1.(a) What are those geological and structural criteria used for classification of geothermal provinces. **(b)** What do you understand by magnetic and geomagnetic poles and equators? **(c)** How the Euler poles of rotation is different from geographic poles of the Earth? Explain it with a diagram. **(d)** How do you interpret geometrical that RRR triple junction is always stable, and the FFF triple junction is always unstable? R and F for oceanic ridge and transform fault. **(e)** How the virtual geomagnetic pole can give the supportive evidence for the continental drift theory? Explain it with a diagram. Seafloor Spreading

Ans. (a) The geological and structural criteria that have been used in the identification of the geothermal provinces are as follows:

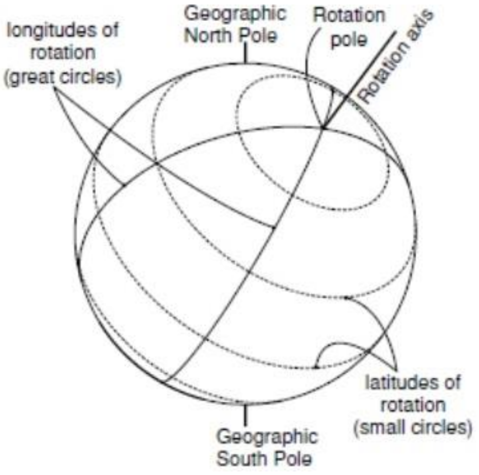
i) Occurrence in an orogenic belt, which has undergone Cenozoic folding and uplifting.

ii) Occurrence in structural depressions/grabens associated with Late Tertiary and Quaternary upliftment in no-orogenic belts.

iii) Related to deep fault zones associated with recent seismicity.

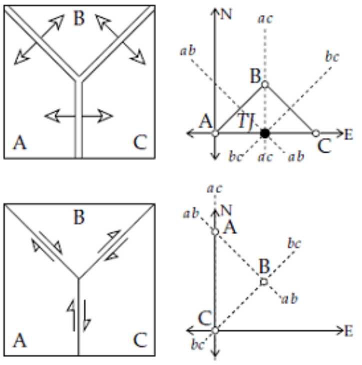
iv) Occurrence in the areas of Tertiary or Quaternary volcanic activity.

(b) The two points on the earth's surface at which the magnetic field is vertical and has no horizontal component are called magnetic poles. The magnetic equator is the line along which the magnetic field is horizontal and has no vertical component. The best-fitting dipole is aligned at about 11.5° to the Earth's geographic north-south axis (spin axis). The geomagnetic poles are the two points where the axis of this best-fitting dipole intersects the Earth's surface. The geomagnetic equator is the equator of the best-fitting dipole axis.



(c) Euler's fixed-point theorem states that the most general displacement of a rigid body with a fixed point is equivalent to a rotation about an axis through that fixed point. Accordingly, every displacement from one position to another on the Earth's surface can be regarded as a rotation about a suitable chosen axis passing through the centre of the Earth. This suitable chosen axis is called rotation axis, and cuts the Earth's surface at two points called the Euler pole of rotation. The geographic north and south poles are where lines of longitude (meridians) converge in the north. The south and north poles are directly opposite to one another.

(d) Diagrams represent triple junction formed by three ridges (right top) and three transform faults (right bottom), and vector diagrams of the relative velocities are explained at the three boundaries. The loci of the velocity vectors ab, bc and ac are passing through a point (circumcenter), and in velocity space this point satisfies the velocities on all three ridges simultaneously, so the RRR triple junction is always stable. Conversely, a triple junction formed by

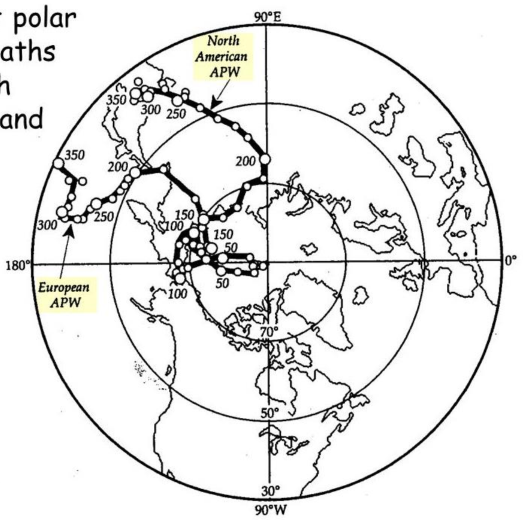


three intersecting transform faults is always unstable, because the loci can never pass through a point.

