GEOLOGICAL TIME SCALE

EON	ERA		PERIOD		EPOCH		
PHANEROZOIC	CENOZOIC	0	QUATERNARY		ANTHROPOCENE		
					HOLOCENE		11.8 ka
					PLEISTOCENE		
		2					
			TERTIARY	NEOGENE	PLIEOCENE		
					MIOCENE		
		23					
				PALEOGENE	OLIGOCENE		
					EOCENE		
					PALOCENE		66 Ma
	MESOZOIC	65					
			CRETACEOUS				
		145					
			JURRASSIC				
		200					
			TRIASSIC				252 Ma
	PALEOZOIC	250					
			PERMIAN		Pale		
		300					
			CARBONIFEROUS		Peter	Pennsylvanian	
					Make	Mississippian	
		355					
			DEVONIAN		Does		
		415					
			SILURIAN		Soup		
		445					
			ORDOVICIAN		Ordinary		
		495					
			CAMBRIAN		Campbell's		541 Ma
80% PRECAMBRIAN		540					
			PROTEROZOIC				
		2500					
			ARCHAEN				
		4,000					
			HADEAN				
		4,600					

EVOLUTION OF LIFE AND EARTH

Geology

It is the science of earth – origin, history, processes and dynamics of how it changes

What makes earth unique is –

- Existence of life on earth
- Active geological activities such as volcanoes and continental movement (continents are plates which are floating on the mantle; the convection currents of the mantle draw continents together [& mountains are formed – Himalayas] or pull them away [basin of the Red sea keeps expanding])

Earth is 4.56 billion years old. Life appeared on earth 3.5 bya.

250 mya – Permian-Triassic extinction: 90% of marine species and 75% of terrestrial species became extinct

- One of the major reason for this was the great volcanic eruptions in Siberian flood plains: the dust particles wouldn't let sunlight penetrate
- Rise in temperature
- Major change in the carbon cycle

Research Interest in ECS

→ Formation of oceans and mountains

→ Great oxidation event (2.4 bya) – plotting curves of that

→ Formation of the crust: initially earth's surface was an ocean of magma, 90% of the crust was formed 2 bya

→ Extinction events – Cretaceous mass extinction occured 65 mya due to meteorite fall. This is known by checking the sediment strata (of mountains which rose from oceans) for iridium [present in large quantities in meteorites].

Applicative:

→ Checking rocks and predicting the best location for mines. (1.8 bya dissolved iron in marine water started combining with dissolved oxygen to form iron oxides which deposited on the ocean floor abundantly).

→ Exploration of gas and oil

→ Radioactive wastage – how ocean beds are affected

→ Marine polymetallic nodules (also called Manganese nodules) – rock concretions on ocean floor formed of concentric layers of iron and Mn hydroxides around core – economically valuable.

02

Spheres of Earth : Interlinked reservoirs

1) Atmosphere – Thin layers of gases that covers the earth's surface
2) Hydrosphere – contains earth's water; 97% in oceans.
If everything is smothened, global ocean would cover the surface in 2.25 km of depth
⇒ Average depth of ocean floor is 4 kms
3) Geosphere – consists of solid earth
4) Biosphere – composed of living entities on earth

Greater temperature causes more erosion

Subduction : When 2 tectonic plates come together, because of the density, one plate goes up & forms the ocean bed while the other goes down and the sediment melts into the mantle – this is called subduction.
Eg. Island in Andaman.

Exogenic : Processes that occur on earth's surface
Endogenic : Processes inside earth

Residence time
Its the average length of time a substance spends within a reservoir in a steady state with respect to abundance of that substance.

First approximate age of earth
Assume all the Na in the ocean is x kg and that all of it has come from mountains as rivers flow down from it – at a rate of Y kg / year.

Then, age of earth $= \frac{X}{Y}$ years [~350 million years]

But the fallacy here is that Na doesn't stay in the water (it goes down as sediment or is taken out by ion exchange).
So, this calculation actually gives us the residence time of Na in hydrosphere – 350 million yrs.

* lithophile, siderophile, chalcophile, atmophile (volatile) : Goldschmidt's classification

Microscale inhomogenity required?

 6/1/20

The Solar System

The milky way galaxy has over 200 billion stars, spans about 100,000 light years, its 13.6 billion years old.

There are a lot of holes when it comes to our knowledge of the formation & evolution of solar system. Mostly because its difficult to get pristine samples.

Some ways of studying this are –

- Remote sensing
- Meteorite study
- Astronomy
- Feild expedition
- Experimental methods.
- Mathematical models

Meteorites

Solid bodies of extra-terrestrial material that penetrate earth's atmosphere and reach earth's surface

Their composition is different based on whether they were formed before the solar system – they have silicon carbides and nano-diamonds

They are chunks of asteroids or planets

Two kinds of meteorites –

Falls : recovered following observed falls

Finds : which cannot be definitely associated with observed falls

The impact of meteorites causes great ecological and biological change on earth – extinction of dinosaurs & formation of Lonar (crater) lake.

Meteorites are mostly constituted of heavy metals like Fe, Ni, iridium i.e. siderophile* elements. Siderophile

There can be different kinds of meteorites – iron and stony

Formation of planets

When an interstellar gas cloud is affected by shock waves (∵ Supernova blasts) from all sides, it condenses under its own weight & forms a star # and then a sequence of rapid, highly energetic, large scale, sequential and often simultaneous set of events involving condensation, collission and runaway growth leading to formation of proto-planets and planets.

Other ways to identify meteorites – Magnetic property, Irregular shape, fusing coating (a thin layer of dark glass), chemical composition, isotopic composition.

If these processes occured billions of years ago, then how do we know this for sure?

Chemical analysis – ratio of radioactive isotopes

But any element with halflife ~10k years will become undetectable after about 100k years because after 10 half lives, amount left is negligible.

These are called extinct radionuclides. And the presence of excess of the daughter nuclei will give us an idea of the range of time when the meteorite was formed.

The radioactive elements considered are Fe60, Ca40

The abundance of each isotope should be precisely known (by astronomy, big bang estimates & nuclear reactor models) so that we can calculate the excess

Cosmic timeline

$T = 1.5 \times 10^{10} \times t^{-1/2}$

Increasing radius means decreasing temperature

Between 10^{-33} s and 10^{-32} s, the universe grew from practically 0 to 10 cm

Early universe was composed of very energetic photons and subatomic particles.

To form a proton –

$$m_p c^2 = \frac{3}{2} k T_p \quad \Rightarrow \quad T_p = 7 \times 10^{12} \text{ K} \; ; \; T_e = 4 \times 10^9 \text{ K}$$

3 degrees of freedom

$\Rightarrow$ (All these) protons subatomic particles are produced only in the first 10 seconds of the universe. After that the Temp decreased

No elements heavier than helium were formed in the Big Bang Nucleosynthesis. Then universe was compoud of 28% of He^4 & 72% of H^2 atoms by mass

Very small amounts of ^2H, ^3He, ^7Li — $\frac{Li}{H} = 10^{-9}$

Element formation occured in first 15 mins of Big Bang, after which temperatures dropped to 10^9 K & after this expansion and cooling, it wasn't hot enough for nuclear reactions to occur.

For most stars this burning of H → He occurs at a stable ~~st~~ rate for over 90% of star's lifetime : MAIN SEQUENCE

05

Chemical composition of solar system is a result of various processes such as
- nuclear reactions to produce elements
- gravitational collapse to produce stars & proto-planets
- condensation to produce solid grains
- accretion to accumulate grains into planets.

Over 99% of atoms in the sun are H and He ; beleived to have formed during the origin of universe.

7/1/20

How are so many elements formed from only H, He & other subatomic particles.

Life of Star
Greater the ~~mass~~ temp, more the luminosity
There is a minimum mass required for a cloud of dust to form a star
Most of stars spend most of their life span as a main-sequence star
Stars are divided into different spectral types based on their surface temperatures
Each kind is divided into 10 subgroups hotter 0 to 9 colder, so that they can be studied individually.
Sun is a G5 star O B A F G K M
increasing luminosity ⟶
Most of star's life span is spent in main sequence
It took 20 million years to form, but it'll spend 10 billion years in main sequence

$10\ M_{SUN} \rightarrow 20$ million
$\frac{1}{2}\ M_{SUN} \rightarrow 80$ billion.

Main sequence stars are very dependent on mass.
Greater the mass, more the gravitational pull inwards and hotter the core gets.

During red giant phase, neutrons are produced
$^{13}C(\alpha,n)^{16}O$ $^{22}Ne(\alpha,n)^{25}Mg$

Stellar Evolution
→ Hydrogen Burning : Produces He as main product
- $4H \longrightarrow {}^{4}He + 2e^{+}$
- Requires core temp of $\sim 10^{7}$ K.

So, as hydrogen burning happens on surface, the core reaches higher temperatures and He is formed

Due to H burning, there has been gradual increase in solar luminosity over geological time scale — about 30% in last 4 billion years — but temp of earth's surface has remained constant
This gave rise to Gaia hypothesis

Fission track dating method?
Chondroits - stony meteorites that have elemental composition that closely match to that of sun (except volatile elements)
06 Chondrules - solidified molten droplets (<1mm) that get accreted to chondroits

Then, if star is big and hot enough, the burning occurs and stellar nucleosynthesis can go upto formation of iron. C - triple α fusion at 10^8 K. If $T > 10^8$ K Fe can be formed.
The greater elements are formed during a supernova explosion where these elements pick up nucleons and higher & greater elements are formed.
s and r-process of nucleon capture.
Once, the nucleus becomes too heavy, it decays to give new elements.

Cosmic abundance of elements
Hydrogen, deuterium and helium are most abundant ~~requi~~ with respect to 10^6 atoms of Si.
The elements heavier than Fe are less abundant.
Elements with atomic number which is an integral multiple of 4 nucleons is more common.

Age of Earth
Conventionally, we consider the time when 66% of the body was formed as the time when 'earth was formed'. We can talk about this with an error of 1 million years in a scale of 4560 million years i.e. an error of 0.2%.
But in a million years, the formation of earth might have gone from 66% to 100%.
Age of earth can be calculated by -
- Uranium-lead dating of the oldest rocks or better, least altered minerals by zircon crystals.
- Use other dating like Argon-Potassium & Rubidium-Strontium dating methods
- Analysing lunar crust because it doesn't change much.

