GEOLOGICAL TIME: PRESENTATION NOTES

INTRODUCTORY SLIDES

SLIDE 1: GEOLOGICAL TIME

Presenter notes: Planet Earth is more than 4500 million years old (or 4.5 billion years). Such a vast abyss of time is hard to comprehend. When geologists talk about this kind of 'deep time' they use the term geological time to distinguish geological ages from the shorter timescales involved in human history. In this talk we will learn about geological time and how geologists first discovered the deep history of our planet.

Background notes: One way to convey the vastness of geological time is to use the analogy of a 24 hour clock. If the earth was formed at midnight, then life did not appear until 06:00, the first animals and plants only made it onto land as late as 22:00, and humans evolved about 23:59, less than one minute before midnight.

SLIDE 2: OUTLINE OF TALK

Presenter notes: There are three parts to this talk. In the first part we will learn about early ideas concerning the age of the Earth. It was through trying to work out the age of the Earth that geological time was first discovered. In Exercise 1, you will have a go at calculating the age of the Earth using a nineteenth century method (now considered incorrect) based on the saltiness of the ocean.

In the second part we will learn about how geologists divide up geological time into different eons, eras, periods and epochs based on fossils and other evidence. This is important for sorting out the order that events occurred through the history of the Earth. In Exercise 2, you will investigate whether humans have altered the planet to such an extent that we are now entering a new geological age.

In the final part, we will explore how a twentieth century technique called radiometric dating revolutionized our understanding of the age of the Earth. As a result we will see how geologists can now precisely date events like the extinction of the dinosaurs rather just talk about the relative order that events occurred.

PART 1: THE AGE OF THE EARTH

SLIDE 3: ETERNITY

Presenter notes: So let's begin by looking at early ideas about the age of the Earth. As we do so, it's worth reminding ourselves that this fundamental question did not arise for many of the earliest societies. In Hindu thought and especially in the classical Greek world most people thought the Earth was eternal. For Greek philosophers like Aristotle time was a circle and there was no beginning or end. To him, the question of the age of the Earth was entirely irrelevant.

SLIDE 4: THE BIBLE

Presenter notes: In a sense, thinking about the age of the Earth began with birth of Judaism and the belief in a God that had created the world out of nothing. Following the rise of Christianity, interest in God's creation increased further and most early attempts to establish the age of the Earth were based on the Bible. Scholars used the chronological records in the Bible, together with dates found in other Middle Eastern literature to establish the amount of time between the creation of Adam and the birth of Jesus.

The first person known to attempt this kind of calculation was Theophilus of Antioch in AD169 but other notable attempts were made by the physicist, Sir Isaac Newton (1643-1727), and most famously by Bishop James Ussher (1581-1656). All these calculated dates were roughly the same (as they relied on the same method) but Ussher's date of 4004 BC became so popular that it was printed as a marginal note in the Book of Genesis.

Background note: Although often ridiculed today, in their time, these Biblical calculations were the height of good academic scholarship (see Stephen Jay Gould, "Fall in the House of Ussher." *Natural History 100 (November 1991): 12-21*). That said, creationist groups that promote a Young Earth today (often citing Ussher's 4004 BC) are examples of bad scholarship. They ignore or distort the advances in understanding that have accumulated since Ussher's day.

SLIDE 5: EXPERIMENTS

Presenter notes: Following the Renaissance and the birth of modern science, thoughts about the age of the Earth moved away from Biblical evidence. Instead it became popular to rely on the new science of Physics for answers.

In 1760, a French naturalist called Comte de Buffon, aka Georges Louis Leclerq (1707-1788), hypothesized that the Earth had originated as a fiery ball after a comet had collided with the Sun. He experimented by heating iron balls of different sizes and then measured how long they took to cool down.

Using this information, he scaled up to the much larger size of the Earth and predicted that would have taken about 75,000 years for the planet to cool down from a molten state. This seemed like an eternity to the people of Buffon's day who were used to hearing that the Earth was only 6,000 years old based on the Bible.

