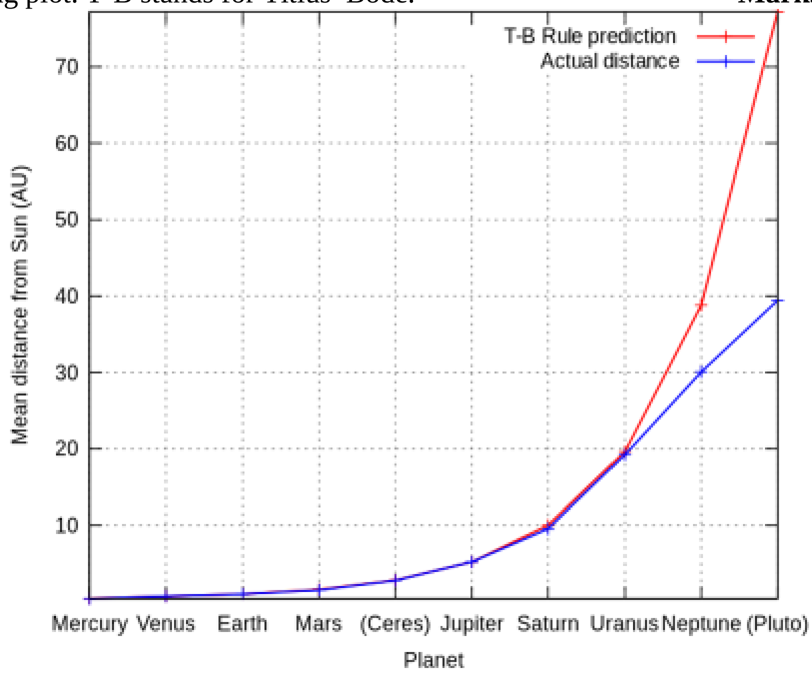
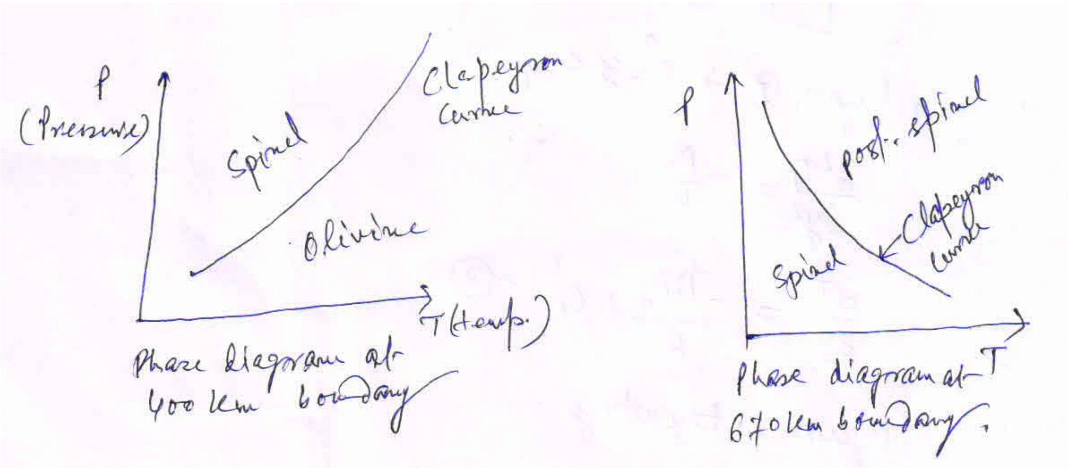
Question 1.

(a) Explain the reasons for elevation of the olivine-spinel phase boundary and depression of the spinel–perovskite phase boundary in a subducting oceanic lithosphere. Discuss the signification of such boundaries in mantle dynamics. **(b)** The concentrations of U, Th and K in the mantle of the Earth are 0.025, 0.087 and 70 p.p.m. by weight. Calculate the total heat production per kg inside the mantle by these radioactive nuclides. **(c)** Explain the following plot. T-B stands for Titius–Bode. **Marks:** 12+4+4



Ans: (a)



