Q1. Explain the process of mantle convection and its role in plate tectonics.

(a) Describe mantle convection currents with a suitable diagram. *(4 marks)*

Definition & driving physics.
Mantle convection is the slow, buoyancy-driven flow of the Earth's mantle produced by thermal gradients (heating from the core and internal radiogenic heat) and compositional contrasts. Although the mantle is solid on short timescales, it behaves as a very viscous fluid over geologic time and therefore convects. Convective instability arises when buoyant forces overcome viscous resistance; this tendency is quantified by the Rayleigh number

$$Ra = \frac{\rho g \alpha \Delta T\, d^3}{\kappa \eta}$$

where ρ is density, g gravity, α thermal expansivity, ΔT the temperature contrast across the layer, d the layer thickness, κ thermal diffusivity and η effective viscosity. For the Earth's mantle $Ra \gg Ra_{crit}$, so thermal convection is vigorous.

Characteristic structure of convection in the mantle.

- **Thermal boundary layers:** a cool, stiff lithospheric boundary layer at the top and a thermal boundary layer at the core–mantle boundary (CMB) at the bottom. Instabilities in these layers produce downwellings (slabs) and upwellings (plumes).
- **Upwellings:** broad, buoyant upwellings form beneath mid-ocean ridges and as narrow thermal plumes (hotspots) that can create volcanic chains or flood basalts.
- **Downwellings:** cold, dense oceanic lithosphere sinks at subduction zones forming narrow, fast conduits that return surface material to depth.
- **Transition zone effects:** phase changes (≈410 km, ≈660 km) and viscosity variations modulate vertical coupling; whole-mantle vs layered convection is debated but modern seismic tomography and geochemistry suggest significant vertical mass transfer (at least episodic) between upper and lower mantle.

Schematic diagram (cross-section):

```
          Surface
-------------------------------------------------
  Continental/oceanic lithosphere (rigid plates)
-------------------------------------------------
  Asthenosphere (weak, convecting upper mantle)
   ↑   ⟵     convective cell   ⟶   ↓
   |           upwelling             |
   |        (mid-ocean ridge)        |
   |                                 |
   |             /|\                 |
   |            / | \                |
   |           /  |  \               |
   |          /   |   \    plume     |
   |         /    |    \   tail ↓    |
```

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  |       /     |     \          ↓|
  |      /      |      \         ↓|
-------------------------------------------------
     Transition zone (phase changes ~410 & 660 km)
-------------------------------------------------
   Lower mantle (slower, higher viscosity flow; plume heads rise)
   ↓               ↑
   slab            plume
   sink            root
-------------------------------------------------
   Core-mantle boundary (hot; source of bottom heating)
-------------------------------------------------
```

Labels to note: lithosphere (mechanically strong), asthenosphere (deforming layer), upwelling beneath ridges and plumes, downwelling slabs at subduction zones, CMB supplying basal heat.

(b) Discuss how mantle convection drives lithospheric plate movement. *(3 marks)*

Mechanical coupling & forces.
Mantle convection imposes tractions (basal drag) on the base of the lithosphere and generates buoyancy contrasts that create the principal plate-driving forces:

1. **Slab-pull:** the dominant force for many plates — dense, cold oceanic lithosphere that has become negatively buoyant at subduction sinks into the mantle; its gravitational pull on the trailing plate is a major driver of plate motion. Slab-pull is a direct expression of a convective downwelling.
2. **Ridge-push (gravitational potential energy):** upwelling produces elevated mid-ocean ridges; newly formed lithosphere slides away under gravity, producing a push. This is tied to mantle upwelling and thermal buoyancy at divergent boundaries.
3. **Basal traction / mantle drag:** shear stresses from horizontal mantle flow beneath plates can drag plates along; the sense and magnitude depend on relative plate velocity and mantle viscosity structure.
4. **Mantle suction and dynamic topography:** 3-D convective flow near subduction zones produces suction that can aid trench migration and influence plate kinematics and surface uplift/subsidence.

Coupling requirement.
For convection to produce plate tectonics, the lithosphere must be sufficiently strong to behave as discrete plates (brittle failure and faulting) but also weak enough in narrow zones (e.g., mid-ocean ridges, transform faults, subduction interfaces) to allow plate boundaries. Thus mantle convection supplies forces and boundary conditions, while lithospheric rheology determines how those forces are expressed as coherent plate motion.

(c) Give two examples where mantle convection has influenced geological features. *(3 marks)*

Example 1 — Mid-ocean ridges and seafloor spreading (upwelling):
At divergent plate boundaries, buoyant upwelling of mantle material causes decompression melting. The melt forms new oceanic crust (basalt) that accretes at ridges and is carried away by plate motion — the classical seafloor-spreading system. Observable consequences tied to mantle convection include high ridge elevation (thermal buoyancy), symmetric magnetic striping (age progressive crust), and high heat flow. Thus the upwelling limb of convective cells directly builds oceanic basins and drives ridge morphology.

Example 2 — Hotspot tracks and large igneous provinces (plume upwellings and plume heads):
Thermal plume activity — a deep mantle upwelling — produces large volumes of alkali-to-tholeiitic ocean island basalt (OIB) and can generate flood basalts when a plume head impinges on the lithosphere. Classic examples:

- **Hawaiian–Emperor seamount chain:** age progression of volcanic edifices on the Pacific Plate records motion of the plate over a relatively stationary mantle plume (plume tail producing the linear hotspot track).
- **Deccan Traps / Siberian Traps (LIPs):** interpreted as surface expressions of plume head arrival producing rapid, voluminous basalt emplacement. Seismic tomography sometimes images low-velocity anomalies beneath these provinces consistent with mantle thermal anomalies.

(Alternative valid examples: the formation of subduction zones and associated orogeny where slab rollback and mantle flow control trench migration and mountain building — e.g., Andes system behavior influenced by slab dynamics.)

Conclusion (brief).
Mantle convection is the fundamental engine of Earth’s long-term tectonic evolution. Its upwellings and downwellings create the thermal and mechanical forcings (ridge buoyancy, slab pull, basal tractions, plume impingement) that, together with lithospheric rheology, produce plate motions, volcanism, mountain building and the large-scale reconfiguration of continental and oceanic crust through geologic time.