SLIDE 6: THE SUN

Presenter notes: By the mid-nineteenth century, physicists were proposing ingenious new ways to date the age of the Earth. In 1858, a German scientist, Hermann von Helmholtz (1821-1894) started to think about the origin of the Sun. He thought that the Sun had formed by the contraction of a nebula of gas and dust. He calculated that if would have taken about 20 million years for the Sun to shrink to it's current diameter and brightness. Therefore the Earth could be no older than 20 million years.

SLIDE 7: MORE PHYSICS

Presenter notes: In 1862, William Thomson (1824-1907), aka Lord Kelvin, tried a different approach based on Physics. Kelvin knew that the temperature of the Earth increased by 1 degree of Fahrenheit for every 50 feet you went into the ground. He also assumed that the temperature of the early Earth had been around 7000 degrees of Fahrenheit when molten. Applying his knowledge of how fast heat is conducted through rocks he calculated that it would have taken around 20 million years for the Earth to cool to it's present state.

The fact that two independent approaches had arrived at roughly the same answer gave Physicists a lot of confidence that they were right. However, as we will see later their age calculations were quite wrong because they assumed that the Earth was steadily losing heat. In fact the discovery of radioactivity in the early twentieth century showed that the Earth was also producing some heat. Therefore the Earth must have been much older than allowed by Lord Kelvin's calculations.

SLIDE 8: GEOLOGY

Presenter notes: One group of scientists who had a hunch that Lord Kelvin's age of the Earth was far too young were the geologists. The geologist Charles Lyell (1797-1875) thought that the key to understanding the age of the Earth might lie in the way that mountains slowly erode down.

Lyell thought that the rate at which the erosion and deposition of sediment occurs had stayed more or less constant through geological time. If he was correct and 'the present was the key to the past' then it must have taken many hundreds of millions of years to form the vast repository of sediment seen in the geological record, much longer than the ages allowed by Lord Kelvin and the Physicists.

Background notes: Through the nineteenth century there was many attempts to use this approach to estimate the age of the Earth. To do this calculation one needed to know the total thickness of sediment on the Earth's surface and also the average rate at which sediment accumulates today. However, it proved enormously difficult to get hard numbers for either of these figures. The main problem was than sediment accumulates at widely differing rates in different environments so in the deep sea a single millimetre of mud might take a thousand years to build up whereas in an active river channel, a metre of sand might be deposited in a few hours. These problems made geological estimates of the age of the Earth seem very inaccurate compared to the precise numbers put forward by the Physicists.

SLIDE 9: EVOLUTION

Presenter notes: One nineteenth century scientist who anxiously followed the debate about the age of the Earth was Charles Darwin (1809-1882). Darwin had argued in 1859 that life had evolved through small incremental changes by a process called natural selection. As he envisaged that this process acted extremely slowly, the Earth had to be really really old; in fact much older than Kelvin's calculations allowed. Lord Kelvin repeatedly attacked Darwin's theory of evolution and, in 1869, Darwin confided to his supporter Alfred Wallace that Kelvin's "views on the recent age of the world have been for some time one of my sorest troubles".

Evolution by natural selection was an enormously controversial idea in the nineteenth and wasn't widely accepted by the scientific community until the 1920s. If the Earth was relatively young, as Kelvin argued, then there simply wasn't enough time for the kind of evolutionary change that Darwin proposed.

SLIDE 10: SEA SALT

Presenter notes: At the end of the nineteenth century, a new approach to understand the age of the Earth was put forward by the Irish geologist, John Joly (1857-1933). This approach relied on Edmund Halley's work on the saltiness of the ocean. Halley (who is more famous for his comet) had earlier shown how salt is weathered out of rock on land and carried by rivers to the oceans, where it gradually builds up.

In 1899, Joly argued that if you knew how salt was in the ocean and you knew how much salt was being added each year by rivers then you could work out the time when there was no salt in the the oceans, and hence the age of the Earth. After several attempts the figure he finally came up with was an age ranging between 80-150 million years.

Unfortunately, what Joly didn't realize is that salt doesn't simply accumulate in the oceans over time. Rather there are geological processes that are constantly taking salt out of the oceans. Hence, Joly's age was far too low.

SLIDE 11: ASSUMPTIONS

Presenter notes: As we have seen, all the methods put forward in the nineteenth century to figure out the age of the Earth relied on certain assumptions that couldn't necessarily be proven. Kelvin assumed the Earth was steadily cooling from a molten state, Lyell assumed that the rate of sedimentation had been constant through history, and Joly assumed the saltiness of the ocean was being added to year after year. This meant that all these estimates of the age of the Earth were highly uncertain.