The olivine-spinel boundary is elevated in the descending oceanic lithosphere as compared with its position in the surrounding mantle because the pressure at which the phase change occurs depends on temperature. The left sketch is a plot of the Clapeyron curve, which gives the pressures and temperatures at which two phases of the same material, such as olivine and spinel, are in equilibrium. The slope of the Clapeyron curve γ is given by

$$\gamma = \frac{dp}{dT}$$

$$\text{or,} \frac{dz}{dT} = \frac{\gamma}{\rho G}$$

where dp = gρdz. For the olivine to spinel phase change at 400 km depth, the slope of the Clapeyron curve is positive. Since dT is negative for the lower temperatures in the interior of the descending lithosphere, and the olivine-spinel phase change occurs at a shallower depth in the slab. Therefore, the olivine-spinel boundary is elevated inside the descending lithosphere. The elevation of this phase change boundary inside the descending

lithosphere increases in density associated, and thereby adding more forces driving the plate downward into the mantle.
Instead, for spinel–perovskite phase boundary (right plot) at 670 km depth, the slope of the Clapeyron curve is negative. Since dT is negative for the lower temperatures in the interior of the descending lithosphere, and the spinel–perovskite phase change occurs at a deeper level in the slab. Therefore, the spinel–perovskite phase boundary is depressed inside the descending lithosphere. The mass deficiency happens inside the descending lithosphere because of the depression of this phase boundary, and the top of the lithosphere is impeded, and suffers back-thrust, which is responsible for the generation of deep focus earthquake. This also opposes the migration of the lower mantle materials into the upper mantle, and allows layered-earth convection.

(b)

Given that, $C_U = 0.025$ p.p.m

$C_{Th} = 0.87$ p.p.m

$C_K = 70$ p.p.m

Formula → Heat production is given by

$$Q_r = (95.2\,C_U + 25.6\,C_{Th} + 0.00348\,C_K)\ \mu W/kg$$

then

$$Q_r = (95.2\times0.025\times10^{-6} + 25.6\times0.087\times10^{-6} + 70\times0.00348\times10^{-6})\ \mu W/kg$$

$$Q_r = (2.38 + 2.23 + 0.2436)\times10^{-6}\ \mu W/kg$$

$$= 4.8536\times10^{-12}\ \mu W/kg$$

(c) The plot illustrates the approximate distances of planets from the Sun. It is found that this law correctly predicts the distances of all known planets from Mercury to Uranus, but failed as a predictor of Neptune and Pluto.

Question 2. (a) Discuss the limitations of the new nebular hypothesis for the evolution of the solar system. **(b)** Derive an expression of geoid height anomaly for an Airy-compensated mountain range of height h_1. **(c)** Using the equation derived in **(b)**, calculate the geoid height anomaly for a compensated mountain range of 4.5 km high. Consider crust and mantle densities of 2.8×10^3 kg/m^3 and 3.3×10^3 kg/m^3 respectively, and a reference crust of 35 km thick. **(d)** Write short notes on (i) Peclet Number, (ii) Prandtl Number, and (iii) Reynolds Number.
Marks: 5+6+3+6

Ans: (a)
Although the nebular theory is widely accepted, there are still problems with it that astronomers have not been able to resolve.
For example, the distribution of angular momentum between planets and Sun. More than 99.9% of the total mass of the solar system is concentrated in the Sun, however more than 99% of the angular momentum is carried by the orbital motion of the planets, especially the four great planets. Of these, Jupiter is a special case: it accounts for over 70% of the mass and more than 60% of the angular momentum of the planets.
There is the problem of tilted axes. According to the nebular theory, all planets around a star should be tilted the same way relative to the ecliptic. But as we have learned, the inner planets and outer planets have radically different axial tilts.
Also, the study of extrasolar planets have allowed scientists to notice irregularities that cast doubt on the nebular hypothesis. Some of these irregularities have to do with the existence of “hot Jupiters” that orbit closely to their

stars with periods of just a few days. Astronomers have adjusted the nebular hypothesis to account for some of these problems, but have yet to address all outlying questions.

So, the current models of star and planet formation, and the birth of our Universe, we have come a long way. As we learn more about neighbouring star systems and explore more of the cosmos, these models are likely to mature further.