(c) By connecting mean VGP positions of different ages for sites on the same continent a line is obtained, called the apparent polar wander (APW) path of the continent. A schematic plot of the European and North

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.

Apparent polar wander paths for North America and Europe



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

The European continent has thus 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.”

2. (a) Derive the expressions of equilibrium geotherms for two-layered crustal model of the Earth with upper layer of thickness Z_1 and radioactive heat generation A, and lower layer of thickness Z_2 and radioactive heat generation zero. Assume the heat flow from the mantle to be Q and the temperature 0°C on the surface (depth = 0-km). **(b)** Derive an expression of depression in the spinel-perovskite phase boundary in a subducting oceanic lithosphere using Clapeyron’s P-T curve, and hence **(c)** calculate the depression, assume the slope of the Clapeyron curve is -2.5 MPa-°K^{-1}, density of the lithosphere is 3700 kg-m^{-3}, acceleration due to gravity is 10 ms^{-2}, and the temperature difference across the slab is 750°K.

Ans. (a)

Here, for the first layer,

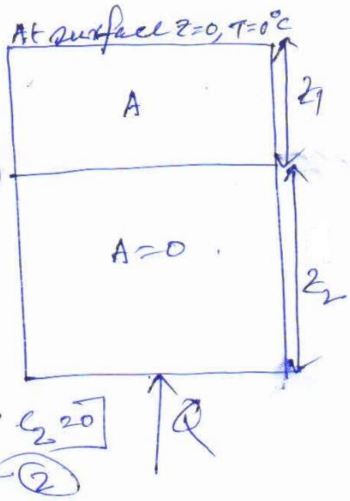
$$\frac{\partial^2 T}{\partial z^2} = -\frac{A}{K}$$

or, $\frac{\partial T}{\partial z} = -\frac{A}{K}z + c_1$ — ①

∴ $T = -\frac{A}{2K}z^2 + c_1 z + c_2$

At $z = 0$, $T = 0°C$

∴ $T = -\frac{A}{2K}z^2 + c_1 z$ [∵ $c_2 = 0$] — ②



For 2nd layer, $\frac{\partial^2 T}{\partial z^2} = -\frac{A}{K} = 0$.

∴ $\frac{\partial T}{\partial z} = c_3$ —— ③

At $z = z_1 + z_2$, $\frac{\partial T}{\partial z} = \frac{Q}{K}$ —— ④

∴ from ③, $c_3 = \frac{Q}{K}$ —— ⑤

At the boundary, both the temperature gradients are same.

∴ $-\frac{A}{K}z_1 + c_1 = \frac{Q}{K}$ [from ① and ④]

∴ $c_1 = \frac{A}{K}z_1 + \frac{Q}{K}$

∴ for first layer, the geotherm is given by

$T = -\frac{A}{2K}z^2 + \left(\frac{A}{K}z_1 + \frac{Q}{K}\right)z$ and

from ④,

$T = \frac{Q}{K}z + c_4$.

At $z = z_1$, $T_1 = T_2$

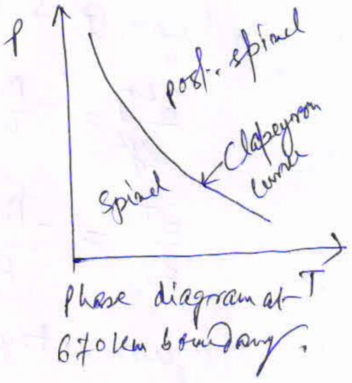
∴ $-\frac{A}{2K}z_1^2 + \frac{A}{K}z_1^2 + \cancel{\frac{Q}{K}z_1} = \cancel{\frac{Q}{K}z_1} + c_4$.

∴ $c_4 = \frac{A}{2K}z_1^2$.

∴ the geotherm for 2nd layer,

$T = \frac{Q}{K}z + \frac{A}{2K}z_1^2$

(b) The spinel–perovskite phase boundary is depressed 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 spinel and perovskite, are in equilibrium. The slope of the Clapeyron curve γ is given by



phase diagram at 670km boundary.

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

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

where $dp = g\rho dz$. For spinel–perovskite phase boundary 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–*p*erovskite phase boundary is depressed inside the descending lithosphere.

Thus, dz would be increased, and the spinel-perovskite 670-km phase boundary gets depressed inside the slab.

(c) The amount of depression is given by

$$dz = \frac{2.5}{3700 \times 10} \times 750 \times 10^3 \text{km} = 50.68 \text{ km} ,$$

Therefore, the depression of the spinel-perovskite 670-km phase boundary inside the slab is 50.68 km.