SLIDE 12: PRACTICAL EXERCISE 1 (See handout sheet)

Presenter notes: To illustrate some of the problems and uncertainties in nineteenth century calculations of the age of the Earth, let's look at an example. As we have seen, John Joly tried to determine the age of the Earth using the saltiness of the ocean. In Exercise 1 we will attempt to reproduce Joly's calculation and think about why it was flawed. All the instructions are given on the handout and you should spend about 35 minutes on this exercise.

PART 2: GEOLOGICAL HISTORY

SLIDE 13: STRATA

Presenter notes: So far we've looked at early attempts to determine the age of the Earth, let's now consider how other scientists were trying to work out it's history. The term geological history refers to the sequence of historical events from the formation of the Earth to the present day.

One of first people to try and understand the history of our planet was a Danish priest called Nicolas Steno (1638-1686). In 1669 he argued that sediment gradually built up on the sea floor as layers which are both laterally continuous and horizontal. The sediments at the bottom of the pile are the oldest and the sediments at the top are the youngest. Steno showed that in much the same way that the pages of a book are read from left to right, the history of the Earth must be read from bottom to top in a layered succession of rocks.

Background note: Steno's insight that sediments accumulate in continuous horizontal layers is known as the Principle of Horizontality and the Principle of Lateral Continuity. His insight that the oldest sediments are at the bottom and the youngest at the top is known as the Principle of Superposition. These three principles are fundamental to understanding the order that events occurred through Geological Time.

SLIDE 14: NEPTUNISM

Presenter notes: A century later, Abraham Werner (1749-1817), a mining engineer from Saxony, started to apply some of Steno's principles to understand the history of the Earth. He thought that all the Earth's rocks had been deposited from a worldwide ocean (think Noah's Flood in the Bible). This idea was later dubbed 'Neptunism' after the Roman god of the sea (Neptune).

Werner thought that crystalline rocks like granite were the first to form in this worldwide ocean while the most recent sands and muds on top had been deposited by rivers after the great sea had withdrawn. On this basis, Werner's supporters divided the Earth's rocks into four groups – Primary, Secondary, Tertiary and Quaternary – representing four intervals of geological time.

Background notes: Two Wernerian terms are still widely used today for the youngest rocks on our planet: Tertiary and Quaternary

SLIDE 15: GAPS

Presenter notes: Hot on the heels of Werner came another influential geologist called James Hutton (1726-1797). In the late eighteenth century, Hutton realized that there were 'big gaps' in the geological record of time.

At several places like Siccar Point in Berwickshire, Scotland, Hutton's noticed beds of layered rocks that stood on their end overlain by other layered rocks that dipped away at a shallow angle. Hutton was quick to realize what this meant. In the real world, sediment is not deposited continuously. Rather through convulsions of the Earth's crust, sediments laid down as horizontal layers in the sea might be pushed up to form mountains. The layers might then be tilted at an angle and partly eroded away before new horizontal layers accumulated on top.

Hutton's name for this kind of angular contact between two sets of sedimentary layers was an unconformity. In the time between the formation of the lower and upper layers of rocks, a mountain had been born and eroded down. This would have taken tens of millions of years. Therefore the unconformity represented a massive time gap in the geological record. Hutton referred to this phenomenon as 'the abyss of time'.

SLIDE 16: MAPS

Presenter notes: At the turn of the nineteenth century, 'maps' followed 'gaps' in the discovery of geological history. In Britain railways and canals were being constructed all over the place. More than ever before, rocks were being exposed all over the country.

William Smith (1769-1839) was a surveyor who saw more than his fair share of rocks. He realized that sequences of different rocks occurred in the same order in different places. To be sure that a rock type in one place was the same as a rock type in another place, he compared the fossils that they contained.

Soon he started to draw maps of where the different rock strata occurred and by 1815 he had produced a complete geological map of Britain. Building on the insights of Steno, Werner and Hutton, William Smith's map showed the relative order in which the rocks of Britain formed and whether there were any big time gaps within the succession. For the first time, the geological history of a whole country was known.

