Earth and Environmental Systems Podcast

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Part A: The Geosphere

Lecture 1: Earth and Environmental Systems

The Nature of Science

What is a scientific fact?

- In science, 'fact' does not mean proved true with absolutely no doubt. This is only possible in mathematics and logic, which make unrealistic assumptions that do not relate to the real world directly (i.e. they are theoretical abstracts)
- Rather, a fact is something that is 'confirmed to such a degree that it would be perverse to withhold provisional assent'
- By these definitions, evolution is both a fact and a theory (natural selection is the theory part of it, the change in animals over time is the fact)

What is Truth?

- Hence, science is not the truth, but a search for the truth; you can never prove beyond all doubt that a hypothesis is true, only fail to prove it false
- Unlike religions, science does not pretend to be 'true' or 'final', but ever changing based on improved facts and improved research

Fact, Hypothesis and Theory

- A fact is an observation or measurement about the world
- A hypothesis is a conceptual idea put forward to explain these facts. In order to count as science, a hypothesis must be falsifiable
- A theory is a hypothesis that has been extensively tested from many points of attack so that we can have more faith in it
- Hence we see that a theory (a conceptual model explaining something that has a lot of evidence to support it) is totally different to a fact (an empirical observation about the world), and not a 'less certain' version of a fact

Systems Analyses

What is Systems Analyses?

- Systems analyses studies the earth as a whole entire system
- Systems theory is usually set against reductionism, which holds that something can be understood by reducing it down to its smallest components, and studying them separately
- Systems theory is based on the idea that many complex phenomena cannot be understood in this way, as the interactions between elements produce effects not observable in the elements themselves

What is a System?

- Any isolated portion of the Universe of interest to the investigator
- Must define its boundaries
- Must track all inputs and outputs of energy and material across the system boundaries
- Must break down the system into component parts (subsystems) and determine relationships between these parts

Three Types of Systems

- Isolated system: no exchange of energy or material across the system boundary (about the only true example is the universe as a whole, a bomb calorimeter is a close approximation)
- Closed system: energy can be exchanged across the system boundary, but material can't (space shuttle in space is a good example)
- Open system: both energy and material can be exchanged across the system boundary (any biological lifeform)

The Earth as a System

- Earth is best approximated as a closed system. Though there is some incoming of meteors and some escaping of light gases, these losses are relatively so small that they are not significant
- The entire system of the earth can be referred to as the ecosphere, subdivided into the lithosphere, the hydrosphere, the atmosphere and the biosphere

Characteristics of a closed system

- 1. The amount of matter in a closed system is fixed and finite
- 2. Matter and energy exchanges within the system make subsystems interdependent
- 3. If changes are made in one part of a closed system, the results of those changes will eventually affect other parts

Box Model Analysis

Reservoirs

- Reservoir: A place where material is held for a period of time (e.g. atmospheric water versus deep ocean water)
- The more we break down reservoirs into smaller and finer reservoirs, the more detailed, but also the more complicated and cumbersome our model becomes

Fluxes

- Flux: The movement of material between reservoirs (a flow into a reservoir is called sourcing, a flow out is called sinking)
- Movement of material between reservoirs always requires energy
- On the earth there are three ultimate sources of energy: geothermal, solar, and gravitational (mainly in the form of tidal forces)

Turnover and Residence times

- Residence time = the average time a unit of matter (atom, molecule, compound) spends in a
- given reservoir
- Turnover time = the amount of time it takes a reservoir to gain a completely new set of material
- If we are worried about an unbalanced reservoir (for example, increased CO_2 in the atmosphere), we need to look at both reducing the sources and increasing the sinks

Perturbation

- Perturbation = a sudden change in the source and/or sink fluxes to/from a reservoir
- Humans are currently perturbing the carbon content in the atmosphere

Negative and Positive Feedback

- Feedback occurs when an initial change in a particular reservoir (subsystem) causes changes in other reservoirs which result in further change in the first reservoir
- Example: a change in water content in an organism (water concentration in blood drops) causes a reaction in the endocrine system of the organism (release of activation hormones) that cause a drive in the organism (thirst) which will result in an increase in water content of the organism
- Positive feedback occurs when an initial change in a reservoir leads to changes in the system which cause a further change in the initial reservoir in the same direction
- Examples: pothole growth, planetary ice cover, chemical addiction
- Negative Feedback occurs when an initial change in a reservoir leads to changes in the system which reverse the change in the initial reservoir
- Examples: thermostat in your house, homeostasis in the body, gaia hypothesis

Thermodynamics and Entropy

- Energy also flows between the different subsystems within the earth system, according to the laws of thermodynamics
- Most important is the second law, which says that Energy always changes from a more useful, more concentrated form to a less useful, less concentrated form
- Entropy always increases in an isolated system, by which is meant that the disorder of an isolated system always increases

Lecture 2: Atoms to Minerals

Quantum Mechanics

What is the the complementarily principle?

- In the double-slit experiment, any modification of the apparatus that can determine which slit a photon passes through destroys the interference pattern, illustrating the complementarily principle, that the light can demonstrate both particle and wave characteristics, but not both at the same time
- However, an experiment performed in 1987 produced results that demonstrated that which-path information could be obtained without destroying the possibility of interference
- This showed the effect of measurements that disturbed the particles in transit to a lesser degree and thereby influenced the interference pattern only to a comparable extent

The Copenhagen interpretation

- The Copenhagen interpretation of quantum mechanics says that before one actually observes which slit the electron (or photon) passes through, it really does pass through both at once
- It is in all places at once until the act of measurement is made, which act itself is what causes the particle to adopt a single position

Schrödinger's Cat Experiment

- Schrödinger disliked this interpretation, and attempted to prove its nonsensical nature by devising the cat experiment

- According to this thought experiment, a cat is located in a box, and will be killed if a hammer falls to smash a bottle of poisonous gas, which hammer will fall if it is triggered by the decay of a certain radioactive particle
- As this decay is determined probabilistically by quantum mechanical laws, what state will the cat be in before the box is opened and examined? Is it alive and dead at the same time?

Possible Resolutions

- One possible explanation of this is that a cat is so much larger than quantum scales that is 'leaks' information to the sample (or outside the box) in the form of stray atoms or neutrinos
- Another possibility is that the cat itself acts as the observer, collapsing the quantum state by its own presence
- Another interpretation of quantum theory holds that every time a wave function is collapsed into a real state (e.g. when the box holding the cat is opened), a new universe is created corresponding to every possible state
- Though impossible to disprove, this theory seems rather wastefully extravagant in the number of universes it requires

Elements and Origins

Why is silicon life unlikely?

- Though silicon has the same number of outer shell electrons as carbon, it has double carbon's atomic mass, which means that it reacts and bonds much more slowly and sluggishly than carbon
- This means that any silicon-based life is unlikely to be anywhere near as complex as carbon-based life

What is isotope fractionation?

- Isotopes are atoms with the same number of protons but different numbers of neutrons
- They have similar chemical properties (tendencies to form ions and bond with other elements) but differ in their mass
- This mass difference can allow certain isotopes to accumulate in a given reservoir more readily than other isotopes of the same element
- This difference in turn allows us to use isotope fractionation to determine where rocks or soil samples came from on earth, or what environment they were formed in, etc

Nebular Hypothesis of Solar System Formation

- 1. Start with contracting cloud of H and He & a millionth of everything else
- 2. As cloud contracts any rotation increases owing to conservation of angular momentum
- 3. The cloud forms a disc owing to centrifugal force
- 4. Particles are drawn toward center by the force of gravity, forming a proto-Sun
- 5. Proto-Sun collapses, Temperature increases until H fuel is ignited. After the initial outbreak of fusion, the star cools down substantially, after which it gradually continues to warm up throughout the remainder of its life
- 6. Proto-planets begin to accrete from orbiting dust and gas as temperature cools
- 7. Solar system gets cleared of debris
- 8. Gas-Solid Separation - elements with gaseous affinities were blown from terrestrial planets by solar wind, while rocky materials accumulate closer in

- 9. Differentiation also occurs within planets, as heavier elements "sink" toward core (Fe, Ni), and lighter elements in mantle and crust (O, Si, Al, Fe, Ca, Na, K, Mg)
- 10. Age of Earth estimated to be 4.56 billion years old
- The silica tetrahedron is the most important covalently bonded structure in the earth's crust
- It is essentially one silicon atom surrounded by four oxygen atoms in a pyramidal shape. It is involved in virtually all minerals in the crust

Elements, Compounds and Molecules

- Element: most fundamental substance matter can be separated into by ordinary chemical means
- Compound: one or more kinds of anion combined with one or more kinds of cation in a specific ratio – Formula always written with cations first.
- Molecule: the smallest unit that retains all the properties of a compound

Minerals

What is a mineral?

- Naturally occurring
- Inorganic
- Solid
- Orderly internal structure (crystalline)
- Chemical composition and physical properties that are fixed or vary within a defined range

Primary physical properties of minerals

- Color: not very useful for identification owing to contamination by trace metals
- Streak: the color of streak on porcelain
- Specific Gravity: ratio of the weight of an object to the weight of an equal volume of water. Most minerals have a specific gravity of 2.5-3
- Luster: can be metallic, earthy (dull) or vitreous (glassy)
- Crystal form: shape of crystal when allowed to grow in open space
- Cleavage: the manner in which minerals break when they break into regular flat sheets. The number of cleavage directions is a very useful identifying property of different minerals
- Fracture: refers to totally irregular breakage
- Hardness: the Moh's scale of hardness ranks the resistance a mineral has to being scratched on a scale from 1-10
- Some minerals have more than one hardness value depending on the direction they are scratched, owing to the crystalline structures being different in different dimensions

Special physical properties

- Feel
- Taste
- Odor
- Radioactivity
- Fluorescence
- Effervescence
- Striations
- Triboluminescence
- Optical properties

- Magnetism

How many minerals are there?

- There are over 4000 known minerals
- Only 25-30 are commonly found in rocks

Silicates

- The most common mineral type at the Earth's surface are the silicates, making up some 92% of all minerals
- All silicate minerals are based on the silica tetrahedron: SiO_4^-

ilicate bonding

- Because the SiO_4^- molecule has a charge of negative one, it tends to bond together in specific ways in order to neutralise this charge
- One way of doing this is by intermixing with metal cations (often iron or magnesium), in a kind of ionic lattice structure
- Another method is for one or more of the oxygen atoms to form covalent bonds with oxygen atoms in nearby silicate molecules

Silicate Cleavage

- Depending on the number of oxygen atoms that are bonded to other oxygens, the mineral will have varying cleavage properties
- For example, micas cleave into sheets because three of the oxygens are covalently bonded, while quartz has all four oxygens bonded, and so has no preferred cleavage dimension, but instead fractures

Non-Silicate Mineral Groups

- Carbonates, Contain the CO_3^{2-} complex
- Halides, Contain Cl-, F-, or Br-
- Oxides, Contain O^{2-}
- Sulfides, contain S^{2-}
- Sulfates, Contain SO_4^{2-}
- Native elements

Lecture 3: Igneous Rocks

Introduction to Rocks

What is a rock?

- A rock is any mass of mineral or mineral-like matter that occurs naturally
- For example, coal is considered to be a rock, but is made out of organic material, hence the need for the term 'mineral-like'
- The three main rock types are igneous, sedimentary and metamorphic

Magma versus Lava

- When liquid rock is underground it is called magma; when it is on the surface of the earth it is lava

Differences between Intrusive Versus Extrusive Rocks

- When igneous rocks form underground, they naturally have a thick layer of insulating rocks on top of them, which trap in the heat and cause the magma to cool slowly
- This slow cooling gives all the atoms time to line up and arrange themselves into complex and large crystals
- Conversely, rocks that form from lava on the surface cool much more quickly, and so the atoms do not have time to form as large crystals
- Magma that cools underground is called intrusive rock, also called a plutonic rock
- Rocks that form from lava aboveground are called extrusive rocks, also called a volcanic rock
- Large grain igneous rock must have formed underground, and so must have been brought up to the surface by the processes of uplift and/or erosion

What is rock texture?

- The texture of an igneous rock refers to the sizes of its crystal grains
- Igneous rocks can be identified as having closely interlocking crystals which are not oriented in any particular direction (no 'fabric')

Igneous Rock

Types of igneous rock textures

- 1) Glassy = no crystals, formed on the surface very quickly, too quickly for crystals to form
- 2) Aphanitic = crystals too small to see, formed on the surface
- 3) Phaneritic = visible crystals, form underground, taking thousands to millions of years
- 4) Pegmatitic = crystals are larger than 1 inch across, formed underground, taking tens to hundreds of millions of years

Special Case: Porphyritic rocks

- These consist of large crystals surrounded by small crystals
- These rocks begin to form underground, cooling slowly to form large crystals that are still surrounded by a liquid or semi-liquid rock material
- At this point, they erupt onto the surface, which causes the remaining liquid particles to cool quickly and form smaller crystals embedded between the larger crystals

Two additional igneous rock textures

- Vesicular = full of bubbles, indicating high gas content
- – Usually occur in the upper portion of a lava flow, where bubbles migrate
- – Makes scoria or pumice
- Pyroclastic = composed of ash and rock fragments from explosive eruptions
- – Also called "fragmental texture"
- – Makes welded tuff or volcanic breccia

Basaltic (Mafic) Rocks

- Magma types are defined by chemistry (silica content)
- Low silica
- Tend to be dark colored (black to green)
- Low viscosity (runny)

Andesitic (Intermediate)

- Medium silica
- Tend to be grey to grey-pink or black and white (“salt and pepper”)

Rhyolitic (Felsic)

- High silica
- Tend to be pink to red
- High viscosity (sticky)

Factors Affecting Magma Viscosity

- The three factors that influence viscosity of magma are chemical composition (silica content), temperature and dissolved gases
- The higher the scilica content of a magma, the higher its viscosity
- This is because the chains or sheet of silica tetrahedrons tend to stick to each other, and hence resist flowing
- Viscosity also reduces with higher temperatures and more dissolved gases

Implications for Early Earth Atmosphere

- Largest gas output from volcanoes is water, second is CO2, no oxygen
- Oceans & atmospheric water was low to begin with and increased over time
- CO2 increased over time
- There was no oxygen

Rock Names for the Main Magmas

- Basaltic and Phaneritic: Gabbro
- Basaltic and Aphanitic: Basalt
- Andesitic and Phaneritic: Diorite
- Andesitic and Aphanitic: Andesite
- Rhyolitic and Phaneritic: Granite
- Rhyolitic and Aphanitic: Rhyolite
- Rhyolites generally have shards of glass embedded in them, as being very viscous, they tend to explode out of volcanoes, and in the process some of the rock is flash-frozen
- All flash-frozen (glassy) rocks, regardless of the composition, are called obsidian

Bowen’s reaction series

What is Bowen’s reaction series?

- Minerals do not crystallise out of a magma or lava at the same time: they crystallise at different temperatures
- Bowen’s reaction series tells us the order in which minerals crystallize from a melt
- The order in which minerals crystallise is inversely proportional to the complexity of their silicate structure: free silicates crystallise first, then those forming chains, then complex chains, then sheets, than complex sheets, and then quartz last
- The Bowen’s reaction series can also tell us the order in which minerals will melt when heated; it is the reverse order of crystallization, beginning with quartz

What it says about weathering

- The reaction series can tell us which minerals are most likely to be stable at the surface, meaning which will survive longest on the surface, as they are resistant to chemical erosion
- This is because those rocks that crystallise at the lowest temperatures tend to crystallise near or closer to the surface
- This means that they form under conditions (particularly pressure) closer to those found on the surface than other rocks; hence they are more suited to surviving on the surface

The reaction series and igneous rock types

- The Bowen's reaction series can also be divided into four horizontal bars, each of which corresponds to a particular type of rock
- From the top down these are ultramafic, mafic, intermediate and felsic
- The minerals that fit within each of these bars are those that go into making the corresponding rock type of that bar
- Because of this fact, examining the relative amounts and positions of these types of rocks as they formed underground can tell us something of the geological history of the area

Other influential factors of melting point

- The melting and crystallisation temperatures of rocks tend to decline significantly with higher water content
- Higher pressures also lower crystallisation temperature, as the force presses the atoms into a crystal structure

Igneous Rock Formations

Country Rock, Sills and Dikes

- When magma rises up and intrudes into existing rock, the existing rock is called country rock
- When magma forces its way up in between two layers of country rock and crystallises parallel to these layers, this is called a sill
- When the magma crystallises perpendicular to the layers of country rock, it is called a dike

Volcanic Necks and Batholiths

- A volcano has a pipe of magma that rises up in the centre. Once the volcano has cooled, this solid core of igneous rock tends to be stronger and more resistant to erosion than the flanks that surround it
- As such, often the materials surrounding this central core erode away, leaving behind what is called a volcanic neck
- If erosion proceeds far enough down, it will expose the large flat plain of rock from which the magma which formed the volcano originally rose; this is called a batholith

Distinguishing lava from sills and dikes

- A sill or dike can be distinguished from a cooled lava flow by the fact that extrusive lava or magma tends to burn the surrounding rock, creating a so-called 'baked zone'
- Dikes and sill extrude between two layers of country rock, and so have baked zones on both sides; lava flows on the surface, and so only has a baked zone on one side
- Lava flows also tend to have more air bubble on one side (the top) than the other, whereas the higher pressure on sill or dike magma keeps the gases in solution, not forming bubbles

What are Xenoliths?

- Xenoliths are pieces of country rock that have been ripped off the wall by intrusive magma, and then fallen into the magma
- The magma, however, cools sufficiently quickly so as not to completely melt these pieces of rock, and so they are frozen in place inside the intrusive rock
- Xenoliths such as this can be very important for determining what kind of rocks lie very deep down, as xenoliths can be created at great depths and then carried upwards by the magma as it rises to the surface

Lecture 4: Volcanoes

Volcano Basics

How do volcanoes work?

- A volcano is a mass of pressurised liquid, with large amounts of dissolved gases only kept in solution by the high pressure
- Once this pressure is released, the gases will come out of solution, bringing significant amounts of liquid up with them, which then rapidly freezes once it reaches the surface

Viscosity and the type of eruption

- The most important determinant of the type of eruption is the viscosity of the lava
- As the magma rises through the magma chamber, it tends to fractionate according to mineral content; other minerals come out of solution, thereby causing silica enrichment
- This process tends to increase the viscosity of the maga
- At the same time, depending on the nature of the country rock through which the magma is rising, different materials will be incorporated into the magma, thereby potentially raising or lowering silica content
- The most explosive volcanos are the most viscous volcanos, as the magma gets clogged up, causing a build-up of pressure

What are pyroclasts?

- Pyroclasts are fragmented rock materials from exploding volcanos, including ash and rock fragments
- Andesitic and Rhyolitic magma is more viscous and has a higher gas content
- When this type of magma erupts, bubbles can come out of solution so rapidly that the magma gets "shattered" into fragments, which are called pyroclasts

Types of Pyroclasts

- The smallest pyroclasts are called ash, which remains suspended in the air for a long time, and only gradually settles
- Particles up to pea size are called lapilli, things up to golf ball size are cinders, and anything larger than this are called bombs
- Volcanic bombs can be thrown for miles away from a volcano

Types of Volcanoes

Mafic Magma Volcanoes

- Mafic magma as the least silica and so are the least viscous, and so have few Pyroclasts

- They tend to form shield and cinder volcanos and large lava plateaus called basalt plateaus

Intermediate Magma Volcanoes

- Intermediate magma has a moderate amount of silica, and so tend to be moderately viscous
- They form composite volcanoes, which sides are a mixture of cooled lava and ash
- These are formed because intermediate magma volcanos tend to begin with a violent eruption, then experience a period of runny lava flow as pressure builds up again, then experience a second eruption, and so on in a repeating cycle, thus building up the composite cone of lava and ash

Felsic Magma Volcanoes

- Felsic magma has the most silica, and most explosive of the volcanos, with the most Pyroclasts and pyroclastic flows

Shield Volcanoes

- Are formed by basaltic lava
- Easily the largest types of volcanos
- Have gentle slopes, 5-10 degrees, owing to the runny lava
- e.g., Mauna Kea volcano in Hawaii, Olympus Mons on Mars

Composite Volcanoes or Stratovolcanoes

- Emit both tephra and viscous lava
- Have steep slopes, 10-30 degrees
- Major stereotypical volcanos are this type
- E.g., mt. Fuji, mt. Rainier, mt st helens and mt. Baker

Tephra (Cinder) Cones

- Formed by the gradual accumulation of cinders
- Are formed by andesitic to basaltic lava
- Smallest volcanoes with slopes 25-35 degrees
- They tend to have very large mouths
- sometimes form on the slopes of giant shield volcanos, in which case they are called parasitic cinders

More on Volcanoes

Two types of Lava Flows

- Pahoehoe = smooth and ropy, hotter and have more dissolved gases, so move more quickly
- Aa = sharp and blocky, cooler with fewer dissolved gases, move more slowly

Underground Lava Tubes

- Sometimes a portion of lava will freeze in such a way that it insulates the lava still flowing just beneath it, thereby forming an underground lava tube
- These can allow lava to travel great distances

Fissure Eruptions

- Usually shield volcanos are formed by one or more feeder pipes that well up and reach the surface in thin tubes

- Sometimes, however, entire sheets of upwelling magma called dikes reach the surface, in what are called fissure eruptions (the lava extrudes along the entire length of big cracks in the ground)
- They tend to spread lava over a much wider area, forming what are called basalt plateaus

Columnar Joining

- Columnar joining is a phenomenon whereby lava flows form tall, thin, interconnected crystal structures, which extend down from the surface through the solidified lava
- They occur because as lava cools it contracts, thereby forming these cracks
- Columnar joining is a dead giveaway that the rock was formed from lava

Other hazards with volcanoes

- Earthquakes (and landslides)
- Poisonous or suffocating gas
- Acid lakes
- Lahars (hot mud flows) caused by snow melted by lava; they can reach for miles
- Volcanos can also cause updraughts of moist air, causing rain which then brings down large amounts of ash, and sometimes acid as well
- Caldera collapses, the collapses of land into the now empty magma chamber

Predicting Volcanic Eruptions

- Increased seismic activity
- Increased gas output
- Ground swelling
- Increased temperature
- Strange animal behaviour (less reliable owing to selection bias; one doesn't report odd animal behaviour if nothing happens afterwards)

Case Studies

Mammoth Lakes California

- Extremely high CO_2 concentrations in the atmosphere and especially the soil can suffocate and kill plants, as they have adapted to current relatively low levels in the atmosphere
- This is what has occurred in Mammoth Lakes in California, as massive amount of CO_2 coming up from the ground
- This is a particular danger to small children and animals, as CO_2 is a relatively dense gas, so tends to stay close to the ground
- Lava flows cannot be stopped by ice or snow; a tuya is a volcano which erupts under a glacier, and these have been known to melt and collapse hundreds of meter thick glaciers

Mt Pinatubo Philippines

- This volcano put out a large amount of gas and dust straight up into the atmosphere, reaching as far as the stratosphere
- When ash reaches the stratosphere, it tends to stay up there for a fair while, and hence has time to spread across the globe (this is because the stratosphere is more stable than the troposphere)
- This global spread of ash was also aided by the location of this volcano near the equator
- The effect of all this dust up in the atmosphere was a two-year reduction in average global temperatures during 1992 and 1993, caused by additional sunlight reflecting off the dust particles

- This illustrates how volcanoes can have the short-term effect of cooling the global climate
- The longer term effect of volcanos, however, is to raise average temperatures, as they release significant amounts of CO_2

Lake Nyos Cameroon

- At this lake, carbon dioxide is rising up through the ground as a result of volcanic activity, gradually turning the lake into carbonic acid (water saturated with carbon dioxide)
- On one particular day in 1986, there was an underwater landslide in the lake, which agitated the carbon dioxide in solution in the lake, causing a large amount of the gas was ejected out of solution, bubbled out of the lake
- Being a dense gas, the CO_2 moved along down the side of the mountain, and killed over a thousand people in a nearby town
- When these people were discovered, it was initially a great mystery indeed, as there was no sign of disease or violence
- To resolve this issue, a number of pumps have been installed in the lake which pump the water from the bottom of the lake and eject it into the air in fountain jets
- As the water falls back down, the CO_2 escapes; this prevents a catastrophic build-up of CO_2 from occurring again

Hawaii

- All the Hawaiian islands are basically big volcanoes; some active, some inactive
- One thing that is unusual about the Hawaiian volcanoes is that they are located in the middle of a tectonic plate, rather than near the edges as are most volcanos
- The lava erupting from Hawaiian volcanoes is highly basaltic, meaning that it is not explosive, but tends to flow along the surface as slow moving lava
- Though these flows damage buildings and roads, they kill very few people, as it is possible to outwalk them

Mt Paracutin Mexico

- This was a volcano was began erupting from a farmer's field in 1943
- It was studied until it stopped erupting in 1952, by which time it had formed a several hundred foot high gently sloped cone
- A pyroclastic flow is a fast-moving current of hot gas and rock, which travels away from the volcano at speeds generally as great as 700 km/h
- These so-called 'glowing clouds' are responsible for more volcano deaths than any other volcano-related phenomenon
- They can kill be the sheer force of impact, heat, or asphyxiation

Tambora Indonesia

- This volcano erupted near the equator in 1815, spewing an enormous amount of ash straight up into the atmosphere
- It caused such a degree of global cooling that the year of 1816 was referred to as 'the year with no summer'; some areas even snowed during the summer

Yellowstone Wyoming

- A chaldera is a region of collapsed ground which occurs following a volcanic eeruption, as the evacuation of materials from the underground magma chamber leaves an empty space which then caves in
- For a long time the chaldera for Yellowstone volcano could not be located
- It was not until aerial photographs were taken was it realised that the entire national park was one giant chaldera
- Like Hawaii, the Yellowstone volcano is a 'hot spot', or in the middle rather than the edge of a continental plate
- The massive eruptions that have occurred in the past at Yellowstone seem to have been caused by large amounts of magma upwelling and coming into contact with water-rich rock
- The water is instantly converted into steam, which them expands and basically completely pulverises the rock
- The last of these massive eruptions occurred about 150,00 years ago, and as they seem to occur at about this interval, some are worried that another one will occur soon
- Interestingly, the hot spot of the Yellowstone volcano has been moving relative to the continental United States, forming a smooth streak of land which is visible to a satellite
- It is believed that this is caused not by movement of the hotspot itself, but by the slow motion of the continental plate to the south-west

Toba Lake Sumatra

- This eruption, which occurred about 70,000 years ago, is the largest eruption to have occurred whole humans have existed
- It is yet another case of an equatorial equator blasting a great deal of ash and dust straight up into the atmosphere, and thus causing widespread global cooling
- According to ice core records, six of the coldest years during the last glacial period were the six years following the toba eruption
- There is also some evidence that these harsh climactic conditions drastically reduced the number of humans living on the planet to about 10,000 individuals, thereby explaining the remarkable lack of genetic diversity amongst humans today

Lecture 5: Sedimentary Rocks

Introduction to Sedimentary Rocks

Importance of Sedimentary Rocks

- Source of many construction materials
- Sediments can store information on past climate
- Type of rock can indicate environment of deposition
- The only rock type to preserve fossils

How to make a sedimentary rock

- Weathering = the breaking down of rock into smaller pieces (sediment)
- Erosion = the movement of sediment from one place to another
- Deposition = the placement of sediment at a new location
- Lithification = turning loose sediment into a sedimentary rock

Chemical Weathering

- Rock dissolved (in water) into individual molecules (ions)
- Especially effective if the water is acidic or hot

Mechanical Weathering

- Rock is physically broken into smaller pieces
- Happens from impact, thermal expansion, or frost wedging

Clastic Sedimentary Rocks

Agents of erosion

- 1.Water – by far the most important on Earth, even in deserts
- 2.Wind – the only process that can move sediment uphill
- 3.Gravity
- 4.Ice

Three methods of erosion by water

- 1. Bed load: Material that rolls or bounces along the bottom of the stream (usually the largest particles)
- 2. Suspended load: Turbulence in water keeps smaller sized particles in the water and off the bottom
- 3. Dissolved load: Rock material is dissolved into individual molecules and transported in solution, can be a significant portion of total sediment

Stream speed and sediment size

- The faster the water is flowing, the larger the particles that it can move
- Interestingly, the exception to this rule are silt and clay particles (anything smaller than sand), which require the same velocities to get moving as particles of about 1cm in diameter
- The reason for this is that these small particles have a higher surface area to mass ratio
- This is important because the surface of sedimentary particles tends to attract ions
- Hence, these small particles attract enough ions to stick together, thereby avoiding motion
- This is why modelling clay sticks together
- The flip side to this is that as water flow slows down, the largest particles come out of the water stream first
- Clay and silt particles are not an exception in this case – they are hard to stop and hard to get going

Deposition

- 1. Chemical deposition
- – Dissolved molecules dissolved in water reaches saturation and begins to precipitate out of water
- – Makes a chemical sedimentary rock
- 2. Clastic (detrital) deposition
- – Rock pieces being eroded without being dissolved in water get deposited
- – Makes a clastic sedimentary rock

Clastic sediment size

- Clay (mud) <4 micrometers – collectively with silt known as mud
- Silt <63 micrometers – collectively with clay known as mud
- Sand <2mm

- Pebble or gravel <64mm
- Cobble <256mm
- Boulder >256mm

Clastic sedimentary rocks

- Mud sized = mudstone or shale (usually brown or black because of lots of organic matter)
- Silt sized = siltstone
- Sand sized = sandstone
- Rounded pebbles or bigger = conglomerate
- Sharp angular pebbles or bigger = breccia

Environments of clastic deposition

- The larger the sedimentary particle that is deposited in an area, the faster the stream must have been travelling in that location
- Need high energy to move large particles, and need low energy to deposit small particles
- Pebble sized and larger deposited in floods, debris flows, and mountain streams
- Sand sized found at the base of mountainous areas, fast moving stream beds, and beaches
- It is possible to differentiate between sand deposited under streams and that deposited under beaches, as sand deposited under beaches tend to occur in flat layers, whereas that under streams tends to occur in bulging u-shapes
- Silt must have slow moving or still water to deposit, usually near shore
- Clay must have still water to drop out, usually deep calm water far from shore

Dam Lifespan

- This means that when humans dam a river to produce electricity, the resulting reservoir will gradually become clogged up by deposited sediment, in a process known as siltation
- This means that all artificial dams have a limited lifespan

Chemical Sedimentary Rocks

Types of Chemical Rocks

- Carbonates: $CaCO_3$, Limestone; (Ca,Mg), Dolostone
- Silicates: SiO_2, Chert (including flint, jasper, and agate)
- Evaporites: Rock Salt, Rock Gypsum

Where Carbonates form

- Limestone and dolomite form very slowly, as small skeletons of plankton and other creatures build up over time
- This formation is so slow that it will get overwhelmed by any clastic particles that are being deposited
- Hence, for pure dolomite or limestone you need water with no clastics, either far from shore or in areas with no clastic input (e.g. a sheltered bay)

Where Evaporites form

- Evaporites require a body of water with high evaporation rate
- Usually need a “closed basin” where water can run in but can’t run out
- Forms as water evaporates out, leaving behind dissolved particles which slowly precipitate out
- Hence, salt or gypsum deposits tend to occur in closed basins located in hot, arid regions

The formation of an oil deposit

- A number of factors must come together for an oil deposit to be formed
- First, you need rock with a high enough density of organic matter for oil to form
- Next, you need permeable enough rock to give the liquid oil somewhere to be stored
- Third, you need some kind of impermeable rock above the permeable layer, which prevents the oil from extruding up to the surface (it tends to do this because oil is a relatively light liquid)
- If oil does make it to the surface, much of it will evaporate, leaving behind only tar, which is not very useful

More on Sedimentary Rocks

Other things to examine on a sedimentary rock

- Sorting: Poorly sorted, moderately sorted, well sorted
- Size: Clay, silt, sand, pebble, cobble, boulder
- Roundness: Angular, subangular, subrounded, rounded, well-rounded

Particle sorting

- Refers to the degree to which particles are of the same size
- Well sorted = particles all of the same size
- Moderately sorted = particles within a relatively narrow range of sizes
- Poorly sorted = particles of very different sizes
- Bimodal sorting = particles of two distinct sizes

Information from sorting

- Well sorted = constant energy level
- Moderately sorted = energy fluctuates within a certain range
- Poorly sorted = energy levels fluctuates drastically over time (e.g. a flood) or the material has been dropped all at once (as by melting ice)

Information from rounding and size

- Rock clasts usually start out large and angular
- As they are eroded, sharper edges get worn down quickly
- The farther clasts have been eroded from the site of weathering, the rounder and smaller they tend to be

The process of Lithification/Diagenesis

- 1.Compaction: physical squashing of sediments, often reducing volume of sediment by removal of water
- 2.Cementation: the cementing together of sediment particles owing to the crystallisation of various dissolved minerals from water percolating through the rock into the pore spaces
- 3.Recrystallization: the fusing together of two previously separate mineral crystal structures caused by extreme external pressure forcing atoms from each of the separate crystals to migrate over to the other crystal, thereby merging the crystal grains into one

Sedimentary Patterns and Structures

Rhythmic layers

- Repeated sequences of sedimentary rock

- For example, the sequence sandstone, shale, limestone indicates that there has been a transgression of the sea onto land, or a rising of sea levels (as we have gone from shore, offshore, to far offshore sediment, the sea must be moving)
- A sequence limestone, shale sandstone indicates he reverse, a falling of sea levels or a regression of the sea
- These patterns can occur on all sorts of scales, from mm to hundreds of meters thick

Cross bedding

- Lineation inside layers of rock that go across the rock
- They are formed by the motion of wind or waves that builds up sediment layers on the side of sandbars and similar structures opposite to the direction from which wind is blowing
- By looking at which way the cross bedding points, it is also possible to tell in what direction the wind blew from

Graded bedding

- Layer of sedimentary rock with coarse clasts at the bottom, with finer ones closer to the top
- This tells us which direction was 'up' when he sediment was deposited; this is important, because sometimes rock layers can be flipped upside down

Other Patterns

- Raindrop impressions: dimples in a rock caused by rain
- Mudcracks: usually formed in clay, which expands a lot when wet
- Ripples: symmetrical ripples indicate wave motion, assymetrical ones indicate uni-directional wind or water motion
- Metamorphic rocks - Means "changed shape". Defined as a rock that Has undergone Chemical and/or Physical changes while remaining in the solid state

Lecture 6: Weathering and Soil

- Chemical and mechanical weathering are interrelated: chemical weathering exposes more surface area to mechanical weathering, while mechanical weathering lossens grains to allow more chemical weathering to occur

Weathering of Rocks

The Role of Acidic Water

- Primarily done by water that is acidic
- Rain picks up material from the atmosphere to become acidic as it falls:
- – Carbon dioxide -> Carbonic acid
- – Sulfur oxides -> Sulfuric acid
- – Nitrogen oxides -> Nitric acid

Acid Rain

- Normal rainfall has a pH of 5.5 when it reaches the ground
- Acid rain has a pH of around 3 or 4
- Usually really severe acid rain occurs near heavy polluters of carbon dioxide and sulphur oxides, such as power plants
- Once rain enters the ground it usually picks up more carbon from decaying organic material and becomes more acidic

