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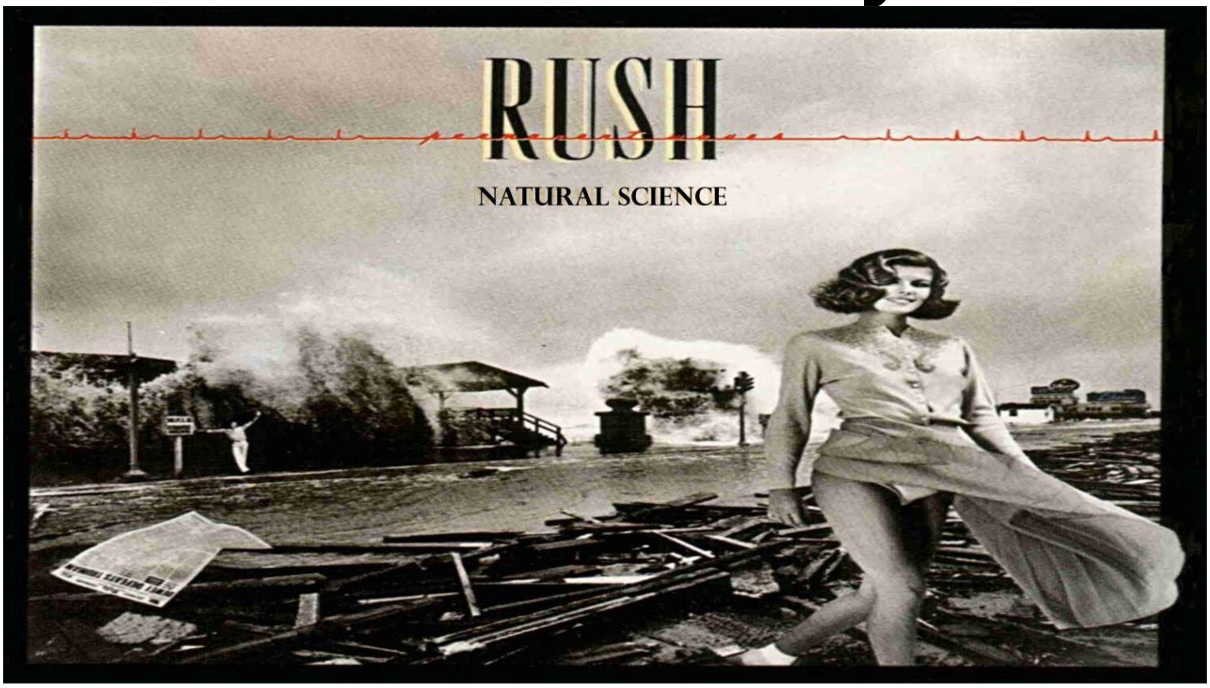
Earth Science Essay Plans



1A Natural Sciences

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DISCLAIMER This guide is based on the syllabus written in the 2023/24 Earth Sciences Course Guide, and the 2018-2023 past papers. Course content and syllabus styles may change with time. We have included 'model' answers to most questions on the theory exam. Please use this for reference only – academic dishonesty is a serious breach of conduct.

The materials in this document will certainly be sufficient for a 2:1, and if combined with your own study beyond the syllabus, should get you a 1st. However, while written to the best of our ability, this has not been proofread and will almost certainly contain errors. We are not liable for any consequences that may arise from using this as your only source of reference material. You should always cross-reference any doubts with academic materials or ask your supervisor.

Answers in red and blue are complete. Answers in green are incomplete. That is the unavoidable consequence of having to study a vast syllabus in a month's time. We welcome any suggestions or alternative answers to tripos questions and will add them to this document if appropriate. We can be reached by the email addresses given above.

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Physical properties of Planet Earth

Plate tectonics

1. Describe the observational evidence that tells us that the surface of the Earth is formed of rigid tectonic plates that are in relative motion. What is responsible for driving plate motions, and how do we know?

Observational evidence for rigid tectonic plates in relative motion:

- **Biostratigraphy:** Matching fossil records on some seashores of different continents suggest that there was once a supercontinent that was split apart, drifted into today's state. This suggests that the Earth has plates that are in relative motion.
- **Earthquakes**: Where earthquakes occur on Earth are mostly in narrow lines on the map. This suggests that the lithosphere is split between many pieces, which are plates. The earthquakes occur where there are relative plate motions e.g. ridges, trenches…
- **Hotspots**: The mantle hotspots (where upwelling of hot plumes occur) is essentially stationary relative to the moving plates. The movement of plates can be seen e.g. in Hawaii, where the chain of islands formed by volcanic activity of the hotspots 'drift' away at a certain speed i.e. islands' age increases linearly along the chain.
- **Palaeomagnetism**: Averaging over secular variations, the changes in inclination of the magnetic field of rocks tell us that the paleolatitude of the plates have been changing, allowing us to construct APWP (apparent polar wander paths). Comparing these paths we see that continents / plates are indeed in relative motion e.g. North America and Europe.
- **GPS measurements**: Exact motion of tectonic plates and there has not been difference in relative movement within the plate.

What is responsible for driving plate motions, how do we know:

- **Forces acting on plates**: The rising hot convection current at ridges causes ridge push and makes the seafloor to spread (active rifting). At the subduction zones, the convection currents (also due to the high density of mantle) pull down the slabs (slab pull).
- **Energy sources**: The energy is provided by the energy from deep within the Earth, especially with heat from radioactive decay as a major source of energy. This energy is converted into kinetic energy of plates through mantle convection.
- **Rejection of Mantle drag**: Rather than viscous drag pulling slabs everywhere in the plate, we plates are driven at the edges. This is because there is no correlation between plate area and plate speed, but there is a positive correlation between % of plate circumference at subduction zone and plate speed.

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Magnetism

1. Outline the main features of the Earth's magnetic field and what we can infer from these observations about the nature of the outer core. How can we use this field to understand the movement of plates
a) in the last 200 million years;
b) before 200 million years ago?

Main features

- Approximately to the lowest order as if produced by a giant magnet (mangetic dipole) inclined at an angle of about 11° to the spin axis (draw diagram, remember that the S-pole of magnet is at the North pole). This is verified by the fact that $2 \tan \varphi = \tan I$, diagnostic of a dipole field. The value of magnetic field at surface is of the order of 20-70 μT (microteslas).
- Is largely time dependent. Secular variations: direction of the magnetic field anywhere rotates irregularly with a periodicity of a few thousand years (e.g. magnetic pole drift seen in past decades). On larger timescales, the North and South geomagnetic poles trade places at random intervals from 0,1 M to 50 M years (geomagnetic reversals).

Nature of the outer core

- Outer core, by thermodynamical equation-of-state analysis, is too hot for ferromagnetism (Curie's law) or magnetostatic production of dipole field. Hence, it is produced by motion of conducting metals, according to the theory of magnetohydrodynamics [$\partial \mathbf{B}/\partial t = \eta \nabla^2 B + \nabla \times (u \times \mathbf{B})$] (η is the magnetic diffusivity). This means that metals have delocalised electrons, i.e. liquid state.
- Current theory suggests that magnetism is generated by a self-sustaining dynamo. Coriolis effect caused by the overall planetary rotation, tends to organize the flow into rolls aligned along the north–south polar axis. The secular variations are due to the convection motion of liquid in the outer core, which again suggests that it is a liquid state. The system is chaotic and unstable, so irregular reversals are expected.

Using the field to understand plate movements.

- *Principle of uniformitarianism*
- **Applies to (a) and (b)– Magnetic field analysis**
- Many rocks have natural remanent magnetization. Ways of obtaining them e.g. thermo-remanent (cooling below Curie temp.), detri-remanent (ferromagnetic sediment in siltstones) the list goes on.
- Average the dip of magnetic field to remove secular variations, then use equation to find the palaeolatitude of the rock. (Assumptions: magnetic pole ≈ geographic pole, dominantly a dipole field)
- Note that this method does NOT give the palaeolongitude.
- Understand relative motion of plates w.r.t. the pole: regard the continent as remaining at a fixed position and plot the apparent positions of the poles for various times to provide an apparent polar wander (APW) path ==> APW paths were different for different continents, implies continental drift
- Example: North America and Europe - correspond very closely from the time the continents were brought together at the end of the Caledonian orogeny, approximately 400 Mya ago, until the opening of the Atlantic.

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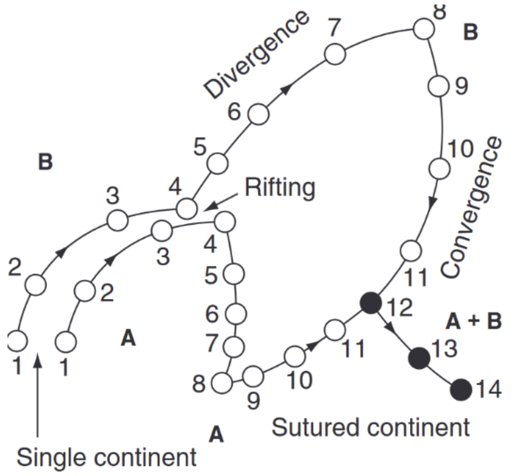

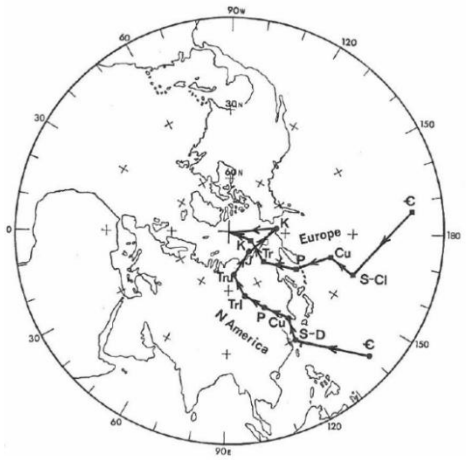

- Any time prior to 200 Ma the constraints provided by the oceanic data are no longer available and reconstructions are based on paleomagnetic results and geologic correlations

- **Applies to (a) only – Ocean basins**
- Magnetic anomaly on the seafloor flips from +ve to –ve as we move away from mid ocean ridges at a rate corresponding to the geomagnetic reversal. This gives information that seafloor spreads at a symmetric rate on both sides. By figuring out the widths of magnetic stripes and the timescale of reversals, we can find the speed of seafloor spreading.
- Like a recording tape, once we reverse the seafloor spreading, we can stitch the continents back together, reveals ancient plate movements.
- Only valid for the past 200 Mya because oceans are relatively young.

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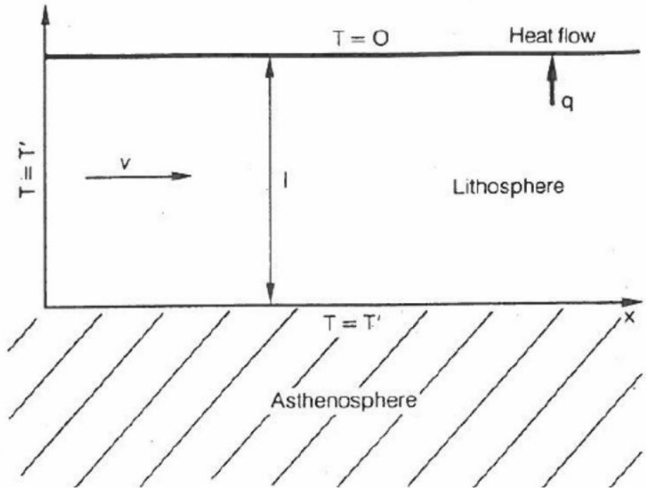
2. It has been observed that seafloor depth in the ocean basins increases systematically with crustal age.
a) Explain the nature and origin of this relationship.
b) To what extent does this relationship hold for plates older than ~70 million years? Explain your answer.
c) Using specific examples, explain how mid-ocean ridge spreading rate (i) affects ocean basin bathymetry today; and (ii) may have caused eustatic sea level change in the past.