Background notes: Simon Winchester's book titled "The Map That Changed The Whole" (HarperCollins 2002) give a lively introduction to William Smith and his geological map. Poor old Smith had the intellectual rights to his map stolen and never really received due reward for his remarkable achievements.

SLIDE 17: FOSSILS

Presenter notes: As we have just seen, William Smith used fossils to check that the age of rocks in one area was the same at the rocks in another. But why should rocks of different ages contain the remains of different life forms? It fell to two other scientists, Georges Cuvier (1769-1832) and Charles Lyell (1797-1875) to answer this question and in doing so discover the concept of extinction.

Cuvier was a French naturalist. In 1796 he studied remains of fossil and living elephants. He convincingly showed that animals like the woolly mammoth had gone extinct. This was a pretty radical idea because up to that point people thought extinction was impossible. After all, if God's creation was perfect why would He let species like the mammoth die out?

A little later in 1828, Lyell studied fossil seashells in Tertiary rocks in France. He showed that the oldest rocks contained mostly extinct shells while the youngest rocks contained shells similar to those living today. He divided up these Tertiary deposits into three epochs which he named, from oldest to youngest, the Eocene, Miocene, and Pliocene. At last here was an explanation as to why the rocks of different time periods contained distinctively different types of life forms

SLIDE 18: STRATIGRAPHY

Presenter notes: Although William Smith had worked out a general geological history of Britain in 1815, that record still was only vaguely understood. In the mid-nineteenth century British geologists started to argue amongst themselves about the precise order in which the strata were arranged.

One famous argument was between Adam Sedgewick (1785-1873) and Roderick Murchison (1792-1871). Both these men mapped the rocks in Wales, which were thought at that time to be the oldest rocks that contained fossils. Both wanted to be the first to name this ancient geological period. Sedgewick proposed the name Cambrian for the the geological period represented by his rocks in Central Wales. Murchison proposed the name Silurian for the the geological period represented by his rocks in North Wales.

As the Cambrian and Silurian strata overlapped, Murchison wanted all of Sedgewick's Cambrian to be included in his Silurian. Based on the fossils they contained, Murchison didn't think there was much age difference between the two time periods. Murchison and Sedgewick had a real tug-of-war over the rocks of Wales and afterwards didn't speak to each other for years to come.

Eventually, in 1879, Charles Lapworth (1842-1920) sorted out the Welsh problem. He carried on using the names, Cambrian and Silurian, but re-named the overlapping beds in the middle as the Ordovician. Hence the oldest rocks in Britain that contain 'visible fossils' comprise three geological periods which are, from oldest to youngest, the Cambrian, Ordovician, and Silurian.

The science of mapping rocks and working out their age relative to one another became known as stratigraphy.

SLIDE 19: PERIODS

Presenter notes: It wasn't just in Wales that disputes raged about the naming and relative age of different rock types. Throughout the nineteenth century, geologists all over Europe were describing the geological record, eager to be the first to name the different geological periods. The Devonian Period was named after rocks in Devon that were a little younger than Sedgewick's Silurian. The Carboniferous Period was named after the coal-rich rocks in Yorkshire. The Jurassic Period was named after the rocks of the Jura Mountains of Switzerland, and so on.

SLIDE 20: THE COLUMN

Presenter notes: Eventually, as geological mapping continued apace, the geological column became sorted into a series of orderly and ever more finely sliced divisions. The largest of these divisions is known as an Eon, which in turn is subdivided into Eras, Periods and Epochs. Hence, we can talk of Charles Lyell's oldest tertiary rocks of France as belonging to the Eocene epoch of the Paleogene Period of the Cenozoic Era of the Phanerozoic Eon. The subdivision of the geological record continues today overseen by the International Commission on Stratigraphy.

SLIDE 21: EXAMPLE

Presenter notes: Before we finish this look at Geological History, it's worth thinking about exactly how geologists decide to place the boundary between one geological period and the next. Boundaries are usually positioned where there is an abrupt change in the kinds of fossils in the rock or a change in the ancient climate or environment.