Why Weathering Rounds Rocks

- Chemical weathering occurs on surface areas, so the more surface area an object has per volume, the faster it experiences weathering
- Surface area is greatest relative to volume near the corners of a cube, hence why objects tend to become more spherical as they weather

Mineral Composition and Weathering

- Quartz does not weather very easily, so its proportion in rocks tends to increase as they are weathered
- Other materials, like silica and metal ions, dissolve into water and are washed away
- The chemical weathering of mafic (dark colored) minerals like pyroxenes, amphiboles, biotite, etc. (all contain Fe +/- Mg) releases iron which can then form iron oxide (Fe2+O) and goethite (Fe3+)(OH)
- These minerals give the weathered rock a red ("rusty") color
- Granite and slate erode much more slowly than limestone and marble, which dissolve in water

Mechanical Weathering

- Mechanical Weathering - Forces act to break rock apart without chemically altering it
- Impact – occurs when rocks fall down a cliff, or when waves hit rocks
- Abrasion – basically the continual impact of very small particles of sand or silt
- Abrasion is responsible for the 'balanced rocks' found in deserts, caused by sand bouncing around along the ground and hitting the rock. These sand particles seldom reach more than 2 feet high, thus explaining why only part of the rock errods
- Frost Wedging – occurs when water leaks into a crack in a rock and then freezes, expanding and hence pushing apart the rock
- Root Wedging – wedging caused by growth of roots within rocks, can pop rocks apart
- Salt Wedging – salt crystals are deposited in small cracks in a rock, which begins to pop open the rock owing to thermal expansion and contraction, which salt crystals respond to unusually strongly
- Unloading – occurs when rocks that formed deep underground (e.g. batholiths) are uplifted and the material above them erodes, bringing these deep rocks up to the surface
- As these rocks have been removed so quickly from a high-pressure environment, they 'remember' this pressure, and so tend to expand outwards and upwards, cracking and popping into distinct layers

Regolith and Soil

Regolith versus Soil

- Regolith = the layer of rock and mineral fragments at the Earth's surface produced by weathering
- Soil = a combination of mineral and organic matter, water, and air, or the portion of regolith that can support rooted plant growth

Soil Forming Factors

- Climate – higher temperatures tend to increase the rate of chemical weathering
- Areas close to the equator have much deeper soils than temperate zones, which in turn have deeper soils than deserts
- This is because soil depth is related to the amount of vegetation, which in turn is related to the amount of rainfall

- Topography (slope) – flat areas don't drain very well, so in these areas tend to form ferrous (oxygen poor) materials
- Sloped areas will have different soil types depending on whether you look at the hilltop, valley or hillside
- Parental rock material – as the rock weathers, it forms the regolith that will make up future soil, thereby affecting soil types
- Organics – different plants live in different types of soils
- Time – it takes thousands of years to weather rocks sufficiently to produce the regolith, which then mixes with organic material to form true soil

The Age of Soil

- True land plants have only actually existed on Earth for about 400 million years, and hence true soil hasn't actually been around for very long

Soil as a Non-Renewable Resource

- Soil is precious, and soil erosion is a very serious environmental issue; it takes about two thousand years to form one inch of soil
- A renewable resource is one that can be reformed or renewed within a human lifescale
- By this definition, soil is a non-renewable resource

Causes of Erosion

- Agriculture is the biggest source of soil loss
- Construction also erodes soil very quickly, though the erosion tends to subside drastically once the buildings and concrete have been completed
- Erosion of topsoil of semiarid marginal lands that the Chinese government encouraged farmers to settle on by wind is also a very severe problem, as after a few years of cultivation the soil nutrients run out, the plants die, and the topsoil has nothing to hold it down

Solutions for Erosion

- Contour ploughing involves ploughing in parallel lines along the natural contours of hills, thereby limiting soil erosion
- Crop rotation reduces the nutrient drain from the soil, as different crops require different nutrient loads
- Use of smaller farm equipment also reduces the rate of erosion
- Organic farming also seems to reduce the rate of soil erosion
- Covering soil with vegetation or mats at times when it is not being used also helps to reduce erosion
- Planting low shrubs around farmland helps to reduce wind erosion
- No-tillage farming does not turn over the topsoil, but instead just punctures smaller holes

Soil Horizons

Five Basic Properties

- The most important characteristics used to define soil horizons are:
- 1. Color
- 2. Texture
- 3. Structure

- 4. Organic Matter Content
- 5. Moisture Content

Soil Color

- Organics turn soil black to dark brown
- Ferric Iron turns the soil yellow brown to red (with oxygen)
- Ferrous Iron turns soil dark grey green (without oxygen)
- SiO2 or CaCO3 turns the soil light gray to white

Texture

- We can define soil texture depending upon the relative proportions of sand, silt and clay
- The best type of soil for agriculture is called loam, and has roughly equal proportions of each
- Sand is important because it allows water to percolate down, but plants will not grow in very sand-rich soil because it holds very few nutrients

Grain Structure

- Structure of soil grains, determined by how the soil breaks apart when it is moved (e.g. into blocks, sheets, individual grains, etc)
- Shape of aggregates of soil particles called peds
- In clay rich material the spaces between peds may be the only way water can travel down the profile

Organic Matter Content

- Organic matter in soils includes Litter (leaves and branches) and Humus (decomposed litter)
- Both tend to be produced more at higher temperatures, with an optimum of about 25° C
- These substances provide chelates, which are organic molecules that can surround metal ions and help to move them with water
- Chelation therapy is the application of this to remove heavy metals from a human body

Moisture Content

- Total quantity of water that can be held in a soil is the available water capacity (AWC)
- Field capacity: the water that remains help inside water due to surface tension
- Plants actually release a substance which reduce the surface tension of water, thereby allowing them to extract some of the field capacity water of a soil
- Permanent wilting point – the water that cannot be extracted even by plants

Five Basic Soil Horizons

- O Horizon = Loose and Partially Decayed Organic Matter (no minerals)
- A Horizon (topsoil) = Loose Rock and Mineral Matter mixed with Partially Decomposed Organic Matter (Humus) – the best growing soil
- E Horizon = Fine-grained Mineral Particles that have been carried down by water (Eluviation & Leaching)
- Water that hits the surface quickly lowers in pH, owing to the presence of additional CO_2 produced by the bacteria that are decomposing the organic material, and also the acidic materials released by the decomposing matter itself
- This is why the mineral particles in the E layer decomposed so significantly

- By the time of the B layer, however, the accumulation of all the minerals in the E layer has increased the pH sufficiently for the minerals to begin accumulating again
- B Horizon = Accumulation of clay transported from above; generally very rich in minerals like iron and aluminium, sometimes to the point that they can even be mined
- C Horizon = Loose and Partially Altered "Parent" Rock Material
- Not all regions have all soil horizons; for example erosion or glaciers can remove the O layer

Lecture 7: Metamorphic Rocks

Metamorphic Properties

What is metamorphism?

- Changes that occur to rocks while remaining in the solid state; if they melt its igneous
- Metamorphic rocks tend to look very messed up; highly folded or stretched
- Lined-up crystals is also another give-away of metamorphic rocks

Swelling Soil

- Clay-rich soil can be responsible for the phenomenon of 'swelling soil', when the soil expands when it absorbs water, and then contracts when the water dries
- This slow but constant pulsation of the soil can cause enormous damage to buildings

Contact and Regional Metamorphism

- Contact metamorphism–small scale metamorphism, usually caused when magma burns the surrounding country rock; a similar effect can also be caused by very hot water
- Regional metamorphism–large scale metamorphism usually caused by tectonic pressure
- Processes causing metamorphism: 1) heat, 2) pressure, 3) chemical reactions with hot fluids

Physical changes during metamorphism

- Reorientation of rod or plate shaped minerals so that they line up in a single direction
- Recrystallization of minerals resulting in fewer but larger grains; this occurs as atoms are forced to move between crystals, which then blur together and eventually merge into a single, larger crystal
- Creation of new minerals – some index minerals (which form only at a specific range of heat and pressure) can tell you what pressure and heat conditions the rock reached

Foliated and Nonfoliated

- Foliated: rod or plate shaped minerals that have lined up so that one direction has a dominant fabric structure
- Nonfoliated: minerals have no dimension longer or shorter than any other, so no fabric pattern appears; generally composed of minerals that are not rod or plate shaped

Foliated Rocks

Slate

- Formed from the regional metamorphism of slate sedimentary rock
- Crystals too small to see have lined up
- Crystals can sometimes be smaller than the wavelength of visible light, and so tend not to reflect very much light, and hence tend to be dark
- Is also very tough and hard, so used for pool table tops and chalk boards

Phyllite

- Slate that has been metamorphosed even more intensely
- Crystals have grown so that they are almost visible
- Crystals large enough to reflect visible light, so rocks have a velvety sheen

Schist

- Phyllite that has been metamorphosed even more intensely
- Crystals have grown large enough to see

Gneiss

- Mafic and felsic minerals have separated to make dark and light bands
- Generally come from deep in the earth's surface, where intense pressures and temperatures produce the extreme metamorphism

Migmatite

- Migmatite is a type of rock that is metamorphed even beyond gneiss; it partially melted so that the bands started to run and bleed amongst each other, but then recrystallised before it could melt completely
- In a sense this rock is a transitional type between igneous and metamorphic, but it is classified as a metamorphic rock nonetheless

Other Metamorphic Rocks

Nonfoliated metamorphic rocks

- Tend to have larger crystals than their igneous counterparts, owing to recrystalisation
- Marble is metamorphosed calcite (sandstone) rock. Because of its low hardness and tendency to dissolve in acidic rainwater, statues made of marble erode fairly quickly if left exposed
- Quartzite is metamorphosed quartz (sandstone) rock

Metaconglomerate

- Pebbles of another rock can be "squished" togther, forming a meta-rock (e.g. metasandsonte, metabrechea, etc)

Hornfels

- Hornfels is the general term applied to the wide variety of rather hard, nonfoliated metamorphic rocks formed during contact metamorphism (rock burned by magma)

Lecture 8: Relative Dating

Rules of Relative Age Dating

What is Bacon's dilemma?

- Bacon's dilemma: 'young' in geologic terms means closer to our time, while 'old' means that it is further back in time

The Law of Original Horizontality

- Most rocks are originally laid down flat (owing to the Earth's gravity field), and tilted only later during geologic events

The Law of Superposition

- Oldest rocks are on the bottom (assuming the rocks have not been inverted)

Law of Lateral Continuity

- Most rock beds don't end suddenly when originally laid down
- Most rock beds either pinch out (progressively get thinner and thinner), or grade out (slowly turn into another sedimentary form
- Hence, if a rock bed does end abruptly, it probably weathered and eroded after it is formed

Law of Cross-cutting relationships

- – A rock being cut by another rock or feature is older than that rock or feature

Law of Inclusions

- –If rock A includes pieces of rock B, then rock B is older than rock A

The Law of Fossil Succession

- Fossil assemblages change in an ordered succession through time
- For example, fossil A is always found above fossil B; B is never found above A
- This law was developed by William Smith in the early 19th century based on his on his many observations of rocks around the country and made a geological map of England

Up Indicators

What are up indicators?

- Up indicators can be very important, as rocks can sometimes be tipped upsidedown, or even if they are tipped vertical, it is still necessary to determine from which direction they were flipped

Deposited Sediment

- One indicator for this is deposited sediment; if sediment has been deposited into cracks within rocks, it will fill the bottom part of the holes, while the upper part will be available to have crystals form in it

Stratigraphic Superposition

- Former stream beds that were gradually filled up by sediment. The u-shaped portion will represent the bottom, and the flat portion the top

Cross bedding

- Sediment deposited on slight slope in water (submarine sand dunes) or air (sand dunes)

Other "up indicators"

- Mud cracks – always crack upwards
- Raindrop impressions
- Infilled voids – Sediment fills lower half, crystals can fill upper half
- Flute and scrape casts – specific shapes of erosion caused by water flowing over mud, and cutting trenches or holes into the mud
- Vesicles (bubbles) mostly found at the top of a lava flow, fewer near the bottom
- Fossils like tree stumps, footprints, animal burrows and root traces all indicate up direction

Fossils and Biocorrelation

What is a Fossil?

- A remnant, impression, or trace of an animal or plant of past geological ages that has been preserved in the earth's crust
- A trace fossil is when the organism itself is not preserved but only evidence of its existence (dinosaur tracks, worm burrows, coprolite)

How are Fossils Useful for Dating?

- The great thing about fossils is that they allow comparison of the relative ages of rocks at different locations – this is called biocorrelation
- Not all regions will have rocks from all time periods, but by combining rocks and fossils form many regions, we can build up a fairly complete picture of the history of the earth

What is an Index Fossil?

- An index fossil is a fossil that was only formed for a limited period of time, and so finding this fossil restricts the range of dates for which the rock and fossil could have formed
- A good index fossil exists for a limited period of geologic history, is easily preserved, and can be preserved in many different sedimentary environments

Ecological indicator fossil

- Because many creatures cannot tolerate significant environmental conditions, finding a certain fossil at a certain time can tell us about the environmental conditions at that time and place – these are called ecological indicator fossils
- Can tell you what kind of an environment the rocks were formed in
- A good ecological indicator exists through a long period of geologic history, and has a limited tolerance for variation in their environment (must live in a specific type of environment)

The Precambrian Era

- The entire period before around 550 million years ago is referred to as the Precambrian era
- It was originally defined as the time before the first fossils became visible
- The Precambrian era is divided into three eons
- The hadeon eon ends about 3.9 billion years ago, and marks the time on earth from which we have no known rocks that are still in existence; we cant say much about it
- The archean eon ended about 2.5 billion years ago, and marked the time when the Earth's atmosphere had no significant oxygen
- Oxygen gradually built up in the atmosphere due to the action of photosynthesising bacteria, until it built up to a high enough level that we enter the proterozoic eon

The Phanerozoic Eon

- The next eon is the phanerozoic eon, which is subdivided into the Paleozoic, Mesozoic and Cenozoic eras
- The Palaeozoic era is divided into a number of periods, most of them distinguished by significant extinction events
- The very biggest extinctions are used to divide the eras

Unconformities

What are Unconformities?

- A break in the stratigraphic rock record when rock was not being deposited; represents missing time of the rock record

Angular Unconformity

- appear one different rocks contact each other at an angle, indicating a period of time when rocks were tilted and then eroded, and hence when no rock was being deposited. This period is the 'missing time'

Disconformity

- An undulating plain of erosion covered by a flat layer of sediment above
- This generally forms when an area was being eroded for a while, and then moved back to a place where deposition dominated (often under the ocean)

Nonconformity

- A place where sedimentary rock borders on intrusive igneous or metamorphic rock
- As these latter two types are always formed underground, while sedimentary rock always forms at the surface, a boundary between them could only exist if there was a period of erosion and uplift when the metamorphic and igneous rock was brought up to the surface, which occurred before deposition resumed. This intermediate period of erosion is missing time.

Paraconformity

- when sediments are not deposited for a while, but without any erosion
- This lack of erosion makes it very difficult to identify, and can only really be identified via biocorrelation of fossils
- Many of these types of unconformities are present in the grand canyon

Lecture 9: Absolute Dating

Early Attempts to Date the Earth

Relative vs Absolute Dating

- Relative dating based on rock layers and fossils is useful, but it cannot give us any information about actual ages of rocks, or how much of a difference there is between different layers
- This can only be determined by absolute dating

Bishop Ussher's Attempt

- One of the first attempts to determine the age of the Earth was made by Bishop Ussher in 1650
- He used ages and overlaps of biblical personalities to calculate back to the time of creation, while also taking into account historical and archaeological evidence
- Creation of the world was pronounced to occur in the year 4004 B.C
- This is because his calculations put the creation at about 4000 years before Christ, which he then adjusted to take into account the four year discrepancy of the AD dating system with the actual date of Christ's birth (Josephus recorded Herod as dying in 4 BC)
- He actually also claimed to know that the Earth was created on the night of October 22
- Though laughable now, at the time this was the best attempt that anyone had made to that time

Sediment Deposit Estimates

- Other early attempts at dating the Earth focused on calculating the rate at which sediment deposits on the Earth, and then multiplying this by the thickness of sediments across the Earth
- Problems with this method included that different sediments accumulate at different rates, no single location has a complete geologic column, and sediment compacts when it lithifies
- Ages calculated with this method ranged from 3 million to 1.5 billion years

Ocean Salinity

- Another method was based on examining ocean salinity, assuming that the ocean began as fresh water, and then calculating how long it would take for the ocean to become as salty as it is based on the rate at which salts are being washed into the ocean by rivers
- Apart from the fact that this would be extremely difficult to measure, it neglected the salt removed from ocean by deposition and wind (e.g. chemical sedimentary rocks)
- Haley and Joly both reached an age of about 90 Million years using this technique

Laws of Thermodynamics

- Lord Kelvin used thermodynamics to make a calculation, which was good because it required few assumptions of things that were unknown (as the other methods did), and were based on precise measurements
- He assumed that the Earth started as molten and cooled to its present condition
- His calculations made it obvious that the Earth could not be older than 100 million, but was pretty close to this age
- However, this flew in the face of Darwin’s theory of evolution by natural selection, as 100 million years was not enough time for this to occur
- Lord Kelvin was wrong, however, because he did not know about the heat that is added to Earth by radioactive decay

Radiometric Dating

What is Half Life?

- Half Life: the time for half of a population of parent atoms to decay to their daughter product

How does radiometric dating work?

- Though we cannot predict when a given atom will decay, when we have a large number of atoms we can predict very accurately what will happen overall
- Hence, by measuring the proportion of the parent left, we can tell how many half-lives have passed: 50% parent remaining = 1 half life, 25% parent remaining = 2 half lives, etc
- For this to work, however, certain assumptions have to be made

Need a Closed System

- 1. Rock or mineral system is closed to parent and daughter elements
- There are, however, ways of determining whether or not this has occurred, and if in certain cases for some rocks this cannot be determined, then the rock cannot be dated
- In fact, many rocks cannot be dated for this very reason. Only specific rocks can and should be dated. If you hear a case of a rock being dated and coming out with an impossible figure, it is probably because the rock should not have been dated, or not with that technique

Need to Know Initial Ratio

- 2. Initial ratio of parent to daughter must be determined
- For certain rocks this can be determined accurately. For example, uranium dissolves easily in water, while thorium precipitates out almost immediately.
- Hence any rocks forming directly from ocean water will have virtually no thorium, and thus the uranium-thorium decay series can be used accurately
- For other minerals this occurs because of melting; for example feldspar rocks with potassium tend to form without any argon
- There are other, more complex methods that can actually work out what the initial proportions of parent and daughter elements were even when they are not 100% parent

Need a Significant Sample Size

- 3. Measurements of parent and daughter must be accurate (need minimum amt)
- Amounts of parent and daughter are measured using mass spectrometers, and so if rocks are too young there will be too little daughter atoms to be accurately measured
- Similarly, if the rock is too old there will be too little parent left to make an accurate measurement: the upper limit is about 7 half lives

Need Constant Half Life

- 4. Half life must be constant through time

Useful Dating Methods

Uranium-Lead

- Uranium is an incompatible element that is concentrated in late-stage granitic crust
- It has a long half life, good for old continental rocks

Rubidium-Strontium

- Rubidium has the same charge and similar ionic radius as Potassium
- Good for dating Kspar and micas in old continental crust

Potassium-Argon

- Potassium is abundant; half life = 1.25 b.y.
- Must guard against argon loss (as it's a gas)

Carbon-14

- Can date any *young* materials with carbon
- Short half life; rule of thumb yields dating range back to about 30,000 years
- Carbon-14 is produced by cosmic rays hitting hitrogen-14 in the upper atmosphere and converting it to C-14
- The more solar activity, the more C-14 is produced; hence the carbon clock changes speed
- This can be calibrated using tree ring data

Using Multiple Dating Techniques

- Sometimes multiple dating techniques can be used on the same rock: for example, uranium dating might be used to calculate the age an igneous rock formed, and than potassium dating can be used to tell when it was metamorphosed (as argon leaks out during metamorphism, but uranium doesn't)

- Rocks are virtually never dated using only a single technique. For example, moon rocks have been dated to very similar ages using many different decay clocks, done by different labs

Feasibility of rock types

- Sedimentary rocks usually not possible to date, as they are made of particles of varying ages
- Some chemically-precipitated sedimentary rocks can be dated though, for example stalactites
- Metamorphic may work but must be careful, as you can get both time of crystallization and metamorphosis in some cases
- Igneous is the best rock type for radiometric dating, as they form all at once in a short time
- Ash beds very useful due to the large areas they cover; if you can find a given ash layer in different locations, you know they date to the same time

Magnetic Reversals

How do we know of magnetic field reversal?

- Earth has a magnetic field, and atoms of Iron act like individual magnets within this field
- When temperature drops below 500 degrees C (the Curie point), the Iron lines up with Earth's magnetic field
- Some rocks are 'normal' (north points north and south points south), while other rocks have been found with reversed polarity
- The only good explanation is that the Earth's magnetic field has reversed

Use in absolute dating

- Use of absolute age dating allows a magnetic reversal time scale, by which we can further constrain the error bars of absolute dating figures

Magnetic Pole Migration

- In addition to periodically reversing, the magnetic pole migrates over time
- It is quite possible that the pole simply migrates slowly over to the other hemisphere and hence flips over
- To us it would seem slow, but in geological terms it would look like an instantaneous reversal

Magnetic Field Breakdown

- Another theory is that the magnetic field could breakdown completely for a time, and then reform with opposite polarity
- Some have claimed that extinction events correlate with magnetic field reversals
- If this is the case, it would support the disappearing field theory, as the magnetic field helps to protect animals and plants from cosmic rays, so it if vanished, massive DNA damage could occur
- The trouble with this idea is that we do not see extinctions at every reversal

The Oldest Rocks and Minerals

The Oldest Rocks on Earth

- The oldest rocks tend to be continental rocks, rather than oceanic rocks (indeed, the oldest ocean floor rocks are only about 200 million years old)
- Acasta Gneiss from the Canadian Shield (NW Territories near Great Slave Lake) has been dated to 4.055 Billion years old (505 million years old after Earth origin)

- This means that the Hadean period (the time from which we have no rocks), is about 500 million years long

How old is liquid water?

- Sandstone and shale rocks have been found dating to 3.8 billion years old, indicating that liquid water existed on Earth at that time, as these rocks are formed from sediments deposited by water

How do we know the age of the Earth?

- We knew the Earth is 4.56 billion years old because we have dated every meteorite as this old, and we assume the Earth was formed at the same time
- Moon rocks also date to this time or sooner

The Oldest Mineral on Earth

- Oldest Mineral Found on Earth is a zircon crystal from the Jack Hills of Western Australia; has been dated at 4.4 Ga

What kind of life existed in the Precambrian?

- For a long time, it was believed that life did not appear until the proterazoic, beginning at the end of the Precambrian about 550 million years ago
- We now know, however, that life did exist during the Precambrian, but was mostly microbial

Life form Mars?

- Life-like shapes have been found in meteors that come from Mars, but it is most likely that these are not really life, but just look like life (for one thing they are too small)

How do we know when life originated?

- The best rocks for finding fossils are fine-grained black sedimentary rocks; metamorphism destroys fossils, and black rocks generally have more organic matter
- The earliest known microbial life was found in a conglomerate rock, and so could not be dated directly
- However, lava flows above and below it were respectively dated to 3.46 and 3.47 billion years old
- The chemical organisation and metabolism processes of all types of life on earth are so uniform that we are pretty sure that life only originated once, and then evolved
- This is important because two distinctly different types of bacteria were found in this oldest rock, thereby indicating that the original life from which they evolved existed before this time
- We can push the date of biogenesis even further back, because the law of inclusions tells us that the rocks in which the bacteria were found must have been formed before the sedimentary rock of which they are now a part
- By this reasoning, we estimate that life originated around 3.8 billion years ago

Lecture 10: Plate Tectonics

Plate Tectonic Basics

Erosion and Plate Tectonics

- The processes of erosion and deposition tend to level out land over time, levelling mountains and filling up oceans; obviously, however, as such irregularities still exist, there must be other processes operating to offset this tendancy

- For example, parts of the top of mount Everest are actually made from limestone, which is made at the bottom of oceans
- Other examples include intrusive igneous rock that is found at the surface

What is the Lithosphere?

- The lithosphere is composed of two layers: the crust and the uppermost layer of the mantle, which is fairly rigid, compared to the more fluidic lower mantle

What are Tectonic Plates?

- The continents do not move about independently; they are actually attached to large pieces of oceanic crust, which move about with the continents
- There are seven main tectonic plates, and several smaller ones
- Some of the plates are moving towards each together, some away from each other, and some are sliding along each other

The Explanatory Power of Plate Tectonics

- We thus see that the theory of plate tectonics explains the location of mountains and valleys, the motion and shape of continents, the mid ocean ridges, and the location and type of volcanos

The History of Plate Tectonics

The Genesis of Plate Tectonics

- Plate tectonics is an example of an enormous paradigm shift in science that explains many things in geology
- It begins with the idea of continental drift, first really developed in detail by Alfred Wegner
- He noticed that Africa and South America seemed to fit together amazingly well
- Having spent a long time studying glaciers and hence becoming accustomed to the idea that some things that look stationary can move slowly over time, he decided to explore this further

Wager's Early Evidence

- He discovered that belts of rock and ice flows joined up across the continents when they were put back next to each other
- He also found similarities between ancient ice cover in south America, Africa, south Australia and India, indicating that they were once all close to the south pole
- He also found many animals and fossils that existed in both South Africa and South America, some also in Australia and Antarctica
- Weger thus hypothesised that all the land was once together in a supercontinent that he called Pangaea

Wager's Failed Mechanism

- Despite all this evidence, however, he did not have any good mechanism to explain how this would occur, and so mainstream geology did not accept his theory
- Weger hypothesised that the tidal forces of the sun and the moon were pulling the continents so that they ploughed through the oceanic crust – this was examined and rejected (rightly) as impossible

Ocean Mapping

- This situation lasted until the development of the bathometer, an instrument to measure the depth of the oceans during WWII
- Early maps clearly demonstrated that the ocean floor was not flat, but instead there was a ridge of mountains running down the middle of all the major oceans
- It was also observed that flat topped sea mountains called "guyots" are near sea level near the ridge (at the ocean centre), and fall deeper below the surface away from it
- This led to the idea that these deep guyots had once been near the ocean surface (where their tops had been eroded off by wave action), before they were moved down
- This then led to the development of the idea of seafloor spreading, which was pushing the continents out and causing them to move
- This alone was not enough evidence to prove Wegner right, but it did provide interesting evidence

Radiometric Dating of Sea Floor

- During the 1950s, radiometric dating allowed us to date the rocks of the ocean floor (which are mostly mafic extrusive igneous rocks)
- It turned out that the rocks were youngest near the ocean ridges, and progressively older further away from them

Magnetic Patterns on Sea Floor

- In 1964, Vine and Matthews published a paper on magnetic patterns on the sea floor
- It had been observed that the magnetic field reversal patterns on the ocean floor were symmetrical about the mid ocean ridges, and were in bands parallel to these ridges
- The only explanation for this is seafloor spreading, with extrusive magma rock being formed from the middle of the ocean ridges
- More than any other evidence, this paper helped to convince people that sea-floor spreading was real and that it could explain continental drift
- This led to the birth of what is now called plate tectonics (as opposed to the old name of continental drift), according to which sections of the lithosphere are moving about on the magma

The Cause of Seafloor Spreading

- We now know that continents move because of seafloor spreading; the next question is why does the seafloor spread?

Mantle Convection Cells

- The asthenosphere is a more plastic, fluidic portion of the mantle called the asthenosphere
- If on the earth's surface it would probably be brittle and crack when hit, but at the immense pressures and temperatures below the earth, it flows very slowly
- Being heated from below by radioactive decay, convection cells form in the asthenosphere
- Between opposite convection cells, we find the spreading ocean ridges, through which basaltic liquid magma erupts and forms new rock

Ridge-Push Hypothesis

- Another theory is ridge-push. When the ocean ridges form, they tend to be higher than surrounding rock, as the mantle material from which they are formed is quite mafic, and hence comparatively light

- As new ocean ridges are formed, old material will naturally tend to fall downwards and outwards away from the high ocean ridges, thereby pulling both of the continental plates apart from each other

Slab-Pull Hypothesis

- The third theory is known as slab-pull. This occurs because the end of a plate opposite that near the oceanic ridge may be subducting under a nearby plate
- As the mafic material is plunged deep into the earth, it is metamorphosed into denser mineral forms, thereby forming a heavy weight on the edge of the plates that tends to pull them down and away from each other

Examination of the Debate

- Geologists argue about which one of these three mechanisms are most important, but all probably play a role
- The fastest moving plates are all connected to subduction zones, so its seems that this mechanism does play an important role in speeding the whole process

Types of Plate Boundaries

- The three types of plate boundaries are divergent, convergent and conservative

Divergent Boundary

- Evidenced by a linear ridge with a downdropped valley at the center
- Once fully developed it always connects ocean crust with ocean crust
- The reason for this is because they are erupting mafic rocks, which are usually denser than the felsic rocks that comprise most of the continents
- Crust formed in this way is also thinner than continental crust, and so tends to sit lower on the mantle, and hence becomes covered in water
- Produces basaltic lava and thus creates new sea floor

Divergent Boundaries on Land

- When new divergent form on land, they are first manifested by a bulge in the ground called a mantle plume. Several of these may form along a zig-zag line along the diverging boundary
- Eventually each of the plumes cracks into three pieces, each cut by a 45-degree angle
- Two of these arms then spread away from the other arm, with an ocean trench forming between
- The gap between the two arms that remain together is called a failed rift, and tends to become a river and a region of high tectonic activity
- This process is occurring right now in east Africa and Arabia; you can see that the angle between the Red Sea and the gulf of Aden are about at a 120-degree angle
- The Red Sea and the Gulf of Aden are widening, making the Great Rift Valley of East Africa the failed rift

Three Types of Convergent Boundary

- Characteristics depend strongly on what types of crust are coming together
- 1. Ocean-Ocean
- 2. Ocean-Continental
- 3. Continental-Continental

Ocean-Ocean Convergence

- One plate "loses" to the other and sinks (subducts) beneath it
- Forms an ocean trench, and an arc of volcanoes on the side of the overriding plate
- This occurs because the subducting plate pulls down water with some sediment
- Water lowers the melting point of sediment, causing it to melt as it is pulled further into the earth, thereby reducing its density and causing it to rise to the surface, forming volcanoes
- These volcanoes tend to have some felsic and some mafic magma, and so are of intermediate composition, and form composite cones
- Zone of earthquakes shallow near the trench, and deep toward the volcanoes; this is very good proof of subductive zones
- Subduction zones are one of the strongest evidences against the idea of an expanding earth
- Aleutian islands are a good example of the volcanic "island arc" behind an ocean-ocean trench
- These islands tend to form in arcs because of the curvature of the earth

Ocean-Continent Convergence

- The Ocean crust always sinks below continental crust, as it is denser
- You will find a trench on the ocean side, and a volcanic arc on the continental side, formed by the same process as oceanic volcano arcs
- The only difference is that as the melted oceanic crust material rises, it tends to mix with the continental crust material and take on some of its composition
- As continents are relatively less dense, they must be made largely of felsic materials, which tend to form explosive ryeolitic volcanos
- Zone of earthquakes that are shallow beneath the trench, and deepen toward the continent
- The coasts of Washington and Oregon are good examples of this type (forming Mount St Helens); also Andes in South America

Continent-Continent Convergence

- One continent may start to go under the other, but eventually neither can sink fully into the mantle
- Instead, they push each other up into large mountain belts with intense compressive force
- Much folding, reverse and thrust faulting, and partial melting causing volcanic action (of a wide variety of magma types)
- Himalayas a good example; this is how deep marine limestone managed to end up at the top of mount Everest; it was thrust up there by continental collision

Conservative Boundary

- Plates slide past each other without creation or destruction of lithosphere
- Intense shear stress at the boundary causes much deformation of the rock there
- Rocks tend to form broken and folded "melange", for example near the golden gate
- San Andreas fault in California a good example of this

Measuring Plate Motion

How present plate Motion is Measured

- Today we measure the exact motion of plates using GPS devices (which interestingly also prove conclusively that the earth is not expanding)

Measuring Past Plate Movement: Hot Spots

- To make determinations further back in the past, we can lock at the motion of volcanic hotspots relative to the continents over time
- An example of this is the Hawaiian Islands, which mark the passage of the Pacific plate over time
- The island of Hawaii is the youngest and hence biggest, and as we progress to islands further and further away, we find that they are older and smaller (having been eroded for longer)
- The Emperor seamounts are actually part of the same chain, but are at an angle because the pacific plate changed direction some 40 million years ago
- Hot spots are located all over the earth, and by tracking their motion over time we can plot the past movement of the plates
- Such evidence actually tells us that some plates are rotating, while others are merely translating

Measuring Past Plate Movement: Magnetic Inclination

- Another piece of evidence is the magnetic inclination of rocks at various locations along the plate
- If the magnetic materials in a rock are close to vertical (pointing downwards), it means that it was formed near the north pole
- If they are roughly parallel to the earth's surface, it means they were formed near the equator
- Extrapolating back, we can tell the Wegner was right, and there did used to be a single large continent

Lecture 11: Earthquakes I

Earthquake Basics

The Basic Cause of Earthquakes

- When continental plates press into each other (compression), move away from each other (tension) or move along each other (shear), stresses are created
- These stresses on the rocks cause the rocks to fracture
- When a rock fractures, it releases energy that was previously stored as elastic energy, releasing it as waves of energy that ripple through the ground

The elastic rebound theory

- Elasticity reforms to the ability of a material to bend when subject to high forces, and then snap back to their previous shape and position after the stress is relieved
- Earthquakes begin when relative movement of continental plates causes rocks that transcend the two plates to either compress, stretch or bend in response
- These rocks slowly bend and deform, but once the stresses reach a certain critical level, the rocks break, releasing the stress forces, and releasing energy in the form of earthquakes

What is a fault?

- A fault is a break of rocks along which movement occurs; they are the site of earthquake generation
- Usually there is not one single crack, but a series of cracks in a general region called a fault zone

What is a fault trace?

- If the fault breaks all the way up to the surface, we will see it as either a fault trace (crack in the ground), or a fault scarp (one section of land pushed up relative to another)
- Movement along an entire fault plane is rare; usually only a small section of the plane moves

What is the focus?

- The place where the rock breakage actually occurs is called the focus; it is here that the stress is released, and here whence the earthquake waves propagate out

What is the Epicenter?