One cannot analyze terrestrial rocks because the earth's crust keeps getting recycled (ocean bed - 250 m.y. old)
Oldest zircon crystal is 4 billion years old.
Moon was formed quite later, so anything there can't give us the correct age

Strontium — 84, 86, 88 : 3 isotopes

Rubidium — 85, 87

07 Only Rb87 gives rise to Sr87 so that is measured.

So, we can't use anything terrestrial. We examine the consistency and composition of various meteorites and planets and pre-Solar bodies and date them using various dating methods & compare it to earth's composition and decide the age of earth.

Many dating methods exist — ~~but most~~ ~~as~~ one of them is the Rubidium - Strontium dating which has a half-life of 41 billion years.

So, it has to be measured very accurately.

13/1/20

A major chunk of knowledge about earth comes from ~~radioactive~~ radiometric dating of chondrites which also tells us of the age of earth.

Dating is done using formula —

$$N = N_0 e^{-\lambda t} \qquad \lambda = \frac{0.693}{t_{1/2}}$$

N_0: Initial activity

N: Current activity

Unit for N : disintegration per minute per gram (dpm/g)

β-decay scheme of Rubidium

$$^{87}Rb \xrightarrow[\beta^-]{} {}^{87}Sr \qquad t_{1/2} = 49 \times 10^9 \text{ years}$$

When we're aiming to measure something around 4.6 b.y the instruments used to detect disintegrations of Rb must be very sensitive ⇒ they can measure in ppm

Rb	Sr
85 (78%)	84 (0.5%)
	86 (10%)
87 (22%)	87 (7%)
	88 (82.5%)

Isotopic abundance by number.

For Rb : $N = N_0 e^{-\lambda t}$

For Sr : New atoms formed : $D_t = N_0 - N_t$

$$(^{87}Sr)_t = (^{87}Sr)_0 + (^{87}Sr)_t$$

$$(^{87}Sr) = (^{87}Sr)_0 + (^{87}Rb)_t (e^{-\lambda t} - 1)$$

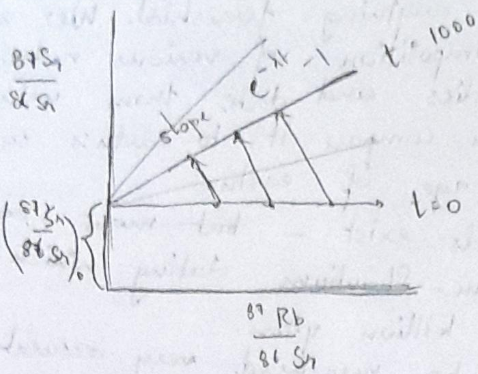
Isochron equation

$$\left(\frac{^{87}Sr}{^{86}Sr}\right)_t = \left(\frac{^{87}Sr}{^{86}Sr}\right)_0 + \left(\frac{^{87}Rb}{^{86}Sr}\right)(e^{-\lambda t} - 1) \quad : y = mx + c.$$

Mass spectrometer

08 How to make a habitable planet — Willie Brokes

Graph:



refractory - opposite of volatile

Limitations

- Chondroids are closed systems i.e. the conc of Rb and Sr have remained same since crystallization. So this method works only if the crystals have remained intact without any alteration.
- The initial $\frac{^{87}Sr}{^{86}Sr}$ in all minerals must be the same i.e. they must have formed from a homogenous mixture.
- Heterogeneity in $\frac{^{87}Rb}{^{86}Sr}$ ratio — for each mineral it should be different
- Precise information about λ — this is important to get accurate dating.

14/1/20

Earth Differentiation

Interior of the Earth —

- Crust : 0–40 km, 0.4% of earth's mass
- Mantle : 40 - 2890 km — 67% of mass
- Outer Core : Liquide Fe → 2890 - 5150 : 30.8%
- Inner Core : Solid Fe → 5150 - 6370 : 1.7%

Depending on temp, & pressure & elements present

If we compare the elemental composition of solar atmosphere, chondrite (CI & ordinary) and the whole earth, we see the numbers are comparable. This shows us they all came from same source, at the same time.

Even though all began from same composition, the volatality of elements plays a part in whether the

Magmaphile - elements that are concentrated into silicate liquid
liquid phase can accommodate larger elements easily - larger
09 lithophile elements like Rb, Cs, Ba, Sr, La, Pb, Th and U

elements remain as vat - i.e. H and He vaporized, from earth's atmosphere during its formation, but they can still be found in other icy planets

If we liquefy all the elements of chondrite composition and pour them in a container, they'll settle in this way - atmophile - volatile
lithophile
Chalcophile - combine as sulphides
Siderophile - combine with metals (iron)

All elements of Periodic Table were classified on this basis by Goldschmidt

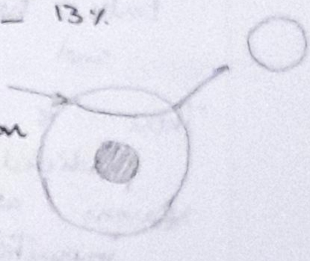
Atmosphere - atmophile
Crust - lithophile
Mantle (silicates) - lithophile + chalcophile
Core - siderophile

Formation of Moon

By Giant <u>Collission</u> Impact Hypothesis - once earth was already kinda differentiated, another planet (size of Mars - Theia) collided with earth and when they reformed, some material from earth's surface coalesced and condensed to form Moon.

→ Moon (returned basalt samples) has very low Fe conc.
Primitive ~~ca~~ chondrite - 27%
Earth - 34% ; Moon - 13%

→ Also, the core of the moon is small as revealed by geophysical investigation
Makes up only 3-4% of its mass



→ More refractory lithophile elements - Al is more abundant on earth

→ Oxygen isotopic composition of Earth and Moon are very similar

→ Siderophile element patterns of silicate moon are similar to terrestrial pattern for some elements, but are strongly depleted for others

These chemical trends point that an Impactor (6×10^{23} kg, ~10% mass of earth) collided at an oblique angle with an almost fully-formed earth to form iron-poor moon.

This collision melted Earth - it had a silicate vapor atmosphere and much of the planet was in a molten state. Theia's core (if it had one) combined with Earth's

5. Moon formed through giant impact.

⇒ Timing of Core formation

This is done using Hf - W isotope system.

Hf is a lithophile W is a siderophile

$^{182}Hf \longrightarrow {}^{182}W$ $t_{1/2} = 9$ million years

⇒ After 50 Million years, this chronometer is dead.

As the core forms, tungsten goes down to be a part of it. If the core was formed in ~ 50 Ma then, all of Hf → W and no tungsten would be in mantle, all of it would be in core.

But if it was formed ~~after~~ before / within 50 Ma, the there would be some ^{182}W in the mantle.

We measure this and calculate the ratio to find the time of core formation.

Recent studies indicate that the bulk of silicate metal seperation was complete before first 30 Ma

Other similar, extinct radioactive dating are used to get as accurate a data as possible.

⇒ Formation of Core

Earth has a liquid Fe-Ni-S outer core (3500 - 4500 K) and Fe - Ni solid core (5000 - 6000 K)

There is a 10% (5.14% - revised value) mismatch between measured and predicted density of outer core - one of the reasons attributed is the presence of light element impurities (such as S (6%), O, K (2%), Si, C) in the outer core.

These impurities act as a sort of 'antifreeze' & keeps the outer core molten

Study of Earth Interiors

- Study of meteorites - this gives us insight into our own interior
- Study of ultramafic rock - mixture of minerals & their source area in upper mantle
- Geophysics : Here, the seismic waves are studied on broad scales. The wave velocity depends on layer density & elasticity. Calculations are made.

* crystallized to form inner core

Crust —— Mantle —— Outer core —— Inner Core
Mohorovicic Gutenberg Lehman

Two types of waves —

- p-wave : particle motion is $\parallel^{l}$ to direction of propogation. Its faster. Travels through all states. So, if crosses diametrically across earth
  compressional waves
- S-waves : particle motion $\perp^{r}$ to propogation. Cannot travel through liquids. (This is how we got to know that outer core is liquid)
  Shear waves

The oceanic continental plates are slightly ~~more~~ denser. Outer core is homogenised. In the inner core — there is anisotropy i.e as Fe, Ni were crystallizing, they ~~were~~ are on the $\perp^{r}$ plane to the rotating axis. The travelling time for the wave is longer on the equatorial plane than on the axial line.

Density of Core : Earth – 5 g cc⁻¹ Moon – 3 g cc⁻¹

In the formation of earth — there were a lot of impacts due to which a lot of thermal & radioactive energy was released ⇒ silicates melted and formed the mantle. Through this, the metals, metal droplets started seperating out* & sinking to form the core. In the process, there are some discontinuities in between the layers of earth.#

For this to happen, the earth should have been sufficiently molten

The liquid outercore is why we have a magnetic feild around the earth.
(?)

Mechanism of Core Formation

Thermal constraints

- Most of heat in early stage of planetary accretion was due to decay of short lived isotopes Al^{26} (now extinct)
- Planetary impacts generated a lot of heat, causing formation of magma ocean.
- Important impacting event — formation of moon – lead to widespread melting at about 30 Ma

Geochemical constraints
- Siderophile elements provide an important control on process of core formation.

- Excess siderophile problem: the concentrations of siderophile elements in mantle are depleted, but there is huge disparity b/w calculated depletion (much lesser) & observed depletion. This problem is Excess siderophile problem (in mantle)
Different models have tried to explain this problem:

Tutorial 03

Minerals — Defined as naturally occurring, solid crystalline substances (generally inorganic) with a specific chemical composition

i) Naturally formed
ii) Solid
iii) Particular chemical composition
iv) Crystalline structure
v) Inorganic.