To give an example, let's take a look at the Cretaceous-Paleogene boundary. One of the most important changes that happened at the end of the Cretaceous Period is that dinosaurs like *Tyrannosaurus rex* went extinct. However, it wasn't just the dinosaurs that disappeared at this time but a whole load of other animals and plants as well. Geologists now believe this 'mass extinction' was caused by a giant meteorite colliding with the Earth. This event led to a dramatic change to the kinds of animals and plants on the planet and therefore can be recognized in rock successions all over the world.

We'll further explore how geologists divide up geological time in the next practical exercise.

SLIDE 22: PRACTICAL EXERCISE 2 (see handout)

Presenter notes: We've just seen how geologists divide geological time into eons, eras, periods and epochs. The boundary between two geological intervals is always marked by some recognizable change in the ancient environment, climate or life. In the Cretaceous-Paleogene example we've just discussed, the boundary is marked by a mass extinction event probably triggered by a huge meteorite impact

In this practical we will consider whether we have just crossed the threshold of a new geological interval. Today, human beings are radically altering the face of the planet including it's climate and ecosystems. We've build gigantic megacities like New York and Shanghai and farm more than a third of the Earth's surface. All this raises an interesting question. Have we changed our planet sufficiently to have embarked on a new geological age? Some geologists think we have and have called this new epoch, The Anthropocene.

All the information you need to complete Practical Exercise 2 is found on the handout sheet and you should spend about 35 minutes on this task.

PART 3: RADIOMETRIC DATING

SLIDE 23: DISCOVERY

Presenter notes: So far we have looked at early ideas about the age of the Earth and how geologists gradually discovered the relative order that events had occurred through the history of the Earth. However what was still unknown was the precise age of each geological period while the total of the age of the Earth was still uncertain. In 1896, the discovery of radioactivity by Henri Becquerel (1852-1908) was to begin answering these questions and revolutionize our understanding of geological time.

SLIDE 24: DECAY

Presenter notes: Radioactivity refers to the way that some chemical isotopes are inherently unstable and slowly lose mass by emitting particles called protons and neutrons (radiation). In the diagram, the original isotope, or parent isotope, has decayed into a daughter isotope by emitting alpha radiation. An example of this phenomenon in nature is the way that Uranium-238 spontaneously decays into Lead-206.

SLIDE 25: HALF LIFE

Presenter notes: The rate at which a parent isotope decays into a daughter isotope depends on it’s half life. The half life is the amount of time it takes for half of the parent isotope to decay into the daughter isotope. To illustrate this, look at the image on the left. If we imagine that the Red Isotope decays to the Green Isotope with a half life of one hour, how much of the Red Isotope will be left after two hours? The answer is, of course, that after 1 hour there will be 50% left, and after 2 hours there will be 25% left, and so on. Because of this repeated halving, the rate of decay of the parent isotope is said to be exponential. To illustrate this look at the image to the right where the exponential decay of an isotope is shown in blue. Compare it with a linear rate of change as seen, for example, when sand runs through an hour glass. The amount of sand in the upper vessel of an hour glass is eventually exhausted, but the exponential decay of an isotope means the parent isotope is never completely used up.

SLIDE 26: CLOCKS

Presenter notes: Different isotopes have different half lives. For example, it takes 4486 million years to convert half of the Uranium-238 in a sample to Lead-206 but only 704 million years to convert half of the Uranium-235 in a sample to Lead-207.

If you know the proportion of parent to daughter isotope in a rock sample and you know the half life of the isotope then you can work how long ago there was only parent isotope present, and hence the age of the rock. It works a bit like a natural clock. To illustrate this look at the diagram on the right. Here the relative proportion of different isotopes have been measured in a rock sample. Half of the Uranium-238 has been converted to Lead-206 (1 half life) but 98.8% of the Uranium-235 has decayed to Lead-207 (6.4 half lives). This tells us that the rock is around 4500 million years because one half life of Uranium-238 equals 4468 million years and 6.4 half lives of Uranium-235 indicates a similar age.

Most of the isotopes shown in the list on the left have half lives that last hundreds of million years. Consequently they are good for measuring the age of really old thing (i.e. the geological timescale). However, C-14 decays in N-14 with half life of only 5370 years. After about eight half lives there is too little parent isotope left in the sample to measure. Consequently C-14 can only be used to date thing up to about 40,000 years old (8 half lives) and is only used in Archaeology.