(a) Nature of seafloor depth vs age relationship

- $h \propto \sqrt{t}$. (Draw a pretty graph!)
- Mathematical proof: Assume the spreading rate is much faster than conduction rate. Use a half-zone Thermal diffusion equation: $\partial T/\partial t = \kappa\, \partial^2 T/\partial z^2$ (κ is the thermal diffusivity) Let $T = 0$ at $z = 0$. For $z < 0$, $T = T_1$ at $t = 0$. Solve the equation to get $T = T_1 \operatorname{erf}\{z / 2\sqrt{(\kappa t)}\}$. Therefore, the height of the seafloor is, using α (thermal expansion coefficient): $H = \alpha \int_0^\infty (T(z) - T_1)\, dz = -2\alpha T_1 / \sqrt{\pi}\, \sqrt{(\kappa t)}$



- Intuitive explanation: As seafloor spreads out, it cools by conduction of heat from the surface. The temperature drops and the slab becomes colder. By isostasy, the slab sinks. Rate of conduction depends on temperature difference, so the cooling gets slower over time and rate of sinking decreases as well.

(b) Beyond 70 Mya

- For age >80 Mya, h plateaus out to a fixed depth and can be assumed almost constant at ~6400 m depth (precisely of the form $d = 6400 - 3200 \exp(-t / t_0)$.)
- Intuitive explanation: Eventually the slab becomes so cool it becomes unstable (**Rayleigh-taylor instability**). Convection of the asthenosphere helps to bring heat to the slab so that it reaches equilibrium temperature and no longer cools.

(c) Mid-ocean spreading rate

- (i) Slow-spreading ridges such as the Mid-Atlantic Ridge have spread much less far (showing a steeper profile) than faster ridges such as the East Pacific Rise (gentle profile) for the same amount of time and cooling and consequent bathymetric deepening.
- Slow ridges have large rift valleys and a rugged landscape especially at the ridge crest, but fast ridges lack rift valleys.
- (ii) Influences to eustatic (global) sea level change: faster spreading rates give rise to a broader ridge, so the overall average age of the seafloor of the globe is younger. So, the

avg. depth of the ocean is shallower, and given that the globe is not expanding, sea level will rise

- Example: in the Cretaceous the global sea level is 100-170 m higher than it is today; it is because the average seafloor spreading rate is ~92 mm/year, about 2-3 times higher than today (~30 mm/year). Glacial melting and thermal expansion are insufficient to explain the ridiculously high sea level.

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Earth's interior

1. Describe the observational evidence and theoretical arguments that support the idea that Earth's mantle is convecting. What methods are available to Earth scientists to estimate the range of temperatures present in the convecting mantle?

Evidence for a convecting mantle

- **Seismic tomography**: Using seismic waves which travel all around the mantle, the velocity distribution of the mantle can be reverse engineered. As velocity depends on the temperature, we see hotter and colder regions that match up with predictions of convection models.
  - A temperature increase of 100 °C reduces the speed of an S wave traveling through peridotite by ~1%
  - In particular, it is clear from 3D images that subducted slabs go the whole way down to the mantle-core boundary, so we even know that convection goes whole way.
- **Geochemical evidence**: Stable isotope ratios of samples obtained in hotspot volcanic eruptions are comparatively similar to known ratios in the crust, meaning that oceanic crustal material has been largely recycled. This is only possible with a convecting mantle.
- **Existence of hotspots**: Many hotspots (Iceland being a famous example) are indication that some parts of the mantle are hotter, implies convection
- **Isostatic rebound of ice sheets**: When the glacier melts and is unloaded from continents, the original weight of the glacier which presses the crust down is removed. The slow rise of the land implies that denser mantle below is flowing in to restore isostatic balance (e.g. Scandinavia, raised beaches in Arran). Also confirms that mantle is viscous.
- **Rayleigh number (theoretical)**: Ratio of time taken for conducting heat around vs time taken for heat transfer by material flow. $Ra = \rho g \alpha \Delta T l^3 / \kappa\mu \sim 10^7$, so we know the mantle is convecting rather than conducting. Pattern is chaotic so instabilities arise quickly and no stable convection cells.

Estimation of range of temperatures in a convecting mantle

- **Sampling**: At mines and volcano eruptions
  - Mines dug at a few kilometres confirm that the continental crust has a geothermal gradient of ~20 °C/km. We can extend this to the Moho / petrographic boundary to determine the upper mantle temperature.
  - Bulk composition in igneous rocks tell us the temperature where mineral equilibria occurred (e.g. %olivine) because the degree of partial melting in peridotite (depending on temperature) can be deduced
  - Volume of melt produced at MOR corresponds to temperature (e.g. thicker
- **Thermodynamics and numerical modelling**: Pressure correlates depth in a simple fashion predicted by physics. Fluid dynamic models have been built for the convecting mantle so to predict the temperature gradient in the mantle.
  - Convection speeds fast so adiabatic compression and decompression in the mantle convection; mantle temp. gradient is only ~0.5 °C/km

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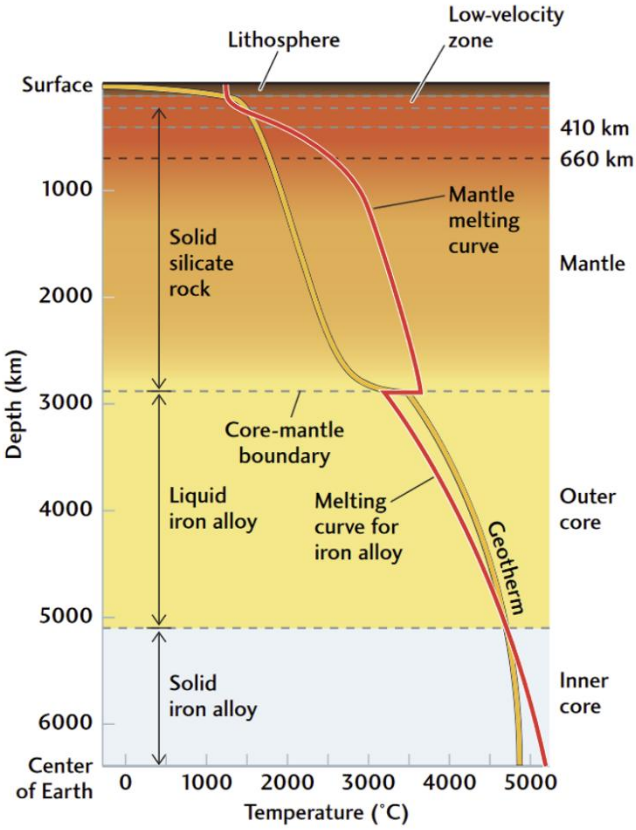
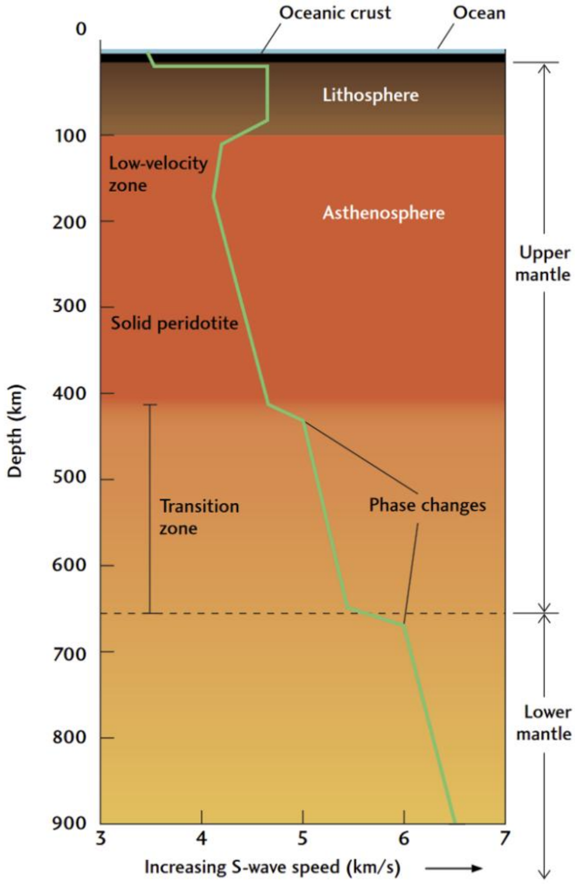
- **Seismic waves**: The shear modulus of the mantle has temperature-dependent components, so P and S wave velocities can allow us to determine the temperature of the mantles.
  - Furthermore, a low velocity zone at the upper asthenosphere imply that mantle material is partially molten, so the solidus is intersected by the geotherm.
  - At deeper depths, there is a sudden increase in velocity -> phase transition occurred (compaction of olivine ==> wadsleyite & ringwoodite). Using high-*P*, *T* experiments in labs, we can tell the temperature which this occurs.





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7. What evidence is used to determine the structure and composition of Earth's interior? How might we estimate the structure and bulk composition of planets a) in the solar system, and b) that orbit other stars?

Overview – Earth's Structure

- Compositional boundary: Crust, Mantle (upper mantle mostly peridotite), Outer core (liquid; mostly Fe-Ni, also light elements), Inner core (solid)
- Mechanical boundary: Lithosphere (brittle) vs Asthenosphere (ductile)

Evidence for internal structure & composition of the Earth

- **Seismology**: Shear (S) and compressional waves (P). Non-linear d-t dependence shows continuous refraction (Snell's law) => gradual change in material composition.
  - Moho – crust-mantle boundary
  - P wave shadow zone & S wave shadow zone ($v_s = \sqrt{\text{shear modulus / density}}$) shows that 1. outer core is liquid and 2. velocity change at the core-mantle boundary
  - Certain Earth vibration normal modes can only be explained by a solid inner core; PKJKP (where P waves turn into S waves at inner core) waves are theoretically predicted for a solid inner core, but controversial due to low amplitude
  - Using seismic tomography, create a 3D model of seismic velocity structure, determine radial dependence of material properties
- **Magnetism**: Earth has a magnetic field like dipole field. Created by self-sustaining dynamo, and thus requires conducting liquid metals in outer core (too hot for ferromagnetism; Curie's law).
- **Rotational Inertia**: Earth's rotational moment of inertia is kMR^2, where $k \sim 0.3$, showing that the density is concentrated at the centre.
- **Differentiation**: Iron meteorites give insights into elements that might be in the core, but these meteorites are products of low-pressure differentiation (from the same planetary nebula), whereas the Earth's core likely formed under markedly different conditions.
- **Mantle composition**: Upper mantle is mostly peridotite. Xenoliths from the mantle are mostly peridotite. Oceanic ophiolites contain peridotite near the base. Peridotite partially melts to form basalts at MOR.
  - High P-T experiments show that compaction of olivine ==> wadsleyite & ringwoodite in deeper parts of the mantle.

Other Planets in Solar System

- Space missions: Determine seismic waves in Mars, Gravitational (shape of the geoid, denisty & elasticity of the interior) & Magnetic fields (properties of the core) of other planets known (e.g. *Juno* determines that Jupiter's interior isn't evenly mixed so its core might be a heterogenous mixture.)
- Terrestrial planets tend to have a similar structure as the Earth, use Earth as a template
- Spectroscopy of gas giants tell us that mostly H and He. Equation of states are used to determine phase of material inside interior. Most gas giants have a core made up of metallic hydrogen (H behaves like a metal)

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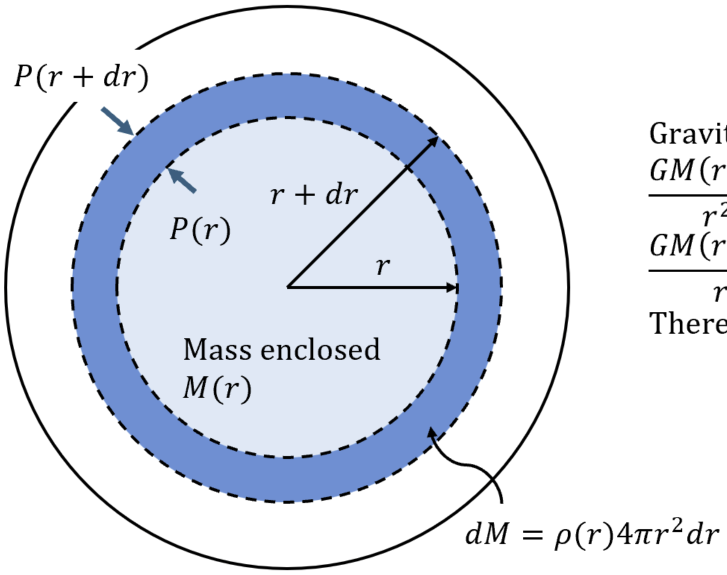

Gravitational force = Pressure gradient force

$$\frac{GM(r)dM}{r^2} = [P(r) - P(r+dr)]4\pi r^2$$

$$\frac{GM(r)\rho(r)}{r^2} = \frac{P(r) - P(r+dr)}{dr}$$

Therefore,

$$\frac{dP}{dr} = -\frac{GM(r)\rho(r)}{r^2}$$

Exoplanets

- Mass (doppler shift), Size and distance from the star (Transit method); compare with a known exoplanet curve, classify as terrestrial, icy giants, gas giants...
- Spectrum of the star will give an idea of the elemental composition of protoplanetary material => numerical modelling of equation of states to get the compositional profile inside

Miscellaneous

1. You are a geologist assigned to study a coastal region of Antarctica that shows evidence of recent volcanism and earthquakes associated with rifting. Describe the effects that are likely to have controlled relative sea-level change in this region over the Cenozoic. Discuss the size, areal extent and time characteristics of each of these effects, using examples from elsewhere on the Earth to justify your arguments.

