography -bare pavement, ice moulding of uplands of Outer Hebrides and NW Highlands. V-shaped river valleys eroded away into huge U-shaped troughs; deep rock basins in trough floors (e.g. Loch Ness, Loch Lomond) High mountains eroded into hollows/cirques and ridges/arêtes (e.g. Aonach Mhor) Indented coastlines - fiords/sea lochs etc (e.g. Loch Linnhe) Roche moutonnée and crag and tail features (e.g. Edinburgh Castle Rock) Powerful meltwater streams cut channels (even uphill under ice). Ice dammed lakes gave shorelines (e.g. Glen Roy)	Bedrock covered by loose sediments which partly smooth out the highs and lows of the mountains and troughs. Glacial deposits: boulder clay/drift, now called 'till', various moraines. As ice melted it left behind moraine below the ice, a hummocky ground moraine. Erratics. Fluvio-glacial deposits of sand and gravels: eskers, kames, alluvial fans, outwash plains, deltas.

Books

Geology and Landscapes of Scotland; Con Gillen, Terra Publishing, 2003 (highly recommended!)

Ice Age Britain; Nick Barton, English Heritage/Batsford; 2005 (mainly archaeology)

Frozen Earth: The Once and Future Story of Ice Ages; Doug Macdougall, Univ of California Press, 2006 (thorough!)

Scotland: The Creation of its Natural Landscape; Ian McKirdy and Roger Crofts, SNH & BGS, 1999 (brief overview)