(b)

The geoid height anomaly at any point P is given by

$$\Delta h = -\frac{2\pi G}{g}\int_0^D \Delta\rho(z) z dz \qquad (1)$$

where g is the reference gravity value, Δρ(z) the anomalous density at depth z beneath point P and D the compensation depth. Depth z is measured positively downwards with z = 0 corresponding to the spheroid. The above equation gives the geoid height anomaly due to long-wavelength isostatic density anomalies. Geoid anomalies can be used to estimate the variation of density with depth.

Considering the Airy model, the reference structure is an upper layer of density ρ_u and thickness t and a substratum of density ρ_s. All density anomalies are with respect to this reference structure. The geoid height anomaly over a mountain range of height h_1 is given by

$$\Delta h = -\frac{2\pi G}{g}\left(\int_{-h_1}^{0} \rho_u z dz + \int_t^{t+r_1} (\rho_u - \rho_s) z dz\right) \qquad (2)$$

$$= -\frac{\pi G}{g}\left[(-h_1^2\rho_u + (\rho_u + \rho_s)(2tr_1 + r_1^2)\right]$$

$$= -\frac{\pi G}{g}\rho_u h_1\left(2t + \frac{\rho_s h_1}{\rho_s - \rho_u}\right) \qquad \because r_1 = \frac{h_1\rho_u}{\rho_s - \rho_u}$$

Also, see through Ocean Basin Anomaly

For crustal and mantle densities of 2.8×10^3 and 3.3×10^3kg-m^3, respectively, and a reference crust 35 km thick, the geoid height anomaly is

$$\Delta h \simeq 5.98 h_1(0.7 + 0.066 h_1)\text{m}$$

where h_1 is in km. Thus a compensated mountain range 3 km high would result in a positive geoid height anomaly of about 16.11 m.

(c)

Therefore, $\Delta h \simeq 5.8642 h_1(0.8 + 0.08 h_1)$m

Here, h1 = 4.5 km, So, Δh = 30.61 km, the geoid height anomaly for a compensated mountain range.

d(i)

The **Péclet number** is a dimensionless number relevant in the study of transport phenomena in fluid flows. It is defined to be the ratio of the rate of advection of a physical quantity by the flow to the rate of diffusion of the same quantity driven by an appropriate gradient. In the context of the transport of heat, the Peclet number is equivalent to the product of the Reynolds number and the Prandtl number.

For diffusion of heat (thermal diffusion), the Péclet number is defined as:

$$Pe_L = \frac{LU}{\alpha} = Re_L \times P_r$$

where L is the characteristic length, U the velocity, D the mass diffusion coefficient, and α the thermal diffusivity,

If Pe_t is much larger than unity, advection dominates; If Pe_t is much smaller than unity, conduction dominates. In the mantle Pe_t is about 10^3, showing that the heat is transported mainly by advection.

(ii)

The Prandtl number Pr is a dimensionless number; the ratio of momentum diffusivity (kinematic viscosity) to thermal diffusivity. It is defined as:

$$P_r = \frac{\nu}{\alpha} = \frac{viscous\ diffusion\ rate}{thermal\ diffusion\ rate}$$

Where ν: kinematic viscosity, α: thermal diffusivity

Prandtl number is the physical property of the material and is independent of any flow. For the mantle with ν ~ 10^{18} m^2/sec and κ ~ 10^{-6} m^2/sec, Pr ~ 10^{24}, demonstrating that the viscous response to any perturbation is instantaneous compared with the thermal response.

(iii) Reynolds number can be defined for a number of different situations where a fluid is in relative motion to a surface. These definitions generally include the fluid properties of density and viscosity, plus a velocity and a characteristic length, depth or characteristic dimension. It measures the ratio of the inertial to viscous forces.