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Geology beyond the Solar System

Typicality of our Solar System

9. What methods are used to detect and characterise exoplanets? In light of such studies, discuss how typical our solar system appears to be

Transit method

- Difference in perceived brightness of a star as a planet orbits.
- Light is blocked when planet passes in front of sun (eclipse) and extra light is reflected when planet is behind sun but not directly blocked by it (secondary eclipse)
- Orbital period: time taken for graph to repeat
- Size: percentage of light which is blocked
- Composition: Wavelengths of light specially absorbed by planet during the eclipse (contrasting with light received during non-ecliptic stages)
- Used when planets are close to host star.
- Limitation: When telescope out of plane with system, no ecliptic stages detected.

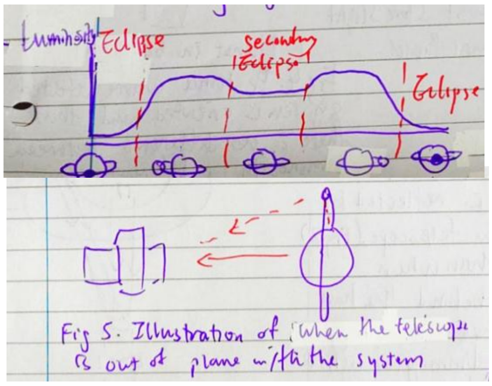

Fig 5. Illustration of when the telescope is out of plane w/ the system

Radial velocity

- Planet orbits host star -> exerts gravitational pull, star moves closer/farther away.
- If star moves away -> red shift of spectrum of light emitted by star.
- Calculate mass of planet by the gravitational pull it exerts on the star (proportional to the shift the star experiences)

Direct imaging

- When planet is resolvable from host star
- Captures light scattered by planets directly
- Planetary system must be close to be resolvable; planet must have high luminosity.

Is our solar system typical?

- Most solar systems have one or two planets;
- Solar system not fully atypical, as TRAPPIST system has 7 planets.
- Lacks hot Jupiters (gas giants close to host star) or super Earths (rocky planets larger than Earth but smaller than Uranus) which are commonly found in other systems.
- May have bias towards detecting these planets via methods described above (favours high luminosity, large planets) so maybe solar systems without these aren't that atypical
- Presence of habitable zone (insolation -> liquid water on surface)
- TRAPPIST also has habitable zone with 3 planets in it
- Only 1 star in solar system; 85% of stars are in binary star systems, so theoretically 1 star systems should be rare
- Solar systems are more prevalent if only one star is present.

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Planet formation

B7. By comparison to exoplanets, does the solar system architecture appear to be universal template for planet formation? What are the key similarities and differences, and how might these impact the prospect of life in these extra-solar systems?
10. Discuss the differentiation processes responsible for the large-scale structure of the Earth since its accretion. How will a planet's mass and accretion age affect its differentiation history?

Habitability, climate of exoplanets

2. An exoplanet has been discovered by the transit method. For this system, explain:
(a) how the concept of energy balance can be used to define the habitable zone around the star;
(b) how accurate an estimate of the average surface temperature of the exoplanet the energy balance approach provides, using illustrative examples from the solar system where appropriate; and, (c) what additional observations could be made, given existing technology, to further characterise the climate of the exoplanet.

7. How does a planet's composition affect its habitability? How is habitability compromised for planets a) just inside the inner edge of the habitable zone, b) at the outer edge of the habitable zone.

CHNOPS as bioessential elements [10]; H as forming liquid water oceans and warming the planet [10]; C as an important greenhouse gas and climate regulator [10]; Fe to form a core, geodynamo and protective magnetic field [10]; Use the energy balance equations to support answers that focus on the climatic requirements for life. [20]; The second part focuses specifically on the climate side, asking the students to identify the consequences of increasing and decreasing stellar insolation in terms of climate feedbacks. a) runaway greenhouse through ocean evaporation [15]; b) runaway icehouse through CO2 condensation. [15]; 1st class answers might think about the atmospheric composition resulting from a or b [10]. Out of 100.

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Earth's Climate System

5. Using the concept of global energy balance, account for the global average temperature at the Last Glacial Maximum (LGM). How can you reconcile your account with the Milankovitch theory of the ice ages, given that global average insolation at the LGM was similar to the present day?

Energy balance at LGM

- LGM was ~20 ky ago when global average temperature was ~6 K colder than now. -> both outgoing and incoming radiations low (energy balance equation & diagram)
- High albedo -> ice covered larger extent of the planet (both cause and effect) and reflects light more than oceans and land. Engages in positive feedback where high albedo encourages negative climatic forcing and formation of ice sheets.
- Also, high emissivity (due to low CO_2 content), but the lower σT^4 compensates for it. Again, a positive feedback as lower T -> higher ocean CO_2 solubility -> even less CO_2
- These feedback are fast on the scale of kiloyears, but they must have been balanced by the deglaciation factors (which we are not too sure even today) to give $dT/dt = 0$

Milankovitch's Theory

- Global average insolation today is similar to at LGM because the average Sun-Earth distance is almost the same (conservation of orbital energy), so the solar constant is about the same ($L_{sun} / 4\pi D^2$). The difference is the uneven spatial-temporal distribution of temperature.
- Milankovitch's Theory relies on 65° North insolation (controlled by astronomical factors)
    - **Summer**: always cold enough to snow in winter, accumulation of snow depends on degree of melting in summer
    - **65°**: Plate tectonics resulted in a lot of land at this latitude -> low heat capacity -> sensitive to local insolation change -> continental ice sheets
    - **North**: Not much land at 65°S
- This means at LGM, even though overall insolation remains generally constant, insolation at 65N changes as a function of obliquity and precession.
- At LGM, more land at 65N -> 1) available for ice sheets to be constructed 2) more land -> higher albedo than water -> Ein decreases -> T decreases at that latitude -> at summer, cannot melt ice -> (Although the difference is <5%) glaciation; high ice sheet volume.
- Despite the small difference, was amplified by the aforementioned positive feedbacks so leads to the temperature difference -> no contradiction in astronomical theory.

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7. Discuss the differences in the Earth's radiation balance during glacial and interglacial stages of the Quaternary, including the roles of orbital geometry and climate feedbacks in altering the budget. How would these differ in a world with no ice sheets?

Overview of Earth's radiation balance

- Incoming: short λ solar insolation S_0 + effect of the surface albedo α – % of radiation reflected into space
- Outgoing long λ radiation (Stefan-Boltzmann law σT^4), reabsorbed and emitted back to surface by GHG - emissivity ε: fraction of emitted rays that make it out
- Balance of the two give the equilibrium T.

Orbital geometry

- Based on Milankovitch's theory: even though solar insolation is roughly constant, global climate is controlled by ice sheet volume, controlled mainly by solar insolation at 65 N in summer (always cold enough to snow in winter, melting is variable; continental ice sheets the least stable and there is plenty at 65 N)
- Fourier transform of temperature proxy (d18O) records in marine sedis (23ka, 41ka, 100 ka) match precession, obliquity & eccentricity cycles of the planet. (Note that precession has another component at 19ka which is matched in the records too)
- Orbital conditions at glacials and interglacials:
  - Both: highly eccentric orbit
  - Low obliquity at glacials but high obliquity at interglacials
  - Precession: determines the tilt towards the Earth changing relative timings of seasons. Summer at perihelion (interglacials) vs at aphelion (glacials)

Role of climatic feedbacks

- Explains why ice sheets so important; and why orbital variations end up being amplified into large temperature changes
- ice-albedo feedback: since ice ($\alpha \approx 0.8$) is much more reflective than land ($\alpha \approx 0.2$) or the oceans ($\alpha \approx 0.05$), the growth of ice sheets will reduce Earth's albedo and lower its temperature further, creating a positive feedback loop. This could be enough to sustain glacial conditions across multiple precession cycles until another feedback tips the climate back to an interglacial state.
  - When we transition between the two states, the climate system reaches a tipping point in albedo (hysteresis)
- CO2 feedback: The exsolution of the greenhouse gas CO2 from the oceans at higher temperatures also acts as positive feedback, reducing Earth's emissivity and raising temperatures further
- Biological feedback: Higher CO2 and T -> higher productivity -> higher rate of removal of CO2 from the atmosphere and increase ε (but factors affecting productivity is very complicated, e.g. ocean circulation)

World w/o Ice Sheets

- In a world without ice sheets, the albedo of the surface will be lower, so we would expect a warmer earth in general (similar to early Palaeocene / Eocene / Triassic ; likely hothouse Earth) (also consider the methane stored in the permafrost)
- In a world without ice sheets, the theory of Milankovitch will render less useful as ice-albedo effect no longer occurs
  - Other effects e.g. oceanic CO2 sink more important (esp. When water volume is greater), or land-based sink as there are much more terrestrial environments for plants and animals, or other longer-term feedback play a bigger role (e.g. silicate weathering)
  - Overall, the *climate sensitivity* of the planet Earth is lower, so cyclic variations in climate are less pronounced (it is doubted whether that would happen at all –

but still orbital geometry may affect global low-altitude circulation patterns periodically).

7. Discuss how evidence of past climate change preserved in the geological record is relevant for assessing present and future climate change resulting from human activities.

Overview of Past Climate Change and its evidence (not the focus):

- General hothouse / warmhouse Earth in Palaeocene and early Eocene; Cooling during Cenozoic; oscillations between glacials and interglacials in Quaternary
- Climate change before (in Mesozoic and before) is much more unclear
- Evidence in d18O in marine sediments (foraminifera) and ice sheets. Vibrational energy level (given quantum number) depends on mass of isotope – bonds with lighter isotopes weaker and easily broken – evaporate readily – most 16O trapped in glaciers. -> d18O is proxy of ice volume, i.e. temperature
- Past Global emissivity / GHG concentration in the Cenozoic: Mainly from trapped CO2 in ice cores, phytoplankton, stomatal density, Boron proxies...

Relevance to Present / Future Climate Change

- Anthropogenic increase in CO2 concentration that might result in doubling of CO2 concentration (depending on the IPCC predictions); An unprecedented rates of climate change
- In some scenarios we can see the geobiological effects of a warmer Earth similar to previous warmhouses (e.g. Mid-Cenozoic; SSP 2-4.5), or hothouses (e.g. Early Eocene & Mid-Cretaceous; SSP 5-8.5)
- **Equilibrium temperature**: These warm periods serve as upper limits (under recent geological circumstances) for the Earth and therefore determine the sensitivity of the Earth to changing ε (and GHG conc.).
- **Feedback**: Understand how different timescales and strength the feedbacks are. Palaeoclimate data helps numerical models to simulate the relative effects of feedbacks; e.g. land ice, carbon cycles, deep ocean feedback may be of centuries / millennia, but albedo, methane, shallow seas feedback could be much quicker. Help inform policy making and understanding the climate up to near future e.g. 2100
- **Ice sheets and Eustatic sea level changes:** Paleoclimate records help to reaffirm model of hysteresis of ice sheets: When ε increases and reaches a critical point, sudden drop in ice sheet volume, different behavior when Earth is cooling. => help understand the tipping points to anthropogenic CC.
    - Antartica ice sheets are formed at late Eocene (Tasman gateway); Sea ice at Arctic formed near end of Miocene. Cryosphere stability can be seen.
    - Geomorphology can also inform us of eustatic sea level changes due to melting ice sheets; hence understand relate the two and know how future climate
- **Effect on ecosystem:** Understand the effects of climate (temperature, precipitation, seasonality) on ecology worldwide through fossil records; e.g. extinction rates; migration; speciation.
    - e.g. increased natural selection rate for species stuck in suboptimal habitats compared to those with access to a habitat corridor under CC.
    - e.g. resilience of palaeoecological communities depends on their access to dispersers from other similar environments
    - e.g. sensitivity of coral reefs to climate change in the Phanerozoic
- **Limitations**: The rate of change of climate due to human effects is of a much shorter timescale. We can only assume CC depends on CO2 concentration, less so on its rate of change. Therefore understanding feedback is especially important.