- The Epicenter is the point on surface of the ground directly above the focus

Modes of Generation

Tectonic earthquakes

- Most common, occur most frequently along plate boundaries
- Divergent boundaries have tensional stress, and so tend to form small, shallow earthquakes
- Conservative boundaries have shallow to intermediate depth earthquakes
- Convergent boundaries have subduction zones, and so tend to have very strong and deep earthquakes

Non-Boundary Tectonic Earthquakes

- Other tectonic earthquakes do not occur along plate boundaries
- Some are caused by the erosion of mountains, which causes them to be thrust upwards, hence generating significant forces
- Earthquakes like this are likely to occur closer to the centre of continents
- Energy waves propagate more effectively through consolidated than unconsolidated media, and so these centre of continent earthquakes tend to propagate much further than plate boundary earthquakes, which must pass through all the pulverised rocks between the plates

Volcanic earthquakes

- Magma causes popping and cracking as it passes through rocks, thereby generating seismic waves
- Earthquakes also often accompany the volcanic explosion itself

Collapse earthquakes

- Includes mine bursts (the outward explosion of mine shaft walls or quarry floors after a lot of material is dug out very quickly, thereby removing the counterbalancing pressure and causing explosion) and landslides, both of which are usually fairly small

Explosion earthquakes

- Some nuclear explosions have reached amplitudes of moderate sized earthquake
- Also asteroid impacts, which probably account for the largest earthquakes the planet has ever seen
- The richter scale is a logarithmic scale that measures the energy released by an earthquake
- Each unit represents about 31 times the energy output as the previous one

Seismic Waves

What are Seismic Waves?

- Seismic waves are the waves of energy released by earthquakes that travel through the ground
- There are four wave types which fall into two main categories
- Body waves: travel through earth’s interior
- Surface waves: travel only across the earth’s surface

Body Waves

- As we have never drilled through the crust, the only way we know anything about the interior of the earth is by examining how body waves travel through it
- Two types of body waves: P-waves and S-waves

P-waves

- P-waves are the fastest of all the wave types, and can travel through solids and liquids
- They take the form of compression and rarefaction (think of P as standing for pressure)

S-waves

- S-waves are slower than P-waves, and so are called secondary
- They are transverse waves, and can only travel through solids
- S-waves are more destructive shaking at the surface

Wave Refraction

- Because of refraction, seismic waves tend to bend upwards towards less dense material, in this case towards the surface
- This means that many people tend to be first hit by waves coming from directly beneath them, rather than from either side
- The first such waves to arrive will be the P-waves, which will be felt as an up and down motion
- Afterwards come the S-waves, which unlike P-waves move the ground from side to side, hence destroying more buildings and causing more people to fall over than P-waves
- S-waves can only go through solids; wave energy is lost as heat if transverse waves enter a fluid

Surface waves

- Surface waves come in two types: love waves and rayleigh waves
- They are about as fast as each other, but are both slower than body waves, and so they arrive last
- Love waves are basically like S-waves that are trapped on the surface, and are probably the most damaging of wave types
- Rayleigh waves have a circular rolling motion, just like ocean waves

Measuring Earthquakes

What are Seismograms?

- 'Ground acceleration' is the proper term for the shaking of the ground
- This can be measured by devices called seismographs
- The earthquake records produced by these instruments are called seismograms
- The first instrument ever used to detect earthquakes was invented by Chang Heng in China about 132 A.D.
- The first seismogram was recorded in Germany in 1889
- Today we usually use seismogram in small groups, one recording motion in each direction

What does an earthquake look like when observed?

- When there is no earthquake, a seismogram records a straight line
- The first indication of an earthquake will be observe as a series of squiggles, representing the arrival of the P wave
- Then comes the larger S wave, followed by an extremely intense period of shaking as the surface waves arrive (if one is close enough to the epicentre)

Locating the Epicenter and Focus

- 1) Use seismometers to measure the difference between P-wave and S-wave arrival times
- 2) Use known velocities of these waves to calculate the distance of the epicenter from the seismometer
- 3) Use distance calculations from three stations to triangulate the exact position of the earthquake epicentre (at the intersection of the three circles)
- To locate the focus we can use four seismometers and use spheres

Measuring Earthquake Intensity

- We can also use a seismogram to calculate the intensity of the earthquake
- We take the distance from the epicentre and the amplitude of the maximum shaking, and plug them into an equation to find the richter scale magnitude
- The further away one is from the focus, the less damage one usually experiences, but it also depends on the kind of ground one has built on (e.g. loose sediment is much less stable than rock)
- The Mercalli Scale is based on the perception of residents (felt) and damage caused
- Depends on soil/rock through which earthquake wave travels and construction techniques and materials

Exploring the Earth's Interior

- Use of seismic waves to look inside the Earth can be thought of as the first form of remote sensing
- Seismic waves reflect and refract (bend) within the Earth and can reveal layers of differing composition and physical state
- Because S-waves cannot travel through liquids we can also delineate non-solid portions of the Earth interior
- The earth has a solid inner core, a liquid outer core, a plastic mantle (which is solid from the perspective of seismic waves, but over longer time periods can flow), and the crust

The Interior of the Moon

- Seismometers placed on the moon by Apollo astronauts detected a number of moonquakes, though because they were only placed in a small range we still don't know much about the interior of the moon
- From what we know, it looks like that the moon has a solid iron core, surrounded by a semi-liquid mantle, and then an earth-like plastic mantle

Lecture 12: Earthquakes II

Earthquake Damage

Shaking

- Causes objects and buildings to fall
- Foreshocks are little quakes before the big one, aftershocks are little quakes after the big one
- Smaller aftershocks can topple buildings initially damaged by the main shock
- Overpasses are notorious for falling down, as the support structures are pulled out form underneath what they are supporting
- Buildings of different heights and shapes tend to vibrate at different frequencies, so if two buildings are joined together or if one building has multiple heights at different points, the structure will tend to rupture along these joints

- Vibrations also tend to become amplified as they move up a building, potentially causing rupturing of upper floors, or buildings to crash into each other as they wobble

Wave amplification

- Unconsolidated sediment tends to shake more than solid bedrock
- Damping and reinforcing of waves by multiple waves striking at once
- This effect has led to some instances of buildings being totally destroyed on one side of the street without being touched on the other side

Liquefaction

Refers to the fact that water-logged sediments hit by seismic waves can turn liquid

- This occurs because as sediment is shaken up, it settles into a more consolidated structure, thereby extruding some of the water to the surface, causing the ground to become liquid
- This can cause buildings to fall over

Fires

- Fire is also a common issue with earthquakes. In the past lanterns and candles would get knocked over, but an even bigger problem then and now is that the water mains are ruptured by the quake, thereby preventing the firefighters don't have water pressure to fight fires (also roads tend to get blocked, stopping them from getting to fires)
- Also, gas mains tend to get ruptured, causing fires

Ground rupture

- Opening of cracks or chasms in the ground, caused by fault traces that reach the surface
- It is very rare, however, that these are wider than a few meters

Tsunamis

- Also known as "Tidal Waves", but this is a poor name as they have nothing to do with tides
- Tallest one recorded was 24 meters high
- Geological evidence for even taller waves

Resonance and Destroying the Earth

- If an object is struck by seismic waves of this same resonance frequency, it will resonate, vibrating faster and faster until it finally fractures
- If this occurs with a building, it doesn't really matter how well built it is, it will probably collapse
- One of the only ways to really destroy the earth would be to rely on this fact of resonance
- If we set off a bunch of dynamite on one side of the earth, waited for the shockwaves to return, and then set off another lot at exactly the right time so that the energy superimposed, the earth would gradually vibrate stronger and stronger until it was destroyed
- In practise it might not be possible to do this owing to the reflection of waves off the inner layers of the earth

D

Predicting Earthquakes

- Earthquake prediction has never been very successful

Animal Behavior

- Many reports of animals acting strangely before earthquakes, for example fish jumping out of water, cows running around, dogs barking, etc
- Though it is possible that they are detecting something real (e.g. foreshocks), the datset is very biased, as people only report strange animal behaviour when it is followed by an earthquake, not when nothing comes of it

Other Dubious Techniques

- Earthquake weather: reports of eerie calm and clear skies just before an earthquake
- Some have theorised that calm weather is indicative of high pressure systems, which push more strongly on the ground, and hence causing earthquakes
- This is patently absurd, as the difference in air pressure is simply not enough to make a difference
- Greenish glow in the sky: it is possible that stresses in the rocks release free radicals or other unusual particles, that react in the atmosphere to produce glow effects
- This is not very well documented, and so is dubious at best
- Tidal pull of sun and moo: Semi-successful near volcanoes for minor quakes, but not that great
- Psychic Friend Hotline: psychics claim to be able to predict earthquakes, and since there are so many of them making these claims, it is likely that there will always be some hits, and these will be the cases that are publicised, while the misses are ignored

More Reliable Techniques

- Changes in P-wave velocity preliminary to the quake
- Ground uplift and tilt: this always indicates stress in the ground, which is a good sign that an earthquake might be coming
- Radon emission: microfractures produced due to rock stresses release pockets of radon gas just before an earthquake; hence spikes in radon gas levels indicate coming of a quake
- Electrical resistivity of the rocks should diminish, as stresses and movement of rocks releases electrons and other charged particles that can carry current
- Number of local earthquakes (foreshocks) – probably the most reliable method
- Geyser activity (changes in water table) – reports of geysers changing their period of activity just before an earthquake; has potential, but still preliminary

Paleoseismicity

- If we can determine when past earthquakes took place we may be able to judge the frequency and intensity of major events
- Historical records
- Tree ring data – tree roots are disturbed by earthquakes, which can disrupt tree growth
- Sand boils – caused by the liquification of water during earthquake
- These are often visible in the sedimentary record of an area, and so if we can date the rocks or organic material in the surrounding layers, we can find out when the quake took place
- Sea terraces due to uplift, which can be dated
- These techniques can all enable us to predict the approximate periodicity of major earthquakes

Geological Activity

- Another method for predicting earthquakes involves analysing areas known to be geologically active, and attempting to identify regions that have not had quakes for a long time, where stresses may be building up

Reducing the Damage

- Instead of predicting earthquake occurrence, the U.S. has chosen to focus on predicting earthquake intensity as being a more reliable option
- Building codes designed to match expected earthquake intensity – the greater the risk of an earthquake, the smaller should the size of buildings being built
- One good piece of advice is not to build on unconsolidated sediment, only on solid bedrock
- It is also possible to build skyscrapers with special springs in the foundations, which help to absorb the shock of the earthquake

History of Earthquakes

History of Earthquakes

- 856 - Corinth, Greece – First well documented earthquake, 45,000 killed
- 1556 - Shesi, China– Most disastrous quake in known history; 830,000 killed, mostly in collapse of poorly built buildings
- 1663 - St. Lawrence River, Canada – Broke chimneys in Massachusetts
- 1755 - Lisbon, Portugal – Very well documented, 70,000 killed, caused a great tsunami
- 1811 - New Madrid, Missouri – Largest known earthquake in the U.S; several large quakes followed into 1812
- 1906 - San Francisco, California – Richter scale 8.25, caused the San Francisco Fire
- 1960 - Southern Chile – Largest quake of this century (8.5)

The Only Ever Predicted Earthquake

- 1975 - Liaoning Province, China – This was the first earthquake ever predicted, by observation of increase amounts of Radon gas rising up from wells, and also by observing a number of small preliminary shocks
- The officials warned people to say outside for a few days, and so when the earthquake occurred, no one was killed, as no one was under any of the collapsing buildings

The 2004 Tsunami

- Shifted N-pole by approximately 1 inch to the East
- Decreased the Earth’s oblateness, as it was caused by a subduction zone near the equator, so the width of the earth actually diminished by a bit
- Because the earth became less oblate, to conserve angular momentum it also increased the daily rotation by 2.68 microseconds
- Earthquake had a depth of 10 km
- Every object has its own unique resonance frequency

Man-made Earthquakes

- Rocky Mountain arsenal began pumping contaminated water into deep wells (well below aquifers) for disposal in 1962, and earthquakes were felt in Denver soon after
- They ceased pumping in 1963 and earthquakes diminished, and when they began again in 1964-65, earthquakes increased
- The idea is that pumping of water into the ground places pressure on the rocks, which tends to generate earthquakes
- This phenomenon also occurs underneath the reservoirs that form behind newly built dams, as the enormous weight of the water pushes on the ground, causing small quakes

Lecture 13: Structure and Mass Movement

Structural Geology

Strike and Dip

- Geologists use the two numbers strike and dip to measure more precisely the exact alignment and position of beds of rock
- Strike is the direction of the line that is formed by the intersection of the plane of the rock bed with a horizontal surface
- Dip is the direction in which the steepest angle is formed between the plane of the rock bed and the horizontal surface
- Strike and dip can also be specified for faults and folds
- Geologists take these numbers and plot them on special maps and graph, and are the common means of communicating such information with other geologists
- By examining the strike and dip of different rock beds, we can determine what tension, compression and shear forces acted on that area

Stress and Strain

- Stress is a force applied over a volume of rock – Compression, Tension, and Shear
- Strain is the deformation of a rock in response to stress – rocks can strain brittlely (break into pieces), ductilely (flow), and elasticaly (bend and then snap back into shape)
- The same rocks or other objects can strain differently depending on the size of the stress and how long it is applied for

Three Types of Strain

- No rock structural forms are made by elastic strain, as by definition the rocks snap back into shape after the stress is removed, so there is no permanent change
- Brittle strain always produces faults, which are defined as breaks in the rock along which movement (of the rock) occurs

Simple Processes

Reverse and Thrust Faults

- Compression stress on brittle rocks produces reverse or thrust faults
- Thrust faults are just reverse faults with an extremely shallow angle, such that the rock is thrust a very long horizontal distance; tens or hundreds of kilometres
- Mineshafts are often dug along faults, as faults are places where fluid can flow, and hence they tend to become deposits for crystallised minerals of gold and silver
- This is how the nomenclature of footwall and hanging wall comes about
- Reverse faults are faults where the hanging wall moves upwards relative to the footwall

Folding

- Compression with ductile strain is called folding; it produces curved patterns in the rocks called anticlines (if they curve upwards) or sinclines (if they curve downwards)
- Anticlines are often contain good deposits of oil, as the oil layers in the anticline can become trapped below an upper layer of impermeable rock

Joints
- Tension stresses on brittlely straining rocks can produce either faults or joints
- Joints are simply fractures along which no movement occurs
- If movement does occur along these factures, we call them normal faults, as the footwall moves up relative to the hanging wall

Boudinage
- Tension stresses on ductile rocks produce Boudinage, meaning sausage in French
- These are repeating segments of fat and thin rock, caused by the stretching of rock as it is pulled from both ends

Strike-Slip Faults
- Shear stress with brittle strain produces strike-slip faults
- This is where two regions of rock or sediment move horizontally relative to each other, such that surface features no longer line up

Complex Processes

Monoclinal Folds
- Nature does not like to be pidgeon-holed, and so there are many types of geological motions that involves multiple types of stresses
- Monoclinal folds occur when we have shear stresses and ductile strain
- They appear as hoops in the ground, or bent letter s's in the ground

Slickensides
- Slickensides are stepped formations that appear on rocks that have slid along another rock in some kind of fault
- As they always appear such that the 'upstairs' direction is the direction in which the rock moved, we can use them to tell what kind of fault we have

Domes and Basins
- Sometimes we find fold formations of rock that are symmetrical in all directions in a ring bulls-eyed pattern
- If they point up they are domes; if they point down they are basins
- One way basins can occur is by glaciers sitting on an area of rock and pressing it down (glaciers are very heavy)
- The locations of the Great Lakes in the US were all formed in this way

The Principle of Isostacy
- The principle of isostacy refers to the fact that (for objects of a given density), the higher a floating object sticks up out of a liquid, the lower its roots must extend into the fluid
- The geological application of this is that tall mountains must have deep roots in the mantle
- This means that if mountains are eroded, they will tend to rise back upwards, owing to buoyancy
- This is what is happening to the Great Lakes region; the entire region is in isostatic disequilibrium, and so is rising upwards. This means that the lakes are shrinking

Isostacy and the Mississippi River
- The Mississippi river dumps about a ton of sediment per second into the Gulf of Mexico

- At this rate, we would have expected the Gulf of Mexico to have completely filled up already
- The reason it has not is because this weight pushes the Basin down into the mantle, thereby increasing the amount of time it takes to fill up a Gulf

Forming Mountains

- There are basically three ways to make a mountain
- The first is volcanic; spew up a whole bunch of ash and lava
- The second is fault block mountains, caused by normal faults which push blocks of rock upwards, while the other block of rock moves downward to form a valley
- The third type are the tectonic compression mountains, like the Himalayas
- Any mountain building event is called an orogenic uplift event

Differential Erosion

- Differential eroding is also the cause of many interesting geological formations, as different rocks weather at different rates, and hence some rocks disappear sooner than others, the result being a series of ridges and outcrops
- Epeirogenic movements are gradual upward or downward movements of the continental crust, without significant faulting or folding
- Can still produce spectacular landforms when uplift occurs due to downcutting of stream systems (river tries to maintain its level as the land rises up around it) – this is how many canyons form, notably the Grand Canyon

Mass Wasting

What is Mass Wasting?

- Mass wasting refers to gravity acting on a slope producing a shear stress
- At the same time, shear strength is provided by the internal friction within the slope material
- Mass wasting occurs when shear stress exceeds shear strength
- Shear stress depends on the mass of the material and the level of slope

The Safety Factor

- The safety factor is the shear stress divided by shear strength; as soon as the safety factor hits one, the region becomes unstable and a landslide occurs
- The closer a slope's safety factor is to one, the closer it is to failing

Slope Stability Determinants

- Mass and slope
- Climate, Vegetation (e.g. roots can stabilize slopes)
- Water (groundwater)
- Materials: Rock type, sediment (fine vs coarse), soil
- The structure of the rock is also important: for example, landslides are more likely to occur in regions where the rock bed is parallel to the slope, as opposed to perpendicular

Classification of Mass Wasting

- Rate of movement: Extremely slow (1mm/year) to very rapid (>100 km/hour)
- Type of Material In Motion: Bedrock or debris (soil or sediment)

Types of Movement

- Flows : materials mix together as they fall, not staying as a solid block, e.g. soil creep, mud, debris, avalanche
- Slides: coherent blocks/units fall together, can be translational or rotational
- Falls: free falling objects
- The top of a slope is called the head, and the bottom is called the toe

Factors Which Raise the Safety Factor

- Adding weight to the head, thereby increasing the gravitational shear force (e.g. building on the top of a hill)
- Removing weight from the toe, thereby reducing material that was previously helping to keep the head up (e.g. cutting a road at the bottom of a hill)
- Any change to the hill that makes it steeper increases the safety factor
- Removal of vegetation, as roots help to hold the soil together and withdraw water from the soil
- Higher water contents in the soil raise the safety factor, as water adds weight, can freeze and cause ice wedging, and also lubricates the material
- Draining water out of a hill is a good way to avoid landslides
- Building houses on the top of hills and then watering the lawns is also a bad idea
- If a slope has a safety factor of close to one, an earthquake can set off a mass wastage
- Changes in climate can also alter the water content or vegetation levels, thereby changing the safety factor

Preventing Mass Wastage

- Slope stitching is a way of preventing rockslides by inserting large metal bolts into rocks or soil, securing them to the underlying bedrock, and helping to prevent landslides

Part B: The Hydrosphere

Lecture 14: Oceans and Shorelines

Cyclical Movement of Water

Why Water is Special

- A universal solvent; can dissolve just about anything
- Can exist in all three of its phases simultaneously on earth
- Forms a crystalline structure such that its solid form is less dense than its liquid form, thereby preventing the planet from freezing over
- It is also very mobile; flows downhill, evaporates, rains down, etc
- Extremely high specific heat capacity, so it can carry a lot of energy

The Hydrological Cycle

- The movement of water is called the hydrological cycle
- Rainwater that clings to the leaves of plants is called interception
- Runoff is all water that flows on the surface of land, back to the ocean (lakes, rivers, etc)
- Volcanic emission of water as a gas also acts as an input into the hydrologic system

- Water from comets also contributes a certain amount; indeed, it is theorised that much of the water on earth came originally from comets

Infiltration and Transpiration

- Water that sinks into the ground is called infiltration; much of it also moves back to the ocean, or returns to the surface
- Vegetation on land also takes water up through its roots and transpiring it out through its leaves during the night
- The sum of transpiration and land evaporation is called evapotranspiration; taking water from land and putting it back into the atmosphere

Why we Need Fresh Water

- Land animals including humans cannot drink ocean water, as it is so salty that if we had too much of it in our bloodstream osmotic pressure would force the water out of our cells, and we would die of dehydration
- Because so much of the fresh water on the planet is locked up in ice and glaciers, there is enormous potential for any method of accessing this water economically
- It has been proposed to tow ice bergs from the poles, but they tend to incorporate too much salt into the ice pores, and too much of the ice melts for it to be economical

Residence Time and Ice

- The bigger a reservoir is, the longer the residence time tends to be
- For example, water only spends about a week in the atmosphere, while water in the ocean stays there for thousands of years
- The oldest ice ever dug up (form Antarctica) is 600,000 years old

The Oceans

Basic Ocean Data

- Contain 97 % of Earth's free water
- Cover 71 % of Earth's surface
- 60 % of northern hemisphere
- 80 % of southern hemisphere
- Average depth of 3.8 km
- Maximum depth in trenches up to 11 km
- Mostly water and dissolved salts (3.5%); a dilute mixture of everything
- Also contains dissolved gases from atmosphere
- Regulates short term CO_2 content of the atmosphere – atmosphere 380 ppm, ocean 25 ppm's
- Major repository of chemicals and sediments brought from land by rivers

Ocean Two layer system

- Surface layer: Thin, warm, and less dense, higher light levels
- Deep layer: Thick, cold, dense, dark
- Separated by thermocline region of sharp temperature change

Antarctic Bottom Water

- Water can be even further reduced down into specific packets, traced by chemical composition

- One such packet is Antarctic bottom water, which lies at the bottom of the Atlantic and Pacific Oceans
- It forms around Antarctica. As ice begins to form on the surface, it excludes salt, which then moves down into the water beneath the ice
- This water then becomes very dense, as salt tends to make water more dense
- Cold water is also more dense than warmer water, and the water underneath the Antarctic ice sheets it very cold
- This cold, dense water tends to sink to the bottom of the oceans, and then move northward along the bottom of the Atlantic and the Pacific
- There are many other similar packets of water that are in motion relative to each other

Downwelling and Ocean Currents

- Movement of ocean water from the surface to the bottom is called downwelling; the reverse is called upwelling
- Downwelling of cold, salty water drives the motion of the deep ocean currents, while wind motion drives the surface currents
- Surface currents in the northern hemisphere tend to have clockwise motions, reverse in the southern hemisphere; these circular motions are called guyers
- The downwelling, upwelling, and circular surface currents all join together to form what is called the oceanic conveyer belt

The Gulf Stream

- One important part of this is the Gulf Stream, which is the surface current that flows along the east coast of the north American continent towards western Europe
- As the water moves towards Greenland, it slowly evaporates, thereby becoming more saline
- Once it reaches northern latitudes the water cools down, and then sinks to the bottom and moves south again
- This motion is very important to driving the motion of the entire world conveyer belt

Global Energy Conveyer Belt

- The lines of about forty degrees latitude mark the boundaries of the central equatorial region of the globe where incoming radiation energy exceeds outgoing energy
- The regions to the north and south of this are the reverse, and the two balance out exactly
- The global conveyer belt is very important for maintaining this heat transfer

Causes of Sea-Level Rise

- 1. Melting of glacial ice
- 2. Thermal expansion of sea-water
- 3. Increased rate of sea-floor spreading, thereby raising the overall level of the seafloor
- This happened to the most extreme during the Cretaceous period, when it is though that sea floor spreading was significantly slower, and also the ice caps were completely melted

The Tides

Causes of the Tides

- Ocean tides are caused by the gravitational influence of the sun and the moon, mostly the moon

- The moon exerts a tidal influence on the earth such that it tends to be stretched slightly lengthwise in the direction of the moon
- The rocks experience this force as well, but of course water flows much more easily
- There will actually two bulges of water on earth, one on the side near to the moon, and one on the opposite side of the earth
- This is why there are usually two tides per day

Spring and Neap Tides

- Because the sun also plays a role in this, the biggest tides are observed at times when the sun and moon are aligned with each other
- This is known as a spring tide, which occurs at new moon or full moon
- The lowest amplitude tides occur when the sun and the moon are at a 90 degree angle, which occur at times of first and third quarter moon (these are called neap tides)
- Other factors that affect tides include whether it is on the east or west coast of an ocean, the shape and slope of the shoreline, and other factors

Tidal Friction and Moon Slowing

- The friction between the earth and the water as moved about by tidal motion is actually slowing down the Earth's rate of rotation, at the rate of about one second every 100,000 years
- So, about one billion years ago, the day was only about 18 hours long
- Even more interestingly, as the earth spins about its axis it tends to push the tidal bulges ahead of it a little bit
- These tidal bulges then exert a gravitational force on the moon, causing its orbit about the earth to speed up
- This in turn has the effect of causing the moon to recede from the earth, as any orbiting object does when it moves away from an object
- We can measure this directly by bouncing laser beams off of mirrors left on the moon by Apollo astronauts

The Fate of the Moon

- Eventually, the moon will recede far enough such that the rotation of the moon will match the slowing orbit of the earth
- When this occurs, the moon will become tidally locked with the earth
- Long before this actually happens, however, the sun will expand and then consume the earth and the moon

Waves and Erosion

Factors Influencing Wave Size

- 1. Wind speed: Faster wind makes bigger waves
- 2. Wind duration: The longer the wind blows, the larger the waves will be
- 3. Fetch: The farther over the water the wind blows, the larger the waves will be

Circular Wave Motion

- Waves cause the water to move in circles, with decreasing radius with increasing depth
- The top of the wave is a crest, the bottom a trough, and the place where the motion of water ceases is the wave base

- The wave base is about half the wavelength of the wave on the surface

Waves Near the Shore

- When the wave base approaches the shore, the wave base eventually hits the bottom of the sea
- As this occurs the wave begins to stir up and agitate the sand, thereby losing some energy and slowing the wave down
- As such, the waves tend to bunch up as they approach the shore, reducing the wavelength
- Because the amount of water in the wave does not change much, the wave height must increase
- At the same time, the bottom of the wave is slowed down more than the top, thereby causing the wave to lean forward, and eventually topple over

Wave Refraction and Headlands

- Wave refraction refers to the bending of waves as they approach the shore
- As a wave approaches a region of shore with bays and headlands, the waves near the headland are slowed down before those near the bays
- This leads to wave refraction such that wave energy is directed toward the headlands, which becomes sites of erosion, while the bays become sites of deposition
- This interesting negative feedback mechanism therefore acts to smooth out shorelines over time

Longshore Current and Beach Drift

- Often, waves do not hit a shore exactly perpendicular to the beach; this is called a longshore current
- On the beach, these waves will push the sand slowly in the direction of the longshore current – this is called beachdrift
- This tells us that a beach is a dynamic changing system, with the sand turning over after a period of time
- This is why building on the sand of beaches is never a good idea

Beach Erosion

- Beach erosion is an increasingly common problem in many areas
- One reason for this is that the construction of dams preventing rivers from flowing all the way to the ocean, thereby starving the beaches of their main supply of sediment
- Construction of seawalls or jetties out from a beach blocks the movement of sand by the longshore current, thereby leading to the build-up of sand on one side, and a starving of sand and hence erosion on the other side

Storm Surge

- The most damaging thing about hurricanes is not the wind itself, but the storm surge that the hurricane produces
- Storm surge is the flooding of coastal areas as a combined result of the water pulled over by the wind of the hurricane, and also the fact that hurricanes are low air pressure regions, and so tend to cause the water to expand upwards
- The degree of flooding will of course depend upon the altitude and slop of the shoreline
- This storm surge is what caused the disaster of Hurricane Katrina

Lecture 15: Streams and Flooding

Describing Streams

Stream Terminology

- In geography, all surface water flows are referred to as streams
- The very beginning of a stream is referred to as the head, while the end of the stream where it empties into a larger body of water is called the mouth

Flow velocity

- Measuring the velocity of a stream can be difficult, as any objects placed on the surface of the stream are affected by surface winds
- The fastest water in a stream tend to occur at the centre, farthest away from the friction of the banks, and just below the surface, as water at the surface is slowed down somewhat by friction between the air and the water

The Manning Equation

- Used to calculate velocity of a stream without actually measuring it directly; $V = \left(\frac{1.49}{n}\right) R^{2/3} S^{1/2}$
- n=Manning roughness coefficient, based on the type of sediment
- R=Hydraulic radius=A/P
- A is the cross-sectional area and P is the wetted perimeter
- S=slope of channel
- A rating curve is a graph that shows the relationship of the gauge height of a stream and its discharge volume at that point, thereby allowing us to determine stream speed by simply measuring gauge height at that location

Stream Discharge

- Stream Discharge (Q) is the volume of water that flows past a given point per unit of time
- Q=WxDxV, measured in cfs or m^3/s
- W is width
- D is average depth
- V is average velocity

Uplift and the Base Level

The Longitudinal Profile

- Between the head and the mouth, virtually all streams adopt a similar shape known as the longitudinal profile
- This longitudinal profile begins with a steep gradient, and gradually flattens out into a smooth gradient near the mouth
- All streams tend to adopt a shape as close to this longitudinal profile as they can
- Usually streams are not this smooth, but are composed of a series of steps or riffles and pools
- The base level is the level of the mouth of the stream; streams finally become horizontal at this level

Uplift and the Grand Canyon

- If the land around a stream is uplifted, the stream will tend to erode down into the land so maintain its longitudinal profile

- If the land is moved downward, it tends to deposit material to maintain this level
- This is an explanation for how the Colorado river formed the Grand Canyon

Changing Base Level

- Streams can also change if their base level changes
- For example, if ocean levels rise, the base level rises, and so the entire longitudinal profile becomes somewhat less steep
- The same thing happens when a new dam is built, thereby changing the base level

How Waterfalls Form

- As land is uplifted and the stream begins cutting down through it, it may pass through rocks that weather at different rates
- At this occurs, some regions will tend to be eroded lower than other regions, thereby forming waterfalls
- When water falls onto the less resistant layer of rock at the bottom of the cliff, it slowly cuts out a hole, which eventually leads to a notch forming at the base of the waterfall

Waterfall Migration

- Eventually a portion of rock form the top of the waterfall will fall down to the bottom, where it is slowly eroded by the falling water, and the process starts again
- The end result is that waterfalls tend to slowly migrate upstream

Stream Landscaping

Floodplain Levies

- Rivers on floodplains tend to form levies, which are small naturally-formed embankments of earth on the edge of the stream
- These form because when a river floods, it has much more water, and so speeds up substantially
- As soon as the river breaks its banks, however, the pressure on the water is released, and so the water slows down very rapidly
- As it does so it deposits sediment, which therefore falls on the very edge of the river, forming the levies
- As the floodwater recedes back into the river, some of it is left behind on the plains, thereby forming back swamps

Oxbow Lakes

- Another common formation are so-called oxbow lakes
- These are hoseshoe-shaped lakes that form as a result of two meandering sections of the river merging into each other, thereby forming a cross-section
- The stream will then travel through this cross-section (as it is a shorter route), thereby cutting off the big u-shaped section from the river
- As sediment is deposited at the entrance to this cut-off section, it is separated from the main body of the stream, forming an oxbow lake
- If an oxbow lake dries up, is formers what is called a meander scare, which marks where the river used to flow

Terracing

- Terracing is a phenomenon whereby streams are found to be surrounded by staircase-like shapes of stepping rocks
- These are in fact the remnants of old floodplains, which the stream has now abandoned because either the land uplifted or the base level fell, and hence the stream has tried to adjust
- Dating of floodplain terraces can be a means of measuring past levels of earthquake activity, as earthquakes can cause uplifting and hence new flood plain levels
- Very rapid uplifting can cause rejuvenation, whereby an old stream begins to look more like a young stream

Drainage Basins

- A drainage basin is an area of land where all the water that falls in the area ends up in the same place
- The measured size of the drainage basin depends on at what point of the stream system you decide to measure it; the further downstream, the wider the area
- Drainage divides are highlands that separate two different drainage basins (for example, hill or mountain ridges)
- The US has two major drainage divides; along the Rocky Mountains and the Appalachian Mountains

Stream Shapes in Basins

- The streams that run through drainage basins can have four main different shapes
- The type of drainage pattern can tell us about the geology of the area
- Dendritic (fractal like a tree), diverging form a central point (radial), moving in straight lines and around right angles (rectangular), and one major stream with many tributaries intersecting in at a ninety degree angle (trellis); they tend to form over homogenous flat layered sediments
- Radial patterns tend to form over conical mountains, such as volcanoes
- Rectangular patterns from on rocks that tend to join at right angles
- Trellis forms occur when a main stream cuts across the gain of a rock layer, while all the smaller tributaries run parallel to the grain
- When dendritic forms appear in areas where we would only expect to find trellis, we can surmise that the river originally formed in flat sediment, but this has since eroded away, leaving folded sediment that is producing new trellis patterns

Wind Gaps and Stream Capture

- Wind gaps are regions that look like a tributary stream used to run through, perpendicular to the main stream, but are now empty
- These are caused by stream capture, which is a phenomenon whereby one stream steals the water of another, thereby leaving the other stream and its tributaries dry
- Stream capture can occur as streams are uplifting, and hence they move around a bit

Sediment Deposition

Capacity and Competence

- Stream capacity is the total discharge of sediment the stream is transporting – Bed, suspended, and dissolved load
- Stream competence is the largest sized particle being moved by the stream – Bed load material

- When the suspended load of a stream exceeds its stream capacity, it forms a braided stream, whereby many channels run separately next to each other

Young Rivers

- Young rivers tend to be mostly straight, and have v-shaped valleys; during floods, they tend to overflow very rapidly and very severely
- Young rivers mostly exist up in mountains, and tend to be relatively low volume, as there has been little time for many stream to join together

Middle-Age Rivers

- Middle-age rivers are usually found on flat floodplains, and tend to be more windy and curvy
- Floodplains are always formed by the flooding of rivers and consequent deposition of sediment; as such it is a bad idea to build on flood plains, as they will always flood again

Old-Age Rivers

- Old-age rivers are still more voluminous and more curved or meandering
- This occurs because the water on the outside of curves must always travel faster on the inside of the curves, and so erosion occurs more rapidly on the outside of the curves, while sediment will tend to be deposited on the inside of the bend
- These are called point-bars (inside) and cut-bars (outside)
- This also means that the entire river moves over time, snaking back and forth and becoming wider and more meandering

Alluvial Fans

- Alluvial fans are fan-shaped regions of sediment, which often form at the edge of mountains
- They are caused because the stream will deposit sediment in one location for a while, until that area is built up so high that the stream becomes unstable, and so runs down an adjacent area
- This process continues until the entire fan is formed
- Note that coarser sediment tends to be deposited closer to the mountain, while smaller particles are deposited further away
- As groundwater can flow through coarse but not fine sediment, vegetation tends to occur only on the regions of the fan closer to the mountains

Coastal Deltas

- A similar process occurs as streams run into lakes or oceans, forming deltas
- The shape of deltas can differ depending upon the effect of tides and waves
- Just as in alluvial fans, the region of deposition where the stream runs moves about over time in deltas
- This is currently occurring with the Mississippi, which were it not for the efforts of the army corps of engineers would have moved away from New Orleans in search of a shorter route to the ocean

Flooding

Hydrographs and Flood Development

- Hydrographs are graphs that have time on the x-axis and stream discharge on the y-axis; they are generally used to graph flooding events

- Every flood begins with a rain event, which appears as a gradual rising limb on the hydrograph (as it takes time for the water to enter the stream), which culminates in a peak, and is followed by a falling discharge
- Some streams rise slowly with a longer lag time (which is the time between peak rain and peak stream discharge) – this is called sluggish discharge
- Other streams could have the rising limb rise much more quickly, with a higher peak discharge, but shorter overall duration of the food event (these are flash floods)
- Flash floods are more dangerous, as they reach higher levels, and have less warning

Flood Recurrence Interval (R)

- The average time elapsed between floods of a given size/magnitude
- Recurrence interval concept used for other natural disasters too; just replace "floods" in the above definition with the disaster de jour
- To determine this, first measure the peak discharge during each year for a period of time
- If the station has a long record these can be useful statistically
- R=n+1/m; where n is the number of years of record and m is the magnitude (order of rank)
- The largest flood on record is m=1, then m=2, and so on down to however many years we have on record
- The flood Probability: P=1/R, where P is the probability of flow being equalled or exceeded in any one year

Calculating the Probability

- Another useful formula is $q = 1 - \left(1 - \frac{1}{T}\right)^n$, where q = the probability of flood with a recurrence interval T occurring in the specified number of years n
- Using these equations, we see that a 50 year flood has a 2% chance of occurring this year and an 86% chance of occurring in 100 years
- Note that these are only statistical averages; the chance of a fifty year flood occurring this year does not diminish even if one happened last year

Flood-Frequency Curves

- A flood-frequency curve is a graph that plots the discharge against the recurrence interval, thereby giving the size of each particular type of flood
- This curve can even be used to extrapolate out what a 500-year flood might look like
- We can also used these curves to aid in city planning
- Native land, city parks, and agricultural areas work well in flood prone areas
- Libraries, fire and police departments are not such a good idea

Historical Flood Trends

- If we look at historical data, it seems that floods are getting more severe over time; or to put it another way, what used to be a hundred year flood is now a ninety year flood
- The reason for this is that construction of cities removed vegetation, thereby reducing evapotranspiration, while the construction of buildings and roads reduces infiltration
- This excess water then must go into an increased runoff, which in turn means that the peak discharge of the stream is reached sooner after the rain event
- This means a shorter lag time, which translates into a more severe flood
- Deforestation reduces evapotranspiration, thereby increasing the severity of flooding

- Indeed, the term ‘tree-hugger’ originates from a group of women in India who began hugging or attaching themselves to trees in order to stop them from being cut down, and hence saving their village form being flooded

Ice Sheet Melt Floods

- Huge natural flooding events can occur when natural lakes are held in by ice sheets, which then melt, thereby releasing the entire lake in a very short time period
- The resulting enormous floods can produce huge gouges of valleys throughout the region, and can move rocks the size of houses
- Some have theorized that the English channel was originally formed this way

Lecture 16: Groundwater

Water Through the Sediment

What is Groundwater?