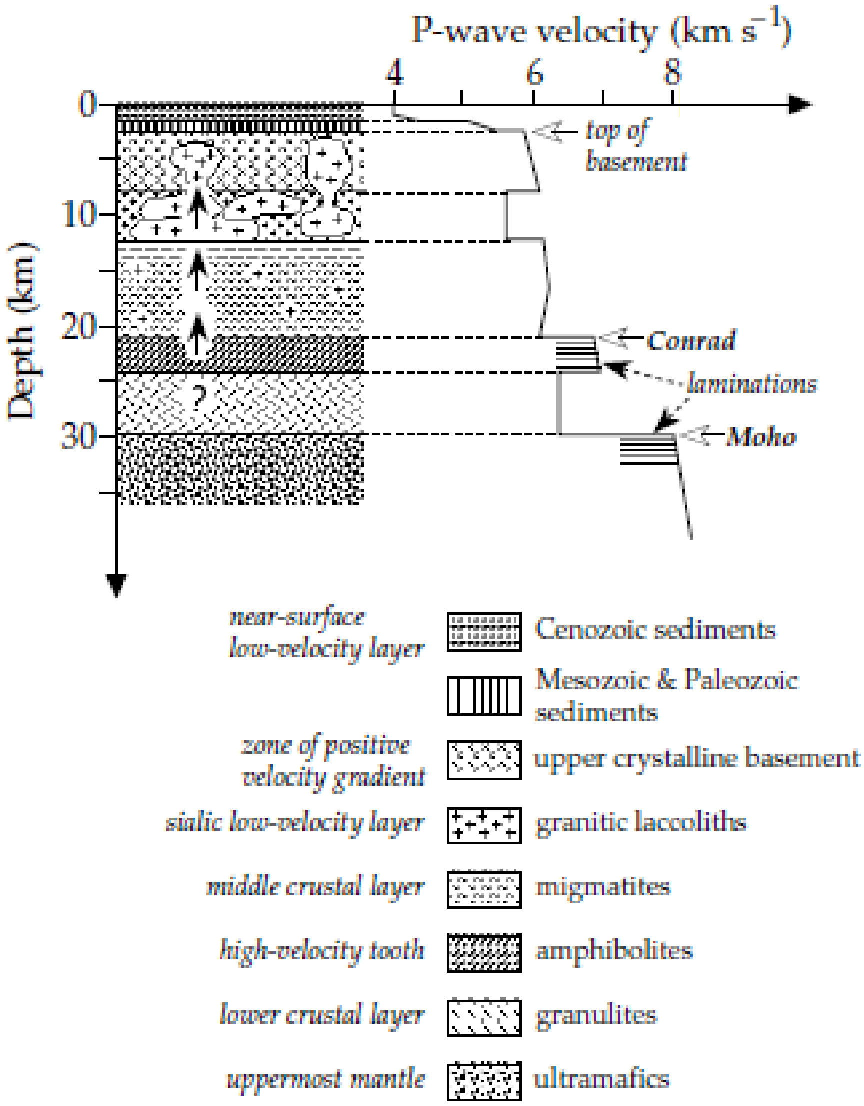
$$R_e = \frac{\rho u D}{\eta}$$

where D is the thickness of the fluid layer, u is the velocity of the flow, ρ is the density of the fluid (kg/m³), η is the dynamic viscosity of the fluid. Re indicates whether fluid flow is laminar or turbulent. A flow with Re<< 1 is laminar, since viscous force dominates. A flow with Re>> 1 is turbulent. Re for the mantle is about 10^{-19} – 10^{-21}, so the flow is certainly laminar.

Question 3.

(a) Draw the vertical structure with characteristics features of the continental crust. Show also the variations of seismic P- and S-waves velocities. **(b)** Temperatures of the asthenosphere at the ridge axis is 1450°C and at the base of the lithosphere is 1150°C. Derive the expression of thickness (km) of the oceanic lithosphere. Take x = 0.89 for erf(x) = 0.7931 and t is in Ma. **(c)** Draw the isotherms for a salt dome. **Marks:** 8+6+6

Ans: (a)



(b)

we know that $T = T_m \, erf\left(\frac{L}{2(\kappa t)^{1/2}}\right)$

where T is temperature at depth L

T_m is the temperature of the hot mantle,

κ is the thermal diffusivity $= 10^{6}$ m²/sec.