Composition of minerals

O	45.2 %	Ca	5.1 %
Si	27.2 %	Mg	2.8 %
Al	8 %	Na	2.3 %
Fe	5.8 %	K	1.7 %

- Breakage pattern / ~~plattern~~ cleavage — tendency of mineral to cleave along the weakest plane
- Fractures — minerals can crack and fracture

\# Different kinds of minerals have different cleavage planes based on their crystalline structure

- Streak — color of fine powder that's left be
- Density — depends on the atoms and packing efficiency
- Color — ionic minerals are colorless. Impurities cause color
- Luster — ionic ones are glassy
- Hardness — strong chemical bonds give high hardness.

Silicate minerals — 90% of minerals are silicates.
70% of earth's crust is made of O and Si as SiO_4

Rocks: Igneous — volcanic eruption
Sedimentary — Deposition of particle
Metamorphic — Pressure and T conditions

Erosion: breakdown, then dispersion of that material to far away places

13

Magma — liquid rocks, crystal & gas

Mafic : 45-55 % SiO_2

Intermediate : 55-65% SiO_2

Felsic : 65-75% SiO_2

24/01

Crust

Earth's crust occupies — 41.2% area & 0.35% mass

- Sheild — Large area of exposed Precambrian igneous & metamorphic rocks that's tectonically stable (Dharwar)
- Orogeny — tectonically active region (Himalayas)

Composition — mainly made of lithophile elements: Oxygen, Silicon, Aluminium & Iron make upto 80% of earth's crust.

Precambrian age : 2.3 to 0.54 billion years (?)

Global distribution of precambrian crust.

Destruction of Crust :—

1. Weathering: There are mainly 2 kinds —

* Physical weathering : Its the breakdown of rock due to mechanical forces like the wind (in arid areas) and water.
There is no change in chemical composition or volume. But when a rock is broken down to grains, surface area increases which means more chemical interaction.
Eg: The most powerful stream power is in the place where the Brahmaputra takes a U-turn to come back to India. A lot of breakdown happens there (about 30-40%)

* Chemical weathering : chemically induced changes in composition of rocks — it mainly happens due to naturally occurring acids like H_2CO_3 (reacting with CO_2 in air & soil) and H_2SO_4 (SO_2 from volcanic vents, oxidation of sulphide ores) & other organic acids

Cenozoic cooling - Temp has decreased in cenozoic era by 40 6°c

Erosion rates :-

- Physical erosion rates (PER) :- There are methods to quantitatively measure the erosion rate

Suspended sediment conc. - 100 mg / L

River water flux to ocean - 10^{11} L / yr

Drainage area - 10^6 km^2

$$PER = \frac{\text{Sediment conc} \times \text{Water discharge}}{\text{Drainage area} \times \text{Density}}$$

This gives rate of ~~eroio~~ erosion is calculated in mm / y^{-1}.

28/1/20

To measure chemical erosion rates, instead of taking suspended sediment, we consider the dissolved content of the water sample.

The dissolved solids in the water can also include

- anthropogenic impurities
- weathering of rock
- dissolved contents of rain.

~~Most~~ components that come mostly from rainfall and anthropogenic activities are constituents of NaCl. So, we calculate the amount of solids from rainfall and other sources and subtract it from the measured value to measure CER.

Importance of Chemical Erosion : → nutrient supply to the ocean

Major sources of CO_2 (in my scale) -

• Volcanic eruption • oxidation of organic matter

Major sinks of CO_2 - • Formation of rocks (carbonate rocks)

• Burial of organic carbon (to form petroleum)

• Silicate weathering

$$\underset{\text{Continental rock}}{CaCO_3 + H_2O + CO_2} \longrightarrow \underset{\text{(dissolved)}}{Ca^{2+} + 2HCO_3^-} \longrightarrow \underset{\text{Oceans}}{CaCO_3 \downarrow + CO_2 \uparrow + H_2O}$$

$$CaSiO_3 + CO_2 + 2H_2O \xrightarrow{} CaCO_3 + H_4SiO_4$$

(weathering)

It is a sink of CO_2 in geological time scales, as it takes in 1 mole of CO_2 - long term temperature regulation?

Composition of river water —

Typical pH : 7-8 (Rain water : 6-7) Sea water : 8.2 (→ alkaline salts)

Major cations – Na, K, Ca, Mg ; Major anions – Cl, SO_4, HCO_3, NO_3

Na, K – Rain & silicates

Ca, Mg – Silicates & carbonates

Cl – Rain & anthropogenic activities

SO_4 – Rain, volcanoes, sulphide minerals

HCO_3 – Carbonates & silicates

$$\Rightarrow \left(\frac{Ca}{Na}\right)_{River} = \left(\frac{Ca}{Na}\right)_{Rain} f_{rain} + \left(\frac{Ca}{Na}\right)_{si} f_{si} + \left(\frac{Ca}{Na}\right)_{carb} f_{carb}$$

(f → fraction)

Apportionment of Sources – Forward & Inverse Model

In a forward model, information is given so that we can find out the simple straight forward answer to a question.

Inverse modeling is more roundabout with boundary parameters and all.

	River Water	Rain	Carbonates	Silicates
Cl	20	20	0	0
Na	100	20	0	80
Ca	400	0		(0.7 ± 0.3) 80
Mg	200	0		(0.3 ± 0.2) 80

Total rate of erosion of silicate ⇒

$Na_{si} + Ca_{si} + Mg_{si} + K_{si} = 80 + 80(0.7 + 0.3) + 50$

⇒ 210

When we compare the CO_2 consumption rate of the Himalayan Rivers and other rivers in the world, their rate is about 4 times higher.

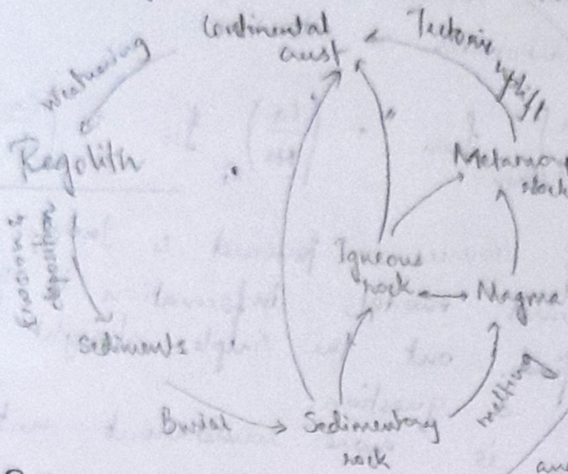
But how do we know that its been the same for last 40 my? If it has, then it would have systematically decreased T by 3-4°C. Also, Antarctic glaciers were forming then

The Rock Cycle

Primary Rocks are igneous rocks — its change in high pressure and temperature forms metamorphic rocks; & its weathering causing sedimentary rocks.

Inside the crust; Sedimentary - 5% Igneous - 95%

On the surface: Sedimentary - 75% Igneous - 25%



Magma - very heterogeneous different mineral constituents (mantle - mafic, crust - felsic), elemental compositions & diff. temperatures.

Origin of Magma -
- Lowering of pressure
- Raising of temp
- changing of rock composition

Partial melt is rich in components that melt at low T and depleted in those that have high melting point

→ Igneous Rocks

They form by cooling & crystalization of magma

Magma - molten rock within earth

Lava - molten rock on earth's face

Silicon, oxygen, aluminium, iron etc are major constituents

H_2O, CO_2 and SO_2 are gases dissolved in magma

Conc. of Silica & water regulates physical properties of magma i.e. higher silica ⟹ higher density & viscosity.

Lower T - more bonds can be formed, so greater viscosity [Dissolved water tends to decrease viscosity]

Two types of rocks -

* Plutonic (Intrusive) rock - cools below the surface, coarse-grained. Eg; Gabbro, Granite

* Volcanic (Extrusive) rock - cooled on the surface, fine grained. Eg; Rhyolite, Basalt

Silica content

Based on content —
Mafic — Magnesium + Iron
Ultrama Felsic — Feldspar (K, Na, Ca) + Quartz
aluminosilicates

Felsic / Silicic	>65%
Intermediate	45 - 55%
Mafic	45 - 55%
Ultramafic	<40%

Texture of igneous rocks —
Slow rate of cooling : larger crystals
Fast rate of cooling : small crystal → No distinct visible grains ions don't have time to migrate
Very fast rate : Glassy structure
Other textures of igneous rocks are —
* Aphanetitic — grains aren't distinguishable, i.e. quite rapid cooling, but not glassy
* Phaneritic — grains are quite big, slow rate of cooling
* Porphyritic — it has larger grains ~~sub~~ surrounded by small crystals ⇒ The cooling occured in 2 stages — rapid and slow cooling
* Pyroclastic — produced from debris of explosive eruption

Graph of Igneous Rock.
Bowen's Reaction series. — It is the ranking of common igneous silicate minerals by temperature at which they crystallize. Single chain tetrahedra → Double chain → 3D network
Olivine, Pyroxine   Amphibole   Feldspar

* Subdution zone
Island arc : Plate subducts → interacts with hot asthenosphere → water driven out of ocean crust → water lowers melting point of rocks → some magma reaches surface (~100 km)
This is how crust is formed.
Subdution zone is found near oceanic islands.

* Rifting of crust
When continental plates move apart, over millions of years, we can create an ocean basin
Rifting of crust is the beginning of ocean formation
* Continental collission — it results in closure of ocean basin
Then, traces of oceanic crust sediments are found in the plane of convergence
Eg: Oceanic crust is found in Himalayes

Mainly dragged, then push & slide also contribute
Oceanic crusts - no older than 200 million years
continental crusts - billions of years

Mechanisms of plate motion: (1) Rising magma & formation of new oceanic crust may push plates apart (2) Cold, dense slab of lithosphere sinking into mantle may drag the rest of the plate with it (3) A plate may slide away from spreading centre along the litho-asthenosphere boundary slope

a) Divergent margins - constructive i.e. produces new crust & ocean margin

b) Convergent margin - destructive i.e. consumes old crust and causes disappearance of ocean basin

c) Transform fault margin - conservative - plates slide past each other.