3. (a) What do you understand by tectonic plate and plate tectonics? (b) Half-space, GDH1, PSM and FHS models are usually used for measuring the heat-flow in the ocean. Which one of these is the best model valid for the entire ocean basin? (c) In a TTT triple junction configuration, the trench (T) between plates C and B has an azimuth of 180°. The azimuth and magnitude of V_{BA} are 300° and 40 mm/yr and the azimuth and magnitude of V_{CA} are 0° and 30 mm/yr. Calculate the magnitude of V_{BC}.

Ans. (a) A tectonic plate (also called lithospheric plate) is a massive, irregularly shaped slab of solid rock, generally composed of both continental and oceanic lithosphere. Tectonic plates basically float on the asthenosphere, or molten mantle. It is a rigid outer most shell of the Earth without any deformation over last one Ma or so. Deformations are only happening at its boundary.

A theory of global tectonics in which the lithosphere is divided into a number of crustal plates, each of which moves on the plastic asthenosphere more or less independently to collide with, slide under, or move past adjacent plates. The process that involves the interaction of moving plates and results in major structural features of the Earth.

(b) FHS model.

(c)

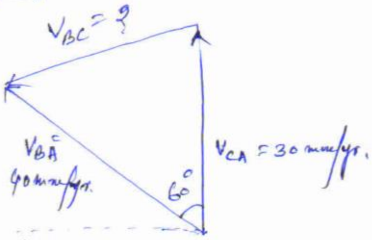
$V_{BC}^2 = V_{CA}^2 + V_{BA}^2 - 2\cdot V_{CA}\cdot V_{BA}\cos 60^\circ$

$= 40^2 + 30^2 - 2\cdot 40\cdot 30 \times \frac{1}{2}$

$= 1600 + 900 - 1200$

$= 1300$

$\therefore V_{BC} = 36.05$ mm/yr. Ans:-

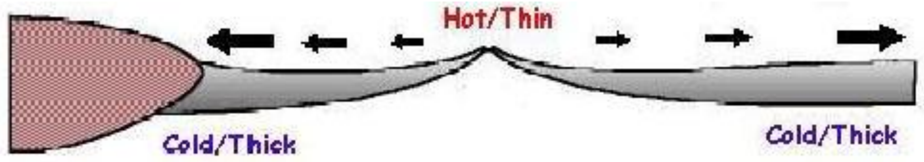


seafloor Spreading

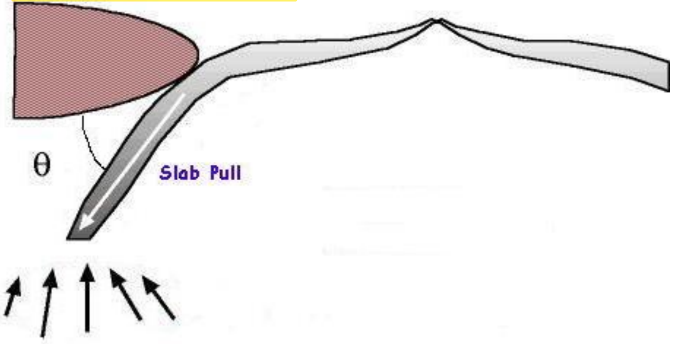
4. (a) Three major plate driving forces are facilitating the movements of most of the tectonic plates. How do you interpret this process of plate movements? (b) On a mission to Venus the surface temperature was measured as 740K, and at a site the concentrations of heat-producing elements potassium (K), uranium (U) and thorium (Th) were 4.0 (in percentage of total volume), 2.2 (parts per million) and 6.5 (parts per million), respectively. The density of the Venusian crust was estimated to be 2.8×10^3 kg-m^{-3}. Calculate the heat generation in μW m^{-3} at the visited site. You may use the equation as $Q_r = 95.2C_U + 25.6C_{Th} + 0.00348C_K$, where Qr (heat generated) in μW kg^{-1}, C_U, C_{Th} and C_K are the concentration of uranium (U), thorium (Th) and potassium (K), respectively.