$\therefore 1150 = 1450 \, erf\left[\frac{L}{2\sqrt{\kappa t}}\right]$

$\therefore erf\left(\frac{L}{2\sqrt{\kappa t}}\right) = 0.793$

$\therefore \frac{L}{2\sqrt{\kappa t}} = 0.89$

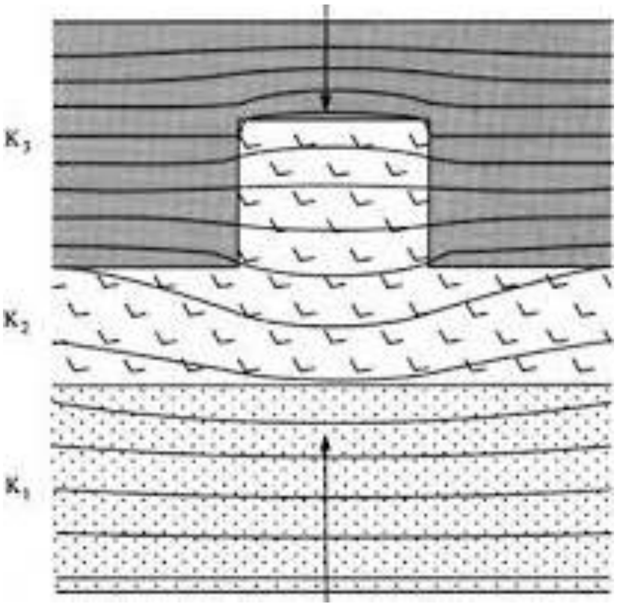
$\therefore L = 2 \times 0.89 \sqrt{\kappa t}$

putting $\kappa = 10^{-6}$ m²/sec, we have

$L \, (\text{km}) = 10.01 \sqrt{t}$

t is in Ma.

(c) Salt domes (diapirs) are common geological features of sedimentary basins. The presence of salt within a sedimentary basin can potentially modify its temperature distribution and history. Figure illustrates the isotherms dome up over salt diapirs, and are depressed beneath them, because of the high thermal conductivity of evaporates.

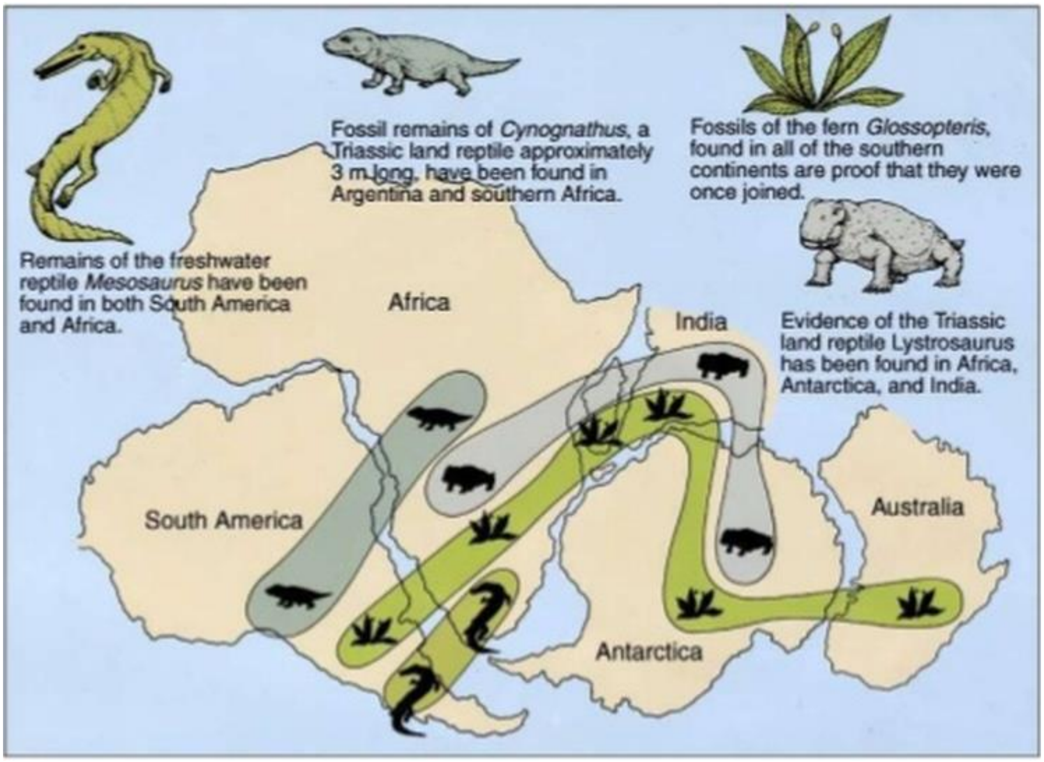


Upto Mid Sem

Figure illustrates the isotherms modelled for a salt dome. The solid lines represent isotherms.