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B1 Increased emissions of greenhouse gases by human activities are rapidly altering Earth's climate. How can the study of past climates help us anticipate the future response of our climate system to anthropogenic radiative forcing?

See earlier essay; basically, the same except we can write less about the records.

3. Why is summer insolation at 65 degrees north latitude such a critical metric of global climate state during the Pleistocene (the most recent 2.5 million years)? What observational constraints in palaeo-climate archives have been used to test this?

Summer insolation at 65 degrees north

- **Summer**: The summer months are singled out because at high latitudes it always cold enough to snow in the winter, so the year-to-year accumulation of snow necessary to build a large ice sheet is likely to be controlled by the amount of melting in summer. ⇒ formation of continental ice sheets
- **65 degrees North**: Three reasons:
    - In the current tectonic state of plates, the amount of land at this latitude is large. As land has a lower heat capacity than the oceans, the temperature is sensitive to local insolation changes.
    - The changes of insolation with season are very large at this latitude as well.
    - There's not much land 65 degrees South
- **Influence of ice sheets to climate**: ice-albedo feedback: since ice ($\alpha \approx 0.8$) is much more reflective than land ($\alpha \approx 0.2$) or the oceans ($\alpha \approx 0.05$), the growth of ice sheets will reduce Earth's albedo and lower its temperature further, creating a positive feedback loop. This could be enough to sustain glacial conditions across multiple precession cycles until another feedback tips the climate back to an interglacial state.

Observation constraints in paleo-climate archives

- The high-resolution oxygen isotope (d18O) time series of planktonic foraminifera was the first record of its kind that revealed variations in the global ice volume over the past 450 kya.
    - The record indicated that variations in the global ice volume occurred in a sawtooth pattern characterized by a 100-ka quasi-cycle superimposed by shorter quasi-cycles of 41, 23, and 19 ka, as predicted by the Milankovitch theory.
    - These periodicities were also found independently in long-term variations of eccentricity, obliquity, and climatic precession using an analytical solution of the planetary system.
    - In particular, the existence of double precession peaks (the so-called "Berger cycles" of 23 and 19 ka) in the d18O records and astronomical solutions become strong validation of the astronomi-cal theory
- Similar observations in marine records.

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Mineralogy

Optics and physical properties

2. "Crystal symmetry links the atomic-scale structure of a mineral to its macro-scale properties". Discuss this statement with reference to the diagnostic features of common rock forming minerals.

Overview

- Crystal growth form is macroscopic expression of atomic level symmetry; Directions related by symmetry have identical properties.
- Reflectional symmetry: identical after reflection about a plane; rotational symmetry: crystal has N-fold rotational symmetry if identical to original after being rotated by 360/n; translational symmetry: identical after moving direction
- Demonstrate a selection of crystal systems and how their unit cells differ; Miller indices and how they differ across systems e.g. rhombohedral systems use 4 axes with 3 on same plane 120' to each other.

Symmetry and crystal habit

- Crystal habit: characteristic external shape of a crystal, a result of atomic scale symmetry. Planes of crystal growth related to length of unit cell vectors a, b, c. (e.g. a 111 plane is different if a=b=c compared to a!=b!=c)
- Hence cubic system forms cubic/octahedral habit, but tetragonal can't
- Limitation: while atomic scale symmetry is always expressed macroscopically, macro-scale structure cannot always be diagnostic of atomic scale symmetry. When crystal growth poisoned or bounded by surrounding crystals -> natural growth shape constrained -> euhedral crystal shape does not form.
- E.g. Quartz: trigonal crystal structure, euhedral crystal hexagon; anhedral in rocks because last to crystallize in between other minerals.

Symmetry and physical properties

- Faces of single crystals form on certain planes *allowed by the symmetry of lattice.*
- Twinning occurs on along the most energetically favourable planes, where the two lattices are most coherent. Twin law – operation which transfers symmetry elements of one crystal to another connected crystal of diff orientation, constrained by symmetry of unit cell. lattice points in one crystal are shared as lattice points in another crystal adding apparent symmetry to the crystal pairs.
- Mechanical properties of minerals: symmetry allows cleavage planes to occur. E.g. Mica structure symmetrical about plane of weakness (001) -> allows perfect cleavage. Pyroxene structure translationally symmetrical about cleavage plane -> cleavage. Directions related by symmetry have identical properties -> infinite parallel cleavage planes of same direction.
- Conchoidal fracturing – no symmetry & preferred cleavage, breaks along random planes
- Anisotropic hardness: stronger bonds in 1 direction infinitely translated -> macroscopic differences in hardness, e.g. kyanite hardness 001 >> 010

Symmetry and optical properties

- Cleavage planes reflect light. Repetition of atoms about a lattice -> plane of atoms with same reflective properties -> additive at some angles. E.g. calcite
- Striations -> cleavage planes related to twinning, e.g. albite twinning
- Minerals with birefringence e.g. calcite exhibit double refraction. Calcite trigonal, anisotropic, planes of CO_3^{2-} and Ca^{2+} arranged in a planar fashion. Light vibrating at permitted direction parallel to CO_3^{2-} has very high RI, whereas orthogonal direction low RI. Light rays split into components with one travelling at a slight angle to the other. This causes 2 distinct rays.
-

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2. Describe the crystal structure of the pyroxene group of minerals. Explain why crystals of pyroxene, when viewed in thin section with the polarising microscope, exhibit (a) different colours in plane polarised light, and (b) different colours in cross polarised light.

Pyroxene – monoclinic (clinopyroxene) or orthorhombic (orthopyroxene)
Monoclinic = a!=b!=c, with b>90, no sym. Orthorhombic = a!=b!=c, a=b=c=90, 3 diads.

3. By contrasting a pyroxene and a mica, explain how and why
a) birefringence,
b) cleavage, and
c) colour in plane-polarized light
are related to **the orientation** of the crystal in a thin section under a petrological microscope.

See 1B guide for reference

8. Compare the optical properties of minerals that can be observed using a petrographic microscope in plane polarised light with those that can be observed under crossed polars. Explain how optical properties can be used to help identify different minerals. How would we use these properties to distinguish between orthopyroxene and clinopyroxene?

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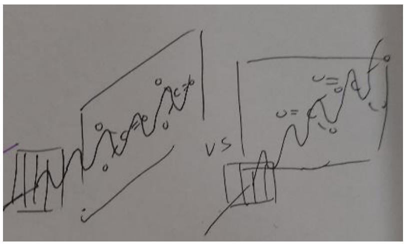
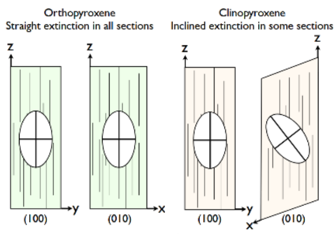
4. Discuss how the physical and optical properties of **minerals** are controlled by their crystal structures. How might we use this to distinguish between clinopyroxene and Orthopyroxene?

Ultimate essay plan for pyroxene (Clino on left, ortho on right)

Crystal structure	
Monoclinic. a = b ≠ c; α = γ = 90°, β ≥ 90°, 1 diad	Orthorhombic. a ≠ b ≠ c; α = β = γ = 90°, 3 diads.
Crystal cleavage and symmetry	
Crystal growth form is macroscopic expression of atomic level symmetry; Directions related by symmetry have identical properties. Pyroxene structure I-beams. Translationally symmetrical about cleavage plane -> cleavage. 2 cleavages only observed on basal sections (001); 1 cleavage otherwise (100, 010). Both pyroxenes exhibit this property.	
Optical features under plane polarized light	
Relief: Contrast of crystal edge with the surrounding medium, owing to a **difference in refractive indices** between the crystal and the medium. In pyroxene, all vibration directions have higher RI than the medium, so both ortho and clinopyroxene have +ve relief. Pleochroism: Colour change resulting from the composite absorption of light of specific wavelengths by atoms in mineral lattice in different directions (by rotating the stage). Refractive index of light changes as light vibrates either parallel or perpendicular to the silicate I-beams. SiO4 tetrahedra. Colour observed – complementary to wavelength of light absorbed. Note: Colour depends on thin section thickness. 	
Colourless to very pale browns or greens, but usually non pleochroic. Uniaxial minerals may have 2 colours.	Colourless to pale green. Biaxial minerals may have 3 pleochroic colours.
Optical features under crossed polars	
Birefringence = light having different refractive indices when passing through the permitted vibration directions of a crystal. $\Delta n = n_e - n_o$. Different RIs represented via indicatrix. Symmetry of the indicatrix must at least match the symmetry of the crystal. As the crystal is rotated, the orientation of the crystal varies and the light entering will vary in speed, which means that the sum of light will vary as you rotate the stage. Extinction = function of relationship between indicatrix orientation and crystallographic orientation. If permitted vibration directions coincide with crystallographic axes, then parallel extinction results.	
1 diad, thus biaxial. Crystallographic axis parallel to y (the diad) by convention, but indicatrix is not. The indicatrix orientation is free to rotate about the y axis, and the rotation angle is often diagnostic of a given mineral. Inclined extinction thus results. Note that sections involving the y/b axis will still have straight extinction; only the b (xz) plane is misaligned.	3 diads, thus biaxial mineral. Crystallographic axes coincide with indicatrix axes;  Fig. 57

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B6 How does the interaction of polarised light with minerals depend on crystal symmetry? Explain how this interaction can be used to distinguish garnet and pyroxene in thin section?

Inclined extinction occurs when the long axis of the mineral is at an angle to the crosshairs either NS or EW

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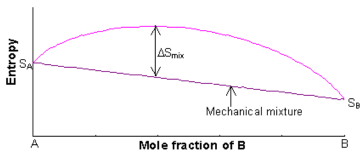
3. What factors control the ability of a mineral to form a solid solution? Illustrate your answer with examples of minerals that tolerate a) extensive solid solution, b) very little solid solution, and c) variable degrees of solid solution.