- Groundwater is by far the largest source of freshwater on earth, with streams and lakes providing very little by comparison, and most of the rest locked up in ice sheets’
- Groundwater is water that is underground, below the water table (in the saturated zone)

Porosity and Permeability

- Porosity = the space between solid particles of soil or rock that can be filled by fluids
- Permeability = the ease with which fluids can pass through a body of soil or rock
- For example, floorboards are clearly impermeable to fluids, but this does not necessarily mean that there is very little empty space inside the boards
- Indeed, the empty space in between packed perfect spheres is exactly the same regardless of the size of the spheres
- In the real world, sediment particles are not perfectly sphere
- In fact, smaller particles tend to be flatter and longer, thereby stacking in such a way that they prop each-other up, thereby increasing the empty space and hence the porosity

Comparing Sediments

- Mud has a very high porosity, but the empty space are poorly connected, and so it has a low permeability, meaning that little water can actually be extracted from mud
- Sand is the reverse: less porous, but very permeable
- Some substances, like limestone, have a very low permeability, but a high unit permeability
- This means that although water may not pass through the rock itself much at all, it can pass into cracks in the rock, causing more of the rock to dissolve, and eventually forming caves and tunnels that make the rock as a hole very porous, even if water cannot actually pass through the rock material itself

Infiltration and Aquifers

- Infiltration = the movement of water from the surface into the ground
- Aquifer = a body of soil or rock that can hold a useable amount of water
- This is a very subjective definition, and usually refers to what can be used economically

Aquicludes and Aquitards

- Aquiclude = a body of soil or rock that blocks the flow of water (Aquitard slows the flow)

- Technically, there is not pure aquiclude that totally stops the flow of water, just substances that that are relatively poor at transmitting water
- Indeed, materials that are aquitards in one area may be described as aquifers in another area, owing to differences in the surrounding materials with which they are being compared

The Zone of Saturation

- The zone of saturation is the region of sediment where the porous between the grains are filled with water
- In the area above it, the zone of aeration, there is some water that clings to the side of sediment by surface tension, but for the most part is filled by air
- The level of the zone of saturation is called the water table
- This model works best when it is applied to a region where there is no aquitard rock covering the aquifer

Groundwater Flow

The Water Table Profile

- The profile of the water table basically follows a subdued pattern of the contours of the surface of the earth
- Anywhere were the water table intersects the surface of the earth, we find surface water; rivers or lakes
- The only exception to this are rivers or lakes formed rapidly due to flash floods, though they generally drain away and evaporate rather quickly

Movement of Groundwater

- Groundwater moves, flowing downhill just like surface water
- Flow of groundwater into streams and rivers is what explains the ability of streams and rivers to survive even weeks or months without rain
- Streams that are receiving water from the groundwater are called gaining streams; streams that are above the levels of surrounding groundwater are called losing streams

Drainage Divides

- Just as there are drainage divides for above ground water, there are also drainage divides for groundwater, depending upon where the high points of groundwater are located
- By mapping out the drainage divides for groundwater, we can actually determine which areas are most at risk of being affected by underground contamination

Darcy's Law

- Just as streams have a discharge, so do aquifers: $Q=KIA$
- Q is the discharge of the aquifer
- K is the permeability of the aquifer (the hydraulic conductivity)
- I is the hydraulic gradient
- This is measured by taking the height of the water table at two locations, and dividing the change in height by the horizontal distance between the locations
- This is done because height is indicative of water pressure
- A is the cross-sectional area the groundwater is passing through

'Natural' Streams?

- Just because water comes from a natural stream does not mean that it is clean and pure, although flowing water through sediment does tend to be filtered by the sediment particles
- Much irrigated agriculture relies on pumping water from aquifers below the ground

Surface Features

Confined Aquifers

- A confined aquifer is an aquifer that has an aquitard both above it and below it (normal aquifers only have an aquitard below them)
- One way that water can get into confined aquifers is if water has formed along with the rock
- Another possibility is that a confined aquifer might be connected to an unconfined aquifer somewhere else, such that the rainwater is able to flow into it

Artesian Wells

- Water in these confined aquifers can be under such sufficient pressure that if drilled into, the water can be ejected at a great rate, without any pumping
- These are called artesian wells

Geysers

- Geysers are bodies of underground water that are superheated by nearby magma pockets (superheating is possible because of the high pressure of the water at the underground depths)
- Eventually the pressure reaches high enough levels that some of the water is pushed upwards, where it cools and expands, thereby allowing it to form a gas that escapes
- This releases some of the pressure on the water beneath, thereby allowing it to evaporate to a gas
- Thus is instigated a run-away process which soon leads to the evaporation of all the water within the underground pocket
- It then takes the water some time to build up in the pocket once again before the cycle can repeat itself
- This is why geysers occur periodically, and also why they occur in regions of surface volcano activity

Water Towers

- The same principle of water pressure pushing water upwards is why water towers are used to generate water pressure in nearby faucets
- Water pressure of this sort tends to diminish with distance from the tower, owing to friction

Confined Aquifers

- Unconfined aquifiers are closer to the surface of the earth, and so are cheaper to drill into, but are also much more susceptible to water pollution, as any contaminants can seep down into the aquifer
- Conversely, confined aquifers are deeper and so more expensive, but have better protection against contaminants

Limestone and Caves

How Caves Form

- Caves form in areas of cavernous limestone
- When limestone has enough caves, it becomes very permeable to water

- Sandstone and other rocks and sediments can filter out contaminated water, but the very high porosity of the caves means that this does not happen

Rubbish in Sink Holes

- Sink holes are caves whose roofs has caved in
- Often people dump their rubbish in sinkholes, seeing them as convenient dumping grounds
- This is very stupid, however, as the caves will connect right into their groundwater, and so if they are polluting their caves they are also polluting their groundwater, which probably means they are also polluting their water supply

Stalactites and Stalagmites

- As water falls as rain, it dissolves carbon dioxide from the atmosphere, and becomes carbonic acid
- When it hits the ground, it dissolves organic materials, and becomes even more acidic
- When the acidic water percolates through the limestone, and being acidic it begins to dissolve the calcium and other materials in the limestone
- Once the water reaches the roof of the cave, the carbon dioxide tends to be lost to the cave room, which has a lower concentration of carbon dioxide
- This loss of carbon dioxide causes the water to become supersaturated with calcium, which then precipitates out of the solution, forming stalactites and stalagmites
- When these two formations join, they form a column
- Stalactites and stalagmites tend to form in patterns along the lines of the fractures in the overhead rock, as these are where the water can percolate down

Cast Topography

- One should be careful when building in a cavernous limestone area, as buildings can easily sink down into the caves, forming a sinkhole
- Regions of this gradually form cast topography, which is very pitted and hilly
- Sometimes the entire ceiling of the cave can fall in and be eroded away, leaving behind only the columns, which stick up out of the ground like tree trunks

Groundwater Problems

Cones of Water Depression

- If a single well is pumped excessively such that the rate of water removal exceeds the recharge rate, it will actually lower the water table at that area
- The water table does not move down as a flat line parallel to the ground, however, as it takes time for water to flow to the well
- Hence, a depression in the water table called a cone of depression tends to form
- This can actually reverse the flow of groundwater in regions either side of the well, causing any wells in those regions to go dry
- We can actually use this fact in our favour if we need to stop a spreading patch of groundwater contamination

Groundwater Drawdown

- Groundwater drawdown is a serious environmental problem across the planet
- The supply of groundwater across the planet is diminishing, but is not very obvious because we don’t see it

- If we draw out so much water that we dry up the aquifer, we get what is called watershock, which is when we cannot draw out any more water than infiltrates in from rain
- This has already happened in regions of Africa and the Middle East

The Ogallala Aquifer

- The Ogallala ("High Plains") Aquifer is a massive aquifer in the US near the Rocky Mountains
- It holds enough water to fill one of the great lakes, and is what enables much of the agriculture in surrounding desert regions
- Most water is pumped for irrigation of crops principally used to feed livestock
- From 1940 (when really effective petrol pumps came into use) to 1980, the aquifer water table fell an average of 10 ft/decade (up to 100 ft in some places)
- During the 1980's it only fell another foot due to improved irrigation techniques
- The amount of water that has already been removed would take about 2000 years to be replaced

Salt Water Intrusion

- Fresh water is less dense than salt water, and so near the ocean there will be groundwater deposits of fresh water sitting on salt groundwater
- Overpumping of these freshwater deposits produces a cone of depression in the fresh water
- This in turn leads to inflow of salt groundwater, so effectively if you suck out too much freshwater you can end up sucking in salt water

Land Subsidence

- As water is pumped out of the ground, sometimes it is under pressure and is actually keeping sediment particles apart
- When the water is removed, the particles move closer to each other, thereby compacting the land and causing the land to subside
- As it falls, buildings and roads are cracked and damaged
- It is not possible to pump the water back in and reinflate the land; it would require too much pressure

Sources of Groundwater Contamination

- Gas stations and fuel storage
- Mining operations giving off chemicals
- Salt dumped on roads that dissolves and trickles into the ground
- Fertilisers and pesticides
- Landfills and septic tanks
- Anything poured down a well or sewage system can also cause contamination

Underground Petrol Tanks

- In most countries, including the United States, are called LUSTs, or leaking underground storage tanks, usually at old gas stations
- Groundwater is slightly acidic, and so over time it gradually corrodes the underground gas tank, thereby causing it to spring leaks
- Groundwater contaminated with gasoline is very dangerous
- When the contaminated water is brought to the surface, however, the volatiles evaporate and the contamination is cleared

Groundwater Pollution Types

- Light Non-Aqueous Phase Liquid (LNAPL) – are less dense than water so float on the top, for example gasoline
- Dense Non-Aqueous Phase Liquid (DNAPL) – more dense than water and so sink to the bottom
- LNAPLs are more mobile than DNAPLs, which tend to sink down and then just sit in one spot

Lecture 17: Water Pollution

Historical Cases

Benefits of Surface Water

- Sustains ecosystems that fulfill important roles in biogeochemical cycles and the water cycle
- Source of food
- Major source of drinking water
- Recreational/aesthetic value

Flaming River

- Back in the 1950s and 1960s, organic flammable compounds were commonly disposed in rivers (sewer systems)
- In the 1960s it was common for children to set small fires on the water for fun
- In 1968, the river actually caught fire, destroying seven bridges

Love Canal Background

- In the 1930 to 1950s, the Hooker Chemical (Occidental) company dump chemical wastes in barrels (over 80 different chemicals, 20,000 tons) in a canal (Love Canal) close to their factory site
- In the 1950s, the city decided they wanted to the land for building, but the company warned them that it was not safe
- Nonetheless, the city insisted, so the land was sold for the token sum of one dollar, and the city proceeded to develop the area, building schools and houses

The Pollution Incident

- These structures remained for several decades, until in the winter of 1976-77, heavy rain/snow caused some of these wastes to percolate up through the ground to the surface
- Vegetation began to die, and rubber disintegrated
- Dogs developed sores
- Appearance of puddles of toxic or noxious substance, basement flooded
- Claims of miscarriages, birth defects, blood and liver abnormalities
- Beverly Paigen did a systematic study, and found that the homes above and near the canal had a much higher rate of diseases and birth defects
- In 1978, the state identified numerous toxic and noxious chemicals in the area, including benzene, dioxin, dichloroethylene, and chloroform
- The State and Federal government bout and demolished over 200 homes, relocating some six hundred families; by 1990 $275 million had been spent in cleaning up the site

Outcomes of the Incident

- The case of Love Canal did a lot to promote awareness in the problems of water pollution and chemical toxicity in the United States, and helped to secure funding to clean up similar sites

- Triggered or aided critical environmental legislation (superfund sites, CERCLA: Comprehensive Environmental Response, Compensation, and Liability Act)

Definitions and Classifications

What is a Pollutant?

- A pollutant is defined as any substance that does not belong in a natural system, and that disrupts the natural processes of the system
- In the case of water, this usually degradation of water quality in a manner that disrupts/prevents its intended or original use, harming the organisms living in or around it
- Pure water can even be a pollutant, as for example occurred in a case where a company began dumping pure water into a region, only to find that it disrupted the ecosystem by lowering the nutrient content of the water

Pollution Sources

- Point-source: There is a single identifiable source of the pollution, for example a smokestack, industrial effluent or oil tanker spill
- Non point source: There is no specific identifiable source, but rather it is an area-wide phenomenon, for example air pollution and farm field runoff
- Naturally, non point sources of pollution are much harder to regulate

Hazardous Waste

- In 1976, the Resource Conservation and Recovery Act (RCRA) defined a hazardous waste as
- A waste/combination of wastes, which because of its concentration, quantity, or physical, chemical, or infectious characteristics, may
- 1. Cause or significantly contribute to an increase in mortality or an increase in serious irreversible or incapacitating reversible illness, or
- 2. Pose a substantial present or potential hazard to human health or the environment when improperly treated, stored, transported, or disposed of
- Generally, hazardous wastes exhibit one or more of the following properties: Flammable, explosive, irritant or sensitizer, acidic or caustic

Toxic Materials

- A material is said to be toxic if it is in one of the following categories:
- Allergens and immune system depressants
- Neurotoxins – affecting the nervous system
- Mutagens – increasing rate of DNA mutations
- Teratogens – causes birth defects
- Carcinogens – causes cancer
- Ricin, a protein found in castor beans, is the most toxic substance known; a very good example of how substances are not safe just because they are natural

Heavy Metals

- Heavy metals are neurotoxins: examples include Lead, Mercury, Arsenic, Cadmium, Tin, Chromium, Zinc, Copper
- In large enough concentrations they can cause visual impairment, motor disfunction, learning difficulties

- Arsenic is known to cause skin numbness, thickening, discoloration, and cancer

Organic Chemicals

- The most troublesome are Halogenated Hydrocarbons that contain Chlorine, Fluorine, Bromine, or Iodine
- These cause developmental problems due to their ability to mimic hormones or disrupt metabolic pathways in grown animals
- About 71% of hazardous wastes in the United States is caused by the chemical and petroleum industries, with about 22% coming from the mining and metal processing industries, and all other industries making up the rest

Water Pollution Contaminant Types

- Infectious agents
- Oxygen-demanding Wastes
- Plant nutrients, which cause cultural eutrophication
- Toxic tides
- Inorganic Pollutants: metals, nonmetallic salts, acids and bases
- Organic Chemicals
- Sediment
- Thermal Pollution and thermal shocks

Pollution Toxicology

Maximum Contaminant Level

- MCL=Maximum Contaminant Level, based on the fact that contaminants are more dangerous in higher concentrations
- The highest concentration of a pollutant allowed in drinking water by law
- Concentration above which adverse health effects are believed to occur
- It is determined by giving a variety of dosage levels of the contaminant to lab animals, determining the concentration for which the first statistically significant adverse effects are identified, and then halving this level
- One problem with this method is that humans might react differently to the tested animals

Secondary MCL

- Concentration of a pollutant above which the water is unpleasant in odor or taste
- May not be hazardous to your health at that level

Toxicology Models

- The threshold model says that very low concentrations of the contaminant do not have any effects, which only begin to appear after a certain threshold
- The linear model rejects the idea of a threshold, arguing that negative health effects occur for and in proportion to all levels of the contaminant

Hormesis

- The newest model is called hormesis, and it states that in lower concentrations a substance may actually be beneficial for the organism, but higher doses are harmful
- Hormeises is not evidence for the effectiveness of homeopathy, as for the lower level beneficial effects to be felt you do actually have to have at least some molecules of the substance left!

Oxygen and Stream Life

Photosynthetic Organisms

- Light is essential for them to live
- These organisms form the bottom of the food chain
- Phytoplankton: microscopic, floaters, include green algae, diatoms, cyanobacteria
- Benthic Plants: submerged (plant fully under water), include pond weed, muskgrass
- Emergent (plants partial above water), include water lilies, cattails

Non-Photosynthetic Organisms

- Zooplankton: microscopic, floaters
- Fish, Amphibians, Reptiles (Crocs, Turtles, Snakes)
- Mollusks (snails, clams), Crustaceans (crayfish)
- Birds (ducks, geese, swans)
- Mammals (otters, raccoons, muskrats)
- Different parts of the stream (edge, middle, bottom, top, etc) will all have different types and mixes of life in them

Essentials for Stream Life

- Light - essential for primary producers
- Oxygen - essential for all consumers
- Nutrients - in balanced quantities to maintain equilibrium between populations
- Photic or Euphotic Zone - depth to which adequate light for photosynthesis can penetrate
- Controlled by amount of particulate matter (sediment, plankton, and organic debris) in the water column

Dissolved Oxygen Content

- Dissolved Oxygen (DO), refers to the amount of oxygen available in the water
- Oxygen in water maintained by
    - Exchange with the atmosphere
    - Production of oxygen by photosynthetic organisms (vegetation)
    - Circulation of water (essential to maintain oxygen levels in deeper waters)
- Oxygen consumed by decaying organic matter and oxygen breathing organisms

Biochemical Oxygen Demand

- Biochemical Oxygen Demand (BOD): Measure of the amount of oxygen required for the aerobic degradation of organic and non-organic compounds in the water
- Highly polluted waters have very high BOD implying that oxygen is consumed rapidly, and hence also have a low DO
- Apart 5ppm of oxygen in the water is about the minimum required for a healthy stream

Stream Oxygen Profile

- Oxygen levels are lowest at night owing to the cessation of photosynthesis
- Beginning at the point source of pollution, the biochemical oxygen demand shoots up drastically, preventing most fish from living in that zone

- As water moves further downstream the organisms in the water decompose more of the organic pollutant, using up oxygen and therefore continually reducing oxygen concentrations until they reach a minimum in the septic zone, where no fish can live at all
- After the septic zone, however, oxygen from the air enters the water, raising its oxygen levels again, and the pollution intolerant species return
- Waterfalls can be used to accelerate the rate at which oxygen returns to the water, owing to the mixing of the water
- Interestingly, colder water is better at holding oxygen than warmer water, so it is less susceptible to pollution
- Nutrients can be supplied by recycling internally through decay of the organic matter, or sediments and particulate matter from land sources

Reoxygenation of Lakewater

- Oxygen levels are generally higher near to the surface of lakes, owing to the nearness to the air, presence of photosynthesising plants and the fact that decaying matter falls to the bottom of the lake, where it uses up oxygen
- Usually the top of the lake is also warmer, being closer to the sun, but in the lead up to winter the atmosphere can cool sufficiently such that the upper part of the lake becomes cooler than the lower depths, causing the upper water to become denser and sink
- In this way, the entire body of lakewater turns over, reoxygenating the bottom of the lake with oxygen-rich surface water

Eutrophication

Oligotrophic Condition

- Under normal conditions (preanthropogenic perturbation) most surface waters are:
- 1. low in nutrients (particularly phosphorous and nitrogen)
- 2. well oxygenated
- 3. have few particulates in the water column

Excess Nutrients

- Excess nutrients in a water body are actually not a good thing, as it tends to cause an explosion of algae growth on the surface, thereby reducing the light that can get to the benthic plants on the bottom of the water
- These plants then die, reducing the amount of oxygen produced and at the same time increasing the demand for oxygen to decompose the dead plants
- This reduces the DO of the water, preventing life in much of the water
- The same can occur if excessive particulate matter is dumped into the water
- Note that algae does produce oxygen, but because it lives on the surface most of it is released into the atmosphere rather than the water
- Particulate matter in the water also increases the absorption of solar radiation, thereby heating up the water and hence inhibiting its ability to hold oxygen

Eutrophic Condition

- Caused by the excess nutrient and sediments (sequence of event outlined in prior slides).

- Major cause is the use of fertilizers, excess erosion from farmland or nutrient rich soils (deforestation), and disposal of phosphate bearing compounds (many detergents) through sewer systems

Reducing Eutrophication

- Reduce nutrients and sediments that enter water by vegetation barriers
- Chemical Treatment
- Aeration
- Harvesting plants (the algae)
- Dredging to make the water deeper, thus cooling it down and increasing circulation

Eutrophic Zones

- Eutrophic zones can also occur in oceans, for example the 'dead zone' in the Caribbean adjacent to the mouth of the Mississippi river, owing to all the sediment and pollutants dumped into the river by farmers

Other Forms of Pollution

Sediment Pollution

- In some lakes, however, especially ones with lots of particulate matter (which makes all the water much denser and warmer), this turnover does not take place, so the bottom can become highly anoxic
- Sediment pollution is the biggest cause of water pollution in the United States, the major cause being agriculture, though sewage, dams, urbanisation, and removal of vegetation can also contribute
- Construction is extremely harmful for streams, as the digging up of so much land (usually without adequate measures to prevent erosion) can significantly increase the rate of particulate matter build-up in nearby streams

Chemicals and Biomagnification

- Herbicides and pesticides can accumulate in certain biological systems in a process known as biomagnification or bioaccumulation
- For example, DDT becomes concentrated as it moves up the food chain from plankton to small fish, large fish and finally birds that eat the fish
- High concentrations of DDT in fish-eating birds are known to have cause thinning of bird shells, and were the motivation behind the book Silent Spring
- This same process is why pregnant women are advised not to eat tuna, which are near the top of the food chain

The Yellowboy Effect

- The yellowboy effect refers to the apparent coating of rust of plants and landscapes downstream from a chemical mining operation
- It occurs because the chemicals used in mining allow the water to dissolve more iron, but as these chemicals are purified downstream, the iron drops out

Wetlands Clean Water

- Wetlands have a great ability to remove pollutants of various types
- For one thing they buffer water, removing particulates

- They consume excess nutrients, preventing a eutrophic situation
- The plants also absorb and thus remove heavy metals from the water
- As such, natural and artificial wetlands are very effective for treating water

Water Color

- Clear may or may not be of high quality – could be heavy metals
- Brown usually due to eroded soil
- Green often indicates lots of algae – excess of nutrients
- Oily Sheen can be caused by petroleum or chemical pollution
- Reddish or orange usually due to iron oxides often in areas of historic acid mine drainage
- Black water may look bad, but is common in the autumn owing to leaf fall; leached pigments from leaf packs can make the water look murky
- Chalky usually caused by salts or detergents in the water

Lecture 18: Glaciers and Glaciation

Glacier Basics

The Cryosphere

- The portion of the Earth system frozen all year is called the cryosphere
- It will be substantially different to the rest of the water on the planet, as being frozen it is technically a mineral, not a liquid

How to Form a Glacier

- A glacier can only form in a place where the total accumulation of snow in the winter is greater than the total amount of ablation in the summer
- The snowline is the altitude/latitude at which winter snowfall equals summer ablation

Six Types of Glaciers

- 1. Cirque glaciers – exist near the top of mountains in bowl shapes
- 2. Valley glaciers – form when glaciers begin to slide down the mountainside, often through valleys previously formed by streams, but enlargened and flattened by the glacier
- 3. Fjord glaciers – when valley glaciers reach the sea they form fjord glaciers
- 4. Ice caps – ice is in a dome shape, but is reasonably small
- 5. Ice sheets – also dome shaped, but larger than a cap
- 6. Ice shelves – glaciers form on land by slide onto the ocean; not the shape as sea ice, which forms over water

Thermal Classification

- Warm glaciers (Temperate glaciers): Glaciers in which the ice is at or near its pressure-melting point (the melting point at a particular pressure, where higher pressures lower the melting point) throughout the ice mass
- Because glaciers are so thick, their lower layers are under tremendous pressure
- Hence, warm glaciers can actually have some liquid water in their lower regions
- Sub-polar glaciers: Glaciers in which the ice mass is generally below the pressure-melting point except for summer melting of the upper few meters

- High-polar glaciers: Glacier characterized by an ice mass that is below the pressure-melting point at all times
- Warm glaciers tend to move faster, transport more sediment, and hence produce more impressive morphological effects

Glacial Aquifers and Geysers

- Because there can be liquid water below a glacier, there can actually be an aquifer below a glacier, with the bedrock and surface ice acting as aquicludes
- It if thus possible to have artesian springs shooting out water from under a glacier
- If these springs dry up, it is possible to form large ice caves

Glacial Movement

Temperature at Base of Glacier

- Temperature of basal ice relative to melting temperature is perhaps the primary determinant of a glacier's ability to do geomorphic work
- Glaciers with basal ice at melting temperature tend to move faster, erode more, and carry greater loads than polar glaciers

Mass Balance/Glacial Budget

- Accumulation = water (volume) equivalent of ice and snow added to a glacier over a period
- of time in question
- Sources of accumulation include snowfall, rain, and other water that freezes on the surface, avalanches from the valley walls, and the "freeze-on" of meltwater at the base of the glacier
- Ablation = removal of snow or ice by melting, evaporation, wind erosion, sublimation, and calving in the period of time in question
- Positive mass balance = more accumulation than ablation
- Negative mass balance = excess of ablation
- Zero mass balance = accumulation and ablation are balanced
- In the case of glacial advance, the overall mass balance of the entire glacier should be positive
- The front end of the glacier moves downhill, as does the equilibrium line

Zones of Accumulation and Ablation

- The upper part of the glacier usually has a positive mass balance, and lower part a negative mass balance (owing to temperature differences)
- These zones of accumulation and ablation are separated by the equilibrium line
- The equilibrium line is usually fairly close to the firn line (snowline), which is usually marked by snow above the line and dense blue ice below it
- The accumulation zone generally builds up during part of the year, and then slides down to a lower altitude where is becomes a zone of ablation

How Glaciers Move

- 1. Internal flow: Ice deforms under gravity as ice crystals shear past each other
- 2. Basal sliding: The glacier's base slips along its contact with the soil/bedrock floor
- Because of friction with the sides and floor of the valley, the zone of fastest flow is generally around the upper middle of the glacier
- This differential rate of lowing produces strange ripple shapes in the top of the glacier

- Most of the glaciers on the planet today are retreating
- Some glaciers are advancing, as global warming changes weather patterns such that some regions can have more precipitation

Glacial Surges

- Glaciers can undergo surges, periods where they move a number of meters in only a matter of weeks – very fast for a glacier
- This may occur if water builds up under a part of the glacier, which continues until there is enough pressure to lift the entire glacier on the body of water, allowing the water to flow out and the glacier to move very rapidly with minimal friction

Landscape Features

Terminal Moraines

- When a glacier moves over a rock, the ice near the upflow end of the rock increases in pressure, potentially causing the ice to fall below its pressure melting point
- The water then percolates through cracks in the rock
- On the downhill side the pressure drops, causing the water the refreeze and rick or pluck out chunks of the rock in a process called glacial plucking
- The rock then becomes incorporated into the glacier
- These rocks and other pieces of sediment will be deposited at the very front of the glacier in a pile called a terminal moraine

Changing Valley Shapes

- As glaciers flow down a valley they flatten out the bottom and steepen the sides
- As such they tend to turn river v-shaped valleys into u-shaped valleys

Erosional Features

- Horn peaks – sharp mountain peaks formed when glaciers slide down the peak along multiple sides
- Arêtes – a thin ridge of rock formed between the valleys made by two adjacent glaciers
- Cirques – bowl shaped remaining after glaciers have disappeared (these can be filled with water, forming tarn lakes)
- Glacial valley and hanging valley – one glacier at a higher altitude flows perpendicularly into another, forming a connected 'hanging valley'
- Glacial polish and scour – glaciers cut groves in or polish rocks underneath it
- Roche moutonnee – when a glacier erodes down to bedrock, it can form tear-drop shaped hills that taper in the up-ice direction

Glaciers are Soft

- Surprisingly, ice is right near the bottom of the Mohs scale of hardness, being very soft
- Thus, scouring actually is done by fragments of other rock trapped inside the ice
- These glacial groves can be used to tell in which direction the glaciers has been moving

Glacial Depositional Features

- Erratics – boulders that are dropped by ice when it melts. They are called erratics because they are very different from the local bedrock
- Moraines – terminal moraines are described above, when lateral marines run along the edges of glaciers

- Medial moraines occur when two or more glaciers join together, and the lateral moraines on two of the sides merge to form a single band in the middle
- Kames – mounds of sediment that fall onto the ground from the top of the glacier
- Eskers – long ridges were water used to be flowing beneath the ice, forming long formations of dropped sediment which was left behind when the glacier retreated
- Till – unsorted dropped sediment material
- Drift – stratified sediment material
- Kettle lakes – small lakes that occur in the depressions in the ground made by pieces of ice left behind by the glaciers
- Drumlins – the opposite of a Roche moutonnee in terms of direction. They are also made out of unconsolidated sediment rather than bedrock

Icebergs and Sea Ice

Icebergs and Heinrich Events

- When glaciers reach the ocean, the edges break off as icebergs
- These icebergs drop out pebbles and sediment on the ocean floor, forming regions of unusually large sediment called Heinrich events
- When seawater freezes it excludes salt from the ice lattice, increasing the saline content of the water beneath

Pancake Ice

- Sea ice begins as 'pancake ice', thin sheets of ice across the surface that gradually come to overlap owing to wave motion, forming a flaky appearance
- This type of ice is easy for ships to move through, but as it gets thicker the ice becomes very dense, and indeed strong enough to support significant animal migration, such as polar bears

Sea Ice Melting

- When sea ice melts it does not significantly change the sea level, but if it removes a barrier for the flow of continental ice into the sea that it could lead to significant rises
- This is a major concern, as the polar regions are warming much more rapidly than the rest of the planet

Other Effects of Sea Ice

- Ice is more reflective than water (higher albedo), so reflection of solar radiation keeps the area cooler than it would be with water
- Sea ice separates the ocean from the atmosphere and reduces evaporation, thereby making the dryer than if water was exposed to atmosphere
- Allow migration routes for some organisms, thus the loss of sea is a major concern for them

Permafrost

- Permafrost is permanently frozen soil, though the area of this is diminishing in size
- One potential problem is that the organic substance frozen in the thawing permafrost will begin to decompose, releasing methane and other greenhouse gases, forming a positive feedback loop

Ice Ages and Glacial Periods

- There have been glaciation events throughout earth history, although not so much in the Mesozoic or early Cenozoic

- We are presently in an ice age that began about 2 Ma, marking the Pleistocene epoch of the Quaternary period of the Cenozoic era
- The last glacial period began about 75,000 years ago
- We are presently in an interglacial period which we call the Holocene epoch that began 10,000 years ago

Causes of Ice Ages

- 1. Plate tectonics – continents grouped over the poles increases amount of ice over the poles, increasing reflection of sunlight (this idea has largely fallen out of favour now)
- 2. Reduce greenhouse gas in the atmosphere – burry organic material or increase weathering of continental crust
- 3. Changes in the orbit of the Earth around the Sun (Milankovitch cycles)

Part C: The Atmosphere

Lecture 19: Atmosphere

Energy From the Sun

Light as Radiation

- Virtually all the energy that drives that atmosphere comes from the sun
- The only method of transferring energy without a medium is radiation, which is how we get our energy from the sun
- This radiation can be conceived as either a wave or a stream of particles
- In the wave perception, each peak corresponds to a photon, with the number of peaks corresponding to the number of photons

Light Frequency and Colour

- High frequency light has more energy both because of the increase in energy with higher frequency and simply because there will be more photons with the shorter period
- Light comes in many different frequencies, with different frequencies of visible light corresponding to different colours
- We normally identify seven colours of the rainbow, although really there are only six distinctive ones, with indigo only being added at the last minute by Newton in order to make up seven colours, which he believed to be a number with some kind of mystical or holistic universal properties

Three Ways Light Interacts with Matter

- Transmitted: the light just passes right through, for example air
- Reflection: the light bounces off with the same wavelength, like a mirror
- Absorption: the light is absorbed by the atoms and then is later re-emitted, usually at a longer wavelength, with the remaining energy increasing the temperature or state of the material

The Colour of the Sun

- From space, the sun would look white; the reason it looks yellow from the earth is because the sky removes the blue light from the sunlight, leaving the yellowish colour left
- The reason for this is because blue light is absorbed by the molecules of the atmosphere (such as oxygen), and re-emitted/scattered in all directions

- Some of this will be re-emitted into space, while the rest will be directed down to earth from all directions in the sky, probably after being reflected and scattered multiple times
- When the sun has to pass through more atmosphere, such as near dawn and sunset, more blue light is extracted, and hence the sun appears redder
- The moon turns red during a solar eclipse because the only light that is able to fall on the moon is the light that has been passed through the atmosphere and scattered, hence having most of the blue extracted

Why Suntans are Harmful

- Ultraviolet light can resonate with our DNA, which can lead to catastrophic failure of the DNA molecule; hence we are lucky to have the ozone
- Such genetic damage can be particularly bad because there are particular genes in the DNA that regulate the pace of cell division, and if these are damaged it can lead to cell division getting out of control, causing cancer
- A sun tan is indicative of the fact that damage has already been done to the skin, which has then produced melanin in order to try to limit future damage

Radiation from the Sun

- Most of the energy from the sun comes in the visible range, and our atmosphere blocks most of what light there is in the gamma ray, ultraviolet and x-ray spectrum
- 25% is reflected back by atmosphere and 5% by the surface of earth
- 25% is absorbed by the atmosphere and re-radiated back to space
- 45% is absorbed by surface of land and water, heating them up
- This can then be transferred back to the atmosphere by conduction and convection

Factors Affecting Ground Radiation

- How much solar radiation reaches the ground is dependent on:
- 1. Solar intensity (increases over geologic scales, fluctuates slightly with sunspot cycle)
- 2. Distance between Earth and Sun (affects solar constant)
- 3. Reflection and absorption by the atmosphere, hence changing atmospheric composition will change the amount of energy absorbed
- 4. Angle at which solar rays hit the surface (beam spreading and greater atmospheric absorption)

Atmospheric Composition

Homosphere and Homosphere

- The lower 80km of the atmosphere has a relatively consistent composition = homosphere
- The upper reaches of the atmosphere change to greater amounts of Hydrogen and Helium as you go up = heterosphere

Basic Gas Composition

- The atmosphere is mostly nitrogen, oxygen and argon
- Nitrogen is a very tightly bonded and hence very unreactive molecule
- Variable gases are those whose concentration varies significantly with time and place

Water

- Comprises approximately 0.25% of atmosphere
- Its concentration decreases with altitude, with most of it below 5km

- The residence time for a single molecule is approximately 10 days

Carbon dioxide

- Made up 280ppm before the industrial revolution, while now we are up to about 380ppm
- Its residence time is approximately 150 years

Methane

- Comprises approximately 1.7 ppm of atmosphere
- Has been increasing at approximately 0.01 ppm / year recently
- Has a residence time of approximately 10 days

Aerosols

- These are non-gas components of the atmosphere, mostly small solid particles and liquid droplets (also called particulates)
- They have a residence time of a few days to several weeks, and generally come out with precipitation

The Role of Particulates

- The average person breaths in about two tablespoons of solid particulates every day, which is why we have the mucus membranes lining our lungs
- Increases in the concentration of particulate matter in the air, such as caused by dust storms or pollution, can cause respiratory difficulties
- The major source of aerosols is the chemical conversion of sulfate gases to solids or liquids, wind-generated dust, volcanic ejections, sea spray, and combustion by-products
- They play a major role in cloud formation because they act as condensation nuclei

Vertical Structure

Metrics of Comparison

- We can define the vertical layers in different ways:
- 1. Composition
- 2. Electrical
- 3. Density
- 4. Temperature

Troposphere

- Has a depth of 8 to 16 km, with an average of 11 km
- The troposphere is thicker at the equator owing to centrifugal force and the fact that air is warmer at the equator and so expands more
- Contains practically all the phenomenon we call “weather”
- Contains 80% of the mass of the atmosphere
- Heated from below by the earth
- Average temperature is 15°C at the base and -50°C at the top
- Inherently unstable, as the warmer air at the bottom tends to rise upwards, replacing the air at the top

The Tropopause

- The tropopause is the very topmost region of the troposphere where air temperatures begin to stabilise and then increase
- It is responsible for the flattening out at the top of storm clouds, as when they reach this altitude they will no longer have a tendency to rise

Stratosphere

- Contains 19.9% of the total mass of the atmosphere
- The base has an average temperature of -59°C and remains so up to 20km
- Above 20km, the ozone layer absorbs UV radiation and causes a warming with altitude
- The top at 50km has an average temperature of -2°C
- It is inherently stable, as lower areas are cooler, and so there is no tendency for turning over of air
- Because of this stability, it takes a long time for pollutants to be removed from the stratosphere

Mesosphere

- Extends from 50km to 80km above the earth
- Of the two remaining layers, it holds 99.9% of the mass
- Heated at its base by absorption of energy from the stratosphere
- Inherently unstable, as the heat is dispersed upward by vertical air motion

Thermosphere

- This stable layer gets hotter with higher altitudes
- The highest energy photons (cosmic rays, gamma rays, and x-rays) are absorbed at the top of the atmosphere, allowing the temperatures to rise to 1500°C
- However, the heat content is very low, as there are so few molecules present
- Molecules in the upper thermosphere often travel kilometres before colliding with another particle
- An ordinary thermometer would not read 1500°C, as too few molecules would be present to take this measurement

Other Information

How Thick is the Atmosphere?