Wilson cycle - the production & destruction of crust is constant over long periods of time.
↳ means well balanced

Regional Structures of Continents
* Craton: stable core of very ancient rock - complex, heterogenous, stable (appeared b/w 3 to 0.5 bya)
* Orogen - elongate regions surrounding cratons 85% to 90%. They are eroded roots of ancient mountain ranges that formed as a result of continental collision b/w cratons

Building of continents
- Continental mass was present by end of Hadean. 90% was formed by 2.5 Ga i.e. it was developing well into Archaen.
- Initially, the temperature from interior was 3 times more, so the magma convection was very strong
  ⇒ Lithosphere formed was very thin & over time, as earth cooled, it could settle and thicken.

The growth rate of crust is measured by comparing the ratio of two ~~animal~~ elements which have a differential preference to be in lithosphere —
for eg: Nb/U where U is a lithophile element so it prefers to stay in the crust

	Lower mantle	Crust
$\frac{Nb}{U}$	30 (4.5 bya)	10 (constant)
	50 (Today)	

Mapping this increase in ratio ($\because$ U is decreasing) will give us rate of growth of crust.

10/2/20

Ocean & Atmosphere Oxygenation

Present day sea water — 35 g of salt per L.

Na+Cl	:	More than 90%.
+ Mg, Ca & S	:	About 99%.
+ K, Br, C	:	99.9 %.

There are other trace elements which play an important role

Enrichment factor : $\left[\left(\frac{X}{Al}\right)_{sample} \Big/ \left(\frac{X}{Al}\right)_{shale} \right]$

Redox state of oceans —

Oxic	> 2ml of O_2 per ml
Dysoxic	2 - 0.2
Suboxic	0.2 - 0.0
Anoxic	0.0 (sulphide present)

Some regions in Southern Oceans have High Nutrient but low Chlorophyll i.e HNLC regions. → Related to conc of iron.

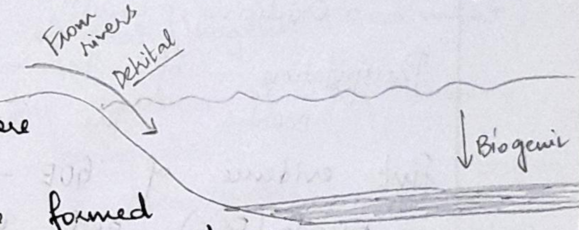
The amount of O_2 in atmosphere increased in two bouts : b/w 2.4 - 1.8 bya and 800 - 500 mya.

The elements in the ocean are also sensitive to the conc. of O_2 in atmosphere.

When O_2 conc. increased, Fe combined with it and precipitated down as iron oxides, forming sediments called Banded Iron.

The abundances of these elements changed at atleast 3 stages & affected the biosphere.

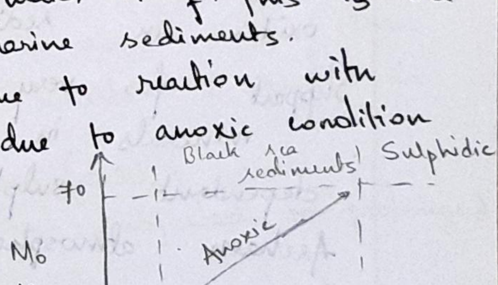
The trend of these changes was reconstructed using marine sediments



- Detrital : from rivers & atmosphere
- Biogenic
- Authigenic - some minerals are formed as precipitates in the sea water itself. This is one of the major sources of marine sediments.

This precipitation can be due to reaction with increased atmospheric O_2 or due to anoxic condition of water column.

Eg: Mo & U exist as dissolved oxide ions in sea water. If water is anoxic or sulfidic, then they ppt as sediments



When we examine the marine sediments, the conc of these elements (anything more than detrital value) indicates if water was anoxic and the degree of it.

Hence, examining marine sediments helps us map the O_2 content in water through ages

Sulphur : 32S , 33S , 34S , 36S

Mass dependant fractionation: biological processes prefer using lower mass S - so its mass dependant.

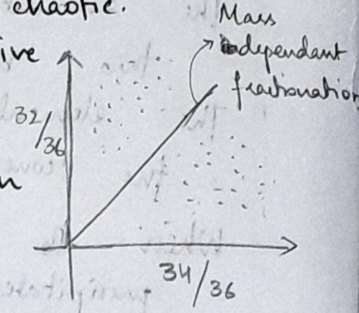
From last 2.4 bya, its been mostly mass dependant

Mass independant fractionation: photochemical reactions involving high UV light flux i.e. it doesn't care which isotope

This was possible in absence of an effective UV sheild that is the ozone layer. This mass independant fractionation is random & chaotic.

And this hasn't occurred in a massive scale in last 2.4 b.yrs

This is due to the Great Oxygenation Event.



Authigenic fraction estimation?

Solubility of Fe and S depends on their oxidation state

Reducing condn : Fe'' soluble, S immobile

Oxidising condn : Fe insoluble, S soluble

Precipitation of Fe - Banded Iron Formation around 2Ga marks the initial rise of O_2

First evidence of GOE - mineralogical changes - reduced pyrite (FeS) and uraninite to more haematite & oxides in sedimentary rocks

Support for very low levels of O_2 prior GOE - reduced minerals in sedimentary rock and non-mass dependant sulphur fractionation.

Archaen atmosphere - $< 10^{-5}$ of PAL

Evolution of oxygenic photosynthesis in cyanobacteria is the source of GOE. Cyanobacteria evolved around 2.9 to 2.7 Ga, but oxygen-consuming reactions prevented rise of atmospheric oxygen.

Moreover, cyanobacteria were restricted to freshwater till 2.4 Ga.

Limestone forms in shallow continental shelves - unstable at high pressure and low temperature

Sedimentary Rocks

Process by which sediment or regolith form a rock is called lithification. Lithification of sediments yeilds sedimentary rock. Two types -

1. Clastic Sedimentary Rock

size of grain	Rock Particle	Rock
> 2mm	Gravel + matrix	Conglomerate or Breccia → angular clasts ⇒ hasn't travelled far
0.05 - 2 mm	Quartz (sand)	Sandstone - resistant to weathering
<0.05 mm	Mud - Silt	Siltstone Soft & easily weatherable Deposits in floodplains
	Clay	Shale or mudrock ← Cleaves as sheets

• Chert - microcrystalline quartz

2. Biogenic & Chemical Sedimentary Rocks -

• Limestone : most important rock that forms by biogenic sediment. Also formed by chemical processes.

• Coal - formed by lithification of peat (biogenic sediment)

• Dolomite ($CaMg(CO_3)_2$) : formed by reaction of Mg bearing groundwater with calcium carbonates.
Also formed by evaporation of sea water : When 50% is evaporated, calcite precipitates & in the remaining brine, if $Mg/Ca \sim 10$ (Normally its around 5.2), then Mg sinks through the porous limestone & replace Ca.

• Evaporites - Halite (NaCl), Gypsum ($CaSO_4$)
They accumulate in basins ~~rest~~ subjected to prolonged evaporation.

• Phosphorites - These rocks are 10% P by mass. Conc of P in sea water is less, but along with F^-, it can replace CO_3^{2-} to form fluorapatite.

• Mn-Nodules ($Fe-Mn(OH)$) - potato shaped, found on ocean floor where sedimentation rate is slow.

→ Proxies for comparison of ancient sea water

1. Archaen limestone

Known from 3.5 Ga onwards

They have an order of magnitude more Fe & Mn than phanerozoic rocks

Mantle-like Sr and Oxygen isotope ratio into Archaen oceans

⇒ Significant mantle flux

2. Banded Iron formations

Fe^{2+} (soluble) was accumulated in Hadean & Archaean.

Its ppt as BIF in Proterozoic is a clear indication of major change in pH and redox conditions i.e. Anoxic & acidic to oxic and basic condition

Early ocean was acidic ∵ greater conc. of CO_2 in the atmosphere.

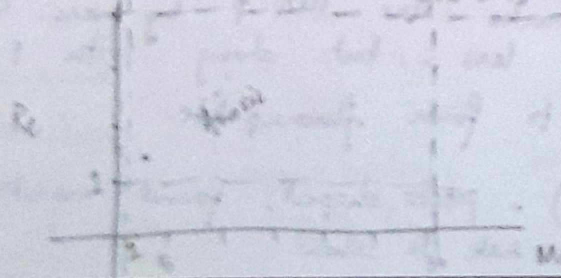
Enrichment factor: $\left[\left(\frac{X}{Al}\right)_{sample} \Big/ \left(\frac{X}{Al}\right)_{shale} \right]$

Problem:

	Al (%)	Mo (µg/g)		Re (ng/g)	
Marine sediment	6.00	1.5	0.25	0.2	0.0333
Avg Upper continental crust	8.15	1.1	0.134	0.2	0.0245
Avg Black Sea sediment	5.00	21	4.2	0.5	0.10

$\frac{0.25}{0.134} = 1.86$ $\frac{0.033}{0.0245} = 1.359$

$\frac{5}{0.134} = 37.34$ $\frac{0.1}{0.0245} = 4.08$



Revise Plate tectonics

Brachipoda - animals that have hard valves

23 Asthenosphere - layer of underlying rocks in upper part of mantle that are much hotter and malleable

II Half

References: Dynamic Earth by Skinner, Porter & Park
Earth System History by Stanley.

Why doesn't the collission of oceanic plates form mountains?
The density of oceanic plate is mainly determined by the age of the ocean. So the possibility of mountain formation is possible only when oceanic plates of exact same age collide, which is very rare.

* Major taxa

Life - Domain - Kingdom - Phylum - Class - Order - Family - Genus - Species
Invertebrata , Chordata

* Geological time scale

How earth science works —

1. Propose a hypothesis based on data collected
criticism and repeated testing against new data
2. Theory - predicts outcome of new experiments, survives repeated challenge.
3. Law - becomes universally accepted.

Why is earth science different?
- The classical problems are inverse problems, & by definition more complex & difficult. We start out with the outcome and come up with reasonable explanation in explaining it. By this virtue, the uncertainities are great.
- Scale of time and space
The planet's systems interact over scales that range from microscopic to global in size, and few seconds to billions of years in time.
Beause of such large scale, it's difficult to design and control experiment.
- Always been interdisciplinary in nature. James Hutton : father of geology : How do species remain constant when environment is changing around them.