Solid solution: *single phase* which exists over a *range of chemical compositions*

Ionic size and properties

- Atoms / ions have similar size -> extensive solid solution (fit in lattice without rattling)
- Draw diagram of cation in anion lattice & demonstrate ideal radius R+/R- for 2D, 3D.
- Cation coordination vs radius ratio. (Cubic -> octahedral -> tetrahedral -> triangular)
- Goldschmidt's rules: Substitution can tolerate 15% size diff & +-1 charge.
- E.g. Mg^{2+}, Fe^{2+} have size mismatch of only 7% -> extensive solid solution (e.g. Olivine)
- Mg^{2+}, Ca^{2+} have 32% size mismatch -> difficult to accommodate.
- **Substitutional** solid solution. E.g. Olivine (Fayalite (Fe) -> Forsterite (Mg))
- Atoms / ions may substitute others of different charge; needs *coupled* substitution to maintain charge balance. E.g. $Na^{+1}Si^{+4}$ <=> $Ca^{+2}Al^{+3}$ in plagioclase
- 2 cases where substitution cannot occur: atoms have High Field Strength (HFS) - Small but too polarising or Large ion lithophile elements (LILE) - too large to substitute
-

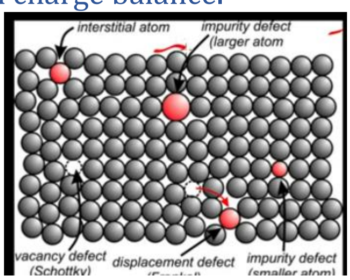
Thermodynamics



- Dependent on Gibbs energy
- Solid solutions have higher entropy than endmembers due to increased entropy; high temperatures -> high KE of ions in lattice
- $\Delta S_{mix} = -R(x_A \ln x_A + x_B \ln x_B)$; x_a and x_b are mole fractions, >0 for x_a, x_b<1
- Ideal solid solution, $\Delta H_{mix} = 0$; ΔG always negative for all T.
- ΔH_{mix} determined by comparison of bond enthalpies A-A, B-B vs A-B in a system.
- When $T\Delta S$ decreases, ΔG decreases; mixing may no longer be favourable for systems ΔH>0.
- Exsolving occurs when limited solid solution is favoured in a highly mixed mineral
- E.g. alkali feldspar form complete solid solution at high T, but at low T limited -> lamellae of albite-rich feldspar grow within orthoclase-rich feldspar -> *perthite texture*
- In contrast, plagioclase feldspar form complete solid solution at any T

Crystal structure, flexibility and bonding

- Structure flexibility -> open vs tightly packed crystal structure; open structures can accommodate abnormally large sized ions; e.g. CaO = MgO solid solution not tolerated, but complete in garnets. (Ca3Al2Si3O12 - Mg3Al2Si3O12).
- Structure may have sites not normally occupied by ions – void spaces. Ties into charge balance: e.g. in amphiboles, tremolite - $Ca_2Mg_5Si_8O_{22}(OH)_2$, if Al^{+3} replaces one of the Si^{+4} ions then Na^{+1} can go into a site that is normally vacant to maintain charge balance.
- When occupied by ions -> **interstitial** solid solution.
- Bonding: Quartz Si-O strong network of covalent bonds, i) lacks interstitial spaces ii) atoms rigidly linked, cannot tolerate differences in size iii) high energy needed to disrupt Si-O bonds



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Igneous rocks, Volcanoes and metamorphic rocks

Igneous rocks and volcanoes

6. What controls the distribution of volcanoes on Earth? Why does continental crust contain a wider range of igneous rocks than oceanic crust?
4. The vast majority of volcanic activity on Earth occurs at mid-ocean ridges. Explain why this is so. Why are almost all magmas that are erupted at ridges basaltic in composition, whereas magmas erupted elsewhere show a much wider compositional range?

B3 What are the processes by which (a) basalts and (b) granites are formed? Explain why granites are almost entirely confined to the continental crust.

Magma generation proportional to **adiabatic decompression**

Volcanic activity at mid-ocean ridges

- Mid-ocean ridges form as a result of stretching and thinning of crust (usually triggered by arrival of mantle plume leading to divergent plate motion). When the crust is totally broken apart, the ridge is formed. E.g. Mid-atlantic Ridges,
- Afterwards, mantle upwelling (pressure gradient), adiabatic cooling leads to partial melting of mantle (decompression melting).
- Draw the intersection of the temperature profile with the solidus

Why Volcanic activity is the greatest at mid-ocean ridges

- Thinned crust reduces distance required for melt to reach the surface (30 km vs 10 km) (given ascent rate of ~50m per year, only need 200 years to reach the surface), especially when fractures in the stretched surface are common (sheeted dyke complex) compared to subduction zones.
- Mid-ocean ridge melting is often the combination of the action of mantle plumes and crust stretching, so altogether increases the rate. The global MOR system generates over 21 km^3 of magma a year - more than all other tectonic settings combined.
- Mid-ocean ridges have a quick rate of mantle upwelling (owing to the mechanism of magmatic focusing), and hence the supply of mantle is quick. The seafloor spreading rate is higher e.g. Mid-Atlantic Ridge 5 cm/year

Magmas that erupted at ridges basaltic in composition vs erupted elsewhere (wider compositional range)

- Magma at ridges draws source material directly from the mantle, which is mostly peridotite. Peridotite (Aluminous lherzolite) = olivine + orthopyroxene + clinopyroxene + spinel
- Basalt = clinopyroxene + plagioclase + minor olivine (due to high melting point of olivine it is removed)
- Melting of continental crust at other places involves not only mantle melting, but the rise of magma also leads to melting of country rocks (assimilation). Furthermore, the rising magma might be stopped, and fractionation towards silicic compositions. Therefore, the acidity of the rock has higher variability.

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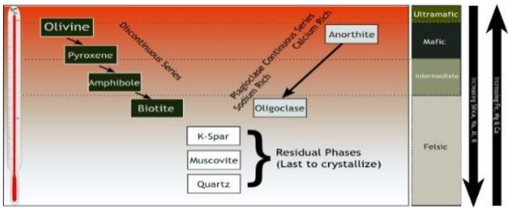
3. What controls the style of volcanic eruptions? Why are explosive eruptions rare at mid ocean ridges and in rifted environments but common at destructive plate margins?

Overview



- Silica content affects magma viscosity and eruptive style of volcanoes; Bowen's reaction series: Olivine, pyroxene, amphibole, biotite kspar & quartz.
- Fractional crystallization in crust;
- Lower temperatures are also more viscous
- More SiO_2 -> more polymerization, more viscous, gas cannot escape from felsic magmas due to increased surface tension-> explosive.

Mid ocean ridges

- Magma at ridges draws source material directly from the mantle - mostly peridotite. Peridotite (Aluminous lherzolite) = olivine + orthopyroxene + clinopyroxene + spinel
- Magma comp: pyroxene + plagioclase + minor olivine (high MP of olivine -> removed)
- Few Si-O bonds, not much polymerization, non viscous. Gas escapes easily.
- On land: (effusive eruptions, e.g. Grindavik. Eruption style - pahoehoe lava, doesn't crystallize during flow, forms shield volcanoes & a'a lava, crystallizes)
- Under water: Water invades magma vent -> transfer of heat flashes water to steam; while quenching magma into pillow basalts. Forms *chilled margin*; e.g. *Arran*
- **Exception:** basaltic volcanism in **shallow water** can be highly explosive
- Water invades magma vent -> transfer of heat flashes water to steam; expansion of water quenches magma, **thermal contraction of magma** shatters into fragments, explodes, creates beds of glassy *tuff*
- **Phreatomagmatic** eruption, e.g. Surtsey (Iceland)
- Does not happen in submarine (submarine too high pressure -> no shattering)
- **Exception:** mid ocean ridge eruptions may be felsic if under mantle plume.
- e.g. Hekla volcano (Iceland) silicic; theories for why involve i) extensive fractional crystallization of basaltic melts ii) partial melting of country rock. **Plinian** eruption.

Destructive plate margins

- Subduction zones: increased P, T in descending slab *expels water* from hydrated minerals (e.g. amphibole -> pyroxene + h2o), water decreases solidus, promotes partial melting and magma differentiation.
- Magma needs to get through 30 km of continental crust instead of 10 km of oceanic
- Stalls and cools in crust, leading to *fractionation*; cite rxn series, more Si-rich. Lower temperature -> higher viscosity
- Assimilation of continental crust via *stoping* & wet mantle -> many volatiles
- High magma viscosity -> bubbles cannot escape due to surface tension
- Explosion when magma loses strength; shatters lava into fragments & glass shards
- Produce large volumes of fine ash, entrains surrounding air, creates eruption column
- When energy of eruption column wanes and cannot sustain, base of column collapses to form incandescent cloud of ash & debris -> *pyroclastic flow*. **Plinian** eruption, e.g. Mt St Helens.

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9. Describe the controls on the rise height and behaviour of volcanic eruption columns during explosive eruptions. How can resulting ash deposits be used to quantify eruption parameters?

Resulting ash deposits

- volcanoes erupt explosively, lava, rock, ashes etc. -> atmosphere, solid parts (*tephra*) cool into rocks with *pyroclastic* textures.

- **Column height is proportional to the fourth root of the mass eruption rate.**

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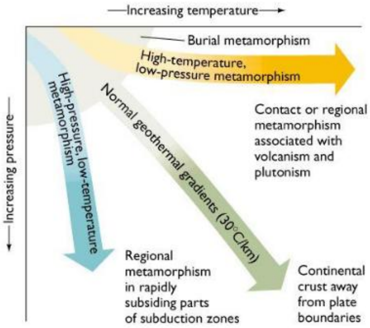
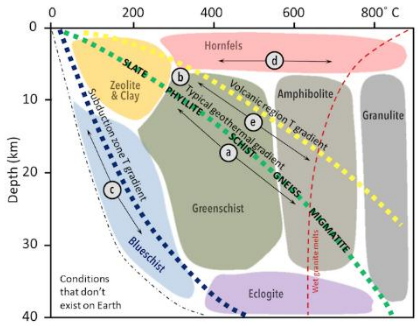
4. Explain, using sketches and examples, how the mineral assemblages and textures preserved in metamorphic rocks formed during continental collision differ from those produced during contact metamorphism. Under what circumstances might melting of the country rocks occur in these two environments?



Overview

- Metamorphism: Subsolidus process where rock changes composition, tending towards stable equilibrium at new pressure and temperature. **Solid-state recrystallization.**
- Metamorphic rock composition not only dependent on protolith composition, but also metamorphic process: i.e. pressure, temperature, time, hydration, stress field.
- Metamorphic mineral assemblage indicates metamorphic grade of rock
- Metamorphic facies: range of P-T conditions that produces distinctive looking rocks.
- Melting of rock: when metamorphic grade is too high -> igneous rocks are created.

Continental collision



- Oceanic crust higher density than continental; subduction.
- Passive margins associated with oceanic crust collide into continental crust. As they have same density and mantle is denser, it isn't possible for passive margins to subduct, and they collide to form an overthickened stack at higher pressure -> **crustal thickening.**
- Prior to collision, passive margins may be limestone, sandstone or pelite. Limestone -> marble; sandstone -> quartzite; pelite (shale) -> gneiss. (>60% aluminosilicate from protolith composition)
- Under **normal P/T gradient** -> **Barrovian** metamorphism e.g. India
- Under **low P/T gradient** -> **Buchan** facies e.g. Buchan, Scotland; may involve secondary heating via a magma source (volcanic), but still has enough pressure to not be contact M
- Please read the 1B guide for a more accurate answer
- Migmatites may also form by intrusion of granitic magmas into mafic country rocks.
- If temperature too hot -> melting, becomes magma (granite) again, igneous rock.
- Melting depends on temperature: wet rock melts at lower T than dry granite.

Contact metamorphism

- Intruding magmas heat crustal rocks very near the surface; **low P/T gradient.**
- Hornfels: fine-grained metamorphic rock without visible crystals, **massive texture,** no foliation. Different facies: zeolite -> hornfels. Different index minerals e.g. andalusite.
- Basalts emplaced at any depth have an aureole (and may induce partial melting if the intrusion is sufficiently large, or if there is significant flow of magma within smaller intrusions such as sills or dykes)

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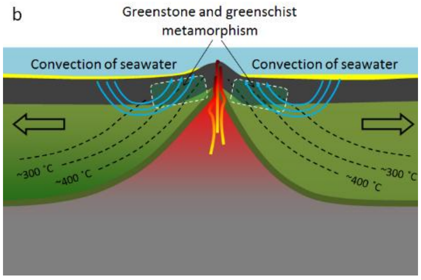
5. Explain how a basalt's mineralogy and texture may be transformed by metamorphism from its formation at a mid-ocean ridge, to its subduction back into the mantle. How is information on the metamorphic conditions experienced by a meta-basalt preserved in the rock during transport back to the surface?

- Please read the 1B guide for a more accurate answer

Overview

- Metamorphism: Subsolidus process where rock changes composition, tending towards stable equilibrium at new pressure and temperature
- Metamorphic rock composition not only dependent on protolith composition, but also metamorphic process: i.e. pressure, temperature, time, hydration, stress field.
- Metamorphic mineral assemblage indicates metamorphic grade
- Basalt minerals formed at high temperatures, unlike pelites; thus, new minerals develop as basalts are placed at low temperatures. *Retrograde metamorphism.*
- Metamorphic facies: range of P-T conditions that produces distinctive looking rocks.