- The total mass of the atmosphere is 5.14 X 10^{15} kg
- There is no set definition of the density of gas molecules for "atmosphere"
- For practical purposes we can say the atmosphere is 100km thick
- For comparison, the radius of the Earth is 6,500km

Density Structure

- Density reduces rapidly with height, with change being more noticeable at sea-level than at higher altitudes
- At sea-level the density is about 1.2 $\mathrm{kg/m^3}$, but at Denver it is about 1 $\mathrm{kg/m^3}$

The Ozone Layer

- CFCs in the stratosphere are broken apart by UV radiation releasing a chlorine atom, which can catalyse the destruction of many ozone molecules

Layers and Temperature Profiles

- Troposphere: Bottom layer in which temperature decreases with altitude

- Stratosphere: temperature increases with altitude
- Mesosphere: temperature decreases with altitude
- Thermosphere: Top layer in which temperature increases with altitude
- The reason for this pattern is because the atmosphere is heated by the earth from beneath, and by the absorption of solar radiation from the top

Temperature Inversions

- These are unusual places in the troposphere where temperature increases with altitude
- Nocturnal temperature inversions, for example, can occur as a result of the fact that while the ground warms up quickly during the day, it also cools off quickly during the night
- As the earth cools off during the night, it absorbs energy from the very lowest layer of the troposphere, causing it to cool down
- This can lead to a situation where the lowest levels of the troposphere are actually cooler than the levels just above
- Temperature inversions prevent the air from rising beyond the temperature inversion, thus leading to traps of the pollution within this layer

Lecture 20: Weather Part I

Measuring the Weather

Climate vs. Weather

- Weather: The physical condition of the atmosphere (moisture, temperature, pressure, wind)
- Climate: Long term pattern of the weather in a particular area
- Weather and climate are the primary determinates of the types of plants and animals that can live in an area, and so are clearly very important

Basic Weather Parameters

- Temperature
- Pressure
- Wind
- Humidity

Weather Maps, Balloons and Satellites

- Weather maps only show the measurements of weather stations of the surface of the earth; to get really good data we also need data from higher regions of the atmosphere
- Two methods of this are satellites and weather balloons
- Many of these balloon devices use hydrogen, as unlike helium it can be produced on the spot and put into use quickly
- Generally these balloons continue to rise until the gas in them expands so much that they burst, at which time they descend on a parachute
- Many of them fall onto the ocean, but some of them do fall back onto land and can be reused

Temperature

Introduction

- Temperature tends to stay the same over large horizontal distances

- However, temperature does change rapidly across "fronts" – narrow zones that separate relatively warm from colder air

Temperature Records

- Reliable temperature records have been kept for approximately 150 years
- Beyond this we have to use a variety of temperature proxies
- There is good evidence that the average T of the globe has risen due to human influence

Temperature Versus Heat

- Temperature is a measure of the average kinetic energy of all the atoms in a body
- Heat (thermal energy) is the total kinetic energy of all the atoms in the substance
- The thermosphere has a very high temperature because each atom is going very fast
- However, it also has a very low heat content because there are very few molecules
- Thus, even though they are fast, there are so few that their total energy is low

Diabatic Processes

- The first method of varying air temperature
- Involve the removal or input of heat
- Heat added by conduction from the ground or lost when passing over a cold surface
- Common in forming fog

Adiabatic Processes

- The second method of varying air temperature
- Involve no heat exchange
- Tends to result from expansion or contraction of air, and resulting changes in pressure
- Important in the formation of higher clouds
- Causes of Fog and Frost
- Fog and frost are the result of the cooling of the air near the ground overnight below dew point, caused by the rapid loss of heat by the ground overnight

Pressure

Introduction

- Air moves from high pressure to low pressure and creates wind
- Pressure at the surface depends on the density of the air above and the elevation:
    - Low density air = low pressure at surface
    - High density air = high pressure at surface
    - Higher elevation=less air above=lower pressure
- Lines of equal pressure (at a given elevation, usually sea level) drawn on maps are called "isobars"
- Measured in millibars (mb – U.S.), kilopascals (kPa – Canada) or inches of mercury (Hg)
- Atmospheric gas is not really an ideal gas in the true chemistry sense, but it is close enough for most purposes

Measuring Pressure

- Mercury barometer must correct for:
- – Elevation (corrected to sea level, average of about 1000mb)
- – Temperature (corrected to 0°C)

- – Gravity (set to 45° latitude)
- Reported in mb, Pa, or inHg
- An aneroid barometer uses no liquid; usually in the form of a collapsible chamber from which some air has been removed

Unequal Pressure

- If two fluids have unequal pressure and there is a pathway between them, the higher pressure fluid will move into the lower pressure fluid to equalize the pressure
- It should be noted that the horizontal changes in pressure are much smaller than vertical changes
- Every ten meters of altitude gained near sea level results in a reduction of about 1mb
- In contrast, total continental pressure differences are often only on the order of around 25mb, which is what could be obtained simply by going up a small hill or elevator in a building

Horizontal Pressure Gradient

- Pressure gradients provide the force to move air and make wind
- Pressure gradient force (PGF): Larger pressure gradient force=stronger wind
- Horizontal PGF can be measured at any altitude
- Gradients can range from 1mb/6km for very strong hurricanes to 1mb/1000km for stable air masses
- Closer isobars indicate stronger pressure gradient, and hence stronger wind

Why isn't the Air Blowing up?

- This is because air is in Hydrostatic equilibrium between vertical PGF and gravity (weight)
- If no other forces in the vertical direction:
- –Gravity > vPGF then air sinks
- –Gravity < vPGF then air rises
- –Gravity = vPGF then no vertical motion

Measuring Wind

- Wind vane gives wind direction
- Anemometer gives wind speed, generally using a propeller driven device
- Aerovane gives wind speed and direction, combining a wind vane with a propeller, and looking something like an aeroplane with no wings

Water Vapour

The Role of Moisture

- Moisture in the air brings precipitation
- Moisture in the air modifies temperature; humidity equalises temperatures across time
- Moisture also carries heat from one location to another, especially as water has a very high specific heat

Evaporation, Condensation, and Saturation

- When evaporation and condensation are equal, the water vapour in the air is at saturation
- Evaporation > condensation: atmosphere below saturation, water droplets decrease in size
- Condensation > evaporation: atmosphere above saturation, water droplets increase in size
- Direct movement of ice to vapor is called sublimation

- Direct transition of vapor to ice is called deposition (can also be called sublimation)
- Deposition in the atmosphere is in some cases more important than condensation for cloud formation

Sensible and Latent Heat

- Sensible heat is the heat (energy) that is added to a substance in the process of increasing its temperature
- Latent heat is the amount of energy required to change the state of the same amount of substance from one state to another
- It takes about 5.5 times as much energy to boil a given amount of water than it does to increase the temperature of that water from zero to one hundred degrees
- This means that the change in state of water absorbs or releases a lot of energy

Indices of Water Vapour Content

- Partial pressure of the water vapor is called vapor pressure
- This is dependent on temperature and density of water vapor molecules
- – Higher T = faster molecules that exert a greater pressure
- – Higher ρ = greater mass to exert pressure
- Warmer air can hold a larger amount of water vapour than cooler air, raising the saturation point

Global Distribution of Water Vapour

- Water vapour can come either form a local evaporation source or advection from other locations
- Most evaporation occurs over the ocean or large lakes
- There is also more evaporation near the equator
- The farther from an evaporation source, the lower the water content of the air
- This is why dry areas tend to occur inland away from the equator, whereas the highest humidities are coastal and tropical regions

Factors Affecting Condensation

- Condensation and evaporation on water droplets in the atmosphere are dependent on more than mere temperature; other factors include
- Curvature: smaller droplets of water have higher curvature, which results in a higher surface tension on the surface of the droplet, hence increasing the amount of energy that is required for water to break through this barrier and enlarge the droplet
- Indeed, if curvature were the only relevant consideration, condensation would not occur until levels of around 300% relative humidity were reached
- Solution: solutes dissolved in water reduce evaporation rates, as these solutes get in the way
- Nuclei: these are particles (e.g. aerosols) that can have water accumulate onto them, and hence promote condensation

Humidity

Density and Pressure

- Density is much more important influence on vapor pressure than temperature
- However because it can vary with these two different parameters, it is not the most useful or widely used measure of water content

Absolute Humidity

- Density of water vapor (g/m3)
- This also changes when the density of the air itself changes
- Air density, in turn, changes with changes in T or P
- This makes this measure hard to compare between locations (horizontally and vertically)

Specific Humidity

- Mass of water in a given mass of air: $q = m_v/m = m_v/(m_v+m_d)$
- Not influenced by changes in P or T, although the saturation point is
- That water makes up 0.25% of the atmosphere is an example of this measure
- This measure is very useful for comparison between places, but is not often used

Relative Humidity

- This is the percent ratio of the specific humidity to the saturation specific humidity
- It is dependent upon and inversely proportional to temperature
- This means that as temperature rises, relative humidity falls, and vice-versa
- This is why the least pleasant time of the day in some hot areas is around evening, as here temperature begins to fall a bit, bringing relative humidity up to 100% and hence preventing sweating from being effective
- At RH = 100%, condensation/deposition = evaporation/sublimation and water will begin to come out of vapor state
- Precipitation tends to occur with RH slightly over 100%

The Dew Point

- The temperature of the air when at which it would be saturated with current water levels
- It is always equal to or less than the air temperature, as otherwise RH would be over 100%, and the excess vapour would come out of vapour state as deposition or precipitation
- This is the cause of condensation on car windows and cold glasses, etc
- Dependent almost exclusively on the amount of water vapor present
- High dew points indicate a lot of moisture in the atmosphere
- When combined with actual temperature it gives a measure of RH

Measuring Humidity

- A sling psychrometer uses two thermometers, one with a wet bulb and one with a dry bulb
- The wet bulb is then swung around, causing some of the moisture to evaporate and hence the bulb to cool
- The degree of cooling of wet bulb relative to the dry will be a function of the humidity
- Higher humidity results in lower wet bulb depression
- We then use look-up tables to calculate any measure of humidity desired
- A hair hygrometer is a device that uses human hair to measure humidity, as hair expands and contracts with humidity changes

How to Reach Saturation

- 1. Add water: a hot shower adds water to bathroom atmosphere that leads to condensation on colder surfaces, then a fog forms
- 2. Mix cold air with warm moist air: this is how jet contrails form, as the cold air from the atmosphere is mixed with the hot moist exhaust of the jet, causing it to exceed saturation

- It is thus possible to take two undersaturated parcels of air, mix them together, and achieve saturation
- 3. Lower T to dew point

Lecture 21: Weather Part II

The Air in Motion

Cause of the Wind

- Air moves from high to low pressure
- Differential pressures are caused by differential heating
- Differential heating in turn is caused by a variety of effects, including the heat absorption of the particular vegetation, whether it is land or sea, and the latitude

Why Warm Air Rises

- As air is heated, it expands and becomes less dense
- Being less dense, it will tend to rise

Which is Heavier: Moist or Dry Air?

- Interestingly moist air is actually less dense, as a water molecule is lighter than virtually all of the other air particles that it replaces
- Thus the least dense air is hot and humid, while the most dense air is cold and dry

Rising and Sinking Air

- As air rises it reaches lower pressure regions of the atmosphere and so expands
- As it expands the air cools down, thereby increasing the relative humidity, as cool air cannot hold as much water as warm air
- This leads to condensation and potentially precipitation
- The opposite effect also applies, so that cooling air sinks, and as it does so it compresses and experiences a reduction in relative humidity
- Thus, rising air is associated with rain, and falling air with clear skies
- When clouds form a clumpy pattern, it means that there are periodic waves of rising and falling air

Air Motion and Precipitation

- Rising air is associated with
- –low pressure (at the surface)
- –clouds and precipitation
- Sinking air is associated with
- –High pressure (at the surface)
- –Clear skies

Five Ways for Air to Rise

- Global convection cells
- Local convective heating
- Orographic lifting
- Weather fronts
- Surface convergence and upper level divergence

Rising Air and Temperature

Dry Adiabatic Lapse Rate (DALR)

- This is the rate at which a parcel of air drops in temperature as it rises
- It is very close to one degree per one hundred meters

Saturated Adiabatic Lapse Rate (SALR)

- Once water in the air begins to condense, it releases its latent heat (of which water has a lot)
- If the air continues to rise, it will gain sensible heat from the latent heat released
- This means that the rising air cools more slowly, at about 0.5 °C/100 m

The Environmental Lapse Rate

- Will a parcel of air begin to rise, and if it does will it continue to rise?
- As a parcel of air rises it expands and cools
- As air rises the temperature of its surrounding air falls
- The temperature of the air parcel must remain warmer than the surrounding air to continue rising
- The temperature of the surrounding air as a function of altitude is known as the environmental lapse rate (ELR)
- The lower the ELR, the more slowly the surrounding air cools off as the air parcel rises, and therefore the sooner will the air parcel reach equilibrium with the surrounding air and hence cease rising

ELR and Air Parcel Stability

- If the ELR is lower than the DALR and the SALR, the surrounding air cools faster than the air parcel, and so the air parcel is stable
- If the ELR is higher than both of these, the surrounding air cools more slowly than the air parcel, and hence the air parcel is unstable
- If the ELR is between the DALR and the SALR, the stability of the air parcel depends upon its altitude, and so it is called conditionally unstable air (i.e. at low altitudes it will be stable, but if something pushes it up higher it may become high enough to become unstable)
- Unstable parcels of air tend to form vertical cumulus clouds, while stable parcels of air (if forced upwards by some external action) tend to form horizontal stratus clouds that blanket the sky

Why Weather Prediction is Hard

- This description may make weather prediction sound easy, but the trouble is that the ELR various with altitude and location, and also air parcels move around a lot, so it is not easy to work out what the atmosphere is going to do

Convection Cells

Global Convection Cells

- Air at the poles receives less sunlight and hence is cooler and also experiences less evaporation, so is drier
- Air at the equator conversely is warmer and moister
- As such, surface air pressure at the poles tends to be higher than at the equator, where the air tends to rise

- If the earth was perfectly circular and not rotating, there would be two giant convection cells, with air rising at the equator, moving north and south towards the poles, falling at the poles, and then cool air moving across the surface from the poles to the equator
- In reality, this is complicated by the fact that the earth is tilted, one half faces away from the sun at any given time, it is not perfectly circular, and it is rotating

The Coriolis Force

- An apparent force proportional to velocity
- Deflects objects to the right in the Northern Hemisphere and to the left in the Southern Hemisphere
- It holds for baseballs, air-masses, spaceships, tornadoes, bullets, etc
- Not very effective for toilets, as the water is not moving much at all
- Strongest at the poles, weakest at equator

Hurricane Rotation

- The coriolis force has an important effect on the direction of the flow of air
- The horizontal pressure force causing air to move is called the pressure gradient force, although one must add to this the coriolis force
- Hurricanes in the northern hemisphere rotate counter clockwise, which is the opposite direction we would expect based on the Coriolis force
- To understand this, it is important to realise that all tropical hurricanes are areas of low atmospheric pressure near the Earth's surface
- If they existed at high altitudes, the coriolis effect would combine with the pressure gradient force to cause the air to spiral in counter-clockwise
- However, hurricanes are always close to the surface, and for low-altitude air currents the friction force comes into play, causing the air to spiral into the low-pressure region of the hurricane in a counter-clockwise direction

Convection Cells and Precipitation

- All places of rising air, namely at the equator and sixty degrees latitude, will tend to get a lot of rain, owing for the tendency of rising air to cool and lose its moisture
- Conversely, locations of falling air, namely thirty degrees latitude and the poles, tend to get little rain

Regions of the Atmosphere

Three Major Convection Cells

- The bending of air due to the coriolis force tends to break up the air moving from equator to poles into three separate convection cells per hemisphere
- This figure of three is largely determined by temperature differences and the strength of the coriolis force
- For instance, Jupiter spins much faster than the earth, and so has many more wind belts
- The divisions between the three cells are found roughly at the sixty and thirty degree latitude levels

The Doldrums

- The equator is a location where there is convergence of surface level winds (although technically the exact latitude of convergence migrates up and down a bit with the season)

- Because of the convergence of the winds at this point, there is very little wind at this point, and hence it is called the doldrums

The Polar Front

- At sixty degree latitude there is also convergence of winds, although in this case the winds are moving in opposite direction and have very different densities (see diagram)
- This produces a lot of complicated wave patterns through the troposphere, which generates such things as jet streams and warm and cold fronts

The Jet Stream

- The jet stream is a passage of very strong winds in the upper troposphere at around the sixty degree latitude mark
- As the air moves from the high pressure area, its speed increases, and so does its Coriolis deflection (which always acts perpendicular to the right of the direction of wind travel)
- The deflection increases until the Coriolis and pressure gradient forces are in geostrophic balance, meaning that the coriolis force is actually acting towards the south (in the northern hemisphere), exactly offsetting the pressure force
- At this point, the air flow is no longer moving from high to low pressure, but instead moves along an isobar
- They are strongest at the sixty degree mark because here air of differing temperatures meets, and so the pressure gradient as at maximum

Lecture 22: Weather Part III

- Dry skin tends to be a particular problem in winter time owing to the lower ability of cold water to hold moisture

The Mountains and the Sea

Land and Ocean Specific Heat

- Different landscapes have different specific heats, and so will tend to heat up at different rates
- In particular, land has a much lower specific heat than water, and so tends to heat up more quickly during the day and cool down more quickly during the night

Sea Breezes

- Warmer surface areas of the earth, such as land relative to water, tend to have warmer and hence less dense air above them
- Thus, low pressure zones tend to occur over hot areas, and high pressure at cold areas
- This is why daytime sea breezes tend to blow from the ocean towards the land, reaching their maximum intensity in the afternoon
- The wind dies down in the later evening as the temperature differential dies down
- At some point during the night, the air over the land will become cooler than the land at sea, and so the wind will start to blow outwards

Local Convective Heating

- Mountains and other rough terrain have larger surface area, and so tend to heat up more quickly than cooler valley regions
- Thus, during the day mountains and hills tend to become low density air pockets

- This low density air cools down very rapidly at night, causing the air to fall back down to the valley regions, following a steady breeze up unto the mountains all day
- Storms and rain usually occur around the mid afternoon owing to the formation of low pressure air regions over the mountains where wet air is rising
- All of these local events are referred to as local convective heating

Orographic Lifting

- This refers to the phenomenon whereby air is forcibly lifted upward and over protruding land features like mountains
- It leads to the expansion and cooling of air, and hence potentially to precipitation
- Orographic lifting can even force otherwise stable air masses to rise and hence precipitate

Mountain Rain Shadows

- As the air moves over the other side of the mountain it falls, warms and compresses, and thereby forming a rain shadow
- These areas downwind from the mountain tend to get very little rain
- One example of this is the Nevada desert behind the Pacific mountains

Weather Fronts

Storm Self-limitation

- Once raindrops or hail begins to fall, the falling rain and ice begins to drag down the air with it, thereby preventing the continued rise of the air mass owing to the energy released through precipitation
- This is why most storms tend to be self-limiting
- The very big storms lean over in such a way that the main updraft is bent over next to the region of falling rain, and so this effect does not occur
- The largest storms are formed by the intersection of weather fronts, the most important of which are warm and cold fronts

Warm Fronts

- Warm fronts occur when packets of warm air move into a region of cold air
- Because warm air is less dense it rides up over the top of the cold air, potentially forming clouds and precipitation
- Because less dense air is pushing away at denser air, it moves it slowly, and so warm fronts tend to move fairly slowly

Cold Fronts

- For exactly the same reason, cold fronts can move faster than warm fronts
- Cold fronts also have a steeper face, as the cold air is ramming directly into and burrowing under the warmer air
- This means that cold fronts push up the air very quickly, and hence tend to produce the more severe storms
- Warm fronts can usually be seen several days off, with the clouds gradually moving closer and closer to the ground – cold fronts can come on much more rapidly
- See the cyclonic models of storm fronts on the notes page – impossible to understand without diagrams

Vorticity

- Vorticity is a concept used in fluid dynamics, referring to the tendency of elements of a fluid to spin
- When air is moving such that it adds to the vorticity of the earth (caused by the earth's rotation), the angular velocity of that region of air increases, causing it to diverge and splay outwards
- The result is a low pressure region which can bring storms
- The reverse occurs with movement of air that subtracts vorticity

Lightning

Types of Lightning

- Eighty percent of lightning is actually cloud to cloud lightning
- Often the bolt is not visible, and it appears as sheet lightning
- Lightning occurs whenever the voltage difference exceeds the level of electrical resistance

Charge Separation

- In cloud-to-ground lightning, the bottom of the cloud tends to take on a negative charge, which induces a positive charge in the ground
- The cause of the charge separation in the cloud is not fully understood
- We do know, however, that it only occurs when there are solid ice particles in clouds
- Hence it seems that the collection of negative charges at the bottom of the cloud has something to do with the collision of ice and hail particles as they fall through the cloud
- Strikes of lightning heat the surrounding air to 30,000 Kelvin

The Journey of a Lightning Bolt

- Usually the step leader, the initial leading band of charge, proceeds near to the ground, and than a bunch of charge comes up from the ground to meet it
- Once contact is made, usually a series of several lightning bolts follows in rapid succession along the same path, removing the charge imbalance
- Lightning is not a very good source of energy, as not very many will strike in any given location, and also most of the energy is dispersed in heating the air and making sound

Positive Lightning Strikes

- There are also such things as positive lightning strikes, which come from the top ends of clouds that are sort of leaning over
- This means that the positive strikes must travel long distances and overcome a great deal of resistance in order to strike, and so they tend to be very severe
- It also means that they can come seemingly out of the blue, miles ahead of the storm

Thunder and Ionisation

- Ionisation of the air around tall pointed objects is also known to occur during storms, marked by crackling noise and changing colours of the air
- Thunder refracts upward in the atmosphere, so if the lightning occurs more than a certain distance away, the thunder will not be heard

Tornadoes

Severe Thunderstorms

- Severe thunderstorms are those that have particularly strong winds, and also are self-propagating, as the downdrafts reinforce the updrafts
- These are particularly common in the tornado corridor of the united states
- All severe thunderstorms require strong vertical wind shear, so that updrafts stay ahead of the downdrafts

The Cause of Tornadoes

- Tornadoes are zones of extremely rapidly rotating masses of air, most of which rotate in the same direction as hurricanes
- The rotation is caused by the enormous pressure differences even just between the inside and outside of the funnel Tornadoes can form anywhere there is extreme weather
- The idea is that some vertical rotating cell inside a storm cloud somehow is rotating so that it is oriented vertically and then drops down out of the cloud

Tornado Duration and Speed

- Most last for only a few minutes and are about 100m across, while some can be up to 1.5km wide and last for hours
- Most of them travel at about 50km/h and travel a few kilometres before burning out

How Tornadoes Cause Damage

- Flying debris and very strong winds cause the most damage as a result of tornadoes
- The most deaths occur in automobiles and mobile homes

Hurricanes

Three Names of Hurricanes

- Hurricanes over the Atlantic and Eastern Pacific
- Typhoons over the western Pacific
- Cyclones over the Indian Ocean and Australia

Hurricane Formation

- They form mostly in near equatorial waters and then tend to head towards the poles
- Most hurricanes are several hundred kilometres wide, and although their winds are slower than those of tornadoes, they are so much larger and last so much longer that they are far more dangerous
- Most of the energy released by hurricanes comes from the latent heat of evaporated seawater
- This is why most hurricanes form in the hottest summer months
- Hurricanes cannot form within five degrees of the equator as the coriolis force is not great enough; they also cannot form more than twenty degrees away as there is insufficient heat
- Wind speeds increase closer to the centre of the hurricane, reaching a maximum speed at the very edge of the eye

Storm Surge and Landfall

- The greatest damage of hurricanes is not actually caused by the wind but rather storm surge

- This occurs because hurricanes are very low pressure environments, so the water pushes upwards and rides onto the land, causing flooding
- Once hurricanes make landfall, however, they lose their source of energy and hence tend to dissipate

Hurricanes and Global Warming

- There is some reason to expect that hurricanes will get worse with global warming, as higher temperatures will provide additional energy to the ocean and hence the hurricanes
- At the same time, global warming will also tend to increase the speed of certain winds in the upper atmosphere that tend to rip apart hurricanes, so the issue is not very clear
- At the moment is seems that the number of hurricanes is not increasing, but that the total energy output of the hurricanes is increasing – this is still uncertain, however

Lecture 23: History of Global Warming

Early Pioneers

Jean-Baptiste Fourier

- In 1824 Baron Jean-Baptiste Joseph Fourier noted that "the Earth's temperature can be augmented by the action of the atmosphere, because heat in the state of light finds less resistance in penetrating the air than in repassing through the air as nonluminous heat"
- Basically he was just referring to the Greenhouse effect
- Without the Greenhouse effect, the average surface temperature of the Earth would be about negative 18 degrees Celsius, all water would be frozen and there would be no life

John Tyndall

- In 1859, John Tyndall found that most of the gases of the atmosphere were transparent to thermal infrared radiation to pass through, with the exception of water vapour, methane and carbon dioxide
- John Tyndall's conclusion: "the solar heat possesses, in a far higher degree than that of visible light, the power of crossing the atmosphere; but, when the heat is absorbed by the planet, it is so changed in quality that the rays emanating from the planet cannot get with the same freedom back into space. Thus the atmosphere admits of the entrance of the solar heat, but checks its exit; and the result is a tendency to accumulate heat at the surface of the planet"
- John Tyndall was also the first to use this conclusion to come to the idea that changes in the amount of greenhouse gases in the atmosphere could be responsible for the ice ages and other climate changes that had been observed to have occurred in the past

Samuel Pierpont Langley

- Samuel Pierpont Langley confirmed these hypotheses in the 1880s by measuring the intensity of infrared radiation at different heights above sea level

Svante Arrhenius Calculation

- Svante Arrhenius in 1896 pointed out that the reservoirs of water in the oceans are so enormous and the turnover time so long that it is highly unlikely that water vapour could serve as a driver for climate change, as the ocean would simply offset any change in atmospheric moisture content
- Carbon dioxide, however, does not have such a large and readily accessible reservoir available, so it can act as a modifier of global temperature

- An increase in the amount of carbon dioxide will increase temperature and therefore evaporation, while warmer water will hold more water vapour, so there will be a positive feedback mechanism with warming and water vapour
- He worked on establishing the climate sensitivity of the atmosphere, which refers to the amount the earth would warm if the amount of carbon dioxide was doubled
- He estimated the value for his day to be about five degrees; the modern value is somewhat lower, but fairly close to this value

The Early Twentieth Century

Global Warming a Good Thing?