Faults: lines along the

Charles Lyell - Geological time scale is much older than human timescale

Charles Darwin - combined the ideas of Hutton and Lyell and claimed that populations are dynamic.

3/3/20

Stratigraphy - studying the strata of sedimentary rocks to come up with a general explanation of how they formed.

Laws of stratigraphy

1. Superposition : what's above is younger - each bed is older than the one above and younger than one below
2. Horizontality : Layers of sediment are generally deposited horizontally.
3. Continuity : No abdrupt truncation.

Stratigraphy - Study of stratified rocks, especially their geometric relations, composition, origin & age relations

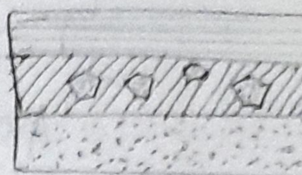
Physical weathering is greatest where there's maximum gradient, so its eroded by gravity. Conversely, the least weathering occurs in flats & floodplains.

Unconformity - indicates missing time i.e. some part of rock can get eroded which means the record of that time is not preserved. Different types -

- Angular unconformity - the layers are at a particular angle wrt to the line of unconformity
- Disconformity - There's an erosional layer along the line of unconformity (erosional contact)
- Nonconformity - Sedimentary rocks are on top of igneous rocks along the line of unconformity

4. Cross-cutting relation : If a body or discontinuity cuts across a stratum, it must have formed after that stratum

5. Law of inclusion



The rock mass adjacent to the one containing inclusions must have been there first in order to provide rock fragments

6. Law of faunal succession.

Fossil groups were succeeded by other fossil groups through time

Correlation of strata

It means matching the rocks of similar stratigraphic units in different regions. This is done using

- Fossils (biostratigraphy)
- Rock or minerals
- Marker beds

The goals of correlations are to understand different rock units and establish temporal and lithologic relations.

Application : William Smith - made a map of England by correlating different strata to fossil records.

5/3/20

Geologic Time Scale - Refer to first page

The time scale is disproportionately divided - the last 540 ma is more extensively divided

There is limited resolution in Precambrian because -

- Less abundant fossil
- Old rocks.

The first rocks we obtain are from Archaen era

We don't have <u>any</u> rocks from Hadean era. The only mineral representative is a few zircon crystals which were preserved through multiple meltings.

* The Great Oxidation Event can also be considered, but its evidence is secondary.

The division between Hadean and Archaean is marked by formation of rocks.

Similarly, Archaean and Proterozoic eras are marked by ~~fo~~ discovery of sedimentary rocks, which we only have records of from Proterozoic. All rocks from Archaen have been metamorphosed.*

The Proterozoic & Phanerozoic is probably marked by finding of fossils.

Journey towards absolute time

1. Ocean salt clock (Edmund Halley - 1715)
   He made a few assumptions: all salt comes from rivers and no salt leaves the system.
   So, by knowing the conc of salt and rate of weathering, he tried to calculate the age of earth through that [80 - 150 Ma]
2. Cooling of a molten mass (Lord Kelvin - 1862)
   His assumptions were that the core is homogenous and that the initial source of heat from the sun was the only source of heat. He followed Newton's directions. But there were other sources of heat
   His estimate was 20 - 400 Ma. which contrasted with Darwin's views and his estimate was favored because of its 'mathematical basis'.

A good chronometer — the product must be detectable

- It must have a time 0
- It must have a regular beat
- It must have a distinct end point.

The drawbacks of using radiometric dating are —

- inaccurate for ~~con~~ measurements too close to the axis
- few elements
- loses precision in calculation

So ~~we~~ we need to pick appropriate chronometers to find the age of something.

Age of igneous rock is straightforward ∵ has a definite 0 hour.

Age of a metamorphic rock — we can find when it metamorphosed and if there are remnants, we can also find the age of unmetamorphosed rock.

Age of sedimentary rock - dating becomes quite complicated, simple radiometric methods don't work. Also, are we measuring the age of constituent minerals, of exposure or of stratification

Example of radiometric dating —

→ $K^{40} - Ar^{40}$ Half life : 1.3 By

Sources of error : changes in temperature, weathering

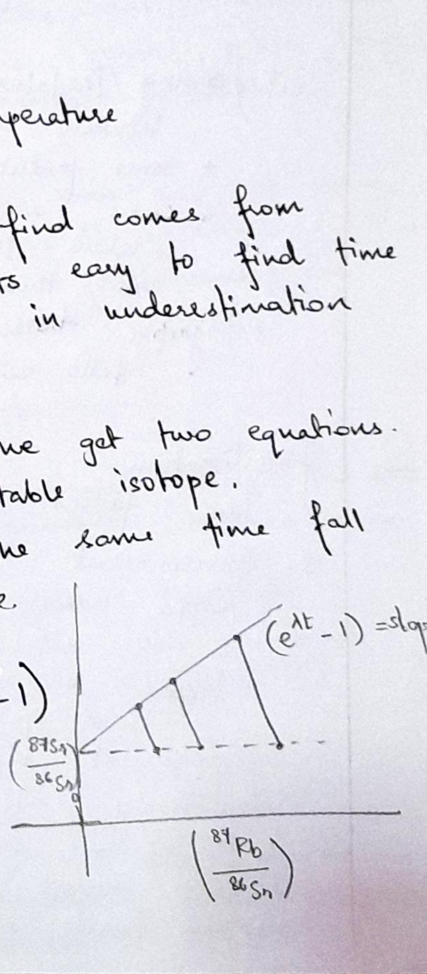
In this system, all argon we find comes from depleted K^{40}, so conceptually its easy to find time passed. The errors can only result in underestimation

→ Rubidium - Strontium chronometers

Here, there are two unknowns, so we get two equations. We divide the equation by a stable isotope.

The values of rocks formed ~~at~~ the same time fall on a line of same slope.

$$\left(\frac{^{87}Sr}{^{86}Sr}\right)_t = \left(\frac{^{87}Sr}{^{86}Sr}\right)_0 + \left(\frac{^{87}Rb}{^{86}Sr}\right)_0 (e^{\lambda t} - 1)$$



FOSSILS

Fossil : Remains or evidence of a life from a previous geological time i.e. before 12,000 years

Current geological time : Holocene epoch

⟹ Types of Fossils

1. Body fossils - Remains of body parts of ancient animals, plants & other life forms
   * Bones of animals are not found attached to each other i.e. disarticulated
2. Trace fossils - provide evidence about movement/activities of ancient organisms. Also called ichnofossils
   * Movement traces : how ancient animals moved in their habitat
     footprints - direction, pace, whether alone or in a group.
     trails & burrows - indicated by bioturbated (sediments heavily mixed due to burrowing) rocks
     absence of such layers ⟹ sediments were well oxygenated which allowed animals to crawl through them.
   * Feeding /Predation traces : record of ancient ecological interaction between species & how it might have changed over time.
     * Some predatory snails would drill holes in other bivalves
     * Crabs are other major marine predators - crack shells but when they're not successful, the shell is repaired and their traces remain.
   * Digestive traces : fossilized excrements called coprolites. tells us about digestive habits of ancient organism.

⟹ Fossilization

Two factors govern the process -

1. Environment where the organism died

- Rapid burial of remains beneath a blanket sediment layer is vital for fossilication
- Where burial occurs - depositional environment : almost always basins where running water can form sediment layers rapidly on top of the remains.
- Taphonomy : all the events that occur between death & burial - scavenged, broken or transported

Fossil record of marine shell-ed animals is prolific whereas dinosaur fossils are rare : require a lot of sediment to bury it

2. Body composition of organisms
- Organisms with hard parts are frequently fossilised ∵ they're easily preserved
  Hard parts → mineralised parts (bones & shells)
- Some times, soft parts are preserved as well - lagerstätten
  key factor: very rapid burial in sediments with anoxic conditions - favors preservation of soft parts as thin carbon films or allowing it to be replaced with geologically stable minerals (pyrite)

→ Fossil Preservation

01. Unaltered remains
Made of original minerals & tissues produced by an organism when it was alive

* Unaltered mineralized remains
  Many organisms (marine invertebrates) have shells & exoskeletons made of minerals like calcite & aragonite
  So, they remain well preserved.

* Frozen remains
  Fossils found frozen in ancient permafrost of Siberia
  Allows direct study of frozen tissues, hair, organs etc.
  Only limited to organisms of Quaternary period, when large ice sheets covered much of northern hemisphere.

02. Altered remains
These fossils have undergone some ~~sho~~ sort of change: materials making up the fossil are partially or completely different

→ Permineralization: pores of materials (bone & fossil plants) are filled up with mirals like calcite & silica

→ Petrification: this takes permineralization one step further. Pores are filled with minerals and original organic material is also replaced with minerals.

→ Replacement & pyritization: A different 2° material replaces the original organic material. Pyrite sometimes replaces calcite in hard shells of ancient animals.
  Sometimes, they also replace soft parts (lagerstätten)

→ Recrystallization: Hard parts of organisms recrystallize after sometime. Crystal structure changes but not chemistry
  In many mollusk shells, aragonite is replaced by calcite (geologically more stable form $CaCO_3$).
  General structure is preserved but not fine details

→ Carbonization: occurs when organisms are rapidly buried in anoxic conditions. They are thin, approximately 2-D films of carbon preserved on rock surfaces. When specimen are preserved in amber its generally through carbonization.

→ Molds and casts
Two types of molds – internal and external
Casts form when external mold is filled by sediment that later lithifies, reproducing the form of original organic structure.