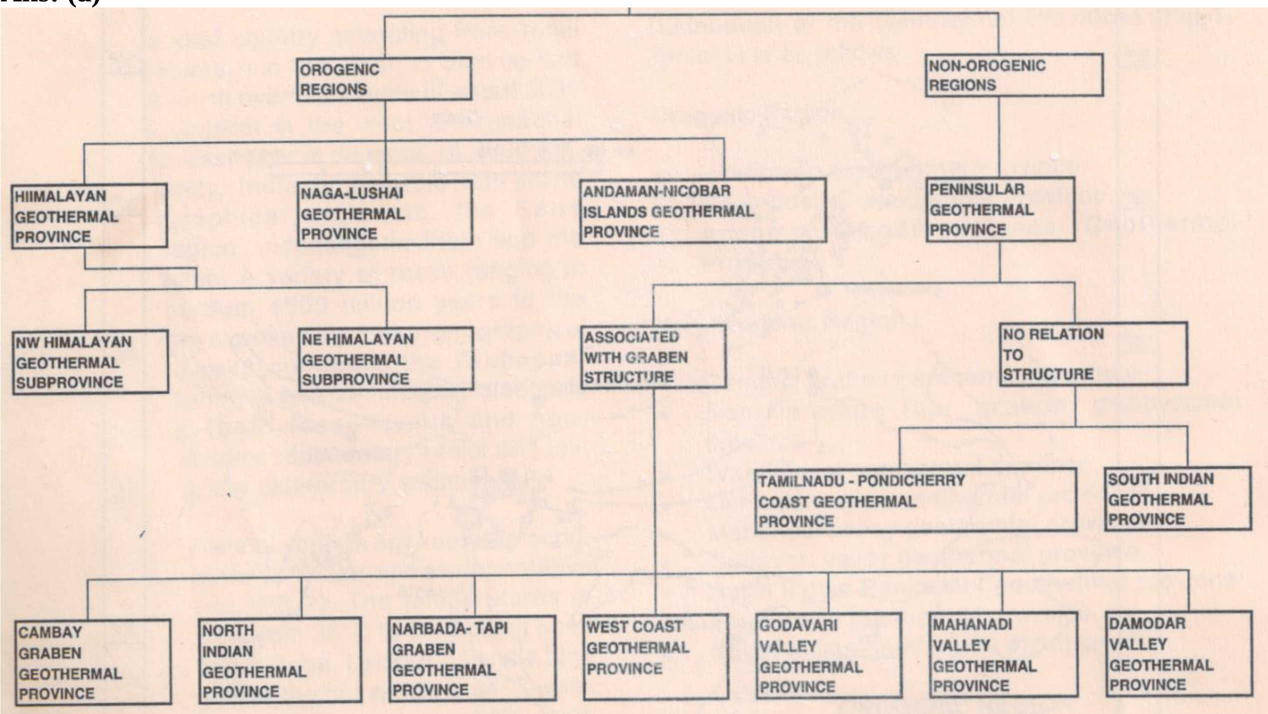
Question 4.

(a) Write the names of all the geothermal provinces and sub-provinces of India. **(b)** Calculate the depth at which the isostatic equilibrium attains, based on Airy hypothesis, beneath a point of a 5-km-high mountain chain with a 35-km-thick continental crust of density 2.8×10^3 kg m^{-3} and a mantle of density 3.3×10^3 kg m^{-3}. **(c)** Write a brief note on the following figure. **Marks:** 8+7+5



Distribution of fossils across the southern continents of Pangea.

Ans: (a)



(b).

We know,

$$t = h\frac{\rho}{\Delta\rho} + T$$

Where t = compensation depth, h = elevation of the mountain at the point of observation, ρ = crustal density at the atmosphere-crust interface, Δρ = density contrast between lower crust and mantle, and T = crustal thickness at the sea level.

$$\text{or}, t = 5 \times \frac{2800}{500} + 35$$

$$\therefore t = 63 \text{ km}$$

Therefore, the depth of the crust-mantle boundary at the location beneath a mountain of height 5 km is 63+5 = 68 km.