SLIDE 27: PIONEERS

Presenter notes: The first person to try and use radioactive decay as a natural clock to date rocks was the physicist Ernest Rutherford. In 1904 he named this technique radiometric dating. Unfortunately, Rutherford ran into all sorts of problems with his geological dating and eventually gave up.

However, his work was followed up by a bright young student called Arthur Holmes. In 1913, when Holmes was only 23, he dated some rocks from Ceylon to be more than 1600 million years ago. This age was much older that the estimates of the age of the Earth made by nineteenth century physicists like Lord Kelvin and caused a great deal of controversy. But Holmes's work was so good that there was no getting round the matter and eventually geologists had to get used to the idea that the Earth was billions of years old, not just a few tens of millions of years in age.

Background note: Remember that a billion years is one thousand million years. Hence Holmes's age of 1600 million years was equal to 1.6 billion years.

SLIDE 28: OLDEST ROCK

Presenter notes: As time went on, the use of radiometric dating became more and more widespread. Very soon, the precise age of different eons, eras, periods and epochs was figured out, but one question remained elusive: what was the exact age of the Earth?

The big problem in answering this question was caused by the fact that the Earth has a dynamic crust that is constantly recycling itself. No rocks have survived intact from the earliest phase of planetary evolution. So far the oldest rock known on our planet is the Acasta Gniess, which is found in Arctic Canada. Radiometric dating of isotopes trapped in zircon crystals in the rock have shown that this is an incredible 4030 million years old.

SLIDE 29: OLDEST GRAIN

Presenter notes: Although the Acasta Gniess is the oldest known rock on our planet, even older fragments of earlier rocks have survived. In 2004, a single grain of a zircon mineral was dated from the Jack Hills of Australia. It was found to be an incredible 4404 million years old. This mineral formed in a rock that made up the Earth's first crust, but was subsequently eroded away and an incorporated into a new rock. So although no actual crust has survived from this ancient time, tiny mineral flakes have been preserved.

SLIDE 30: METEORITES

Presenter notes: And yet, radiometric dating had identified even older materials on our planet: meteorites. Meteorites are debris left over from the formation of the solar system. One large meteorite was found in the Canyon Diablo region of Arizona in southwest USA. Studies show that it probably crashed to Earth about 20,000 years ago but that it had been wandered through space for much longer than that.

Radiometric dating showed, in 1956, that the Canyon Diablo meteorite is around 4550 million years ago. Studies of many other meteorites have subsequently shown similar maximum ages. This tells us that the solar system – and the Earth in it – had formed by 4550 million years ago (4.55 billion years ago). The mineral flake found at Jack Hills Australia therefore tells us that the Earth had cooled down sufficiently to form a crust as early as 4404 million years ago, as little as 150 million years after the formation of the Earth.

SLIDE 31: HISTORY

Presenter notes: Radiometric dating has transformed our understanding of the age and history of our planet. Not only do we know the relative order in which events happened, but now we know precisely when they occurred on an absolute timescale. We know that our solar system – and the Earth in it – formed out of a nebula about 4550 million years ago. We know from well-dated fossils that the first life had appeared by 3800 million years ago and had evolved into complex cells by 2500 million years ago. We know than the first large animals arrived on the scene 800 million years and the famous dinosaurs had their day about between 65 and 180 million years ago. Finally we know that humans are a dramatic late arrival appearing only in the last blink of geological time, some 2 million year ago. However, although late arrivals, we have seen how human have transformed the Earth's biosphere and climate to a unique degree and ushered in a new geological age – the Anthropocene.

CONCLUDING SLIDE

SLIDE 32: GEOLOGICAL TIME

Presenter notes: And that brings us to the end of this talk. Over the course of this session, we have discussed the age of the Earth and it's geological timescale. We've seen how geologists have slowly chipped away at the Earth's rocks for three centuries and in doing so uncovered the extraordinary geological history of our planet. We now know that Earth is not just a few thousand years old as Biblical scholars once believed, but more than 4500 million years old. This extraordinary discovery of geological time ranks as one of the most important scientific discoveries of all time. It has huge implications for our understanding of the origin of human beings and their place in the universe.