Fossil ecosystems representing Proterozoic Life
Ediacaran Period : 635 to 542 Ma
↳ advent of first large and complex multicellular soft bodied organisms
Iconic fossil : Rangeomorphs (575 - 542 Ma)
Feather / bush shaped ; fractal growth pattern
Lived in deep (benthic) sea ; lack evidence of mouth or gut
(Possibly) Primitive metazoans ⇒ evolved before sponges
They might have absorbed nutrients from water – process called osmotrophy.
Several well preserved sites with these fossils have been found – especially Canada (under a layer of volcanic ash)

Early Phanerozoic Fossils
Cambrian Explosion - 542 Ma – crucial to evolution of earth
Refers to the sudden appearance in the fossil record of complex animals with mineralised skeletal remains
Note: Ediacarans disappear from record at this point
* Burgess Shale (505 Ma) recorded the tail end of the explosion
* All major body plans appeared during this time
⇒ every major phylum was established

Origin of modern marine ecosystem – fundamental ecological structure (predation and competition) were firmly established ⇒ seas were teeming with life
By the end of Cambrian, animals had made first temperory forays into land, soon to be followed by plants

Fossil evidence

1. Mineralised skeleton : "small shelly fossils" - sclerites, spicules, tubes, shells ⇒ vareity

   * Trilobites (earliest arthropods) first made appearance in 521 Maya and stuck around for 300 Ma

2. Trace fossils : More complex ∵ animals began to tunnel vertically down ⇒ varied behaviours. This is indirect evidence of mobile, bilateral, organ-tisse differentiated animals.

   * Cambrian substrate revolution - an event where rise of bilaterians permanantly altered the sea floor.

   The Ediacarans only fed on the rich bacterial mats on the sea floor (eg. Kimberella) but the Cambrians dug through them (looking for food - buried plankton - or escaping predators).

   This opened up new ecological niche beneath the sea floor as water and O_2 could now get into the sediment layers.

   The destruction of the bacterial mats (& hence obliterating the even-ness of sea floor), forced the bacteria into more restricted habitats.

   This change in substrate (& changing conditions of water chemistry, & predators) caused the extinction of ~~Ediacarans~~ Ediacarans.

3. Burgess-Shale type deposits

   Exceptionally well-preserved soft bodied fossils of Cambrian age found in many places in Lower and Middle Cambrian rock layers. ⇒ Lägerstatten

   Without this, our knowledge of ecosystems would be incomplete. Charecteristic assemblage of organisms is called Burgess Shale-type biota.

   Similar fossils (spanning 15 Ma) have been found all around the world ⇒ consistency

Explaining the explosion.

It can be mainly attributed to 3 kinds of factors : environmental, genetic, ecological.

(*) Zooplankton making organic material available for bottom dwellers
(or) Evolution of burrowing making new interaction with sediments possible

Triggers of the explosion

→ Environmental explanations

Rise of environmental factors instrumental in evolution of new body plan — • rising oxygen levels
• end of extreme glacial conditions

* Oxygen levels

Multicellular organisms need O_2. The levels allowed evolution of more complex animals with circulatory & respiratory system.

There isn't much change in O_2 levels across Ediacaran - Cambrian border. But —

• earlier increase ⇒ large Ediacaran metazoans
• post-explosion increase ⇒ animals were able to adopt a more active, energy intensive lifestyle (swimming, hunting)

* Glaciation

"Snowball Earth" hypothesis — earth was covered in ice before Cambrian explosion. But last time all of earth was covered in ice (635 Ma) was 90 Ma before explosion.

Nonetheless, melting of glaciers allowed for evolution of multicellular organisms. And once glaciers melted, sunlight was available to cyanobacterial & algae mats.

→ Developmental explanations

Life had to first evolve ability to develop new & diverse body plans.

Developmental genes (eg. hox genes) regulate how and when other genes operate to "build" the organism.

⇒ Cambrian Explosion set off when the genome ~~of all~~ in common ancestor reached a level of complexity sufficient to create new body plans.

This would provide more options for Nat. Selection to act upon.

→ Ecological explanations

Another factor could be the complex ecological interactions between animals. New ecological niches would have been created by animals interacting with the environment. (*)

Eg: Predation could have stimulated skeletalization & swimming

33 Index Fossils - fossils used to define & identify geological ages.
They should be - Wide geographic span
Short temporal span
Appears in all environments. 12/5/20

- Fossilisation can only happen in sedimentary rocks when the remains are buried (without decomposition) at the right temp & pressure.

- Modes of fossilization : Body & Trace fossils
- Unaltered remains - frozen remains, preserved in amber, or "Ida" : mammal preserved in a shale with oil reserves

- Perminerализation
Gaps within hard parts is filled by other durable materials
Eg: Petrified wood : happens only in certain ~~cd~~ conditions (like high temp) so silica is dissolved in ~~ote~~ water
Shells filled with pyrite (fool's gold) : could have only happened in reducing conditions

- Imprints
Impression of a living creature
* Molds (external & internal)
* Cast : the space b/w molds gets filled up by durable material.
* Carbonization : When the sedimentary rock is under high pressure & temp, the gaseous elements escape easily leaving behind carbon imprints of the body.

- Trace fossils *Devil's corkscrew?
- Biostratigraphy - useful tool to determine age of rocks.

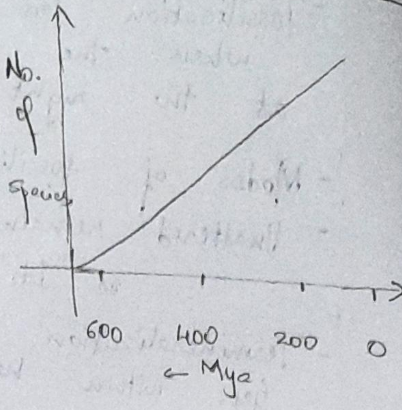
Reliability of fossil record
Fossils are incomplete but not useless
- Is sample enough for representation - to make sure we have enough samples to represent the diversity, a process called Re-sampling Analyses is done.
- To check if diversity is truthfully recorded - we can do a Live-Dead Analyses : compare the fossil samples obtained with recently dead samples (in that area) of its modern contemporaries.
Overall, average diversity over a long period of time is preferred

Biostratigraphy : Faunal succession - fossil organisms succeed one another in a definite order.
⇒ Any time period can be recognized by its fossil content

A small planet folds inwards quickly – with less differentiation

Organismal divesity through time

The number of species has generally increased over time (broadly)



But to calculate the total number of species that have existed since the beginning –

⇒ <u>Area under the graph</u>

Avg. Residence time of species

We find out that: 99.9% of species that have ever existed are now extinct

→ Why do we need fossils?

- Due to the limitation of short-term observation
- Responses take long time & can't be extrapolated
- Response to changes that no longer happens today
- Dynamic nature of life and earth
- Missing perspective from 99% of players of ecosystem

14/5/20

Oldest rocks and minerals – Zircon mineral (4,404 ± 8 My)

The shift from Hadean to Archaean is charactecised by record of rocks.

Hadean Earth [4.5 – 3.8 By]

No direct record of this time. Temperatures were very high, so the rocks remelted. Our source of info on this –

- comparative planetology
- modeling
- chemical composition of earth
- age of zircon crystal.

Archaean Earth [3.8 – 2.5 By]

First datable rocks are from this era.

* There was water – since we've found sedimentary rocks (not pristine i.e metamorphosed but with ripple marks)
* Oxygen ?
* Life ?

Atmosphere on a planet (early stages) is determined by –

1. Distance from sun which determines their temp. profile
2. Size of planet, which determines which gases escape first

* More silica, less iron

35 # Modern stromatolites are oriented & stratified towards sunlight. Same could could be true for ancient ones; but they can also be formed by geological processes

⟹ Oxygen in Archaean World

Earlier, there was no free O_2. Any free O_2 was tied up in minerals, which are buried deep underneath.

Evidence of O_2 : Banded Iron Formation.

Some minerals form in reducing conditions. So, after 2.5 Bya, the record of these minerals decreases.

Iron can dissolve in water ~~with~~ as FeO. But in high conc of free O_2, it forms Fe_2O_3 and precipitates as sediment

In the bands fromed, blue is Fe_2O_3 (due to microcrystals of silica) and red bands* are FeO. So, this shows us that there was (periodic) fluctuation of free O_2.

Source of oxygen : Life.

⟹ Early records of Life

01. Non-radiogenic carbon isotope (indirect) [3.6 By]

C^{12} and C^{13} are non-radiogenic. Living creatures preferentially take more C^{12}, as its lighter.

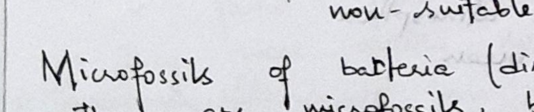
Due to this, inorganic sediments have greater C^{13} while organic sediments have more C^{12}.

Rocks at 3.6 Bya have this seperation in carbon isotopic value

02. Stromatolites# (indirect) [3.5 Bya]

They are microbial mats generally found where conc. of $CaCO_3$ in water is very high.

$CaCO_3$ ppts quickly, forming a layer on the microbial mat. Before they die, the microbes extend their flagella through the pores, so they can grow on top of the next layer and so on. The microbes die, but leave behind the carbon content.



This doesn't happen regularly these days because of predators and non-suitable conditions.

03. Microfossils of bacteria (direct) [3.5 Bya]

There are microfossils, but due to very simple morphology, interpretation of these as bacteria is controversial.

With all this, its clear that first life arose in very early Archean.

There are strong counterpoints to the hypothesis that life began in deep sea hydrothermal vents

→ The hydrocarbons formed would get dispersed in the vast ocean

→ The derivation processes (vital for life) wouldn't have been possible in the sea water.

So, life probably began in warm, salty 'ponds'.

19/5/20

Proterozoic Earth

- We can find unmetamorphosed sedimentary rocks
- Plate tectonics : Larger continents - continental accretion
  thicker continents - orogenic stabilization
- Glaciation Snowball earth?
- Atmospheric oxygen revolution
- Diversification of life

Atmospheric O_2 was really low in Archean - produced by inorganic process.

Sink for O_2 -

↳ Reservoir that grows so as to take up chemical as its produced.

- Early crust → forms in reducing conditions
- Pyrite (FeS_2) transported but not oxidised
- Iron deposition.

Boundary b/w Archean & Proterozoic is characterized by increase in O_2 concentration.

O_2 is a reactive & corrosive gas ⇒ GOE was the first pollution.

Oxygen revolution had these effects

- High conc of O_2 in atmosphere
- More dissolved O_2 in ocean
- Converts N_2 to nitrate

Nitrates are source of nutrition for eukaryotes and they can process O_2 better so, this condition favoured Eukaryotic algae

No predators, but Suspension feeders
Deposit feeders – snails, fish
Predators / Scavengers – chase food

So this was responsible for increase in body size – in low O_2 conc, only small body size can be supported by diffusion.
O_2 helps in better respiration, so high O_2 conc. supports larger body size.