At mid-ocean ridges



- Recently formed gabbro and basalt spreads away from heat boundary. Water within crust near source of volcanic heat rises, creates convective system where cold seawater is drawn into crust and exits near the ridge -> constant supply of water for hydrothermal reaction.
- **Retrograde metamorphism**: Early metamorphic minerals have hydrothermal origins; water alters mineral assemblage into hydrated forms

Facies	P/T	Minerals (index mineral in bold)	Texture
Zeolite (disappears completely at 200 °C)	LPLT (below 200 °C)	**Zeolite** (index mineral of many different types, aluminosilicate, often indicates precise conditions of metamorphism, requires mineral analysis)	Basaltic texture preserved, fills amygdales.
Greenstone/ Greenschist	MPMT	Amphibole (actinolite), **chlorite**, epidote; green, gives green color.	Greenschist foliated; greenstone unfoliated.
Amphibolite	HPHT	**Amphibole (hornblende),** plagioclase, garnet, quartz.	Salt and pepper appearance, some foliation.
Granulite	Highest	**Pyroxene**, plagioclase, garnet, quartz.	May exhibit gneissic banding

- Texture often not seen due to low pressure AND **absence of micas** -> no obvious fabric.
- If rock shows foliations, direction of stress field orthogonal to foliation.

At subduction zones

- Oceanic crust denser than continental -> subducts.
- Oceanic crust old and cool -> takes long time to heat up, but under very high pressure.
- High P low T metamorphism: brought to surface via **rapid uplift of rocks** or **xenoliths in igneous rocks rapidly transported to surface** (e.g. kimberlites)

Facies	P/T	Minerals	Texture
Blueschist	HPLT	**Amphibole (glaucophane)** -> blue color, epidote. metamorphic process must stop BEFORE reach equilibrium & brought up to surface, hence very rare	Does not display schistosity despite the name
Eclogite	HPHT	**Pyroxene** (jadeite), garnets, quartz.	May have gneissic banding

- Eclogites may show signs of retrograde metamorphism when emplaced on surface; forms blueschists. Crystal alignment -> whether retrograde metamorphism happened

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Sedimentology

5. Contrast and explain the different lithological properties and sedimentary structures of limestones and sandstones. Why are these rock types distinct?

4. Describe the typical characteristics of sediments deposited by glaciers, rivers and the wind. Explain why these are so different with reference to the fluid properties of ice, water and air.

B2 Explain how sedimentary processes differ between shallow and deep marine environments. Using examples, describe how these processes are reflected in deposits preserved in the geological record.

6. What observations allow distinguishing between sedimentary rocks which were deposited in a marine vs a non-marine environment? Describe examples from UK geology where sedimentary sequences show cyclical changes between a marine and non-marine environment.

Superposition
Entrainment – when fluid exerts enough force on grain to move it. Bernoulli force, fluid drag.
Rolling (only drag) saltation (both) – bedload, suspended load – both + buoyancy forces.
Critical velocity – hjulstrom. As this wanes, sorting occurs. Grading.

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Paleobiology

Fossilization, taphonomy, etc

2. What factors contribute to the fossilisation of an organism?

- **Organism morphology**: organisms are likely to be preserved only if they have hard parts, a skeleton of some kind. Entirely soft-bodied organisms, such as worms and jellyfish, are only preserved in rare cases. Organism mineralogy also plays a part: e.g. calcite more stable than aragonite, so calcite organisms are more commonly preserved. (e.g. Rugosan corals vs scleractinian corals) However note that aragonite may recrystallize into calcite
- **Living environment**: Animals that live in shallow seas, or plants that live around lakes and rivers, are more likely to be buried under sediment than, for example, flying animals or creatures that live away from water.
- **Paleoecology**: Bias towards species which lived in less dynamic habitats. E.g. hard-shelled organisms are likely to be fossilized in environments without durophagous predators.
- **Environment of deposition**: some environments are typically sites of deposition, and organisms are more likely to be buried there. So, a mountainside or a beach is a site of erosion, and nothing generally survives from these sites in the rock record, whereas a shallow lagoon or a lake is more typically a site of deposition.
- **Preservation filtering**: chemical conditions must be right for the hard parts to survive. If acidic waters run through the sediment grains, all trace of flesh and bones or shells might be destroyed. Or if the sediment is constantly being deposited and reworked, for example in a river, any skeletal remains may be worn and damaged by physical movement
- **Timing of burial**: Extremely quick burial, escapes from TAZ, reduces the chance for scavenging, erosion, decomposition etc.

Examples: Pompeii pyroclastic flows (speed), Burgess Shale of British Columbia (anoxic)...

Should also include trace & chemical fossils in the answer.

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5. Fossil organisms can be difficult to classify using conventional Linnean taxonomy. Using examples, discuss how this difficulty detracts from, or contributes to, our understanding of the evolutionary process? How might taphonomy interfere with these evolutionary interpretations?
8. How might mass extinction events complicate our ability to infer phylogenetic relationships among living species?

Overview: Linnean taxonomy – linear hierarchy of **nested sets**
- Disadvantage: Does not accurately represent the **evolutionary distance b**etween groups, but rather classified based on specific synapomorphies
- Because details of fossil morphology are often not specific, synapomorphies can be based on speculation and comparative anatomy. Linnean classification is thus based on superficial, speculative details; because no DNA comparative biology, analogous structures may be classified together, a misleading evolutionary interpretation.
- Because sets of the same hierarchy have the same importance, this implies they evolved at the same time. E.g. 5 different families of trilobites. This is not true in most case
- Advantage: Binomial classification with standardized names -> easy to find species, global standardized name -> eases cooperation between scientists of different nations.

Cladistics – nested groups based on evolutionary relationships. Draw a clade diagram.
- Branches from a common ancestor -> denotes which organisms evolved from which
- Creates crown groups (and stem groups), removes possible Linnean confusion
- More than one evolutionary relationship can still branch from same point (polytomy)

Polytomy: more than 2 clades diverge from common ancestor at once
Soft polytomy: arises from uncertainty (maybe organisms evolved consequentially very quickly, thus not enough synapomorphies accumulated to distinguish sequence of evolution and seems like they evolved together)
Hard polytomy: Certain that 2 or more clades diverged at the same time (e.g. adaptive radiation)

Taphonomy: Use previous essay plan.
- Organism morphology
- Abiotic environmental factors
- Biotic environmental factors

Stem group organisms useful for deducing how traits arise (diverged earlier than crown groups by definition).

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6. Using at least two examples, discuss how evolutionary innovations have affected the global carbon cycle over the past 500 million years. How has this altered Earth's surface environment?

Terrestrialisation of plants:

- Devonian / Silurian explosion of large-scale plants with vascular systems
- First ferns; first trees. e.g. Rhynie chert. (Large spore-bearing plants w/ vascular)
- Large trees came in the late Devonian w/ vascularised leaves and seeds
- Influence on carbon cycle:
    - Gas exchange drew CO2 from the atmosphere through photosynthesis -> Palaeozoic decrease in CO2 -> suspected to cause a late-Devonian ice age
    - Photosynthesis led to C trapped in biomass (e.g. carboniferous coal swamps and cyclotherms in Arran) and eventually buried in the ground after decomposition
- Silicate weathering: Development of extensive root systems led to enhanced chemical weathering of silicate rocks
    - $CaSiO_3 + 3 H_2O + 2 CO_2 \rightarrow Ca^{2+} + 2 HCO_3^- + H_4SiO_4$
    - (Ocean) $Ca^{2+} + 2 HCO_3^- \leftrightarrow CaCO_3 + CO_2 + H_2O$
    - Net removal of 1 CO2 and ultimately stored as marine carbonate.
- Other surface effects:
    - Consolidation of sediments -> prevents erosion -> more fine-grained sediments e.g. silt, clay appearing in the sedimentary rock records
    - Organic accumulation in soil -> reduction of Iron(III) -> iron-poor, C rich sediments.

Evolution of Coral Reefs

- Gradual evolution of reef builders: corals from the early Cambrian to Ordovician; corals enter photoendosymbiotic relationship (mutualistic) with unicellular dinoflagellates – so-called zooxanthellae around 200 million years ago
    - Calcite exoskeleton of corals for protection in exchange for photosynthesis
    - Positive feedback led to growth of coral reefs
- Other marine photoplankton like coccolithophores evolved (late Triassic).
- Influence on carbon cycle:
    - Oceanic biological pump: CO_2 is absorbed during photosynthesis and converted into organic matter. When these organisms die, their remains sink to the ocean floor, effectively sequestering carbon in deep-sea sediments.
    - Many organisms create calcareous exoskeleton e.g. coccoliths plates --> deposit of marine carbonate
    - Move biological carbonate accumulation from the continental shelves to oceanic basins, the long-term sink for atmospheric CO2 was dramatically enhanced
    - Impact oceanic pH: $CO_2^* + H_2O \leftrightarrow HCO_3^- + H^+ \leftrightarrow CO_3^{2-} + 2H^+$
- Influence on Earth's surface environment:
    - Marine shallow water environments become more heterogenous, morphology less ramp-like, instead create a barrier to increase biodiversity
    - Deposition of fine-grained carbonate as chalk -> geological formations like e.g. White Cliffs of Dover, which are composed largely of coccolithophore remains

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5. Present an outline account of life on Earth from the early Archean through to the early Cambrian (roughly 4000-500 Ma). What types of data are available and to what degree do they reflect true evolutionary patterns?

Life in the Archean (4000-2500 Mya)

- Hypothesized to come from hydrothermal vents, where life was not affected by the Late Heavy Bombardment (extended barrage of meteoroids driven by accretionary instability)
- Chemoautotrophs used CO_2 as a carbon source, oxidizing inorganic materials for energy
- **Hematite** in **banded iron formations** (Greenstone belt, Nunavut, CA, 3.8 bya)
- **Graphite** in metasedimentary rocks (Greenland, DK, 3.7 bya)
- **Microbial mat facies - stromatoliths** (Strelley pool formation, **Pilbara craton,** WA 3.4 bya). Distinct spheroidal permineralized fossils in **sandstone** made of **chert** enriched in **organic matter and pyrite**. Interpreted as deposited in a shallow marine **anoxic spring environment**; **pyrite isotopic signature** consistent with microbial sulfate reduction
- Stromatolite biogenicity is their convex-up structures and wavy laminations, which are typical of microbial communities who build preferentially toward the sun
- oldest evidence for **microbial life on land** in metasedimentary rocks which bear microfossils. (Greenstone belt, ZA, 3.2 bya);
- **LUCA** around this time splits into bacteria and archaea.
- Cyanobacteria start to develop photosynthesis: uses water as reducing agent & producing oxygen. Free oxygen **oxidizes dissolved iron in oceans -> iron ore.**

Life in the Proterozoic (2500-600 Mya)

- Defined by a sudden rise in oxygen levels due to the proliferation of cyanobacteria
- **Peak production of banded iron formation sediments** at the **Siderian period** (~2.5 bya). Evidence of the **Great Oxygenation Event.** Inferred to have been a mass extinction, but not thoroughly supported. **Sulfur isotope geochemistry** suggests a shrinkage of biosphere by 80%, but since fossil remains of that time are very rare -> any surveys of organism abundances cannot be representative.
- First **snowball earth**; oxygen in atmosphere reacted with methane -> carbon dioxide (which photosynthesizers used.) Global temperatures dropped.
- **"Boring billion"** between 1.8 bya (end of formation of BIFs) **–** 0.8 bya (Cryogenian). Lack of mountain formation -> lack of accessible nutrient supply e.g. phosphorus.
- **Eukaryotic cells** evolve through **endosymbiosis.** (biology dump) (**Volyn biota**, UA, 1.5 bya) Exceptionally well-preserved specimens of fossilized microorganisms resembling fungi-like organisms. An *anomaly* within mid-Proterozoic context of high crustal heat flow and low overall biotic diversity.

Life during second Snowball Earth (700 Mya)

- **Snowball Earth – glacial** deposits (e.g. dropstones, diamictites) ~700 Mya at **tropical paleolatitudes** (evidence: dump paleomagnetic theory), suggests **global ice cover.** Reoccurrence of BIFs **after the snowball earth** also suggest **iron accumulation in an** anoxic ocean environment, which is possible in an ocean sealed by sea ice.
- Limitation: **No evidence equatorial currents ceased**
- Slushball hypothesis
- Glaciers ground mountain ranges into powder, made **nutrients accessible**
- Rivers washed nutrients into ocean -> **explosion of algal life**
- Arguably triggered evolution of multicellularity, with first multicellular organisms appearing in the Ediacaran.
- Cnidarians (Charnwood forest)

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3. Outline the major patterns in animal biodiversity during the Phanerozoic. To what extent are geological events responsible for these patterns?
6. Discuss how the Palaeozoic evolution of land plants altered a) the nature of terrestrial sedimentology, and b) the global carbon cycle.