- Arrhenius also first came up with the idea that the temperature change would be greater over the land than the sea, and also would be greater over the poles owing to the feedback mechanism of the melting of the poles
- By the early twentieth century he was speaking of the idea of an industrial-revolution induced greenhouse effect, but he thought that this increase in temperatures would be a good thing
- For some decades after this, however, this idea fell out of favour, as it was thought that there was already enough carbon dioxide in the atmosphere to totally absorb all the wavelengths of the light that it can (saturated), so more carbon dioxide would make no difference

Guy Stewart Callendar

- In the late 1930s, Guy Stewart Callendar used various calculations to calculate that there had been a half a degree increase in global temperatures over the past fifty years, and that this was due to burning of carbon dioxide – like Arrhenius, he thought this was a good thing
- At the time the main scientific consensus was that the ocean would absorb all the excess carbon, and so human activities would make no difference
- However, Callendar did make several predictions that turned out to be true, including the retreat of mountain glaciers owing to global warming

Disproving Saturation of CO2

- During World War Two, there was a significant amount of study into the military applications and hence science of infrared energy
- In the process of this new research, it was discovered that carbon dioxide was not actually saturating the wavelengths of light that it could absorb
- Prior experiments had not revealed this because they had been conducted at ground level, where pressures are higher and hence the absorption and emission lines were in different locations, giving inaccurate results

Gilbert Plass's Models

- Beginning in the 1950s, various scientists began studying the greenhouse effect and the influence of carbon dioxide using newly developed computers and computer models
- Gilbert Plass in the mid 1950s began to develop evidence of sufficient quantity to convince a majority of scientists that humans could indeed influence the climate
- He also concluded that although the ocean could potentially take up all of the carbon dioxide that was being emitted, it would take thousands of years to do so
- Gilbert Plass: "the accumulation of carbon dioxide in the atmosphere is seen to be a very serious problem over periods of the order of several centuries. It is interesting that two of the most

important methods available at the present time for generating large amounts of power have serious disadvantages when used over long time intervals. The burning of fossil fuels increases the temperature of the earth from the carbon dioxide effect; the use of nuclear reactors increases the radioactivity of the earth"

Plass' Caution

- He recognized that it was still a theory and two things needed to be cleared up:
- 1. "The temperature trend during the remainder of this century should provide a definitive test of the relative importance of carbon dioxide in determining climate at the present time"
- 2. "Unfortunately, we cannot even say with certainty whether or not the carbon dioxide content of the air has increased since the year 1900"

The Post-War Consensus

The Ocean Sink Problem Resolved

- Roger Ravelle in 1957 developed an explanation as to why the carbon dioxide was not being taken up by the ocean; the top layer of the ocean was saturated with carbonic acid, and so it would take a very long time for the carbon dioxide to mix in

Carbon Dioxide Measurements

- Charles David Keeting in the 1950s took many measurements in many different places of atmospheric carbon dioxide, and to everyone's surprise he found that they did not differ much at all between locations, land or sea, or even with changes in weather
- Before long it was discovered that there was a daily and annual cycle, corresponding to the photosynthesis of plants during the day and the loss of leaves of trees in the night
- Around 1959 he established a number of monitoring stations in the northern and southern hemisphere which made regular carbon dioxide measurements
- By the early 1970s it was abundantly clear that the amount of carbon dioxide in the atmosphere was increasing, and had increased substantially over pre-industrial levels
- This answered Plass' second caution very well
- Indeed, modern measurements of the amount of carbon dioxide in the air bubbles found in ancient ice cores correlated exactly with these modern measurements of these values, and show that the rise began around the mid 18th century

Smagorinsky and Manabe

- In 1975, Smagorinsky and Manabe's improved on their earlier model, and estimated that climate sensitivity of the atmosphere to a doubling of carbon dioxide to be around 3.5-6.3 degrees
- It was also found that the polar regions should be warming faster than some other regions
- Ironically at this time there was some concern that the earth might be about to enter a new glacial period of global cooling
- However, this should not be seen as an indictment of the discipline, as climate models and understanding have progressed enormously over the past thirty years

James Hansen's Models

- James Hansen constructed a still more comprehensive atmospheric climate model, which in 1979 produced a sensitivity figure of around four degrees
- In 1988, James Hansen testified to congress about the dangers of global warming

Lecture 24: Natural vs Anthropogenic Climate Change

Theoretical Background

The Solar Constant

- Solar energy moves out from the sun in an increasing sphere
- Total solar emission is 3.865 X 10^{26} W/m2 at the sun's surface, but it goes out 1.5 X 10^{11}m to reach the Earth
- About 1367 W/m2 intersects Earth's disc, which means that the energy per surface area is somewhat less, as the earth's surface is a sphere

Intensity of Emitted radiation

- A blackbody is a hypothetical body that emits the maximum possible radiation at every wavelength
- Earth and Sun are close approximations to blackbodies
- $I = \sigma T^4$, where T is in °K, σ is the Stefan-Boltzmann constant, and I is the intensity of the radiation emitted by the black-body object
- The atmosphere does not radiate maximally, and so is called a graybody

Wien's Law

- Wien's Law for the maximum wavelength of output in the emission spectrum of a blackbody: $\lambda max=2900/T$, where T is in °K
- Thus, as temperature is increased, the maximum wavelength decreases
- This is important because the sun's maximum occurs in the middle of the visible spectrum, while the Earth's occurs in the infrared
- The atmosphere, in turn, is transparent to visible light, while large amounts of infrared radiation are absorbed by the different greenhouse gases in the atmosphere

Sources of Carbon Dioxide

- Of the greenhouse gases emitted by human activity, about half come from the burning of fossil fuels, one quarter from industry, and one quarter from agriculture and deforestation
- A gallon of gasoline weighs about 7 pounds, but it produces 22 pounds of CO_2, owing to the bonding with oxygen. Thus a twenty gallon tank of fuel can produce a quarter ton of CO_2

Comparing Earth and Venus

Earth Stats

- Average surface temperature is 15°C
- 1 AU from Sun
- 342 W/m2 reach Earth
- 31% radiation reflected back to space
- 242 W/m2 absorbed
- 0.02% atmosphere is CO_2
- 31°C greenhouse effect

Venus Stats

- Average surface temperature is 460°C
- 0.72 AU from Sun
- 645 W/m2 reach Venus

- 80% radiation reflected back to space
- 130 W/m2 absorbed
- 96% of atmosphere is CO_2
- 285°C greenhouse effect

Analysis

- This means that the real reason Venus is hotter than earth is because of the enormous greenhouse effect; without this effect, Venus would actually be colder than earth
- Earth and Venus have about the same amount of total Carbon, but most of earth's carbon is bound up in rock's, while most of Venus' carbon is in the atmosphere
- Similarly, while most of the greenhouse effect on the earth is due to water vapour, which there is virtually no water on Earth

Global Temperature Self-Regulation

This 'Faint Star Paradox'

- Main sequence stars burn gradually hotter and hotter over their lifespan
- If you extrapolate this backwards, the planet should have been frozen by about 2 billion years ago, even though we know that in fact there was liquid water on earth at least 4 billion years ago
- This would apply if the degree of greenhouse effect that we have today
- Alternatively, if we assume that there was a stronger greenhouse effect in the past, why then did the increasing luminosity of the sun lead to the evaporation of earth's water and its dissociation into oxygen and hydrogen, as occurred on Venus
- This 'faint star paradox' then raises the question as to what has been regulating the temperature of our planet over time to ensure that temperature remained correct for life, despite changes in the luminosity of the sun

Volcanic Activity

- The main natural source of carbon dioxide in the atmosphere is volcanoes
- Thus, reducing volcanic activity over time could reduce carbon output, thereby reducing the greenhouse effect and hence preventing the planet from heating up as the sun became more luminous
- The trouble with this explanation is that there is no way for the atmosphere to interact with the earth's mantle, so there is no plausible feedback mechanism here, and the changes of the correct levels being reached by chance are extremely low

The Ocean as a Carbon Sink

- Carbon is withdrawn from the atmosphere by dissolving in the ocean and thence being incorporated into some kind of rock or mineral, such as calcium carbonate
- When rainwater falls, it dissolves carbon dioxide from the atmosphere, forming a mild acid carbonic acid
- Thus, as rain erodes rocks due to chemical and mechanical processes, carbon, ions and other minerals are released and end up in the ocean
- These in turn are used to produce calcium carbonate by many small marine organisms, which in turn locks up the carbon so that it cannot return to the atmosphere

Hydrolysis as a Regulating Mechanism

- Thus, it seems that this process as hydrolysis is working to regulate the temperature of the earth
- It is expected that higher temperatures would increase the amount of hydrolysis that would occur, owing to the fact that higher temperatures would mean more rainfall and also more rapid chemical reactions
- Higher temperatures and more rainfall will also increase the amount of vegetation, which in turn produces additional acids that increases the rate of weathering of rocks
- Thus we see the mechanism by which a warmer planet can lead to an increase in hydrolysis that in turn leads to the extraction of more carbon from the atmosphere
- This negative feedback mechanism helps to reduce the amount by which the planet changes in temperature in response to external changes

The Gaia Hypothesis

- The gaia hypothesis also purports to provide an answer to the young dim sun paradox through the effect of plants and animals, although these have not always existed or been constant over time, while erosion has, so it is the better explanation

Carbon Levels over Time

- Over the life time of the earth, carbon dioxide levels have been generally decreasing, with particularly low periods of carbon dioxide corresponding with ice ages
- In recent times, of course, humans have been reversing this process somewhat

Global Warming Arguments and Models

Skeptic's Arguments

- There was some debate in past decades over whether or not the planet really was warming, but some older data that shows it wasn't has now been discredited – one set of data was known to be biased by the decay of the orbit of the satellite collecting it
- Another interesting factor is that orbiting satellites must look through both the troposphere and the stratosphere, and while the troposphere is warming owing to the greenhouse effect, the stratosphere is actually cooling owing to depletion of the ozone
- Another argument by skeptics was that the effect of urban heat islands was creating erroneous measurements, but these have been identified and carefully corrected
- Today there is no real debate that the planet is warming up

Urban Heat Island Effect?

- The urban heat island effect cannot explain the recent rise in temperatures, as the effect is simply far too small, and regardless many of our temperature measures are taken over the ocean

The Need for Models

- A newer argument of skeptics is that the planet is warming up, but this is natural and not manmade
- This is a legitimate possibility, as it has happened in the past
- In order to test whether it is or not, we build computer models of the earth's climate system and test what happens with different amounts of carbon dioxide

Global Circulation Models

- John von Neumann established one of the first of these modelling investigations (called global circulation models) in the late 1950s

- Current models are now converging on sensitivity levels of 2-5, with the most likely level of 3 degrees

The Strength of the Models

- These models do a very good job at predicting exactly the temperature trends that actually occurred over the past 150 years
- This is actually very strong evidence that natural effects alone cannot explain the global warming trend, as when natural effects alone are used in these models, they do a much worse job at predicting temperature changes of the past, especially since 1980
- Just because these models are not perfect does not mean that we should not act on them – after all, science can never deliver certainty

Lecture 25: Paleoclimate

Introduction

Instrumental Measurements

- Instrumental measurements of the climate began in the 17th century, but were not accurate and reliable enough to be useful to us now in the mid 19th century
- To go back further than this we need to use so-called climate archives

What is Proxy Data?

- The information contained within these archives is referred to as proxy climate data
- The particular proxy we use will depend upon what timescale we are looking at
- The principle of uniformitarianism says that the present is the key to the past – in paleoclimate we are treating the past as the key to understanding changes in the present

Proxy Dating and Correlation

- To extract useful information from these proxies, we of course have to date them
- Generally we use radiometric dating and then correlation, which can be used to link up dating sequences across time to make a longer record
- For example, if we find an old dead tree that shows the same pattern of rings for part of its life as a live tree, we can work out the exact number of years by which the trees overlap
- Another method of correlation is if we know the age of one annual layer of sediment, ice cores or tree rings, we can simply count backwards to determine the date for the entire sequence
- Another method we can use is to calculate orbital cycles, which can be calculated precisely going back in time, and so if we find a pattern that looks like it was caused by an orbital pattern can be dated

Proxy Resolution

- Resolution is lowered by disturbances to the system, such as bioturbation, storms, erosion, wind or water resorting
- There is something of a tradeoff here, as the faster the sediment accumulates, the faster it can be protected from disturbances, but generally the faster the accumulation, the greater the initial levels of disturbance
- Resolution is greatest for lakes, lower for coastal areas, and the lowest for deep ocean deposits
- Because of all these tradeoffs and uncertainties, we always use as many different proxies as possible and compare them to each other

Geological Proxy Evidence

Terrestrial Sediments

- The usefulness of sediments depends upon the degree to which they are disturbed by moving water, erosion or tectonic activity – the less disturbance the better
- Interior sea sequences – thinner sediments owing to slower deposition rates, thereby leading to less fine detail in the record
- Lake sequences – one downside is that the sediments can take on the contours of the lake bottom, limiting data accuracy
- Ice rafted debris on ocean floor – tells us how far the ice travelled in the past
- Desert sand dunes – shows us where dry areas are, though these tend to be moved around and reworked by wind very quickly

Ocean Sediment

- Geochemical analysis of the sediment can also give us an indication of what continent or region it came from, and hence where sediment was being ground up be moving glaciers
- The ocean sediments are very useful for the past 100 million years, largely because there is continuous records in a quiet environment
- Of course, the oldest sea sediment is only 170 million years old, so nothing very old will be available

Ice Cores

- Ice cores trap bubbles of air that can be individually examined for the composition of the atmosphere of the time
- Ice in Greenland dates back to over 100,000 years
- The amount of detail in the record depends upon the rate of deposition, which tends to be greater in Greenland than in Antarctica

Mountain Glaciers

- Ice cores can also be extracted from mountain glaciers
- The upper portions of these ice cores actually show annual banding, so we can see changes from year to year
- At lower levels, flow has distorted the layering, so we cannot extract as much information
- One problem with ice cores is the geographical range for which we can use them to extract data is obviously limited

Speliothems

- These are records from the stagactites from caves, generally calcium carbonate that is precipitated
- These are particularly useful because caves occur at all regions of the world and are very stable environments
- We can extract climate information from the rate of growth of these formations and also the isotope and chemical rates found in them
- They can provide annual or sub-annual resolution, and date back to a few hundred thousand years
- Stalagmites show us carbon and oxygen isotopes, the former of which are particularly useful for showing what type of vegetation was growing above (as they use different metabolic pathways), and hence what the temperature and rainfall was like

Biological Proxy Evidence

Fossil Analysis

- We can examine the small plankton and other fossils that are found at that time
- As some of the creatures live in different temperature environments, we can infer the temperature of the time based on the presents or absence of particular fossils

Fossil Isotope Inference

- We can also examine the relative abundance of the oxygen-16 and oxygen-18 isotopes
- Because the heavier isotopes tend to drop out at precipitation before the lighter O-16, this means periods of extensive glaciation at the poles correlate with a greater concentration of oxygen-18 isotopes in the shells of plankton in the oceans
- The temperature of the water at the time can also have an effect on these ratios

Pollen and Plankton

- Pollen grains can be preserved in sediment around oxygen poor lake areas, and they can give us indications of the isotope fractionation
- Pollen and plankton are particularly useful as they are found virtually everywhere and in such large numbers that we can get a good level of statistical accuracy

Tree Rings

- Tree rings show us the growth rate of trees, though we can also look at isotope fractionation of carbon isotopes
- These are most useful in mid to high latitude, as they have much greater seasonal differences than the tropical regions
- It should be noted that tree ring bands tend to get thinner as the tree grows older, as the circumference increases, so total material deposited remains the same
- The main piece of information that we want to extract from the trees is the amount of rainfall, though other factors can also affect the rate of growth

Corals

- Corals form annual bands of calcium carbonate, so are a useful source of records

Using the Data

Constructing Climate Models

- Once we extract the data from the climate archives, we need to try to explain them using climate models
- Models will attempt to use real parameters and conceptions of how the climate system should operate and try to replicate the information found in the data

Long Term Climate Trends

- When we put all of this together, we find that over the history of earth there have been a number of large fluctuations of temperature, including ice ages and unusually warm eras
- One explanation for these long-term fluctuations is that they are caused by the action of plate tectonics
- For about the past 65 million years, since the Cretaceous warmhouse, the earth has been slowly and unevenly cooling off

The Recent Ice Age

- We entered the present ice age about 3 million years ago, with glacial periods of around 40 and then 100 thousand years
- The period around 1400-1900 was unusually cold, but since then rising carbon dioxide levels have raised temperatures to the highest level in about 8000 years
- Anthropogenic warming has been the dominant actor for the past half a century or so

Lecture 26: Climate Forcing Mechanisms

Solar Activity

Climate Change Triggers

- Variations in solar output
- Milankovitch cycles
- Elevation and distribution of continents
- Ocean interactions
- Atmospheric composition change (CO2 and other volcanic gasses)
- Biological and physical feedback mechanisms

Increased Luminosity

- The sun has been steadily increasing in output over its lifetime, though the effect of this over the past 150 years would have only led to one millionth of a degree of warming

Varying Sunspot Activity

- Sunspots are cooler spots on the surface of the sun, though paradoxically the more sunspots there are, the more radiation reaches the earth
- There was a period of a small number of sunpots in the 17^{th} century (the Little Ice Age), which seems to provide additional evidence for the correlation of earth's temperature and the number of sunspots
- However, although the general trend over the past fifty years has been to less sunspot activity, the planet has still been warming up, so this cannot be decisive
- Satellite measurements show clearly that there is a correlation between the number of sunspots and the amount of solar energy reaching the earth
- Because we have sunspot records going back many centuries, we can use this as a proxy for solar output, and see if it correlates with known climate fluctuations – it seems that it may
- Another method is to measure the ration of carbon-14 and other such isotopes in tree rings of known age, thereby allowing us to tell the degree of solar activity at particular times, as the production of these isotopes increases with higher solar activity
- We can get data from this method back to 10,000 years, and seems to show a fairly reasonable correlation between solar activity and temperature changes
- However, there are periods of not very good fit, such as during the last deglaciation 10,000 years ago
- In sum, it is clear that solar activity is going to affect climate, but other factors also operate

Cosmic Rays

- These are high energy protons and electrons from outer space

- When they hit the atmosphere they can create particles which act as nucleation sites that increase the rate of cloud formation
- An increase in cloud formation will lead to more sunlight being reflected, thereby cooling the earth
- However, we have been measuring cosmic rays since the 1950s, and there has been no clear trend despite the clear trend in temperature, so this does not seem to be a significant effect

Milankovitch Cycles

What are Milankovitch Cycles?

- These are cyclical changes in the orbit of the earth that are the result of the moon and other planets applying torque and other forces to the earth's orbit, causing it to change over time
- The key factor seems to be the amount of solar energy reaching the northern hemisphere in the summer, as less energy allows more glacial growth, hence reflecting more sunlight

Axial Tilt

- Increased axial tilt brings more solar radiation to the two summer-season poles and less radiation to the two winter-season poles
- This is because the greater angle causes more beam spreading and more reflection of light from the earth's atmosphere
- This changing obliquity runs on a 41 thousand year cycle, between a minimum and maximum a few degrees apart

Eccentricity

- Eccentricity expresses a relationship between the major and minor axes of the earth's orbit, where a value of zero indicates a perfect circle
- Eccentricity runs on two overlapping cycles, one of 100 thousand years and one of 400 thousand years

Axial Precession

- Axial precession is caused by the gravitational pull of the Sun and the Moon on the slight bulge in Earth's diameter at the equator
- This occurs with a cycle of around 23 thousand years
- Precession has the most important effect on temperature in the northern hemisphere, followed by obliquity and then eccentricity

Current Glaciation Cycles

- At the moment, however, eccentricity seems to be driving the hundred thousand year cycle of glaciation cycle, with smaller 40 and 23 thousand cycles on top of that; why precession is dominating is not really understood
- At the moment we should be moving slowly back into a new glacial period, and indeed there are some who argue that the Little Ice Age was the beginning of this trend which was ended by the burning of fossil fuels
- The reason for the change in the glacial cycle from 40 to 100 thousand years may be because of changes in the sensitivity or threshold level of the earth to glaciation

Continent and Ocean Interactions

Plate Tectonics

- This clearly cannot be the explanation of climate change over the past 150 years
- Over longer time scales, however, they certainly can have a significant effect
- The formation of mountain ranges, for example, can change wind circulation patterns which may have global temperature implications
- The presence of ice sheets and/or continents also alter the circulation of wind currents
- The distribution of continents also changes the flow of ocean currents, which can impact global temperature

Falling Ice Sheets

- Another effect is that as ice melts, the overall elevation of the surface of the ice falls, which means that the surface of the ice reaches lower altitudes and hence higher temperatures, thereby leading to a positive feedback mechanism
- This seems to be happening to the Greenland ice sheet, and so it is possible that we may not be able to save it even if we stopped emitting carbon dioxide now
- On the other hand, warmer temperatures tend to increase rain and hence snowfall, thereby potentially working back in the opposite direction

The Gulf Stream

- Some are concerned that the melting of the north pole and Greenhouse ice sheets will lead to an influx of cooler, less salty and hence denser water into the north Atlantic, leading to a disruption of the convection mechanisms that keep water flowing around the globe
- By shutting down the convection of water current up to northern Europe, this could lead to a drop in temperatures in northern Europe
- At the moment we don't have very much data to support this idea – it seems that the Gulf Stream is highly variable, so we cannot identify any clear trends
- It is probably highly unlikely that the Gulf Stream would be shut down completely, though it is possible that it might slow down somewhat
- There is another theory that recent global warming is due entirely or mostly to increases in the rate of ocean circulation, in accordance with a natural cycle
- This idea is possible, but we don't have very good theory about this, and existing global warming can adequately explain recent climate trends without recourse to this

Causes of the El Nino

- Normally there are strong winds that carry warm surface water from off the coast of South America over the pacific to the coasts of Australia and Japan
- The water from these regions in turn is pushed downwards and moves back towards south America along the bottom of the ocean
- The result is that a large amount of cool deep ocean water rich in nutrients is brought up near the South American coast, providing a boon to the fishing industry
- However, with a period of two to seven years, these winds weaken (or sometimes reverse completely), and so warm water stays on the coast of south America

Effects of the El Nino

- Wherever the warm water is, there tends to be lower pressure and hence more rain and storms

- Thus, during an El Nino year, Australia and south-east Asia get less rain than they are accustomed to, while South America gets more rain but poorer fishing
- El Nino years tend to cause rice famines in Asia, bush fires in Australia and floods in South America
- There are also flow on effects that affect climate patterns across the world
- Recently we have been able to use ocean buoys to predict these El Nino events a few months in advance

Pacific Decadal Oscillation

- Two primary nodes of sea surface T exist in the north-western portion and the eastern tropical Pacific
- Abrupt shifts in relative T occur between these two regions at about 20-30 years.
- The years 1947 to 1976-77 were marked by generally low temperatures in the NW portion, ending with an abrupt shift
- A recent shift has just occurred so we are in a "warm phase" (warmer in E tropical Pacific)

North Atlantic Oscillation

- Switching of High and Low pressure systems over the North and Central Atlantic
- In a warm phase Atlantic water pushes farther into the Arctic, and as a result sea ice thins
- During a cold phase, low-level winds are strong, which effectively isolates the Arctic
- Ocean from warmer, saltier water to the south and promotes a thicker layer of sea ice

Greenhouse and Icehouse Gasses

What are Greenhouse Gasses?

- These pass visible light but prevent loss of radiant heat (infrared) from earth, and hence contribute to warming of the troposphere

What are Icehouse Gasses?

- These reflect incoming visible radiation and thus prevents some energy from reaching the troposphere

Greenhouse Gasses

- Water vapor
- Carbon dioxide (CO_2)
- Methane (CH_4)
- Halocarbons
- Tropospheric Ozone
- Nitrous Oxide (N_2O)

Greenhouse Aerosols and Other

- Black carbon
- Mineral dust?
- Aviation induced clouds
- Changes in solar luminosity

Icehouse Gasses

- Stratospheric Ozone
- Sulfates

Icehouse Aerosols and Other

- Aerosols from biomass burning
- Organic carbon
- Water droplets
- Mineral dust?
- Land use (albedo)

Feedback Mechanisms

Physical Feedback Examples

- Positive feedback: More ice will reflect more sunlight which will make it colder and allow more ice and vice versa
- Negative feedback: Warmer temperatures will cause more evaporation which will mean more clouds that can block sunlight and reduce temperatures

Methane Clathrates

- Methane clathrate, also called methane hydrate, hydromethane, methane ice or "fire ice" is a solid clathrate compound in which a large amount of methane is trapped within a crystal structure of water, forming a solid similar to ice
- It is thought that warming of the oceans may cause the greenhouse gases contained in these clathrates (which is a very large amount) to be released, thereby forming an additional positive feedback warming mechanism

Biological Feedback Examples

- Positive feedback: Warmer temperatures will thaw out the tundra and allow microbes to decompose stored organic material and release greenhouse gasses like methane
- Negative feedback: With more CO_2 in the air, plants will thrive and thus the biosphere will have a greater ability to fix carbon into biomass or soil
- Although we see that the system is immensely complicated, at the moment the consensus is that the positive feedback mechanisms outweigh the negative ones

Lecture 27: Climate Effects and Politics

The Ozone and the Climate

Ozone Depletion Summary

- Ozone Depletion: occurs in the stratosphere
- Cools the stratosphere, as less UV radiation is absorbed
- CFC's and NOx – these are largely inert, and so don't react with anything much in the troposphere, so they can migrate to the stratosphere and begin catalysing the destruction of ozone molecules
- Less Ozone means more UV radiation = more skin cancer

Montreal versus Kyoto

- Montreal Protocol meeting set up multinational agreement to phase out CFC's
- It has worked mainly because industry could find alternate chemicals
- Kyoto protocol meeting set up multinational agreement to reduce use of fossil fuels
- Has not worked – Has more potential now that the IPCC 4th report came out in 2007

Global Warming Summary

- Occurs in the troposphere
- Warms the troposphere
- Caused by greenhouse gases like H20, CO2, CH4, etc
- Traps terrestrial thermal infrared
- Less infrared out means more heat in troposphere

Methane versus Carbon Dioxide

- Methane is actually a more potent greenhouse gas than carbon dioxide and has increased by a much larger fraction than carbon dioxide, however there is so much less of it in the atmosphere that it does not cause nearly as much global warming
- At the moment we think that carbon dioxide is causing about half of all the global warming that is the result of greenhouse gases, with CFCs at about 20% and methane about 16%

Consequences of Global Warming

Positive Effects of Global Warming

- The biggest warming will occur in the winter and at night time, which means lower heating bills
- The melting of glaciers in the Antarctic and Greenland will also free up additional land
- We would also expect a longer growing season during the summer (frosts are delayed), while the carbon dioxide in the atmosphere serves as a fertilizer for plants
- Also, human caused climate change may well be keeping us out of the next glacial period, as Milancovich cycles indicate we should be entering the next one
- Finally, we would expect to see more rainfall in a warmer world, which may be beneficial for some areas

Increased Hurricane Damage

- It is also possible that global warming may cause more violent hurricanes, though the evidence is far from conclusive about this
- There is some evidence that Atlantic hurricanes are getting more intense with increased temperature, but this evidence does not exist elsewhere, and there is no evidence anywhere that the number of hurricanes increases
- We would also expect that because there is more moisture in the atmosphere, blizzards and severe storms will get worse (at least the most severe of them will be worse)

Desertification

- We also expect that hot and dry places will get hotter and drier, while wet regions will get wetter
- This is bad news for places like the Sahel in Africa and the deserts in Mexico
- We also expect that human activities are responsible for the increased number of droughts since that 1970s, a trend expected to continue into the 21st century
- Snow packs are expected to melt earlier in the season, potentially causing summer shortages of water for regions that depend upon snow melt
- One thing to note is that climate change is likely to most severely impact third world nations, those with the least ability to deal with it

Increased Extinction Rates

- Climactic changes will also lead to changes in plants and hence animal ecosystems

- The trouble with this is that the climate may be changing more rapidly than animals are able to adapt to it
- It is also likely that warmer days and nights will become more frequent and intense, as will severe heat waves

Rising Sea Levels

- Thermal expansion and glacier melting will lead to sea level rise and coastal flooding in low lying areas like Holland and Bangladesh
- This will in particular make the flash flood damage from hurricanes more likely and frequent
- Since 1993, thermal expansion has been causing an annual 1.6mm per year rise in sea levels, which when added with all the melting ice effects sums to a rise of 2.8mm per year predicted rise
- The actual observed rise has been 3.1mm per year, so our models are missing part of it
- If we assume this rate remains constant, we would expect 30cm of sea level rise over the next century, though some scientists predict up to a 1.5m rise
- Even the 30cm rise puts pressure on coastal areas in densely populated regions like Holland and Bangladesh

Catastrophic Ice Sheet Collapse

- There is also concern that thresholds could be reached which would lead to the catastrophic collapse of the West Antarctic or Greenland ice sheets, causing sea level rise of some 5+m
- However, this is not considered to be the most likely outcome: 30cm is currently the best estimate for the next century sea level rise

Conclusion

Summary

- Overall, current data and climate models show that the greenhouse gases are increasing their warming effect, and that this effect is currently dominating the climate system
- The historical data showing the correlation between carbon dioxide levels and global temperatures are far too great to be coincidence
- Also, while there are some mechanisms by which warming of the planet would tend to increase the amount of carbon in the atmosphere (e.g. more plant growth), there are other mechanisms that would operate in the opposite direction
- As we know we are putting more carbon dioxide in the atmosphere, the most reasonable explanation is that the increased carbon is causing the increased temperatures

The Future

- From the additional radiative forcing that the earth has accumulated since the industrial revolution, we should expect to see about a 1.2 degree increase in temperature
- We have already observed about 0.7 degree increase, so there is still about a half a degree of warming to go, even if we stopped emitting carbon now
- China is currently the largest emitter of carbon dioxide; they are building about one new coal power station ever few days

Part D: The Biosphere

Lecture 28: Sweet Life

Defining Life

What is Life?

- The trouble with all these definitions is that things we know are not alive almost always fit within the definition – fire is the best example, as it grows, nourishes itself, reproduces, responds to its environment, etc
- Really specific definitions that require catalysed organic reactions would exclude any non-carbon based life, which is certainly possible

Three Requirements

- Autonomous Morphogenesis – can operate as a self-contained system
- Telonomy – system is endowed with a purpose, in this case in DNA/proteins
- Reproductive invariance – nucleic acids can reproduce themselves with high precision
- However, the autonomous part doesn't really work, as humans are dependent for existence upon the many symbiotic bacteria living in our bodies
- The storage of information is a crucial element, as salt crystals are ordered and grow, but do not serve any information
- Clearly, crystals are not subject to natural selection

Life and Low Entropy

- Some definitions of life include the definition of low entropy within the system, but the trouble is that many non-living natural systems are ordered, such as crystals, whirlpools and hurricanes
- Schrodinger highlighted the fact that lifeforms maintain their own low internal entropy by consuming resources of low entropy and expelling materials of high entropy
- Level of entropy of the lifeform tends to increase over time, eventually leading to aging and death

Conclusion

- Favoured definition: life has self-reproduction at some level, and stores information that is preserved by natural selection
- Perhaps the best approach would simply be to abandon the concept of a clear definition of life and call it a continuum

Difficult Cases for Life

Silicon Life?

- Life tends to take on the lightest isotope of carbon (C-12) as lighter isotopes tend to react more quickly
- Silicon is heavier than carbon so it will not be able to make and break bonds as quickly as carbon, so it is unlikely the really complicated multi-cellular forms of life would be able to form from silicon

Artificial Life?

- In 2002 researchers at SUNY Stony Brook succeeded in synthesizing poliovirus from its chemical code, producing the world's first synthetic virus

- Scientists first converted poliovirus's published RNA sequence, 7741 bases long, into a DNA sequence, as DNA was easier to synthesize. Short fragments of this DNA sequence were obtained by mail-order, and assembled
- Does this mean that we have created life from non-life?

Viruses?

- These represent a very tricky case for the definition of life
- Funny definition of a virus: a gene wrapped in bad news
- Viruses store information, are subject to natural selection, and reproduce themselves
- The trouble is that if we accept viruses as life, we should probably also accept cars as alive, as they store information in their design, compete on the marketplace, and reproduce utilising the factories of humans just as viruses reproduce using the cellular machinery of other organisms
- Also, unless we have physical structure as one of the criteria we would also have to consider computer viruses as alive

Defining a Species

Sexual Isolation

- This definition is usually based on the presence of a group of potentially interbreeding animals that can produce fertile offspring
- One problem with this definition is the case of hybrids, for example mules, some of which are even fertile
- Another big problem with this is that it doesn't work for asexual reproducing creatures

Typology and Morphometry

- Species can be defined by typology, whereby a single type specimen of a species is placed in a museum and all future candidates are compared to it
- Morphometry is a similar method of classification based on external characteristics and appearance, but is based on statistical analysis of a larger number of specimens rather than comparison to a type specimen
- One problem with both of these methods is that animals can look different while being closely related, and visa-versa
- There is no such thing as an intermediate between species, as species are artificial constructs, and so every creature is simultaneously a separate species and are all related to each other

Genetics

- The final method is based on genetic relationships
- Because the naming of species is a very arbitrary and difficult process, we should not expect to find intermediate forms between species

Analysing Life

Indicators of Life on Earth

- The fact that our atmosphere is out of equilibrium (methane and oxygen) is one of the biggest indicators of life on earth
- Life doesn't just exist on the surface of the earth; it has been found at 3km deep and up to 41km in the stratosphere

Taxonomy

- Regardless of the definition of life, how can we organise the types of life that do exist?
- We can do this on the basis or morphology, genetic relationships, or behavioural relationships
- Lenean classification systems: an ordered system of classifications with increasing levels of specificity down the hierarchy
- Mnemonic: kings play cards over family gravestones
- Archaea: prokaryotes, many of them are extremophiles, binary fission reproduction, wide variety of means of metabolism and nutrients
- Monera: prokaryotes, wide variety of means of metabolism and nutrients, binary fission reproduction
- Protists: eukaryotes, need oxygen for metabolism, wide variety of nutrients, asexual
- Fungi: eukaryotes, need oxygen for metabolism, nutrient acquisition by absorption, asexual or sexual reproduction
- Plantae: eukaryotes, need oxygen for metabolism, nutrient acquisition by photosynthesis, asexual or sexual reproduction
- Animalia: eukaryotes, need oxygen for metabolism, nutrient acquisition by ingestion, sexual reproduction for most

Symbiosis

- Termites work together to construct immensely complicated structures that are their nests; it seems that their intelligence somehow builds off that of the other terminates to reach a critical mass when there are enough of them
- We usually think of life as being a competition between animals and species for resources, although symbiotic relationships are really just as common
- For example, animals that work in groups, bacteria living in animal's guts, mitrochondria in bacteria, etc

Lecture 29: Ecology

The Food Chain

Basic Terminology

- A population is a group of individuals of a particular species that are in communication and contact with each other that are actually capable of breeding with each other
- The biota refers to all the life within a certain area, whereas the ecosystem refers to the life, non-living matter and the self-sustaining interactions between them
- The biosphere consists of all the ecosystems put together

Food Chains and Webs

- Food chains refer to the linear pathways by which matter and energy is moved through an ecosystem by feeding of organisms
- Food webs refer to all of the food chains and their complex interrelationships within an ecosystem

Producers

- Producers – make organic materials out of energy and non-organic materials
- Can be divided into the photosynthetic autotrophs (that photosynthesise) and the chemosynthetic autotrophs (use chemical reactions rather than solar power to generate energy)

- Many of the extromophiles live in places where the sun does not reach, and so are chemosynthetic

Consumers

- Heterotrophs – are dependent upon producers for their energy
- Consumers are those that eat other organisms, and can be divided into primary, secondary and tertiary consumers
- Consumers that eat dead flesh are called necrophages, including decomposers and detritus feeders, scavengers

The Food/Energy Pyramid

- Because the process of consumption and digestion is not perfectly efficient, the amount of energy embodied in levels of the pyramids decreases with higher levels
- The three major sources of loss are part of the biomass not consumed, the part not digested, and the part that goes to respiration and body heat rather than actual growth of the creature
- This is why creatures at the top of the food chain tend to be more vulnerable to environmental change than those at the bottom

Competition and Mutualism

Niche Specialization

- Competition between organisms (same or different species) for a single resource leads to resource partitioning and niche specialization
- A niche is the response of a particular organism to this competition to resources, and the effect of this response in turn on its ecosystem
- The niche is thus more of a behavioural than geographical concept

The Competitive Exclusion Principle

- Competitive exclusion principle says that no two species can occupy the same niche in the same are for a significant period of time, as one will always outcompete the other
- The fundamental niche refers to the area on the niche diagram (plotting a different factor of life on each axis, such as light and nitrogen availability for plants) in which a species can survive

Resource Partitioning and Specialisation

- However, because the fundamental niches of two different species may overlap, they will tend to relegate themselves to separate, particular subregions called the realised niche
- This process is referred to as resource partitioning and specialisation
- One key example of this are Darwin's finches, which probably all diverged from a single finch species that migrated to the Galapagos islands and then diverged into multiple species each with a different niche

Mutualism and Symbiosis

- Mutualism refers to cooperation between species to improve fitness (e.g. bees and flowers), while cooperation refers to cooperation between individuals within a species (e.g. ants)
- Sometimes mutualistic relationships can become so tight that they effectively merge into the same species (e.g. mitochondria, lichen)
- Symbiosis is sometimes used as a synonym for mutalism, but also sometimes refers to any situation where the outcome for one species is heavily dependent upon the outcome for the other

- Examples would include parasitic relationships, commensalism (one benefits and the other isn't really affected either way, like riding on creatures), and enslaving of one organism by another

Optimal Range

- Species are generally best adapted to certain environmental conditions (optimal range), and as these parameters change the species moves into its zone of stress, where the species is infrequent, and then the zone of intolerance, where it is not found at all
- Terrestrial factors: temperature, precipitation, nutrient levels, sunlight, fire, chemistry of soil, pH and salt level of soil
- Many of these are dependent upon climate: generally climate determines what plants can live in an area
- Aquatic factors: salinity and pH of water, temperature averages and extremes, nutrients in water, amount of sediment of the water, texture of the bottom, water currents, light

Ecological Succession

What is Ecological Succession?

- For a given climate, the organisms within an area may change over time if the region is new or has recently been disturbed
- This relates to the idea of ecological succession, which refers to a series of biological communities that live in a given region of climate

Primary Succession

- Primary ecological succession begins in an area that begins with no life at all – for example a new volcanic island
- Usually the first things to develop are lichens and mosses which begin to break down the rock and form soil
- As the soil base begins to form the first small grasses and plants arrive
- As these small plants form and decay, larger and larger plants are able to firm
- This will eventually lead to the climax community, with the largest trees and plants; this is a stable state
- Pioneer communities tend to extract as much resources and energy as quickly as possible, whereas climax communities tend to last longer, do more recycling and careful managing of resources

Secondary Succession

- Secondary succession occurs in a circumstance where an area has been disturbed, but the life not completely removed, such as occurs after plowing a field – the succession will be different, but the basic idea is the same
- Aquatic systems can also go through cycles, for example a pond being converted into a wet meadow

What are Biomes?