Ans: (a) 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 Push Force (F_{RP}) Ridge Force increases away from ridge axis



Slab Pull Force (F_{SP}):

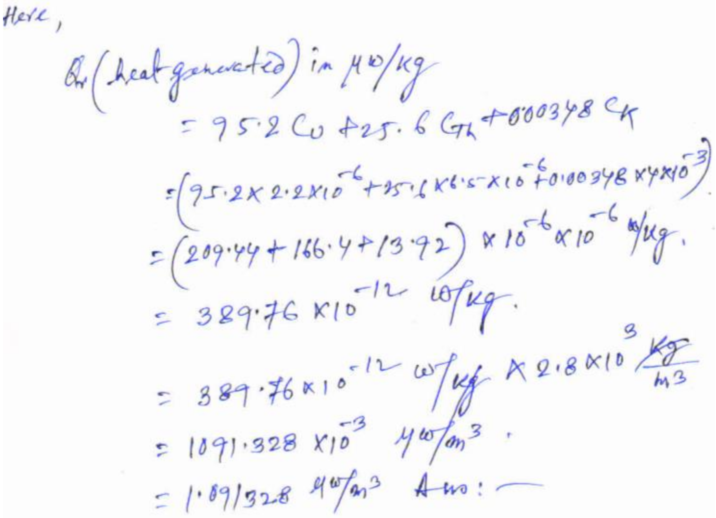


Viscous Resistive Force

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.

(b)



Here,

Q_r (heat generated) in μW/kg

$= 95.2\,C_U + 25.6\,C_{Th} + 0.00348\,C_K$

$= (95.2 \times 2.2\times10^{-6} + 25.6 \times 6.5\times10^{-6} + 0.00348 \times 4\times10^{-3})$.

$= (209.44 + 166.4 + 13.92) \times 10^{-6} \times 10^{-6}$ W/kg.

$= 389.76 \times 10^{-12}$ W/kg.

$= 389.76 \times 10^{-12}$ W/kg $\times 2.8\times10^{3} \frac{kg}{m^3}$

$= 1091.328 \times 10^{-3}$ μW/m³.

$= 1.091328$ μW/m³ Ans: —

5. (a) How can you differentiate the meteoroid, meteor, and meteorite? **(b)** Why was the Wegener's continental drift theory rejected initially? **(c)** Explain the subdivision of different crustal layers in an oceanic area with a schematic diagram.

Ans. (a) A meteoroid is a piece of stone-like or metal-like debris similar to an asteroid, but significantly smaller, which travels in outer space. Mostly debris of comets, sometimes debris of asteroids. Some of the smaller meteoroids may have come from the Moon or Mars.

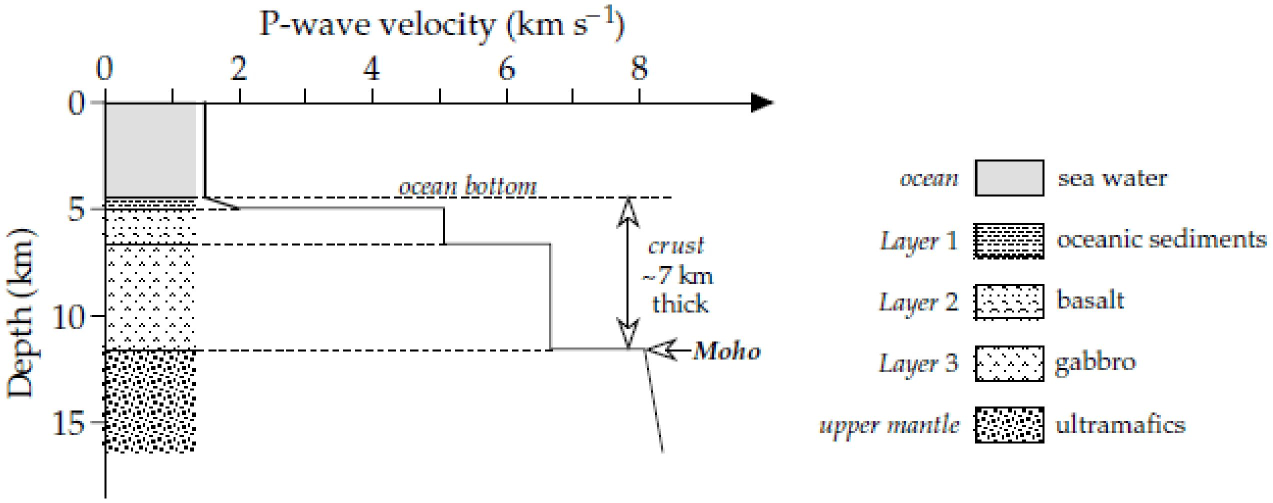
A meteor is an asteroid or other object that burns and vaporizes upon entry into the Earth's atmosphere.

Meteors are commonly known as "shooting stars."

If a meteor survives the plunge through the atmosphere and lands on the surface, it is known as a meteorite.

(b) Some of Wegener's theories were largely conjectural. On the one hand, he reasoned correctly that the ocean basins are not permanent. Yet he envisioned the sub-crustal material as capable of viscous yield over long period of time, enabling the continents to drift through the ocean crust like ships through water. This model met with profound scepticism among geologists. His timing of the opening of the Atlantic was faulty, requiring a large part of the separation of South America from Africa to take place since the Early Pleistocene i.e. in the last two million years or so. Moreover, he was unable to offer a satisfactory driving mechanism for continental drift. His detractors used the disprovable speculations to discredit his better-documented arguments in favour of continental drift.