- Cambrian explosion of marine life: trilobites, molluscs, brachiopods, graptolites. First vertebrates (fish). **Oxygenation of the oceans**. Example: **Burgess shale**
- Fragments of supercontinent Rodinia assemble into Gondwana. Continental landmass in tropical & temperate latitudes; i) no glaciation **–** no continents at poles ii) supported extensive **shallow-water reefs** which kickstarted **marine life explosion**
- **Cambrian substrate revolution –** increase in diversity of benthic burrowing organisms, evidenced by trace fossils e.g. Cruziana. Bioturbation -> breaks up microbial mats.
- Land environments were inhabited only by microbial and algal mats without plants; characterized by **erosion & transport** of **unconsolidated sediments** -> terrestrial sedimentology consisted mostly of **sand & gravel**
- Ordovician: Diverse marine fauna continued; graptolites, conodonts (early fish). **Tetrahedral spores** of **primitive land plants** found; first **terrestrialization of plants**
- Gondwana moved south -> glaciers form, sea level drops -> shallow reef environments **exposed to land** -> 60% of marine invertebrate genera extinct.
- Silurian: Deglaciation and rise in sea levels -> new marine habitats. First **coral reefs** and **freshwater fish**; **terrestrialization of ascomycetes (fungi), arachnids, centipedes.** Evolution of **vascular plants.** Eg. Cooksonia.
- Gondwana split into G & Laurasia. **Caledonian orogeny;** living organisms now can access phosphorus. Orogenic events also **remove CO_2** from the atmosphere through weathering.
- Appearance of **meandering rivers** as plants can **stabilize the soil** through roots (erosion)
- Devonian explosion of plant life: First ferns; first trees. e.g. **Rhynie chert**. First tetrapods.
- Mass terrestrialization of plants with true roots and vascular system. MORE EROSION -> more **fine-grained sediments** e.g. silt, clay.
- **Organic accumulation in soil ->** reduction of Iron(III) **-> iron-poor, C rich sediments.**
- Fossil records shows trace fossils of arthropods adapting to mobility in terrestrial environment similar to myriapod tracks on Arran
- Carboniferous: First **reptiles**; first **amniote egg** -> reproduction on land possible.
- Laurasia collides into Gondwana; more orogeneses e.g. Appalachian, Urals.
- Large expanse of ocean covered the entire surface of the globe -> **uniform climate** (shown in Carboniferous trees that **lack growth rings**). Climate tropical and humid -> large swamps of seedless vascular plants e.g. scale trees -> lots of peat -> thick coal beds.
- Permian: Continuous formation of Pangaea closed seas between continents & continued orogenies. Large continental interior -> **continental climate** with great **seasonal fluctuations**; megamonsoons in coastal regions, deserts in dry regions (encourage xeromorphic adaptations) -> Carboniferous swamp collapse & diversification of insects & amniotes.
- First conifers evolved in dry regions; disappearance of swamps -> no coal beds.
- 1. Siberian Traps -> ocean acidification -> **major loss of animal biodiversity, esp. marine invertebrates** (Trilobites, rugose & tabulata corals, brachiopods, crinoids, ammonites, etc.) decline in sediment accumulation rates -> unconformities. Also no limestone deposited.
- 2. Pangaea formation -> sea level regression -> wiped out shallow marine habitats.

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7. Outline the major evolutionary events in the history of life on Earth. How have they affected our planet? (just compile)

Life during the Mesozoic

- Triassic: Life on earth recovering from the Great Dying. First archosaurs, first mammals. First flying vertebrates – pterosaurs.
- Jurassic: Pangea starts to break up. Atlantic seaway formation. Dinosaurs dominant, filling most ecological niches on land; plesiosaurs and ammonites in water.
- Cretaceous: Rifting continues -> lots of activity at mid ocean ridges (forming large igneous provinces, e.g. Ontong Java plateau) displace water (because the gradient of ocean floor less steep, average depth is less negative); warm climate; sea level >70m higher than present day. Pterosaurs declined, birds diversified.

Life during the Cenozoic

B8 Compare a typical low-latitude reef in the modern ocean with its Proterozoic counterpart, including details of the contributing organisms, their ecologies and metabolic pathways. Which of these two is likely to have been most resilient to environmental perturbation?

Extinctions

e

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British Geology (Arran)

4. Explain the evidence that Britain has drifted northward from Devonian time to the present day. Include your own field observations where relevant.

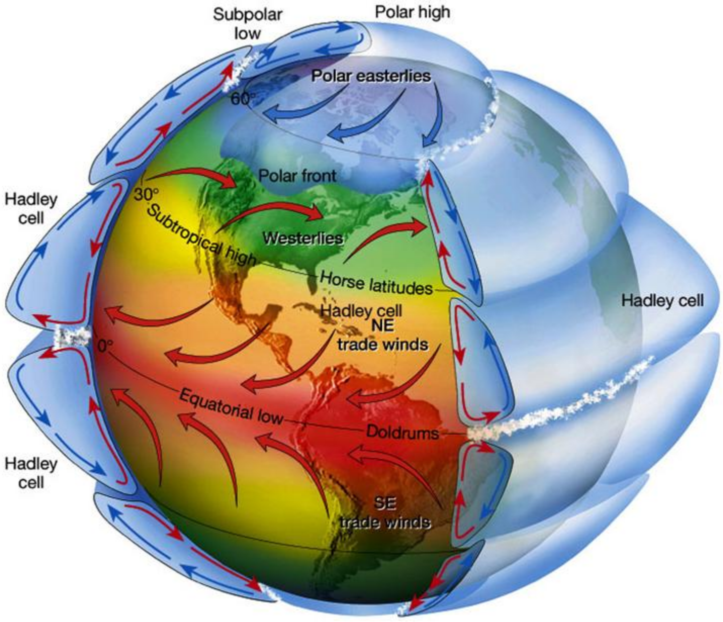
Overview: *Principle of uniformitarianism*

Evidence 1: Palaeomagnetism

- From residual magnetism in rock samples, one deduces that the palaeolatitude (2 tan φ = tan I) of the British isles has shown that its palaeolatitude has increased relative to the north pole. (Assumptions: magnetic pole ≈ geographic pole, dominantly a dipole field)
- Alternatively, construct the APWP (fixing the continents), showing that the north pole has become closer to the UK as time goes on.

Evidence 2: Rock & Fossil Records

- Understand the climate belt the Earth is in. Solar insolation at equator highest (hot air rise), and at higher latitudes are lower (cool air sinks) (Reason behind is the **Lambert's cosine law**; insolation as a function of latitude is $I_0 \cos \lambda$). This causes a pressure gradient to also cause surface flow (trade winds). ==> Circulation belts (Hadley cells, Ferrel cells & the polar cells)C
- When the hot air rises, it cools and forms cumulonimbus and rains (humidity decreases with latitude). When it reaches the descending branch, it is dry, so deserts form at ~30 N/S. Near the equator we have tropical forests. Flow of winds also dictates by the Coriolis effect which rotate the wind directions.



- **Devonian** conglomerates, sandstones and mudstones (the Old Red Sandstone) were deposited by alluvial fans and then by braided rivers. Wadi flows are seen where sudden storm floods deposit pebbles, forming localised deposits.
  - Mostly desert environment with storm floods.
  - southern hemisphere arid belt.
- **Carboniferous** shallow marine limestones (North Shore), Myriapod trail and shales and deltaic sandstones (rugose corals; coarsening up sequence; oscillations between

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sandstone & mudstones -> change in deposition rate -> glacial cycles), shales and coals (1. trees e.g. *Lepidodendron* 2. cyclotherms - oscillations from marine to terrestrial)
  - (shallow) marine environment
  - **equatorial humid zone**.
- **Permian** aeolian sandstones (1. intense crossbedding, dune bedforms on the Corrie foreshore; 2. red colour -> haematite staining; oxidation evident.) and
  - Aeolian deserts
  - **northern hemisphere arid belt.**
- **Triassic** lacustrine mudstones (the New Red Sandstone) were deposited in Arran too. But we can also see evidence of beaches e.g. ripple bedform, desiccation cracks, cubic pseudomorphs of halites.
  - **KETTON:** The Lincolnshire (oolitic) limestone, which imply carbonate precipitated out from the seawater. We know this must have been also a warm marine environment (though this is the Jurassic)
  - Beach-like environment
  - **northern hemisphere TEMPERATE belt**
- **Holocene Glaciation**: Boulder clay at Ketton quarry --> High latitude configuration that Britain is in currently.

8. Discuss the evidence that a major ocean existed between southern and northern Britain in early Palaeozoic time. Explain how and when this ocean closed.

Evidence of Iapetus Ocean

- **Palaeomagnetism**: From residual magnetism in rock samples, one deduces that the palaeolatitude (2 tan $\varphi =$ tan I) is different in the N and S Britain in the late Proterozoic & early Palaeozoic. (parts in Laurentia, Baltica and Avalonia). This means that they are separated and likely separated by an ocean.
- **Fossils & Rocks**: The fossil assemblages and the terranes of N and S Britain were different.
  - e.g. different benthic trilobites in Laurentia (Scotland) – which are connected to those in modern day Pennsylvania & Nova Scotia, and in Baltica (S Britain)
  - e.g. similarly, sediments are seen to be discontinuous across the boundary (belonged to different terranes, Laurentia vs Godwana)
- **Other Geological evidence:** Iapetus Suture can be inferred from mapping as we see faults & orogenic belts (part of the Caledonian orogeny, which extends into Europe, Ireland, N America) at the midway of the British Isles. Devonian unconformity suggests amalgamation of terranes. Shetland & Ballantrae ophiolites show part of the ocean crust thrusted onto land at a collision.

Overview of closure of Iapetus Ocean

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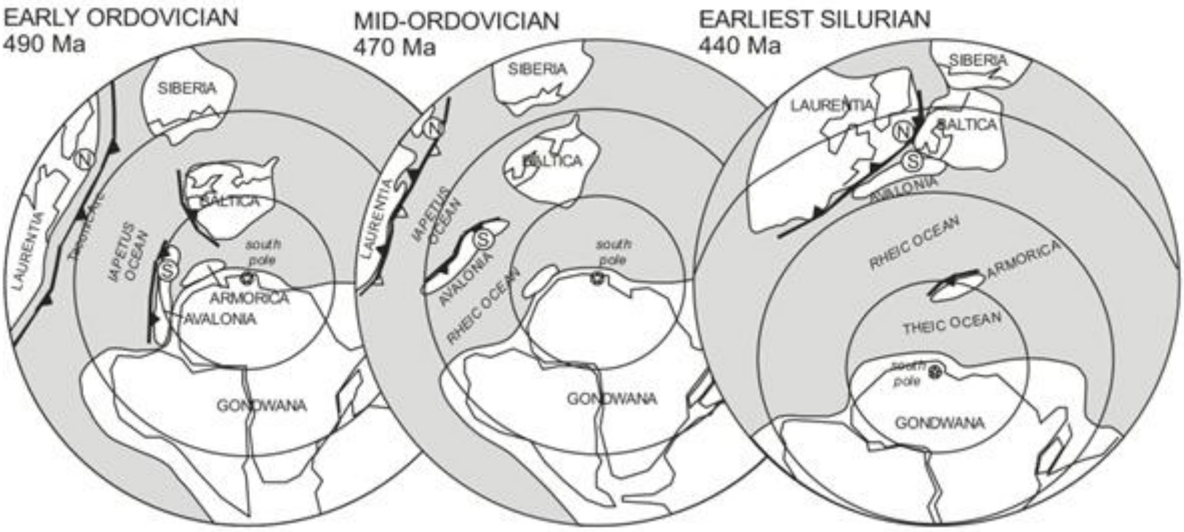

(Draw a simplified version of this)

- **Early-Ordovician**: subduction begin underneath the Gondwana, and at a zone near the Laurentian margin.
- **Mid-Ordovician**: a volcanic arc in the Iapetus Ocean (Taconic Arc) collided w/ the Laurentian margin -> Grampian Orogeny. (Arc-continent collision)
  - e.g. Folding & foliation in deformation shown in Dalradian rocks of north Arran.
  - e.g. old volcanic arc are preserved as pillow lavas on the Ballantrae coast.
  - Polarity flip -> subduction of Iapetus Ocean is N-dipping instead. (draw diagram)
  - Folding analogous in magnitude to that of the Himalayas today.
- **Late-Ordovician to Silurian time:** subduction of Iapetus crust è Avalonia sucked towards.
  - Scandian phase (continent-continent collision): First Baltica & Laurentia, then Avalonia & Laurentia
  - Mountain building events thrusts the Moine rocks (previous deformed in Grampian Orogeny) over older Laurentian shelf sediments

8. How has the continental drift of the UK over geological time been determined? Discuss the evidence that is preserved in the rock record of the UK for changing climate caused by continental drift.