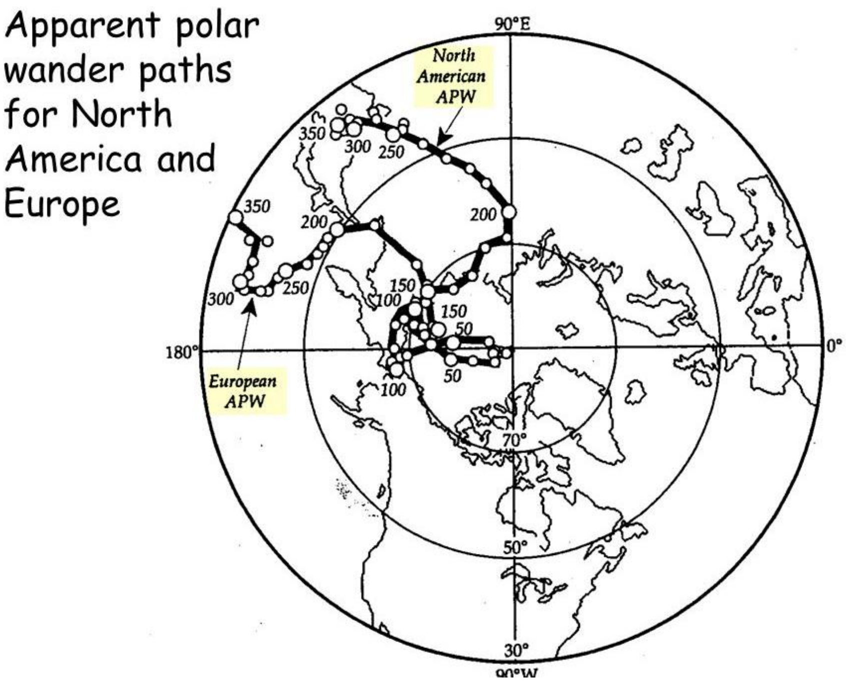
(c)

The figure illustrates the paleontological evidence of continental drift. Distribution of some fossil plants and animals found in different different parts of South America, Africa, Madagascar, India, Antarctica, and Australia. Mesosaurus, a Permian freshwater reptile, is found in both Brazil and South Africa. Glossopteris, a fossil fern, is found on all of the southern continents. Lystrosaurus, a Trissic land reptile, is found in South Africa, South America, India, and Antarctica. Cynognathus, an older Trissic reptile, is found in Argentina and South Africa.

Isostacy

Question 5.

(a) 2 km deep sea is filled to the sea level by sediments over a long period of geological time-scale. Assuming isostatic equilibrium is maintained, how deep will the sediments be? Use these densities in kg/m^3 units: water (1000), sediment (2400), and basement (3200). **(b)** Explain the major plate driving forces for movement of the tectonic plate. **(c)** Write a short note on the following figure. **Marks:** 8+7+5



Average apparent polar wander paths for North America and Europe in the past 350 Ma. Numbers on paths are age in Ma.

(a)

5(a)

Here, t_w = 2 Km deep sea

ρ_w = Density of sea water

t_s = total sediment deep (h_1 Km) + 2 Km deep sea.

ρ_a = Density of the basement.

ρ_s = Density of sediments.

∴ we can write,

$$\rho_w t_w + h_1 \rho_a = (2+h_1)\rho_s$$

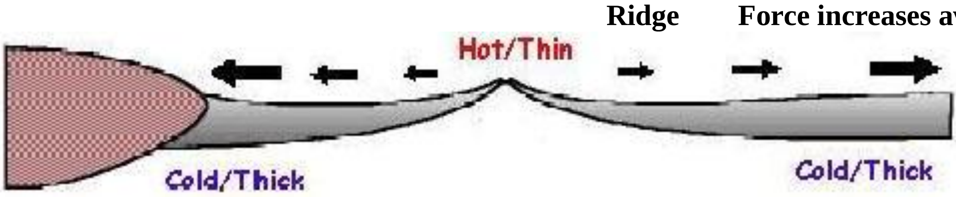
$$\text{or, } h_1 = \frac{2\rho_s - t_w\rho_w}{\rho_a - \rho_s}$$