Eukaryotes
Single & multicelled organism with membrane bound nuclei & organelles
Larger cells : 10 – 200 µm
Found 2.1 Bya

Oldest eukaryote – algal ribbon: Grypania : 2.1 by

Evolution of Eukaryotes
Endosymbiotic Theory [Lynn Margulis]
Origin of eukaryotes from engulfing of two prokaryotes.
The size of prokaryotic cells & organelles are quite comparable.
Explains —
1. Organelles have double membrane (formed ~~by~~ during engulfing)
   Aerobic eubacteria : Mitochondria
   Photosynthetic ~~eubacteria~~ cyano bacteria : Chloroplasts
2. Organelles have similar metabolism to some prokaryotes
3. Organelles have distinct non-nuclear DNA.
   some have similar genes to prokaryotes
4. Comparable size

Appearance of Multicellular form
First found in Ediacaran era [571 – 542 Ma] – metazoans.
Impressions of the organism are left behind on shales.
Eg. Dickinsonia, Rangea, Kimberella
Ediacaran ecosystem – biota was dominated by cnidaria
→ Lived before predators# (as they were all soft bodied)
→ They were mostly sessile & immobile (almost no trace fossils)
   Very few, shallow traces on the surface of sediment is found from about 570 Ma.
→ They were mostly suspension feeders (like sponges)

Taphonomy – study of how organisms decay & become fossilized
Animal activity – Trace fossils provide evidence for past life
None present until 570 Mya, & they only become complex and varied from there.

21/5/20

Phanerozoic Life

Habitat of Marine Animals

→ Photic and Aphotic Zone
Region of ocean where light penetrates to permit photosynthesis (0 - 200m)
Twilight zone - 200 to 1000/4000 m
Aphotic zone - 1000/4000m - 6000/10,000 m

→ There regions : Intertidal region, Continental shelf, Sea floor.

→ Types of fauna found in the sea -
1. Pelagic life - Planktons (floaters) : phytoplankton, zooplankton
Nekton (active swimmers)
2. Benthic life - Suspension feeders
Deposit feeders.

→ The main factors that affects the hab
1. Sunlight - almost none by 4000 m, so the kind of animals found is very different.
2. Oxygen level - it's conc is highest at the surface (due to atm oxygen), then it decreases (as its used up) and again rises slightly around 1.5 km
Complementarily, CO_2 levels are maximum around 1km as its produced the most there, then its decreases.
3. Nutrient - Conc of nutrients increases greatly and is maximum around 1km, then it plateaus out

So, the greatest diversity is found in shallow marine regions. The number of species drops significantly after 4000 m.

Cambrian era saw a lot of shallow inland seas where many species evolved.

Cambrian Explosion
- Appearance of large body & preservable forms
- Evolutionary experimentation - tried out many forms
- Appearance of extensive skeleton ⇒ more preservable
- Appearance of Echinoderms, Arthropods, Chordates
- Cambrian showed an enormous amount of disparity (how different?)

* One of the places where ~~who~~ we find Cambrian fossils is Burgess Shale in British Columbia, Canada

Examples of fossils : Pikaia - chordate [v-shaped muscles along the spine]

People kept finding parts of it & naming it. When scientists found the entire thing - they called it an anomaly

Anomalocaris - predator

* In Cambrian, active swimmers evolved - they had muscles and could move and steer themselves.

* Potential causes include changes in -
  - abiotic environment
  - genetic or developmental capacity of taxa involved.

* The disparity found first in Cambrian is maintained till today. Hence, the change in ecosystem from Ediacaran to Cambrian was vast & dramatic. Hence, it's called the Cambrian explosion.

The triploblastic animals were evolved in Cambrian

→ Causes of the explosion

1. Appearance of skeleton : It facilitates -
   - Body size increases, acts as supporting structure
   - Protects internal organs
   - Damage repair
   - Feeding habit
2. Appearance of predators

   It acts as a selective agent i.e. natural selection pressure

   Predators maintain diversity in an ecosystem

   Began an arms race : to stay at the top of the game

   helped increase body size
3. Increase in O_2 conc.
4. Change in Regulatory genes

   Hox genes control the blueprint of animal body. A slight change could have a dramatic effect i.e. all different body plans were developed then.

Hence, the causes are a combination of - all the factors.

→ Stromatolites decrease dramatically from Cambrian - they are less abundant and more restricted.

One potential cause ~~it~~ is the rise of predators & grazers. They have found a negative correlation between the number of species in the sea and abundance of stromatolites. Another hypothesis is that geochemistry of seafloor somehow changed significantly in Cambrian.

Early fish – marine & found in Early Cambrian Rocks
Freshwater fish appeared in mid-paleozoic

26/5/20

Paleozoic Era [542 - 251 Mya]

We're discussing the Silurian - Devonian Era

There were already many arthropod, mollusc and other groups of animals.

Transition of vertabrates from ~~fish~~ water to land.

Early fish didn't have jaws (Agnatha), and they developed jaws later. This can be observed in fossil records.

Major bony fish –

Ray-finned	Lobe-finned
Fin is supported by fine bone diverging from a common point	Fin is supported by robust bones arranged in complex manner.
More common, recent fish	Eg: Coelacanth – living fossil

Lung fish : * Some lobed-fin fish have lungs ⇒ they can breathe in air.

* Their 'fins' are robust so they can move on sediment surface
* They don't dry out on land.

Earliest lungfish have been found in ~~late~~ Devonian.

The emergence of tetrapods can be traced to early Carboniferous or even late Devonian

We would have to check for fossil record near aquatic sources in rocks that are the age of mid-Paleozoic

We would expect transitional fossils.

Challenges in the transition

→ Locomotion : extra body support.

In water, its density is comparable to body density which is much greater than air. So they would need robust skeletons to support the soft tissue from collapsing. Gravity is the dominant force on land.

In water, fish can use the water currents to move itself – so it doesn't take much energy to move

But on land, moving the entire body would take too much effort – so they developed a neck.

The pelvic and pectoral girdle of terrestrial animals needs to be better developed.

To move on land, the animal would also need strong limbs to move.

→ Respiration : Development of lungs*

Conc of O_2 in air is much higher than in water. So, much more beneficial if it can be utilised

Gills are external organs that can only be used in water. On land, they would be at a high risk of drying out.

Lungs are internal organs with folds bathed in fluid, so it doesn't dry out.

Fossil record of the transition

⇒ Euthenopteron[1]

Standard lobe-fin fish, like coelacanth. Fossil from Devonian era. It only lived in water

385 Mya

Ichthyostega[2]

Its a proper tetrapod – had limbs, strong ribcages, lungs & lived on land. Found from late-Devonian rocks.

365 Mya

Nature of movement similar to present day crocodile

⇒ Tiktaalik[3] – the missing link. (375 Mya)

It was discovered from late-Devonian rocks in Canada

Fish characters –
- Fish gills
- Fish scales

Tetrapod characters –
- rib bones
- mobile neck
- lungs

Transition characters – * limb and bone joints : but fish like fins instead of toes
* half-fish, half-tetrapod ear region

⇒ Main adaptations : Use of limbs to walk on land
Use of neck to catch prey

Advantages due to these adaptations –
- Massive growth of shallow water plants clogged up the marshes & tiktaalik used limbs to move around
- Lungs helped breathe on land
- Even short ventures onto land, could let it escape from marine predators.

Pectoral fin → Transitional foot like structure (with fins) → Hind limb.

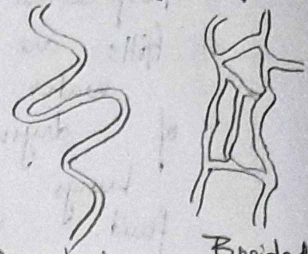
Invasion of Land by Plants

First plants are said to have become terrestrial in the late-Silurian era. The major effects of this land invasion were—

01. River geometry

It resulted in widespread meandering rivers (as apposed to braided systems) by—

- Increasing ground resistance
- Developing true soil by providing necessary organic material



Meandering Braided

02. Late Devonian extinction

It was caused by Glaciation which happened due to lowering of atmospheric CO_2 —

* Absorbing CO_2 during photosynthesis
* Increasing rate of chemical weathering (sink of CO_2) by increasing moisture in the air.

28/5/20

Mesozoic Era [252 - 65 Mya]

This age came right after a great extinction event in the Permian.

We're going to see transition from land to air—

- Flight appeared in multiple lineages independantly
- Its an expansion of niche. Helps them—
  - to avoid predators
  - to protect their young ones
  - to avoid competition
- Insects learned to fly in the Paleozoic — other flying organisms (birds, reptiles, mammals) appeared later.

The most diverse animals that have developed flight are the birds — the feathered wings help them in it. Fossils of birds are only found in Cenozoic. To trace their evolution, we've to go back to its closest ancestor in the Paleozoic.

We find out that birds are closely related to Dinosaurs – they are all amniotes.

Dinosaurs –

- Dino (terrifying), saur (lizard)
- Appeared in Triassic and went extinct in the end of Mesozoic. (same time as mammals)
- Fossils found all over the world.
- They're different from conventional reptiles in two aspects –

1. Locomotion: They have an upright gait & can stand erect unlike other lizards – ie they had a different pelvic girdle: the joint to the femur, allows them to keep their legs at a 90° to the body & the bone could go inside the girdle which allowed them to walk uprightly.

   They were fast and had stamina – could run very fast for a long time. The other reptiles, due to their sprawling movements, squeezed one of their lungs – so they only moved on 1 functioning lung: Carrier's constraint.

   We have come to this conclusion by examining the footprints – the distance b/w footprints is different while walking & while running. Taking into consideration the leg length and stride length, we can calculate the speed of the animal – they could run very fast for miles.

2. Thermoregulation.

   The other reptiles lacked stamina because they were ectothermic ie. their core temperature fluctuates a lot.

Dinosaurs distribution –

Modern lizards are found in the tropical belt, and nowhere near the poles because they're poikilothermic.