- We tend to see a particular type of climax community for a particular type of climate
- Based on this, we can organise the different ecosystems into related sections called biomes
- The two most important variables for this are temperature and precipitation
- Because climate tends to change with latitude, so to do biomes tend to vary with latitude (and also altitude)

What are Ectomes?

- Ecotomes are transitional zones between different biomes, which are interesting because they can form habitats for unique species
- If we know that a particular species only lived in a particular ecotome of biome we can extract climactic information from the fossil record

Biogeochemical Cycles

Introduction

- The movement cycles of material through ecosystems are called biogeochemical cycles
- In order or abundance, the elements in the ecosystem are carbon, hydrogen, oxygen (generally these two are found together in the form of water), nitrogen, phosphorous and sulphur (mnemonic of CHON-PS)
- Whenever any of these cycles are perturbed, there will be inevitable significant repercussions

The Water Cycle

- The water cycle is mostly a climactic and geographical issue, so the remaining four are the ones mostly studied in biology

The Nitrogen Cycle

- Nitrogen is essential for all life, but the nitrogen molecules in the atmosphere are inert, and so cannot be used by most forms of life
- Some of the nitrogen is produced by lightning splitting apart the gas molecules, but most of it comes from nitrogen fixing bacteria that live on the nodules of legume roots and fix nitrogen into the soil
- Humans produce fertilisers containing nitrogen from sources of rich nitrogen such as bird droppings
- The Hobber-Botsch process is an industrial technique that can take nitrogen out of the atmosphere and turn it into ammonia, which can be used on farms as fertiliser
- The downside of this is that the runoff of nitrogen can cause eutrophication

The Phosphorus Cycle

- Phosphorus is the only one of these major cycles that does not involve any significant atmospheric component – most phosphorus is locked up on rocks and the soil
- Once again, humans mine phosphorus and use it as fertiliser, with the undesirable consequence of eutrophication

The Sulphur Cycle

- Most of the sulphur is released into the atmosphere by burning of fossil fuels, volcanoes, and production by bacteria
- The sulphur cycle is the least well understood, especially the elements in the ocean

Lecture 30: Evolution

Explaining Evolutionary Theory

What is Evolution?

- Evolution refers to the change in the frequency of alleles in a population over time
- Alleles refer to the different forms of genes, like perhaps those that govern eye colour
- Evolution can only occur in a population over generations – individuals do not evolve

The Basic Idea Behind Evolution

- Production of too many children and scarcity of resources leads to competition between organisms
- Variation within the individuals within a population leads to some having an advantage over other organisms
- This differential success leads to differential production of offspring, with the difference determined by the particular nature of the genetic variations
- This necessarily requires some system of inheritance so that variation is passed along to offspring
- Darwin actually predicted the existence of distinct hereditary packages, which we now know are DNA, and also the existence of genetic mutations

Allopatric versus Sympatric Speciation

- A subpopulation separated geographically splits off from its parent population; often occurs with the formation of mountains and valleys, and continental drift
- Sympatric speciation occurs when a new species forms in the same region as the parent species, perhaps due to some kind of infection or mutation that produces behavioural or morphological differences that prevent interbreeding

Fitness and Natural Selection

- An organism's fitness refers to the ability of an organism to survive and reproduce fertile offspring
- Any mutations that increase fitness (move up the adaptive landscape on the three-dimensional graph) tend to be selected for, while those that reduce fitness tend to be selected against
- This is why natural selection is not a random process

The Adaptive Landscape

- One way in which a species can evolve even when it is on a local peak in the adaptive landscape is if the landscape itself changes or the species migrates, so in both cases it is no longer on a local peak
- Another method of speciation is if the species mutates 'sideways', neither increasing or decreasing in fitness, in a process called genetic drift
- Genetic drift tends to be faster in smaller than larger populations, as neutral mutations tend to be washed out
- Macromutations that leap from one hilltop to another are also technically possibly, but thought to be very rare, as most big mutations are going to be fatal
- Another possibility is an open barrel, where there are so many resources that even small downhill movement is possible

Punctuated Equilibrium

- This theory was designed to explain the relative stability and periodic jumps in the fossil record, which is not would we would expect with continual gradual change
- The explanation for this was that the fossil record is because of its very nature biased towards large, stable populations
- On the other hand, small isolated populations are more likely to undergo rapid evolution
- If this peripheral population reaches a superior fitness level, it may form a new large, stable species
- Thus, because speciation generally occurs in smaller sub-populations that don't fossilise as well, we tend to see less gradualistic evolution in the fossil record
- Similar mechanisms explain the genetic uniqueness of small isolated populations in the Amish

Evidence of Evolution

Examples of Observed Evolution

- Evolution of bacteria for drug resistance is one example of speciation in historical times
- Another example is the mosquito form that emerged in the London underground
- Several new species of plants have arisen by the process of polyploiti, or duplication of chromosomes
- Incipient speciation is observed in a number of cases, where populations are becoming increasingly separate and fertile breeding is becoming increasingly difficult
- The ring species Salamander in California and greenish warblers in the Himalayas are both examples of speciation in action
- There are some fish species found only in Lakes in Canada, even though all Canadian lakes were frozen solid before 10,000 years ago
- There is a species of flowering plant that exists only in the high-copper tailing soils near a copper mine in Britain that only opened up in 1859

Genetic Evidence

- One very good test is the fact that humans have one less chromosome than chimpanzees and other great ape species
- The only way this could occur if we share a common ancestor is if some time in the past human ancestors had two of their chromosomes merge
- If this occurred, we should be able to find evidence of telomeres around the middle of one of the current human chromosomes
- And in fact exactly this has been found on chromosome two, providing powerful support for evolution

Evidence of Genetic Mutations

- We have seen such mutations occur; bacteria have evolved that have the ability to digest nylon
- Similarly, plant breeders have for thousands of years used the principle of mutations to develop better foods and grains
- Mutation has also led to anti-bacterial medicine resistance and pesticide resistance
- The amazing degree of variety observed in contemporary dog breeds (all of which descend form an initial population of Siberian wolf) is testament to the power of mutation over time, even when these are only guided by the external observations of humans for a few thousand years
- Think how much more change will be able to be wrought by nature, which looks at all conceivable aspects of a species over millions of years

Intermediate Fossils

- Another example is the prediction is that there should be an intermediate creature between fish and amphibians dating to the Devonian period
- When scientists went to look in rocks of this era, they found Tiktalic; exactly as they had predicted

Comparative Homology

- The fact that there are many non-optimal designs in nature is also indicative of the historical contingency of evolution
- Examples include hands on the bat's wing, the appendix (which is not essential but can kill you if it gets infected), the blind spot of the eye

Further Evidence

- Comparative homology and embryo development are also indicative of evolution
- Artificial selection by humans of agricultural crops, bacteria and pets are also strong examples of evolution
- The distribution of species across continents and other geographical regions is also exactly what would be expected if species evolved from each other rather than being created ex nilo

Arguments Against Evolution

What is Orthogenesis?

- Orthogenesis is a principle that says that the mechanisms of macroevolution are very different of those that occur in microevolution (within a species)
- However, the consensus in the scientific community is that this is not the case

Argument from Design

- Natural selection operating through the mechanism of random mutations over millions of years actually has far more power to come up with new and novel solutions to various biological problems than does human intelligence
- Argument from analogy is only effective if the two systems being compared have enough overlapping similar properties
- The Dover case decision was that intelligent design may be true (the court did not take a position on this), but because it was not falsifiable and because it has been rejected and rebutted by the scientific community, it was not science and therefore could not be taught in science classes

Religious Objections

- Would a just god give us brains capable of thinking and putting together evidence in accordance with logic and reason, as well as mountains of evidence to indicate that the earth formed billions of years ago and that we evolved from simpler life forms, just to say 'aha, let's see if they still believe in me know', and reward those who ignored all this evidence and put their faith in a book written thousands of years ago and altered many times?
- About half of Americans believe that humans were created in their present form with no evolution; only about a third believe in unguided evolution

Irreducible Complexity

- One method of achieving irreducible complexity is if we have a functional element of a cell or organism that does something that is essential to the survival of the organism, and then a mutation occurs that is not essential, but that makes the essential function better
- This mutation will be favoured by natural selection, and so may spread throughout the entire population
- It is then possible that a second mutation could occur that inextricably links the two, such that neither can function without the other
- This mutation may not be beneficial in and of itself, but genetic drift over time could spread it throughout a population
- This, in this manner an irreducibly complex system can arise with relatively little difficulty
- If this happens a sufficient number of times, 'Rube Goldberg style' highly complex biological machines (i.e. just the type of things we actually see in the natural world, rather than well designed streamlines mechanisms) could be formed

- One real world example of this is the bolus spider and its sticky web

The Evolution of the Eye

- The very first primitive photosensitive cell may have arisen in an ocean creature as a beneficial mechanism of determining which way is up (hard to tell gravity in the ocean)
- Over time there would have been selective pressure to acquire more and more sensitive photosensitive cells
- Having this patch of cells curve around into a cup shape would be further advantageous, as the shadow that the light casts on the eye would permit determination of direction
- As the depression came to be covered up, the light would be focused more and more precisely, eventually forming something of a pinhole camera
- Of course, as the hole gets smaller the image gets sharper, but also less light gets in
- One solution to this is to develop a lens that focuses light from a wide area on the back of the retina; the lens in turn can be reshaped and focused on the retina
- One statistical and experimental analysis calculated that (using pessimistic assumptions) it would take only about half a million years to evolve a camera lens eye from a flat lens of photosensitive cells
- Compare this to the fact that eyes have existed for about 600 million years
- Indeed, it seems that nature has evolved eyesight several independent occasions, including octopuses, the compound eye, and the eyes of mammals

Evolutionary Scaffolds

- Another mechanism by which complex systems can evolve is the use of scaffolds, just like we use scaffolds to build arches and other 'irreducibly complex' constructions
- An example of this is the air bladder, which emerged in fish originally as a means of controlling buoyancy, but which then came to be coopted for occasional use in breathing out of water
- In this case, the continued existence of gills acted as the scaffold for the evolution of air bladders that could support the fish longer and longer out of water
- Eventually the point came where it was not longer necessary to have the air bladder at all, and so it was selected against

Vitamin C in Primates

- A similar argument has been made to explain why primates have a gene for making vitamin C but (unlike many other mammals) it is not turned in
- The reasoning is that our primate ancestors ate of lot of vitamin-C rich fruit, and so there was no selective pressure operating to keep this gene active; a mutation eventually turned it off
- In this case, the eating of fruit acted as the scaffold

Lecture 31: The Evolution of Consciousness

The Role of DNA

Genetic Clock Dating

- For the most part the dating from the genetic clock comes out with similar dates to the geological dating of fossils
- We prefer radiometric dating to genetic dating in most cases, as we know that the rate of radioactive decay is constant, while the rate of genetic change is altered by the selective pressures

The Background Rate of Evolution

- There is a background mutation rate of DNA which is responsible for evolution
- As such, the maximum possible rate of evolution is equal to this background rate
- However, strong selective pressure actually serves to more strictly weed out organisms with mutations, so it tends to slow down rather than speed up the rate of evolution

Storing Information in DNA

- Interestingly, DNA holds information in a binary format just like computers (either the C/G pair or the T/A pair)
- Three bits of information form a codon, each of which codes for a particular amino acid
- The DNA of each human being holds about 0.35 gigabytes of information, which is very impressive considering the size of DNA
- Theoretically you could store an exobyte of information in a mass the size of a drop of water using DNA storage
- However, only about 5-10 percent of the genome actually codes for proteins, the remainder being 'junk DNA', which may or may not have a purpose

Individuals versus Populations

Natural Selection of Populations

- Natural selection occurs both at the individual level and at the gene level, as genes that work well together to survive and reproduce are groupings that tend to get replicated
- However, what about populations; could natural selection act upon them?
- One apparent example of this is the seven and thirteen year reproductive cycle of cecaters, which evolved owing to the fact that these are prime numbers, and so it is more difficult for predators to synchronise their reproductive patterns with the secaters

What is an Individual?

- Sometimes it is not even easy to distinguish the individual from the population
- Are mitochondria separate individuals, as they have their own DNA, but at the same time they cannot live outside of eukaryotic cells, and visa-versa
- Similarly, a large portion of our bodyweight consists of symbiotic creatures that have their own DNA, and yet we could not survive without them
- Are we then truly individuals?

Gauld's Five Traits of an Individual

- A definite beginning (birth)
- A definite end (death)
- Enough stability in between to be recognised as a distinct entity
- It must reproduce
- Its offspring must reproduce by some kind of inheritance mechanism

Examples of Tricky Cases

- For example, mushrooms are mostly autonomous and certainly look like separate individuals, but actually they are always connected underground by a network of roots (the fungal mass)
- Mushrooms tend to grow in circular patterns called fairy rings, which can lead either to an enhancement or reduction in the fertility of the surrounding soil

- This also applies to many other forms of asexual reproduction (e.g. dandelions)
- Ramets even occur for animals, such as the parthenogenesis in aphids
- A fungus mat has been found producing mushrooms with a total mass of the entire genet of 100 tons, and at least 1,500 years old
- Another similar organisms in Tasmania is over 40,000 years old

Ramets and Gamets

- To deal with this definitional problem, biologists developed the concepts of the ramet (something noticed as a spatially distinct unit) and the genet, referring to all the tissue that grows from a single fertilised egg of a particular species
- Thus, many ramets can form a genet, as for example a clipping from a tree grown as a separate ramet
- If we killed the parent plant while leaving the clipping alive, technically the original plant would still be alive, as the genes are all the same
- Ramets of the same genet could be widely separated and propagate the genet for a very long time

The Nature of Consciousness

Clones and Consciousness

- The above discussion raises the question as to whether or not clones are separate individuals
- According to our definition, identical twins would be two ramets of the same genet, as both originated from the same egg and have the same DNA
- However, they clearly have separate consciousness, so what is going on?

Do Animals have Feelings?

- The fossil record displays a smooth progression of forms from primitive to modern, and comparisons of modern forms with our own show striking resemblances
- Thus, do we also share with animals aspects of our emotions, feelings, consciousness?
- Descartes did not think that animals had souls; they were just machines
- However, because humans could think and reason, they had a soul
- He reasoned that the only way you could determine another creature had a soul or emotions was by talking to it; hence animals do not have a soil or emotions

Types of Emotions

- Background: Well-being, malaise, calm, tension
- Primary/Universal: Happiness, sadness, fear, anger, surprise, disgust
- Secondary/Social: Embarrassment, jealousy, guilt, pride, loyalty, compassion, gratitude

Levels of Life Regulation

- Basic Life Regulation: Relatively simple, stereotyped patterns of response, which include metabolic regulation, reflexes, the biological machinery behind what will become pain and pleasure, drives and motivations
- Emotions: Complex, stereotyped patterns of response, which include secondary emotions, primary emotions, and background emotions
- Feelings: Sensory patterns signalling pain, pleasure, and emotions become images
- High Reason: Complex, flexible, and customized plans of response are formulated in conscious images and may be executed as behaviour

Lecture 32: Population Dynamics

Population Growth

What is Population Dynamics?

- A population is a group of individuals of a given species that life in the same area and are able to interbreed
- Population dynamics studies the change in population levels over time

Exponential Growth

- Interestingly, with a constant exponential rate of growth, the doubling time of a population is always the same
- To calculate the doubling time of any population, simply divide the percentage annual growth rate into seventy (this works if compounding is continual)
- In real natural systems, however, the growth rate fluctuates over time

Biotic Potential

- The maximimum rate of population rate is known as the biotic potential, and depends on the species; this is rarely reached in the real world
- Environmental resistance factors are those that keep it from growing at its biotic potential

Environmental Resistance Factors

- Lack of availability of food
- Lack of water
- Lack of suitable habitant
- Adverse climate
- Excessive predators
- Competition between species
- Disease

Density Dependent Factors

- Density dependent factors (mostly disease and starvation) are those that depend on the density of the population, and so increase with overall population size
- Migration and new resources provide escape valves that reduce the impact of these factors
- Higher reproductive rate, defenseive mechanisms, resistance to environmental conditions and change, and resistance to disease all operate to counteract density dependent factors

Population Stability

Population Equilibrium

- Population equilibrium occurs when resistance factors are equal to the biotic potential
- If growth factors prevail, the population increases; if resistance factors prevail, population shrinks
- Typical population growth curves for logistic breeding animals resemble an S, as growth is at first exponential and then slows to logarithmic as resistance factors kick in

Eruptive Breeding Strategies

- In some instances, the initial population growth will overshoot the equilibrium levels, leading to environmental degradation and excessive competition that temporarily reduces the carrying capacity of the area and hence lowers the population
- This is referred to as the overshoot and dieback cycle
- A number of species do this deliberately, using a breeding strategy known as eruptive or Malthusian
- These species have a high reproductive rate (many kids) but a low recruitment rate (few individuals reach adulthood as all cannot be taken care of)

Logistic Breeding Strategies

- Other species have logistic breeding strategies, with few offspring but good care taken of them so that recruitment rates are high
- As a generalisation, larger mammals tend to be closer to the logistic end of the spectrum

Interrelated Populations

- The population levels of two different species may be linked in complex ways by the food chain (e.g. predator and prey)
- Sometimes they reach a stable equilibrium, while sometimes they oscillate around a particular value
- Some of these interrelated populations can take on the characteristics of a dynamically chaotic system, with a future population that is very difficult or impossible to predict

Chaotic Population Processes

How to Perturb a System

- Alteration of habitat
- Introduction of new invasive species

Stochastic versus Dynamical Chaos

- Stochastic chaos is randomness that occurs only because we lack sufficient knowledge of the operation of the system to make accurate predictions
- By contrast, dynamical chaos occurs even if we have complete knowledge of the system; it is just that sensitive dependence upon initial conditions makes prediction difficult or impossible

The Butterfly Effect

- The phrase ‘butterfly effect’ refers to the idea that a butterfly's wings might create tiny changes in the atmosphere that may ultimately alter the path of a tornado
- The flapping wing represents a small change in the initial condition of the system, which causes a chain of events leading to large-scale alterations of events
- Had the butterfly not flapped its wings, the trajectory of the system might have been vastly different
- While the butterfly does not "cause" the tornado in the sense of providing the energy for it, it does "cause" it in the sense that the flap of its wings is an essential part of the initial conditions resulting in the tornado, and without the flap that particular tornado would not have existed

The Critical Number

- The critical number is the number of organisms required to sustain the population; the exact number depends on the species
- For dynamically chaotic populations, they can by pure 'chance' end up below the critical number, and hence die out completely

The Importance of Biodiversity

- Interestingly, the more diverse ecosystems are, the less likely they are to be chaotic and the more stable they tend to be
- In general, complex systems tend to reach equilibrium more quickly and easily and remain there for longer the larger number of independent individuals there are
- For ecosystems this applies to the number of species and individuals within those species
- Consider, for example, that a natural forest continues to look basically the same from year to year, while a wheat field planted by humans and left alone will not remain stable at all

Human Population

Carrying Capacity of Earth

- The current rate of growth of the Earth's population is about 1.2%, with a current population of about 6.8 billion
- Some argue that we have already passed the human carrying capacity of the earth, as by definition this is the maximum population that can be sustained without environmental damage, and we are already seeing significant environmental damage
- However, localised environmental damage is not necessarily indicative of overall excessive population, only local mistakes and perhaps overpopulation

Varying Growth Rates

- The rate of growth of earth's population peaked in the 1960s and has been decreasing since then
- It is expected that this will continue in the coming decades, with a possible stabilisation at 10-12 billion in the late 21st century
- There are about four births and two deaths globally every second
- Virtually all the highest population growth-rate nations in the world are in Africa
- Most of Latin America and Asia fits into the middle category
- The USA, Australia, and assorted other nations have fairly low rates of increase
- Most of Europe, especially the east, has stagnant or declining populations

Technological Advances in Population Growth

- Public sanitation
- The germ theory/antibiotics/vaccines
- The Hobber-Botsch process to extract nitrogen from the atmosphere
- The Green revolution
- It seems that educational and political rights for females seem to be one of the most important factors in reducing birth rates

Does Science Destroy the Environment?

- Underdeveloped peoples also destroy their environments – for example, forests in Europe were almost destroyed by the search for fuel until the adoption of coal

- Science is neither good nor bad – it is simply a process for investigating the world
- Science can also lead to various technologies, some of which improve the environment and some of which damage the environment

Demographic Transition

- This tends to happen in all countries as they develop economically
- First the nation begins in a situation with a high birth rate and a high death rate
- Next, there is an influx of technology and an increase in wealth, bringing in vaccines, higher yields, sanitation, etc
- This leads to a reduction in death rates, but because of entrenched cultural norms birth rates tend to remain high
- This causes a dramatic increase in the rate of population growth
- However, continued development and higher levels of education over time have the effect of reducing the birth rate
- Eventually the birth rates tend to converge with the death rates, reaching a new, higher equilibrium
- This is happening in developing nations all over the world

Lecture 34: Biodiversity

Aspects of Biodiversity

Types of Biodiversity

- Biodiversity incorporates three aspects: ecosystem, species and genetic
- Species refers to the number of different species in a particular area
- Ecosystem diversity refers to the number of kinds of ecosystems in an area – for example, all wheat crops versus many different types of forest, swamps, mountains, etc
- Genetic diversity refers to the number of different alleles in the population

Why Biodiversity Matters

- About 99.9% of all species that have ever lived on the planet are currently extinct
- This raises the question as to whether biodiversity is really that important
- Alleles can be removed to the population by natural selection, population bottlenecks or simple chance
- One potential problem with lack of genetic diversity is that it can make the population more vulnerable to disease or recessive genetic disorders
- Inbreeding depression is a situation whereby increased recessive disorders lead to a reduction in the population, in turn increasing the number of disorders; ultimately this can totally wipe-out a population

Types and Distribution of Species

- We have named a catalogued about two million species, while estimates for the total number of species on the planet range from four to one hundred million, with a median of about ten million
- It is estimated that since the Cambrian there have been about thirty billion species on the planet
- About 85% of all known species live on land, and about half of those are arthropods, mostly insects, especially beetles
- There are only about four thousand species of mammals, compared to 850 thousand species of arthropods

- About 300,000 species of plants are known, and 69,000 species of fungi
- There are about 70,000 species of microbes known, but since one gram of soil is known to contain about one billion microbes and up to one thousand different species, we know that this figure is wildly incomplete
- There are about 15,000 known species of round worms, though there are many more unknown
- In total there are about 40,000 catalogued species of vertebrates, with four thousand mammals, six thousand birds and the rest amphibians, reptiles and fish

Geographic Variation in Biodiversity

- Species diversity is greatest at the equatorial tropics and diminishes towards the poles
- The explanation for this normally is based on the fact that the tropics have more solar energy, no glaciers, and more stable climactic conditions
- To emphasise how extreme this biodiversity gradient is, researchers in Borneo in one particular study counted seven hundred species of trees in an area of 25 acres, which is the same number of tree species found in all of North America
- The latitudinal species gradient also applies to the sea as well

Measures of Species Diversity

- Alpha diversity refers to the number of species in a particular ecosystem
- Beta diversity refers to the biodiversity compared across neighbouring ecosystems, for example a forest compared to nearby grassland
- Gamma diversity refers to comparison of biodiversity across two similar ecosystems separated by some distance, such as two oases
- It is interesting that so many of the species live on land, even though the oceans occupy some seventy percent of the Earth's surface
- Conversely, about two-thirds of the phyla are exclusively marine, while only three percent are exclusively terrestrial
- This means that marine life has many themes but little diversity within each theme, whereas land life has few themes but much diversity within each
- In contrast to this, about half of all fossil species known are marine, though this may be an artefact of the fossil record, as fossilisation occurs when deposition occurs quickly and frequently

Changes in Biodiversity over Geologic Time

- A Lazarus species refers to one that is thought to be extinct but is later found to be still extant
- Looking at the fossil record is seems that species diversity has been increasing over time, though this is largely a bias of the record, as older fossils are rarer and less likely to be preserved
- In fact new models indicate that there may be an equilibrium number of species on the planet of around ten million, though this seems to have increased somewhat during the Cenozoic
- Based on such estimates, we expect a rate of speciation of about three species per year, with a rate of extinction of about 2.5 per year (each species lasts on average of four million years)

Mass Extinctions

The Five Mass Extinctions

- Mass extinctions are times of rapid extinction and consequent loss of biodiversity
- There are usually said to have been five major mass extinctions since the Cambrian, with a rate of extinction of at least forty percent of species

- Ordovician-Silurian extinction event (27% of all families): 440-450 Ma; the most likely explanation for this was an ice-age and consequent sea-level as Gondwanaland moved over the south pole
- Devonian-Carboniferous extinction (19% of all families): 360-375 Ma; cause is uncertain, though may have been an asteroid impact (or even several, as it was a prolonged event), or global cooling induced by the rise of plants on land and hence reduction of carbon dioxide in the atmosphere
- Permian Extinction (57% of all families): 251 Ma; also called the great dying, easily larger than any of the others, with all sorts of mechanisms put forth from volcanism to asteroids to tectonic plate motion
- Triassic–Jurassic event (23% of all families): 205 Ma; most non-dinosaurian archosaurs, most therapsids, and most of the large amphibians were eliminated, leaving dinosaurs with little terrestrial competition
- Cretaceous–Tertiary extinction event (17% of all families): 65 Ma; it ended the reign of dinosaurs and opened the way for mammals and birds to become the dominant land vertebrates, and was likely caused by the asteroid impact in the Mexican Gulf
- However, many biologists believe that we are now in a six mass extinction event on the order of magnitude of the K-T event, but occurring much more rapidly

The Rate of Species Extinction

- Modern estimates of the rate of species extinction are 1000 to 10,000 species per year, compared to the background historical rate (mentioned above) of four per year
- This is three to thirty species per day; perhaps one every few hours
- Needless to say, this is much greater than the rate of speciation, about three per year
- One study has found that it takes about ten million years for global biodiversity to recover after extinction events, regardless of their size
- The current increased rate of extinction begins around 100,000 years ago, at about the same time as humans developed improved hunting skills (though it is also though that the new glacial period also contributed to this)

Causes of the Sixth Extinction

- Another clear piece of evidence for this is the massive extinction of large marsupials in Australia around sixty thousand years ago, just at the time humans first arrived
- A similar die-off of large mammals in the Americas occurred around 11,000 years ago just as humans first arrived in significant numbers
- Some of the species lost included sabre-tooth tigers, giant beavers, horses and even camels
- Once again, there is debate about how much of this extinction was caused by climate change (the beginning of the interglacial period) or human hunting
- Another substantial extinction occurred in New Zealand in the few centuries following the arrival of the Maori around 1000 years ago, including the Moas
- By the time the human population reached six billion, we had already exceeded by about one hundred times the total biomass of any large animal species that ever existed on land
- In the 1990s, humans consumed over forty percent of the net primary productivity of the planet, which refers to the amount of energy produced by photosynthesis minus the amount needed by plants to survive

Lecture 35: The Sixth Extinction

General Concepts

Biological Hotspots

- A biological hotspot is a region of particularly intense biodiversity, defined by tradition as with more than a certain number of species of vascular plants per region of area, and also a great threat for extinction in the short-near term
- Most of the biological hotspots, unsurprisingly, are tropical rainforests

Rates of Extinction

- It is estimated that the number of species halves when the total habitat area in a particular ecosystem reduces by a factor of ten (based on comparisons of island sizes and biodiversity)
- The current extinction rate is estimated to be about one thousand or more times above background levels
- Based on these trends, some estimate that half of all species will be extinct by 2100

Causes of Extinction

- Causes of human-induced extinction by order of importance
- Habitat destruction
- Introduced species
- Pollution
- Population density
- Overharvesting
- Even if species are not directly made extinct by human activities, we may push their populations below the level whereby inbreeding or natural fluctuations take their tool

Attitudes to Animal Rights

- Anthropocentrism – humans are the sole measure of value; at an extreme, all animals would be killed in order to save a single human
- Pathocentrism – other creatures for which we can feel empathy (especially intelligent life) have special rights to life
- Biocentrism – all life has intrinsic value, without needing to resort to any logical justification
- Perhaps a ‘laws of robotics approach’ would be useful

Methods to Preserve Biodiversity

- Protection and preservation of environmental hotspots – about sixty percent of all global species are located in these regions alone, so preservation of these regions is essential
- Stop logging all old growth forests, and preserve existing pristine forests, especially in the Amazon, Indonesia, Congo and Scandinavia
- Identify the locations of the marine hotspots (especially the coral reefs)
- Complete mapping of existing biodiversity, as currently we do not know much about this, especially in the ocean (remote sensing will be very useful for this)
- This will help us to monitor frontier regions to enforce government regulations, which is a particular problem in places like Brazil
- We also really need to make conservation profitable to the local populations who live in at-risk regions

- Also useful would be to turn zoos and wildlife reserves into effective zones for preservation of threatened species, possibly through breeding in captivity or even cloning
- Global population control may also be necessary

Extinction Causal Factors

Habitat Destruction

- Deforestation is the worst form of this in land, while coral reef destruction is the worst at sea
- The destruction of a tropical habitat can lead to ten times as much extinction as the same destruction in a temperate region, owing to the latitude species gradient

The Extent of Forests

- Maximum forest extent was reached about eight thousand years ago with the end of the last glacial period and just before the rise of agriculture
- Since that time, about half of all forests have been lost
- The total area of tropical rainforests is about the area of continental United States, accounting for about four percent of the total land area of the earth
- However, rainforests are also home to about 44% of all plant species and a third of large animal species

Forest Fragmentation

- The amount of forest land area lost does not tell the whole story, as forest fragmentation also has a detrimental impact
- Reasons for this include disruption of animal ranges, reduction of local populations below a sustainable level, disruption of foodchains
- Edge effects refer to the fact that forest destruction has a negative effect even up to 500m within the forest
- Fragmentation increases the external boundary circumference relative to forest area, thereby increasing the significance of edge effects

Invasive Species

- For most of human history, invasive species have been the major cause of extinction
- Agricultural livestock that we bring with us inevitably reduce biodiversity and outcompete native animals
- Domesticated animals also tend to escape and become feral, notably cats, dogs and pigs
- Cats are estimated to kill about 400 million birds per year in North America
- Some species are introduced accidently, notably rats, which are very adaptable and can devastate local populations
- Other times we introduce a species to serve a particular purpose, but our lack of knowledge leads to unexpected consequences (e.g. the rosy wolfsnail in Hawaii, kudzu in the US)

Pollution

- Nitrogen pollution is a particularly big problem in virtually all industrialised areas
- Indeed, pollution crosses all borders, and so can disrupt species even in conservation areas
- The grasshopper effect refers to the tendancy for industrial pollutants to be pushed to the poles by the prevailing wind motions, where they settle down on local ecosystems owing to the falling of cold air

- This is how fragile polar ecosystems can be effected by pollution emitted thousands of miles away

Overfishing

- Before 1900, the total fish catch of the planet was never greater than ten million tens
- As a result of the industrialisation of the fishing fleet, however, the catch doubled to reach twenty million tons by 1950
- By 1980 the catch had reached eighty million tons, by which time the ocean capacity had been reached, and catches began to stagnate
- It is thought that by now about half of all the fish species (most of which are not known) are threatened
- Though catches have remained fairly constant in past decades, the average fish size has been diminishing
- Another resultant problem is that fewer fish are around to eat jellyfish, leading to an explosion in jellyfish populations

Reasons to Value Biodiversity

Economic Benefits

- Provision of food – at the moment about twenty different plants provide some ninety percent of all global food, making our food supply very vulnerable to diseases (for example the Irish potato famine)
- It is estimated that there are about 30,000 edible plant species in existence, but these cannot help us if they become extinct
- Eco-tourism can also be an important benefit for retaining biodiversity (e.g. Costa Rica)

Raw Materials

- Various genes from bacteria and plants have been extracted and used in genetic engineering to reduce the need for fertilizers, increase nutrient levels and make the plants more hardy in their environment
- Use of raw materials is also important; it is estimated that sustainable use of tropical rainforests would yield $400 per hectare per year (fibres, oil, food etc)
- In contrast, clear cutting the same area would yield $1000 in timber and $3000 over the next few years for cattle ranching until the soil becomes depleted

Medicines

- One quarter of all prescription medicines come from plants, and many more from bacteria and animals
- As just one example, the periwinkle plant of Madagascar was the source of the discovery of penicillin; it could easily have become extinct before this was discovered
- Only about three percent of all flowering plants have been properly analysed for potential use in medicine

Ecological Benefits

- The trees of rainforests pump so much water into the atmosphere that they produce a great deal of additional precipitation
- Thus you cannot assume that farms placed in rainforests regions would receive as much rain as the existing rainforests do

- It has also been observed that more biologically diverse ecosystems tend to be more resilient to adverse environmental changes than less diverse systems

Biomimicry

What is Biomimicry?

- One important technique that we may want to adopt to help us 'do more with less' is to mimic successful designs found in nature
- After all, natural selection has had some 3.5 billion years to come up with necessarily sustainable ways of solving all sorts of problems
- As an example: Velcro was directly inspired by barbed seed plants

Agriculture

- It has been estimated that in Iowa, six bushes of soil are washed into the ocean for every single bushel of wheat harvested
- Aside from erosion, fertiliser pollution is also a big problem
- To improve farming techniques, we might try to mimic the layout of praries and other ecosystems that sustainably manage themselves (useful for temperate regions)
- Ranches could be organised to mimic natural ranges; for example allowing grassland to recover for a time before allowing cattle to graze again, mimicking the migration of wild herds
- Grazing of cattle on marginal land is never a good idea, as such land could barely support shrubs to begin with, and so any additional stress is likely to simply lead to desertification

Production Methods

- Modern materials manufacturing can be summarised by the phrase heat beat and treat, referring to the high use of energy, application of high pressure, and high use of treating chemicals
- Unlike humans, nature produces a wide variety of materials without application of harsh chemicals or use of high temperatures or pressures
- Nature also does not have the option of placing production and energy facilities away from sites of habitation in order to stay away from pollution

Medicines

- Plants and animals have been at chemical warfare with each other for hundreds of millions of years, so it will be very useful for us to learn from their attacking and defensive mechanisms
- Chimpanzees, for example, will seek out and consume a particular herb only when they are infected with a particular parasite
- Another interesting example: how do bears hibernate for six months without poisoning themselves

Examples of Biomimicry

- Look at these examples from nature, and the man-made inventions they inspired:
- Abalone mussel nacre (mother-of-pearl coating): This abalone coating inspired hard coatings for windshields and bodies of solar cars, airplanes, and anything that needs to be lightweight but fracture resistant.
- Antlers, teeth, bones, and shells: You can now buy a three-dimensional printer, which builds 3D objects layer by layer, as inspired by natural biomineralization.
- Barbs on weed seeds: Barbs on weed seeds inspired Velcro, perhaps the most well-known biomimetic invention.