$$= \frac{2\times 2400 - 2\times 1000}{3200 - 2400}$$

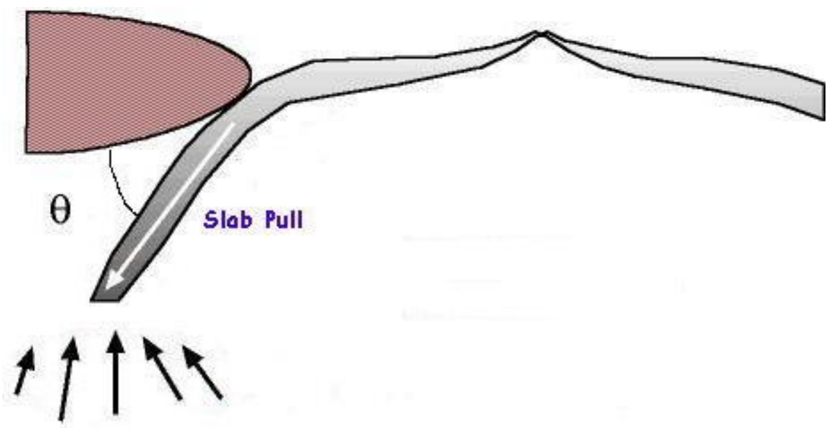
$= 3.5$ Km Ans:-

(b) Ridge Push Force (F_{RP}): Ridge push has been attributed to the cooling and thickening of the oceanic lithosphere with age. This type of force can be thought of as created by the horizontal pressure gradient attributable to the cooling and thickening of the oceanic lithosphere. The result of this thickening with distance from the ridge is that the lithosphere/asthenosphere boundary slopes away from the ridge. The weight of the lithosphere on this sloping surface produces a downslope force. And since the asthenosphere is weak, the weight of the lithosphere near the ridge sliding down the 'slippery slope' of the asthenosphere 'pushes' the older part of the plate in front of it. Here the force would be acting as a boundary force at the edge of the lithospheric plate, proportional to the length of the ridge.

Ridge **Force increases away from ridge axis**



Slab Pull Force (F_{SP}):



Viscous Resistive Force

As lithospheric plates move away from mid-ocean ridges they cool and become denser. They eventually become denser than the underlying hot mantle. After subduction, cool, dense lithosphere sinks into the mantle under its own weight. This helps to pull the rest of the plate down with it. The Slab Pull forces are derived from the negative buoyancy of the cold subducting lithosphere and are dependent on the angle, temperature, age and volume of the subducting slab, as well as the length of the respective trench. Slab Pull is considered a boundary force, and apparently the largest force, or torque in the driving system. Several empirical studies have shown a strong correlation between plate velocities and age of subducting oceanic lithosphere for plates with long subduction boundaries. This might suggest that slab pull is the dominant acting force. However, there are several plates that have little or no portion of their boundaries subducting and it is therefore important to look for other contributing forces.

Viscous Resistive Force (F_{SR}): The sinking slab into the mantle encounters a strong resistance during it descends from the viscosity of mantle material that is being displaced. This resistive force is termed the viscous resistive force, and estimated to be very strong competing with the slab pull force.

(c) Figure illustrates the European and North American APW paths since the Late Paleozoic showing clearly two distinct curves. It shows that when paleomagnetic pole positions are calculated for old rocks from the same continent, they group far away from the geographic pole. Pliocene and Pleistocene poles group close to the geographic pole but Permian poles are located about 45° away. If the axial dipole hypothesis is valid for rocks of all ages, the pole distributions imply that the geographic pole for Europe in the Permian period (about 250–290 Ma ago) lay far from its present position. An alternative interpretation is that the geographic pole has not changed, but the European continent has moved relative to the pole. This suggests that the position about which the Permian poles now cluster was on the rotation axis in the Permian period. The European continent has subsequently moved to its present-day position with regard to the rotation axis. So, the two APW paths evidently represent the separate motions of the European and North American continents relative to the rotation axis. They constitute paleomagnetic evidence for “continental drift.”