But the dinosaurs we found everywhere – from pole to pole. They homeothermic (maintained constant core temperature) while being ectothermic (didn't produce heat).

There are chiper ways to thermoregulate –

Surface area – heat loss

Volume – heat storage

When an animal is biger, its SA : V ratio decreases and they can store heat better.

Thats why Hippos like muddy water and elephants have large ears.

Pterosaur – dinosaur that could fly

44 * First appeared in Jurassic, along with huge dinosaurs

Thus dinosaurs were homeothermic due to Gigantothermy – they regulated temp by being big.

But there were small dinosaurs as well – how did they regulate temperature?

This is where feathers appear* – they helped in insulating the body; and evolution favoured those with longer feathers.

And once the feathers reached a certain length, they could be used for flight.

This is the bridge between dinosaurs & birds.

Archeopteryx – Transition form.

It means : Ancient wing. It must have been a weak flier.

Dinosaur characters
- toothed beak
- wing claws
- tail supported by vertebrae

Bird characters
- feathered wings
- pneumatic bone structure

Hoatzin – Modern day example

It's an Amazonian bird whose young have wing claws. They live on tree branches over rivers, and these claws help the young in climbing the branches to a high level and glide from a height to learn to fly.

Somehow also implies how feathers helped in flight in the Archeopteryx.

Homeothermy in dinosaurs is (questionably) hypothesized by examining the crossection of bones & study bone dissolution – if the body temp is constant then bone growth is faster.

2/06/20

Mass Extinction : Cretaceous - Paleogene [K-Pg]

One of the things that marks the boundary between Mesozoic & Coenozoic.

WKT, 99% of species that existed are now extinct.

Diversity has increased over time. Which means –
- Rate of origination must be increasing
- Rate of extinction must be decreasing.

From records and statistics, we find that the rate of extinction is decreasing — decreasing faster than the rate of origination (which is also decreasing).

In the graph, we see that in some cases, a very high number of species go extinct — they stand out. Other charcterics are —

- They're abdrupt
- On a global scale
- Lack any kind of selectivity.

These extinctions are called Mass extinctions.

Background extinctions : ≤ 5 species per million year(?)

There have been 5 Mass extinctions; The greatest of which was the Late Permian, but we don't understand it well. So, we're going to study :

Late Cretaceous Extinction [K-Pg]

Victims of the extinction were : Non-avian dinosaurs
Marine reptiles
Ammonoids.

Dinosaurs were at the peak of their diversity & they seem to have been wiped out abdruptly, not a gradual decrease.

→ First hint : Iridium Anamoly.

Luis & Walter Alvarez found very high Iridium concentration (in clay residues from pelagic limestones) at the K-Pg boundary. This observation was seen all over the world ⇒ it was added from outside.

We knew that meteorites are rich in Iridium & they hypothesized that there was a meteorite shower.

Other effects of this :-

→ Microspherules and Tektites (mm-sized) by shock and blasted into atmosphere

They're grains of sand that were melted and reforged as spheres or tear-shaped (tektites) recrystallizing into minerals. They're found in all K-Pg sites & nuclear sites.

→ Shocked mineral grains

'Shocked' quartz has been found from K-T boundary globally. They show sets of parallel, welded factures that formed under enormous pressure — also have a plane of cleavage, that normal quartz mineral doesn't. They're common where meteorites are known to have formed craters.

Impact Hypothesis

An asteroid hit the earth 65 mya & the direct and indirect effect of this caused the extinction.

But if there was an impact, we should be able to find a ~~cra~~ crater. But the problems are –

- 70% of earth is covered by ocean – impact might have happened there
- Difficult to find craters in the ocean.
- The crater might have been in the subduction zone & might not exist anymore

Chicxulub crater : Ground zero

- 65 Mya old ~~crat~~ crater in Yucatan Peninsula (near the Gulf of Mexico)
- Crater – 120 miles in diameter ; Asteroid – 6 miles
- All impact features mentioned are present
- Devastation was maximum there & decreases as we go further ⇒ N.A – highest extinction ; Aus, NZ – virtually unaffected.

Direct Effects

The asteroid might have impacted on an oil rich shale and penetrated rock that was rich in sulfur.

1. Massive forest fire : soot & charcoal remains found
   triggered by fiery cloud burst from impact site
   impact on oil shale
2. Tsunami : Tsunami deposits discovered (unexpected marine fossils on top of terrestrials)
   Caused giant waves that drowned coastal areas.
3. Perpetual night
   Soot aerosols ~~cooled~~ caused immediate cooler climates on land & drought conditions. This was followed by surface water cooling in global oceans in a few years.
   Dust and soot aerosols nearly blocked out all sunlight –
   - causing temp. drop
   - major drop in primary productivity.

   Rapid climate change induced terrestrial extinction, and later marine extinctions over several years.
4. Acid rain : Sulphur in the rocks reacted to form H_2SO_4.
   Surface water became toxic

Indirect Effects

1. Collapse of ecosystem
   - Without sunlight, plants died first, others followed
   - Fungi proliferated
2. Global Warming
   - Aerosols in the atmosphere trapped & reflected heat.
   - Asteroid had penetrated carbonate rocks ⇒ lot of CO_2 was released into the atmosphere
   - Temperature increase ~ 5°c
   - Marine realm was affected too.

Alternate Theory: Deccan Volcanism
Criticism – It happened a little before the extinction
– Extant of it is difficult to account for with the volcanism.

4/6/20

Cenozoic Climate & Mammal Evolution

We have a better record & resolution in rocks and fossils when it comes to Cenozoic Era.
Hence, we have the periods divided into Epochs.

Climate
There was drastic climate change in the cenozoic.
Factors affecting it –
We know this by studying the stable isotope ratio of oxygen – by studying the carbonate shells of marine organisms which reflect the seawater composition.
If temp. is higher water with higher O_2 isotope stays behind & similarly, the lighter isotope builds up in glaciers & heavier isotope is left in sea water. Thus, temperature can be reconstructed.
There were multiple glaciations.
Continental change – movement of Indian subcontinent development near Antarctica.

Mammal Evolution
The diversification of mammals is great after the K-Pg extinction event. Even though they first appeared in triassic, they only proliferated in the Cenozoic.

(*) Early cetaceans had nasal opening near the tip of the snout. As they became more aquatic, it migrated to the top of the skull as a blowhole.

Origin of Mammals —

Appeared in Triassic, early mammals were small

Their relationship with reptiles can be seen in modification of lower jaw bone — reptiles have multiple bones in their lower jaw & only one bone against the eardrum; in mammals, the lower jaw is a single bone & other bones have reduced to form smaller bones in the ear.

Paleogene event : Cetacean evolution

Cetaceans (whales, dolphins, porpoises) are descendants of terrestrial mammals because —

- need to breathe air from atmosphere
- vertical movement of spine for locomotion
- Bones of their fins resemble the limbs of land mammals

The closest mammal related to cetaceans is the hippo.

Early aquatic forms : * fossil : Pakicetus

The relation is seen in the middle ear cavity that is still present today.

As the land was arid, if an animal could feed off fish then it was a great advantage. (& reduced competition)

* fossil : Ambulocetus

Means a whale that can walk. It was adapted to brackish water. It's hind limbs were reduced. large, powerful tail

But they were not marine — fully marine whales were only found ~~after~~ during Miocene (Neogene)

→ The cetaceans also had to develop the right nasal opening (farther behind in their snout) (*)

→ The cetaceans had an advantage over sharks — they were warm blooded. When Antarctica moved from S.A & Australia

At the end of Eocene → the circumpolar currents cooled the area — warm adopted species like sharks faced extinction, but it favored the warm-blooded whales.

Note: Basilosaurus : A really big ancient whale that was adopted to an estuarine environment — & because of their body size and shape, they couldn't dive deep. During a period of de-glaciation, the shallow bays they lived in became very deep & these ~~of~~ whales couldn't adapt & went extinct. The smaller whales were hunted by Megalodon sharks — but cooling of Antarctic circle gave them an advantage

Neogene Event : Primate Evolution

Primates : Groups with opposable thumbs

→ Neogene changes in climate -
- change in temperature and rainfall pattern
- rainforests became patchy

Neogene is marked by glacial & interglacial periods
During a glaciation (no ice is formed at the equator) but there is decrease in ~~prep~~ precipitation ⇒ so patches of rainforests became Savannahs

→ Primates are not as big, fast, strong, sharp teeth/claws as other animals but their opposable thumbs gave them an advantage - they took to trees ie explored a new niche. The thumbs, tail and hindlimbs helped them climb easily.

→ The emergence of Savannahs posed a problem - the groups had to travel long distance in extremely hot weather to reach another patch of rainforest.
Challenge: Longer migration
Solution: Bipedality

→ Benefits of bipedality -
It requires different set of modifications in the feet and hip joints to become an obligate bipedal.

* Upright poster : exposes less S.A to the sun
keeps most of body away from the hot ground
Exposed to more wind, so body is cooler

* Bipedal walking is energy efficient

* Gaining height in Savanna : easier to spot predators
food gathering also becomes easy

* Freeing forelimbs : ability to transport things manually.
ability to carry a resource either to save for later or to consume in a safer location

→ First evidence

1. Trace fossil : Series on footprints found in divergent boundary [i.e. lots of volcanoes ⇒ volcanic ash mixed with water acts like cement & helped in preserving footprints]

2. Lucy : Australopithecus (3.2 Mya)
Short height, obligate bipedal, found in East African rift
Ape - Small brain, long arms; long, big toes
Human - Bipedal, broad pelvis.

9/6/20

Recent Biodiversity Crisis

Age : Quaternary Period - Pleistocene Epoch

Background extinction : 2-5 familise/My

Mass extinction : >5 families/My

↳ Its also global and non-selective

The Big Five and Recent

- There is no overlap between Big five and Human race
- Our species originated 200,000 yrs ago & in last 15,000 has experienced 900 extinction.
- Calculated extinction rate : 140,000 species per year.

Extinction since Pleistocene

- Extinction of terrestrial mega mammals - 103 outta 186 genera went extinct
- Pleistocene is marked by rapid climate change