- Blue mussel adhesive: Blue mussel adhesive inspired a man-made underwater adhesive. Unlike traditional glues, this new type of adhesive sets underwater and doesn't need a primer, an initiator, or a catalyst to work. This idea could revolutionize paints and coatings, and enable surgeons to operate without sutures.
- Blue mussel byssus sealant: The natural sealant (called byssus) that a blue mussel creates inspired an alternative to plastics. This time-release coating for disposable cups, utensils, and plates lasts for a few months and then biodegrades, allowing the material underneath to be composted.
- Dolphin and shark skin: Dolphin and shark skin inspired Olympic swimsuits. The hydrodynamic texture of shark skin was the inspiration for these swimsuits, allowing less friction from the water and faster swim times.
- Fish antifreeze: The natural antifreeze in fishes' bodies inspired a type of man-made antifreeze used to freeze human transplant organs without injury.
- Spider web: Spider webs have inspired ultrastrong man-made wires. Fiber is manufactured without using intense heat, pressure, or toxic chemicals, and it's stronger and more resilient that anything we've used in the past. It has inspired innovative parachute cables, suspension bridges, surgical sutures, and more.
- Bat navigation: The sophisticated sonar of a bat was a model of modern sonar technology.
- Bird wings: Vulture wings inspired the invention of the airplane. The Wright brothers were avid birdwatchers, and they modelled the wings of their plane on the shape of bird wings.
- Elastin in the heart: expands and contracts thousands of times per day, whilst also being able to conduct electricity
- Rhino horn: very strong but self-healing

Part E: History of Early Life

Lecture 41: The Big Story

Spacetime

- Humans and objects do not exist in space-time; they are part of space time, and therefore it is not surprising that mass has an influence on spacetime
- Indeed, it is not actually true that the gravitational field of a mass bends spacetime; the gravitational field of a mass is the curvature of spacetime

The Expanding Universe

- Newton explained the lack of change of the stars in the universe as being caused by the fact that the universe was infinite, and that all stars in it were perfectly placed such that net gravitational force on all of them was perfectly balanced
- Both Newton and Einstein believed in a static universe of constant size, the latter through his famous invention of the cosmological constant
- The refutation of this theory began with the discovery of emission/absorption lines in the spectrum of sunlight, and the realisation that these corresponded to different elements
- It was soon realised that that same bodies anywhere in the universe should produce the same emission spectrum, and so by comparing observed stellar spectrum with predicted spectrum, it would be possible to measure radial velocity of distant objects (redshift)

- Note that some of this redshift is caused by gravitational redshift as the light escapes the gravity well of stars and galaxies, but it was calculated that this cannot account for all of the effect
- This was not really useful until later on it was discovered that for a certain class of variable stars, the periodicity of brightness variation was directly proportional to the maximum brightness of the star

The Big Bang Theory

- Hubble brought all this together to discover Hubble's Law, and hence the idea of an expanding universe
- This led to the development of the big bang hypothesis, the model of which accurately predicted the composition of the universe (hydrogen and helium) and also the homogenous isotropic microwave background radiation
- These two predictions provide very strong evidence for the big bang theory
- Space-time came into existence with the big bang, so it is meaningless to ask what came before the big bang – just as it is meaningless to ask what is outside the universe (with no space it is not possible to use the concept of outside)

Lecture 42: Pre-Earth History

Quantum Mechanics

- The delayed choice quantum eraser experiment refers to a variation of the double split experiment whereby creation of an entangled pair of photons when the original photon passes through one of the slits enables observers to detect which slit the photon travelled through without actually disrupting the path of the photon in any way
- This means that theoretically there is no reason for the wavefunction to collapse, and hence no reason for an interference pattern not to appear
- In fact, however, what is observed to occur is that if the experimenters make the observation as to which slit the photon travelled through, the interference pattern is destroyed
- The most bizarre result is that the experimenters can decide whether or not to make this observation after the photon has been detected at the screen (as its entangled pair travels a longer path in the apparatus, and so will not be detected until slightly afterwards
- If the experimenters chose not to make this observation, the interference pattern 'magically' reappears. Some have interpreted this as an example of information travelling backwards in time
- Another way of looking at this is that a physicist is an atom's way of learning about itself
- Analogies are very useful for understanding when sensory data and consistent internal logic are inadequate
- For example, obviously we cannot re-create historical events (e.g. the origin of life), and many such events are also so highly dependent on contingency that we cannot totally rely on internal logic either

Symmetry and the Laws of Nature

- The degree of symmetry refers to the number of ways a system can be altered and still look the same. For example, a cube has more symmetry than a tube, while a sphere has the greatest symmetry of all
- Water displays symmetry, and the degree of symmetry actually increases as it becomes a liquid and then a gas
- Translation symmetry – objects look the same when we move them from one location to another

- Applied to physics, this means that the laws of physics operate the same in all locations in the universe
- We have no a priori assurance that this should be the case, but increasingly astronomical observations are providing more and more support for this
- The universe has actually become less symmetrical over time, as the four fundamental forces separated and space become more lumpy and differentiated
- Another important example of asymmetry in the universe is the asymmetry between the formation of matter and antimatter

The Very Early Universe

- From 10^{-43} to 10^{-35} seconds there were equal amounts of matter and antimatter
- At 10^{-35} seconds X particle splits into quarks and leptons – strong force splits off
- From 10^{-35} seconds to 10^{-32} seconds the universe undergoes inflation – this ends when strong nuclear force splits from electroweak force
- At 10^{-12} seconds the electromagnetic splits from weak nuclear force
- At 10^{-6} seconds quarks bind when neutrinos cease influence – plasma created
- At 400,000 years (46 geo-minutes) photons stop their influence and the first atoms appear

Inflation

- Very early in the universe just after the strong nuclear force split off, neutrinos were so numerous and the universe so dense that they continually interacted with other subatomic particles and prevented quarks from binding together
- Around the same time, the energy released by the first formation of quarks and electrons was 'dumped' into the inflaton field, which then rapidly expanded, thereby leading to extremely rapid inflation of the universe, faster even than the speed of light
- This had a number of important consequences, including the flattening out of space time, the causal separation of the universe, and creation of irregularities in the large scale structure of the universe (caused by the enormous expansion of what were initially quantum fluctuations)
- This inflation cooled down the universe sufficiently to separate out the weak nuclear force
- Eventually, the universe became sufficiently sparse for neutrinos to be able to pass through it without smashing into other particles, thereby allowing the forming of neutrons and protons for the first time

The Radiation-Dominated Universe

- Thus we went from a neutrino dominated universe to a photon dominated universe
- Photons still continued to move around the universe, knocking out electrons from the early nucleons and forming plasma
- The radiation dominated universe lasts for about 400,000 years, by which time the universe became sparse enough for photons not to be continually trapped by matter
- This sudden release of photons produced a burst of light which is now visible as the background radiation

The Matter-Dominated Universe

- Now the matter dominated universe came into existence, where the gravitational force began to clump matter together, forming clusters and galaxies
- The period after the beginning of the matter era and the formation of the first stars is known as the dark ages

- The Pauli exclusion principle states that as particles (like electrons and protons) are pushed closer together, they will tend to fly apart with greater and greater velocities
- When these relative velocities would have to exceed the speed of light for the particles to stay apart, the particles are forcibly squished together
- The first stars are that to have formed around 400 million years after the big bang

The Formation of Stars and Galaxies

- Stars are born on January 16th of the first geoyear
- Milky way galaxy forms on May 16th of the first geoyear
- Stars much more massive than our sun burn out in a matter of tens of geohours
- Stars the size of our sun burn out in two geoyears
- The first galaxies were mostly irregular oval shaped galaxies
- Our galaxy formed only about two billion years after the beginning of the universe; our sun rotates around it once every 200 million years
- Interestingly, only about ten percent of the total mass of a galaxy is likely to go to actually forming stars
- Stars burn hotter and hotter as they get older, thus increasing the outward radiative pressure and causing the star to expand
- Eventually this can lead to a supernova, which can compress nearby clouds of gas and dust, leading to the formation of higher generations of stars
- It is believed that our sun is at least a third generation star
- The universe is so large mostly because it started off accelerating so rapidly, and before complex intelligent life could evolve it was necessary for a lot of time to pass, and hence a lot of expansion to occur

Lecture 43: Hadean Era

The Trigger for Solar Formation

- The formation of our solar system may have been triggered by a nearby supernova
- About two percent of all the matter that made up the sun and our solar system was comprised of elements heavier than helium
- Interestingly, there are actually more neutron rich heavy elements on earth than can be explained by most existing models (e.g. gold)
- One possibility is that this matter could have been formed as a result of the collision of two neutron stars
- This would have been a truly catastrophic event, as the escape velocity of a neutron star is about half the speed of light, and so if matter fell onto a neutron star it would be accelerated so much that its atoms would be totally ripped apart and become indistinguishable from the rest of the neutron star
- Hence one can imagine how catastrophic would be the collision of two of these bodies

Formation of the Solar System

- The gaseous cloud from which the solar system formed continued to contract and hence warm up
- This would have continued until the core of the cloud reached ten million Kelvin, at which point fusion began

- This triggering of fusion generated a temperature gradient across the planetary disc, which meant that different materials solidified at different distances from the sun
- Interestingly, the inner planets all formed in a region where carbon was still a gas, hence explaining the relative paucity of carbon in the inner planets
- Carbon seems to be common on earth only because it tends to accumulate at the surface
- The so called frost line, marking the point where carbon first froze in the early solar system, is located in the vicinity of the asteroid belt
- This explains why many of the asteroids are so dark, as they are covered with rich layers of carbon
- As we move even further from the star, additional elements and compounds (pushed to these far regions by the solar wind) begin to precipitate out. This is why the outer solar system is dominated by gas and ice
- The dust particles that initially comprised the intersolar medium were too small to have much of a gravitational effect by themselves, and so most of the early accretion would have occurred as a result of random collisions, until the particles became large enough (roughly asteroid size) for gravitational influence to become significant
- This process from tiny particles to asteroid size materials probably only took a few thousand years
- Eventually gravity become strong enough to pull these bodies into spheres called planetisimals

Formation of the Planets

- Full formation of the inner planets and clearing of the gas and dust from the inner solar system probably took about one hundred million years
- The outer solar system formation would have occurred in a similar fashion, although in this case ice and volatile gases would also have accumulated
- The outer planets became massive enough to clean up all the gases and other materials in the outer solar system
- Jupiter also was so massive that it prevented the bodies from the asteroid belt from accumulating to form a planet, as any sufficiently large object that formed there would have been slung into an elliptical orbit by Jupiter, and hence would eventually have collided with another body
- Most of the moons of the outer planets probably formed along with their host planets, like a mini solar system in themselves

Comets

- Comets are thought to come from the Oort cloud, which is at a distance of some 15,000 Aus away
- When these icy bodies begin to fall towards the sun they have a very long way to fall, and so pick up a lot of speed
- They also serve as a mechanism by which ices and gases can be transported back into the inner solar system, either through direct collision or simply by passing its icy tail near to the inner planets
- It is thought that Uranus and Neptune formed closer to the sun than they currently are and then migrated out, as there would not have been enough material for them to form where they are now

Early Earth

- The earliest earth would have had no solid surface, as more rapid radioactive decay and intense meteor bombardment (with all the kinetic energy converted to heat) kept the surface molten
- It is hoped that some rocks from the very early earth may have been blasted off by meteor impacts may have ended up on the moon; this would be very useful for studying early earth geology

- The impact theory is the leading explanation for the formation of the moon, but is still far from certain
- Interestingly, the collision is thought to have been oblique and between two mostly liquid bodies; earth and the moon
- After this, it is thought that the moon only took a few years to form completely; very fast
- It is thought that the earth inherited much of the metal core of the colliding body, with the moon being composed mostly of silicate mantle material
- It is also thought that the moon began only four earth radii away from the earth, compared to the current 120 radii away; the day would have been only five hours long
- As the planet continued to cool, the internal layers differentiated, with the outermost layer of lightest materials solidified
- Analysis shows that most of the crators of the earth actually formed around 4.1-3.8 billion years ago, several hundred years after the moon formed
- One hypothesis as to why this Late Heavy Bombardment occurred is because the outward migration of Neptune and Uranus displaced Kuiper belt objects, which in turn would have displaced Oort cloud comets, thereby creating a barrage of comets into the inner solar system
- Despite this late bombardment, it is thought that the earth's solid crust formed at least by four billion years ago, probably before the late heavy bombardment began

Lecture 44: The Origin of Life

History of Earth's Atmosphere

- Earth has had three different atmospheres in its history
- The first atmosphere was composed mostly of hydrogen, helium and a few other noble gases
- This is a bit of a puzzle, as the earth is not massive enough to hold hydrogen or helium in its atmosphere
- The explanation is that these gases were slowly leaking out of pockets in which they had been trapped during the formation of the early earth
- This early atmosphere did not last long, and once it gave way it was replaced by the earth's second atmosphere
- This atmosphere was composed of carbon dioxide, sulphur dioxide, chlorine, nitrogen, water – all the sorts of things that come out of volcanoes
- Thus, we believe that the earth's second atmosphere was very similar to the contemporary atmospheres of Mars and Venus, which are mostly carbon dioxide with little oxygen
- Such anoxic atmospheres are referred to as reducing atmospheres
- The earth's oxygen rich third atmosphere could only form with the birth of life, which in turn required the presence of liquid oceans
- The molten surface of the earth would make the surface far too hot for liquid water (actually the atmosphere would also have been too hot for water vapour to exist, as it would disassociate into hydrogen and oxygen
- The oxygen would then react with silicates, while the hydrogen would escape into space

The Oceans and Early Fossils

- Interestingly, geological evidence seems to indicate that the earliest oceans formed at around the same time as the crust solidified, which occurred by about 4 billion years ago

- Thus, by 3.8 billion years ago (end of the late bombardment) all the conditions were ripe for the origin of life
- The oldest fossils found are about 3.5 billion years old, though it is thought that these do not represent the oldest life
- Indeed, it is thought that life probably emerged about 3.8 billion years ago – as soon as it could

Alone in the Universe?

- Although there is still a lot of wild guesswork involved, most of the best estimates of Drake's equation give figures of a few to a few dozen radio-communicating civilizations in the galaxy today
- Interestingly, it does seem that us (intelligent life on the earth) came about roughly as soon as we possibly could, given all the many pre-requisites that first had to be met
- Thus, even if we are not alone in the universe, we may be one of the first
- Also, even if there are other intelligent species in the galaxy, chances are that they will be so far away that the radio signals will become too attenuated for us to distinguish from background noise
- Abiogenesis is unquestionably a difficult thing, and so it is not surprising that we have not yet managed to do it in our handful of labs in the few dozens of years we have been trying
- This is nothing compared to an entire earth's worth of natural laboratories working around the clock for hundreds of billions of years

The Role of Clay Minerals

- Clay is a mineral made up of small particle with a complex, repeating structure
- Clays can actually serve as a template to make a copy of itself, as the charges on the surface on the surface of one clay act to attract particles that build up to form a complementary layer on top of it
- There is also a bewildering variety of different clays and mineral structures, so variation is possible
- However despite intriguing possibilities and some interesting connections with various mythologies (created from the dust of the earth), it has little empirical support

The Miller-Urey experiment

- Although the Miller-Urey experiment only produced three amino acids and no nucleotides, other experiments since then using different variations of input chemicals and energy input methods have produced all twenty amino acids used in life as well as some nucleic acids
- Although it seems that the linking up of these nucleic acids in the correct order to form a self-replicating molecule is unlikely, we must remember that this 'experiment' was being conducted all over the planet (wherever there was water), all the time for hundreds of millions of years, so there was plenty of time
- Unlike these self-replicating molecules, phospholipid bilayers (which form cell membranes) are actually quite easy to form spontaneously in the lab

RNA World Hypothesis

- DNA is a very good storage molecule, as it is very stable and always forms the same double-helix shape. On the other hand, this very stability makes it useless as a chemical catalyst
- Conversely, proteins can take all sorts of shapes, and so are good catalysts but very poor storage mechanisms or replicators
- This 'chicken and egg' paradox can be solved by RNA, which can act as a mediocre storage molecule and a mediocre catalyst
- Hence the development of the RNA world hypothesis

- Others argue that RNA is too complex to form life initially, and so perhaps was preceded by a simpler and easier to form alternative, such as PNA

Lecture 45: Precambrian Time

Extremophiles

- The most primitive forms of life still around today are archaea extremophile bacteria
- This is highly significant, as these early forms of life clearly can survive in extreme conditions without oxygen or any of the other conditions normally considered necessary for life
- Indeed, in one classic case bacteria were found to have survived for over two and a half years in a camera lens that was left on the moon
- This provides a clear rebuttal to the argument that life is dependent upon life to survive
- It is not surprising that extremophiles would represent the closest living forms of the original life form, as in such extreme environments selective pressures would have been greatest, and hence mutations weeded out most brutally, and hence evolution slowest

The Origin of Photosynthesis

- The early ocean had a lot of silica and ferrous iron dissolved in the oceans, which were the result of the early reducing atmosphere
- Hence before photosynthetic life forms could significantly increase the oxygen content of the atmosphere, they first had to remove this 'buffer' of iron and silica from the oceans, as these materials would quickly react with any free oxygen in the atmosphere
- Among the first photosynthesizers were the colonial cyanobacteria
- These organisms lived close to the surface of the ocean in order to access sufficient sunlight
- As they lived they produced a sticky substance that helped to protect them
- This sticky substance was attractive to sediment, and hence led to a layer of sediment particles to built up over a given colony of bacteria
- This process would then be repeated with the next generation of bacteria, which grew on top of the sediment layer
- Repeated over hundreds of millions of years, this process led to the formation of mushroom shaped rock mounds called stromatalites, the oldest of which are about 3.4 billion years old
- These bacteria colonies actually are still alive today, though they are less common than they were in the Precambrian

Oxygenation of the Atmosphere

- Despite this long history, oxygen did not built up to significant levels in the atmosphere until around 2.3 billion years ago, so it took well over a billion years
- Note that we can make estimates of the oxygen content of the atmosphere at various times in the past based upon isotope levels in the rocks from the time
- Photosynthesising organisms produce oxygen and consume carbon dioxide while they are alive, but once they die they decay and the reverse occurs
- Thus, for oxygen buildup in the atmosphere to occur, it is necessary for some of these photosynthetic organisms to be buried, and hence have their carbon locked away
- This, plus the need to 'scrub' the iron and silicate out of the ocean, is why it took so long to get significant amounts of oxygen in the atmosphere

- We can observe iron precipitation in the ocean in the form of banded iron formations of rock and metal
- It took a long time for the relatively light silicate material that forms the continental plates to rise up from the earth's interior and from the first supercontinents
- Continental growth occurred slowly and probably in spurts as more material was belched up from the earth's interior
- Thus, the first supercontinents were likely very small, and only became large relatively recently
- Interestingly, continental volcanoes tend to produce fewer reducing chemicals than do oceanic volcanoes
- Thus, the rise of continental plates led to the rise of continental volcanoes relative to ocean volcanoes, and hence may have contributed to the rise of oxygen in the atmosphere
- Interestingly, these early forms of anaerobic life produced oxygen as a waste product, and oxygen was (is) toxic to them, just as reducing environments are toxic to us
- Thus the buildup of oxygen in the atmosphere was in a sense the first environmental crisis produced by life, as organisms were emitting a toxic poison that was polluting their environment and building up to dangerous levels
- This eventually led to the rise of oxygen respiring organisms that 'closed the circle' of production and consumption of atmosphere
- The switch to an oxygen atmosphere marks the end of the Archaean eon of geologic time and the beginning of the Proterozoic eon

Ice Ages and Earth's Temperature

- For a time after its formation, meteor impacts and radioactive decay kept the moon geologically active
- This ceased when its surface cooled down too much around 3 billion years ago
- An ice age simply refers to a time during the earth's history when there are ice caps at the poles
- Higher concentrations of carbon dioxide in the past kept the planet warmer than the present in spite of the increasing intensity of the sun

Eukaryotic Life

- Eukaryotic cells more closely resemble archaea than eubacteria, however the chloroplasts and mitochondria inside these eukaryotes seem to be captured eubacteria
- This indicates that there was essentially a rejoining of these two forms of life after they initially diverged
- The two models for this are invasion of the Achaea by the eubacteria as a parasite which later became a symbiant, or failed digestion of a eubacteria by an archaea

Sexual Reproduction

- Sexual reproduction probably emerged sometime around 1.5-1.1 billion years ago, shortly after the origin of eukaryotes
- Around one billion years ago also marks the final series of geological and volcanic activity which brought the amount of continental crust up to about the levels we see today
- The origin of sexual reproduction is very important, as it marks the first origin of completely distinct individuals (rather than one individual continually copying itself), and also the origin of distinct species

- An interesting question is to why sexual reproduction was ever selected for, as only half of genes will ever be passed on at a given iteration, compared to one hundred percent with asexual reproduction
- One important reason is that sexual reproduction keeps the gene pool variable from generation to generation, thereby providing a protection against viruses, as they were less able to adapt themselves to single particular genetic codes
- Another important fact of sexual reproduction is that it increases the rate of variation, and hence increases the rate at which evolution can occur to form new organisms
- Developmental bottlenecking is important, as it ensures that all cells of the next generation obtain the same mutation (whenever one occurs), and hence will be better able to work together

Multicellular Life

- A multicellular organism that just grew additional cells that then budded off would not have this mechanism, and so it is likely that one part of it would evolve a mutation that would lead it to reproduce or consume excessively to the detriment of the other cells
- Multicellular organisms face the difficulty of how to get oxygen and nutrients into their interior cells
- We have complex body systems to do this, but primitive multicellular organisms would probably have had to rely on diffusion, thereby necessitating fairly high levels of atmospheric oxygen
- It is thought that multicellularity emerged dozens of times over the history of life, the first possible fossil evidence of which dates back to 2.1 billion years ago
- There are two possible models of the origin of multicellular life; formation of a colony of single cells working together, or failure of an initial organism to fully divide properly
- It is interesting to note that all animals are more closely related to all fungi than any of the plants, as plants seem to have been the first multicellular eukaryotic organisms to diverge
- However, fungi and plants have since formed a symbiotic relationship with plants in many cases, for example living on the roots
- Even more interestingly, most of the extant single celled eukaryotes (as well as very simple multicellular forms like sponges) are more closely related to animals than either plants or fungi

Early Multicellular Organisms

- The divergence of sponges seems to date to about 900 million years ago
- Around this period of time began a period of cyclical warming and cooling of the earth, with several periods of 'iceball earth', where falling carbon dioxide levels may have cooled the globe so much that ice approached within twenty degrees of the equator
- Another important date is about 630 million years ago, when the first bilaterally symmetrical creatures (acoel flatworms) emerged, as opposed to the mostly radially symmetric creatures that existed before
- Flatworms were just one of many different primitive ocean organisms that diverged from our ancestors between about 900 and 600 mya

Lecture 46: The Cambrian Explosion

The Beginnings of Complex Life

- If the entire history of the earth is condensed to a single year, the pre-Cambrian period would last until the middle of November

- Meteorite and impact crater evidence we can determine that the moon and the Mars used to have magnetic fields, but died out by about four billion years ago
- With no magnetic field, the solar wind was able to blow away most of the Martian atmosphere
- Without our liquid outer core, it is unlikely the earth would be habitable
- The fact that it took until the end of November of the geoyear for complex multicellular life to take hold, it may well be that such complex forms of life are rare in the universe
- Also, the more complex creatures become, the more fragile they will tend to be to geological and astronomical disruptions
- There is geological evidence (in terms of altered ratios of isotopes) that there was a significant global climate change around the end of the Precambrian
- In particular, it seems that there was a widespread loss of mineral clathrates from the bottom of the ocean, causing a great degree of global warming and hence end of the last 'iceball earth' phase
- Most of these early organisms were soft-bodied and so left little in the fossil record – mostly trace fossils, like evidence of worm burrows or impressions in sediment
- We know very little about the evolutionary relationships of these early organisms, and can only really describe them by their shape (including worm-like, discs and bags)
- The appearance of the trilobites is traditionally used to mark the beginning of the Pre-Cambrian

Deuterostomes and Protosomes

- Just before the end of the Precambrian (about 600 million years ago) came the split of deuterostomes and protosomes, with humans fitting in the former
- The great divide between protostomes (meaning 'mouth first') and deuterostomes (meaning 'mouth second') is based upon how the blastula (a hollow ball of cells in the early embryo) indents to form a cup
- In the protosomes, the indentation eventually becomes the mouth, whereas in the deuterostomes it forms the anus
- Animals that make up the protosomes include annelid worms (e.g. earthworms), flatworms (e.g. tapeworms and flukes), molluscs (e.g. snails, oysters, ammonites and octopuses), and arthropods (e.g. insects, crustaceans, spiders and centipedes)
- The next major split (of the deuterstomes) distinguished the Ambulacrarians and chordata
- Ambulacrarians include such things as starfish, sea urchins, sea lilies, sea cucumbers, and other such creatures; this split occurred around 570 mya
- It is interesting to note that starfish are more closely related to humans than 96% of all the other animal species that exist today
- Sea squirt are small sea creatures that resemble a bag of sea water anchored to a rock
- While the adult form looks more like a plant than an animal, the larva looks and swims like a tadpole, and possesses a notochord and a dorsal nerve tube, and moves by undulating its post-anal tail from side to side
- Sea-squirts probably diverged from the rest of the chordates around 565 mya

Causes of the Precambrian Extinction

- The extinction of Ediacara and first appearance of trilobites marks the beginning of the Cambrian period around 540 mya
- Possible explanations for this transition include climate change leading to elimination of the Ediacara niches, or the invention of teeth and claws leading to an increase in predation, and hence a need to evolve protection like hard external shells and armour

- There is some evidence for an increase in ocean upwelling of nutrients, possibly caused by the beginning of the development of Pangaea
- This would have closed many old niches and opened up many new ones
- This in turn led to an explosion of many new types of life emerging in a relatively short time period
- This period of history was much warmer than the present – by an average of about seven degrees Celsius
- Similarly, the carbon dioxide levels in the atmosphere were much higher than present, some 15 to 20 times
- Oxygen was also a smaller portion of the atmosphere, about 60% of current levels. This was still, however, enough oxygen to support complex life
- Primitive light sensitive cells were observed in the worm-like creatures of the late Pre-Cambrian, but it is thought that trilobites were the first to have developed eyes that would have enabled them to see
- The next significant concester were the jawless fishes, such as Lampreys and Hagfish, which occurred about 518 mya

Causes of the Cambrian Explosion

- The Cambrian explosion was a very short time in the fossil record (about ten million years, or a single geoday) where large numbers of new phyla appeared, including all of the extant animal phyla and many that are no longer extant
- One interpretation of the Cambrian explosion is that it was not really an explosion at all, merely a fossil bias that records hard-bodied fossils much better than soft-bodied forms
- However, if we look at soft-bodied fossils only at the times just before and after Cambrian explosion, it still seems that there was a rapid increase in diversity around this time, indicating that the Cambrian explosion is real
- One explanation for this is that the emergence of many new higher orders (e.g. phyla) is only due to the fact that the Cambrian explosion occurred so early in the evolution of complex life
- Thus, branches that today are called different phyla may be classed in the same family if we observed them today
- An alternative hypothesis is that the new phyla sprang into existence in a single macromutational leap
- Such large mutations are possible when genomes are simpler (as these early animals were), and also when entire genomes are duplicated (so multiple copies of the same gene are available and hence produce variation)
- Also, many of these early animals produced large numbers of offspring, which thus made such large mutations more likely (as there are more chances for them to occur)

Experimental Evolution

- Gould has described the process of the Cambrian explosion not has a diverging evolutionary tree shaped like an inverted pyramid, but rather as a spreading bush with many new branches at the bottom, and then a gradual pruning of many of these new branches by the forces of natural selection
- He was also the originator of the concept of evolution being highly contingent
- One recent experiment that seems to support this are the experiments with the ecoli bacteria placed in citrate

- Of the twelve initially identical separate colonies, only one evolved the ability to metabolise citrate within the twenty years of the study
- Further, when this line was reset (using previously frozen samples), before a certain point it too was not able to reproduce this adaptation
- Even by the end of the Cambrian about 500 million years ago, however, there were still no plant or animal species on land, only bacteria and a few lichens and fungi

Lecture 47: The Age of Fish

The Ordovician

- The Ordovician period lasted from about 500 to 445 million years ago
- This period was warmer than the present by a few degrees, and so ocean levels were higher
- Higher oceans meant lower continents, and hence fewer mountains
- A number of continents came together to form Gondwanaland, which drifted towards the south pole, around the start of this time
- Similarly, Laurensia began to form around the equator
- The Ordovician also saw a rebounding of life following the end of the Cambrian explosion
- Important new developments included articulate brachiopods and bio-eroding organisms (things that can bore into and dissolve hard material like rock)
- The next major branching event occurs around the end of the Ordovician, about 460 mya, with the separation of the gnathostomes (vertebrates with lower jaws) into those with bones (our branch) and those with cartilage (sharks and their relatives)
- The beginning of the Ordovician period also shows the beginning of algae and plant life on land, around 450 mya
- These plants, however, were simple non-vascular plants, so would not have looked much like impressive modern trees
- It should be noted that many of the still extant creatures from the early phanerozoic that seem to be 'living fossils' (e.g. sharks, crocodiles, horse-shoe crabs) actually have changed a fair bit genetically, even if they have not changed much morphologically

Ordovician-Silurian Extinction

- The Ordovician-silurian boundary marks the second or third largest extinction event in fossil history
- About 60-70% of all species became extinct, possibly caused by several large events happening in quick succession
- These pulses may have been caused by periodic rises and falls of sea level caused by orbital changes
- These were so devastating probably because the onset of plants led to a reduction in the amount of carbon dioxide in the atmosphere, which in turn led to global cooling and hence an overall fall in sea levels
- This in turn would have greatly disrupted the shallow sea areas where most life made its home at this time

The Silurian

- The Silurian period lasted from about 445 to 420 million years ago, and saw a recovery of shallow marine life as global temperatures rose once again
- This was caused by rising carbon dioxide concentrations, which actually increased somewhat even over Ordovician levels, and caused global temperatures to average about four degrees hotter than today
- Around 440 mya in the Silurian we see the divergence of lobe-finned and ray-finned fish, with us being more closely related to the former
- The evolution of the swim bladder dates to sometime just before this split
- Interesting, it seems that lungs actually evolved and then were co-opted for use as swim bladders, rather than the other way around

- Lungs probably evolved to allow shallow-water dwelling fish in low oxygen waters to gain additional oxygen from the atmosphere
- Around this time we also see the evolution of a number of scary looking armoured fish called dinoecthids
- The Silurian also marks the first emergence of simple vascular plants (though still using spores), probably like ferns
- Around 425 mya marks our divergence from the ceolacanth, which was thought to be extinct for 80 million years but was rediscovered only a few decades ago
- Another very important divergence around 417 mya was that of the lungfish, which has the ability to breath air

Lecture 48: The Late Paleozoic

- The Silurian Period ended with a few moderate extinction events around 420 mya
- Conodonts are jawless fishes that appear to be the first animals have evolved teeth, which is very useful for increasing the richness of the fossil record
- The Devonian period (lasting until 360 mya) was a time of significant geological activity, as the north American and European continents collided with each other
- The first direct evidence of vascular plants appears in the Devonian, including the first clubmosses, horsetails and ferns, as well as the first seed-bearing plants, and first trees
- These early plants had plenty of carbon dioxide in the atmosphere to nourish them, and as a result average global temperatures were about six degrees higher than tody
- Strophomenid and atrypid brachiopods, corals, and crinoids are all abundant in the oceans
- Trilobites and armoured agnaths decline, while jawed fishes (placoderms, lobe-finned and ray-finned fish, and early sharks) rule the seas
- In the land there was also increasing competition between the relatively new jawed fish (who acted as predators), and the armoured fish attempting to defend against them
- The lungfish around this time began to attempt to escape the dangerous ocean predators by using their lungs to hide on the shore for a brief period
- Changes in bone structure enabled some of these first animals to take clumsy steps in shallow water
- Panderichthys is a 90–130 cm long fish from the Late Devonian period (380 Mya). It exhibits features transitional between lobe-finned fishes and early tetrapods
- Another important species was Tiktaalik, which lived approximately 375 mya
- It is representative of the transition between fish such as Panderichthys and early tetrapods such as *Acanthostega* and *Ichthyostega*, known from fossils about 365 million years old
- These begin to evolve into the first amphibians, which were still largely aquatic
- Meanwhile, on land the symbiotic relationship between the fungi and plants (in the roots) first developed, allowing plants to spread further away from the water
- For a time these first significantly sized plants were not able to be decomposed by bacteria (it took a while for this ability to be evolved)
- As a result a significant amount of carbon was locked out of the atmosphere, with trees and other vegetation being buried before it could be decomposed, and as a result going on to form coal and oil
- This spread of plants was shortly thereafter further aided by the evolution of seeds
- The carboniferous era began around 360 mya and lasted until 300 mya

- Its name derives from the fact that most of the world’s fossil fuels supplies date from this period, as a result of the fact that seed plants were rapidly spreading over the land
- The need for early amphibians to give birth to and protect their young led to the evolution of eggs, and hence reptiles
- This finally enabled these animals to gain independence from the water – this split from amphibians occurred about 350 mya
- The continents were all coming together during this period to form Pangea, though this process would not be completed until the Permian
- The enormous amount of carbon deposition by plants greatly reduced atmosphere carbon dioxide levels, increased oxygen levels to some 160% of current levels, and the world cooled sufficiently to enabled ice caps to form once again
- This high level of atmospheric oxygen may have contributed to the presence of enormous insects in the Carboniferous
- The Permian period lasts from 300 to 250 mya
- During this time, the landmasses united into supercontinent Pangaea, creating the Appalachians
- The start of the Permian also marked the end of the Permo-Carboniferous glaciation
- Synapsid reptiles (pelycosaurs and therapsids) become plentiful, while parareptiles and temnospondyl amphibians remain common
- In the mid-Permian, coal-age flora are replaced by cone-bearing gymnosperms (the first true seed plants) and by the first true mosses
- The Permian was brought to a close by the Permian-Triassic extinction event, which was by far the largest extinction event ever
- About half of all marine families were wiped out, and many of those that survived were greatly reduced in size
- About 84% and 96% of all marine species became extinct; about 70% of land species
- It is thus very lucky that life survived at all – if the extinction event had been just a bit more severe everything could have been lost
- It does seem, however, that mammal-like reptiles were more heavily hit than the ancestors of the dinosaurs, thus delaying their takeover of the land
- One of the most important losses of this extinction event were the trilobites
- There is some evidence that lack of oxygen may have been the main cause of extinction of animals, possibly caused by volcanism of the Siberian Traps
- Release of carbon clathrates from the bottom of the sea may also have had this effect
- A significant increase in the rate of decomposition of organic plant matter may also have used up a great deal of oxygen
- Die-off of plants may have been caused by volcanic activity and/or a meteorite impact