(I guess just emphasise more on the climate aspect)

- Dalradians are metapelites from the Cambrian-Ordovician times, which imply a shallow marine environment for sedimentary rocks back then.

8. Using examples from Britain's geological record, explain how
a) tectonics and/or climate may influence a sedimentary environment and
b) marine and non-marine facies may be distinguished within a sedimentary succession.

- As sea levels rise, the layers may go from sandstone (beach), to silty shale or siltstone (tidal), to freshwater limestone (lagoon), to underclay (terrestrial), to coal (terrestrial

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swampy forest). Then as sea levels fall, one may see a shale (nearshore tidal) grade to limestone (shallow marine) and finally to black shale (deep marine).

B9 Using examples of field observations from Arran, or more widely in the UK, explain how: (a) the sedimentary geological record reflects the steady change of UK palaeolatitude in the Palaeozoic and Mesozoic, and; (b) the UK igneous geological record is related to the Cenozoic opening of the North Atlantic ocean.

(a) Done above
(b) Evidence:

- Judd's dykes observed in Drumadoon, intrusions mafic igneous rocks cutting through the Triassic sandstones.
- Drumadoon sill (columnar jointing) and other sills seen also in Kildonan; multiple injections of magma as evidenced by two or more distinct magma compositions mixed
- Dykes are aligned along generally NE or NW --> fracturing occurs perpendicular to the rifting motion (i.e. EW rifting), consistent with moving apart of Europe and N America seen in APWPs.

Earthquakes and geological hazards

1. Explain, using examples, how the geomorphology of regions of continental deformation can provide information about how faults grow, evolve and interact.

9. Using examples of real events to illustrate your answer, contrast the relationship between geological processes and earthquake hazard in (a) subduction zones and (b) continental mountain belts.

B5 Explain what is meant by the "earthquake cycle" on an active fault. Describe and explain, with examples, what you might look for in the landscape near (a) an oceanic subduction zone and (b) a continental thrust fault, to tell you that there is an active fault nearby. What geological investigations in these two places would you suggest to improve your assessment of the earthquake hazard?

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Questionbank

2018

1. Explain, using examples, how the geomorphology of regions of continental deformation can provide information about how faults grow, evolve and interact.
2. What factors contribute to the fossilisation of an organism?
3. Outline the major patterns in animal biodiversity during the Phanerozoic. To what extent are geological events responsible for these patterns?
4. Explain the evidence that Britain has drifted northward from Devonian time to the present day. Include your own field observations where relevant.
5. Contrast and explain the different lithological properties and sedimentary structures of limestones and sandstones. Why are these rock types distinct?
6. What controls the distribution of volcanoes on Earth? Why does continental crust contain a wider range of igneous rocks than oceanic crust?
7. What evidence is used to determine the structure and composition of Earth's interior? How might we estimate the structure and bulk composition of planets a) in the solar system, and b) that orbit other stars?
8. Compare the optical properties of minerals that can be observed using a petrographic microscope in plane polarised light with those that can be observed under crossed polars. Explain how optical properties can be used to help identify different minerals. How would we use these properties to distinguish between orthopyroxene and clinopyroxene?

2019

1. Describe the observational evidence and theoretical arguments that support the idea that Earth's mantle is convecting. What methods are available to Earth scientists to estimate the range of temperatures present in the convecting mantle?
2. "Crystal symmetry links the atomic-scale structure of a mineral to its macro-scale properties". Discuss this statement with reference to the diagnostic features of common rock forming minerals.
3. What controls the style of volcanic eruptions? Why are explosive eruptions rare at mid ocean ridges and in rifted environments but common at destructive plate margins?
4. Describe the typical characteristics of sediments deposited by glaciers, rivers and the wind. Explain why these are so different with reference to the fluid properties of ice, water and air.
5. Using the concept of global energy balance, account for the global average temperature at the Last Glacial Maximum (LGM). How can you reconcile your account with the Milankovitch theory of the ice ages, given that global average insolation at the LGM was similar to the present day?
6. Discuss the evolutionary record of Palaeozoic terrestrialization.
7. How does a planet's composition affect its habitability? How is habitability compromised for planets a) just inside the inner edge of the habitable zone, b) at the outer edge of the habitable zone.
8. Discuss the evidence that a major ocean existed between southern and northern Britain in early Palaeozoic time. Explain how and when this ocean closed.

2020

1. You are a geologist assigned to study a coastal region of Antarctica that shows evidence of recent volcanism and earthquakes associated with rifting. Describe the effects that are likely to have controlled relative sea-level change

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in this region over the Cenozoic. Discuss the size, areal extent and time characteristics of each of these effects, using examples from elsewhere on the Earth to justify your arguments.
2. Describe the crystal structure of the pyroxene group of minerals. Explain why crystals of pyroxene, when viewed in thin section with the polarising microscope, exhibit (a) different colours in plane polarised light, and (b) different colours in cross polarised light.
3. What factors control the ability of a mineral to form a solid solution? Illustrate your answer with examples of minerals that tolerate a) extensive solid solution, b) very little solid solution, and c) variable degrees of solid solution.
4. The vast majority of volcanic activity on Earth occurs at mid-ocean ridges. Explain why this is so. Why are almost all magmas that are erupted at ridges basaltic in composition, whereas magmas erupted elsewhere show a much wider compositional range?
5. Present an outline account of life on Earth from the early Archean through to the early Cambrian (roughly 4000-500 Ma). What types of data are available and to what degree do they reflect true evolutionary patterns?
6. Discuss how the Palaeozoic evolution of land plants altered a) the nature of terrestrial sedimentology, and b) the global carbon cycle.
7. Discuss how evidence of past climate change preserved in the geological record is relevant for assessing present and future climate change resulting from human activities.
8. How has the continental drift of the UK over geological time been determined? Discuss the evidence that is preserved in the rock record of the UK for changing climate caused by continental drift.
9. Using examples of real events to illustrate your answer, contrast the relationship between geological processes and earthquake hazard in (a) subduction zones and (b) continental mountain belts.
10. Discuss the differentiation processes responsible for the large-scale structure of the Earth since its accretion. How will a planet's mass and accretion age affect its differentiation history?

2021

1. Outline the main features of the Earth’s magnetic field and what we can infer from these observations about the nature of the outer core. How can we use this field to understand the movement of plates
a) in the last 200 million years;
b) before 200 million years ago?
2. It has been observed that seafloor depth in the ocean basins increases systematically with crustal age.
a) Explain the nature and origin of this relationship.
b) To what extent does this relationship hold for plates older than ~70 million years? Explain your answer.
c) Using specific examples, explain how mid-ocean ridge spreading rate (i) affects ocean basin bathymetry today; and (ii) may have caused eustatic sea level change in the past.
3. By contrasting a pyroxene and a mica, explain how and why
a) birefringence,
b) cleavage, and
c) colour in plane-polarized light
are related to the orientation of the crystal in a thin section under a petrological

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microscope.

4. Explain, using sketches and examples, how the mineral assemblages and textures preserved in metamorphic rocks formed during continental collision differ from those produced during contact metamorphism. Under what circumstances might melting of the country rocks occur in these two environments?

5. Fossil organisms can be difficult to classify using conventional Linnean taxonomy. Using examples, discuss how this difficulty detracts from, or contributes to, our understanding of the evolutionary process? How might taphonomy interfere with these evolutionary interpretations?

6. Using at least two examples, discuss how evolutionary innovations have affected the global carbon cycle over the past 500 million years. How has this altered Earth's surface environment?

7. Discuss the differences in the Earth's radiation balance during glacial and interglacial stages of the Quaternary, including the roles of orbital geometry and climate feedbacks in altering the budget. How would these differ in a world with no ice sheets?

8. Using examples from Britain's geological record, explain how
a) tectonics and/or climate may influence a sedimentary environment and
b) marine and non-marine facies may be distinguished within a sedimentary succession.

9. What methods are used to detect and characterise exoplanets? In light of such studies, discuss how typical our solar system appears to be

2022

B1 Increased emissions of greenhouse gases by human activities are rapidly altering Earth's climate. How can the study of past climates help us anticipate the future response of our climate system to anthropogenic radiative forcing?

B2 Explain how sedimentary processes differ between shallow and deep marine environments. Using examples, describe how these processes are reflected in deposits preserved in the geological record.

B3 What are the processes by which (a) basalts and (b) granites are formed? Explain why granites are almost entirely confined to the continental crust.

B4 (a) What observational and theoretical arguments can be used to support the idea that Earth's mantle behaves as a viscous fluid? (b) Describe the circumstances under which it is not appropriate to regard the mantle as viscous.

B5 Explain what is meant by the "earthquake cycle" on an active fault. Describe and explain, with examples, what you might look for in the landscape near (a) an oceanic subduction zone and (b) a continental thrust fault, to tell you that there is an active fault nearby. What geological investigations in these two places would you suggest to improve your assessment of the earthquake hazard?

B6 How does the interaction of polarised light with minerals depend on crystal symmetry? Explain how this interaction can be used to distinguish garnet and pyroxene in thin section?

B7 By comparison to exoplanets, does the solar system architecture appear to be a universal template for planet formation? What are the key similarities and differences, and how might these impact the prospect of life in these extra-solar systems?

B8 Compare a typical low-latitude reef in the modern ocean with its Proterozoic counterpart, including details of the contributing organisms, their ecologies and metabolic pathways. Which of these two is likely to have been most resilient to environmental perturbation?

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B9 Using examples of field observations from Arran, or more widely in the UK, explain how: (a) the sedimentary geological record reflects the steady change of UK palaeolatitude in the Palaeozoic and Mesozoic, and; (b) the UK igneous geological record is related to the Cenozoic opening of the North Atlantic ocean.

2023

1. Describe the observational evidence that tells us that the surface of the Earth is formed of rigid tectonic plates that are in relative motion. What is responsible for driving plate motions, and how do we know?
2. An exoplanet has been discovered by the transit method. For this system, explain:
(a) how the concept of energy balance can be used to define the habitable zone around the star;
(b) how accurate an estimate of the average surface temperature of the exoplanet the energy balance approach provides, using illustrative examples from the solar system where appropriate; and, (c) what additional observations could be made, given existing technology, to further characterise the climate of the exoplanet.
3. Why is summer insolation at 65 degrees north latitude such a critical metric of global climate state during the Pleistocene (the most recent 2.5 million years)? What observational constraints in palaeo-climate archives have been used to test this?
4. Discuss how the physical and optical properties of minerals are controlled by their crystal structures. How might we use this to distinguish between clinopyroxene and orthopyroxene?
5. Explain how a basalt's mineralogy and texture may be transformed by metamorphism from its formation at a mid-ocean ridge, to its subduction back into the mantle. How is information on the metamorphic conditions experienced by a meta-basalt preserved in the rock during transport back to the surface?
6. What observations allow distinguishing between sedimentary rocks which were deposited in a marine vs a non-marine environment? Describe examples from UK geology where sedimentary sequences show cyclical changes between a marine and non-marine environment.
7. Outline the major evolutionary events in the history of life on Earth. How have they affected our planet?
8. How might mass extinction events complicate our ability to infer phylogenetic relationships among living species?
9. Describe the controls on the rise height and behaviour of volcanic eruption columns during explosive eruptions. How might the resulting ash deposits be used to quantify eruption parameters?