(c) The structure of the oceanic crust based on data from ophiolite complexes, seismic profiling, and core samples, match the layers with their correct order in the sequence. A generalized model of the structure of oceanic crust is shown in the following Figure. The Figure summarizes general features of the crustal structure, and the corresponding petrological layering in the ocean. Oceanic crust is only 5–10 km thick. Under a mean water depth of about 4.5 km the top part of the oceanic crust consists of a layer of sediments that increases in thickness away from the oceanic ridges. Seismic evidence indicates that the oceanic crust has a vertically stratified structure. The uppermost part, seismic Layer 1, consists of a layer of slowly accumulating marine sediments; the thickness of the sediments increases progressively away from the ridge crest. The sediments are so weakly magnetic that they are essentially transparent to the Earth's magnetic field. In layer 2, Layer 2A consists of a 500 m thick layer of oceanic basalts that are extruded as submarine lava flows or intruded as dikes. These basalts are strongly magnetic and are chiefly responsible for the strong magnetic anomalies observed at the ocean surface. The metamorphosed basalts of the underlying Layer 2B are too weakly magnetic to have much signature. The rocks of the deeper gabbroic Layer 3 may be sufficiently magnetic to add to the skewness of the magnetic anomalies.



6. (a) How was the initial Earth heated? **(b)** The region of Indo-Gangetic plain is thought to be over-compensated isostatically. Present a model in support of this statement.

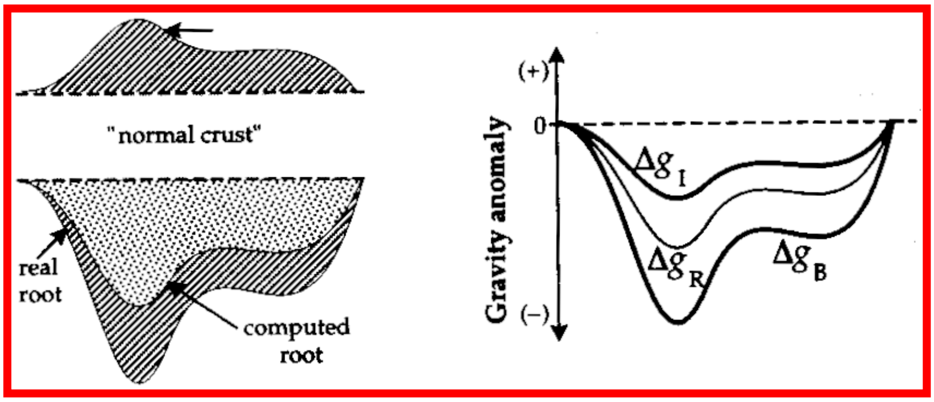
Ans. (a) The Earth formed by the process known as accretion. This process is "gravity-driven", and involved gravitational attraction of material in the vicinity of the solar disk to the growing Earth. The process continues to this date with meteorite impacts, but must have occurred at a very high rate while the planet was initially forming. Release of energy during impact of the accreting bodies produced heat. Owing to the fact that the rocky material which comprises the Earth is a good heat insulator, heat from the accretion process was maintained below the Earth's surface, as each hot layer was subsequently covered by, and insulated by overlying accreted debris.

As the Earth grew larger, its gravitational field increased and began to compact as a result of the growing mass of largely unconsolidated material. The process of compaction also produced heat, which further served to increase the temperature within the still-forming planet. At this stage of planetary formation, the Earth was "warm" with internal temperatures probably reaching as high as 1500°C.

In addition to heat generated by the processes of accretion and compaction, the newly formed Earth also contained radioactive elements of both long- and short-lived. The long-lived isotopes are ^{238}U, ^{235}U, ^{232}Th and ^{40}K have half-lives comparable to the age of the Earth, and spontaneously disintegrating released energy in the form of heat. The short-lived radioactive isotopes are ^{26}Al, ^{36}Cl and ^{60}Fe have smaller half-lives of less than 10 Ma, and heated the Earth at its initial stage of evolution.

Other physical processes are adiabatic self-compression and tidal effect because of rotation of the Earth contributed heat for its initial heating. During the self-adiabatic compression, the internal pressure was progressively increased during the process of accretion, and increased the inner temperature of the Earth. The diurnal rotational period of the initial earth was about one-fourth of its present rotation rate. Part of the energy lost is dissipated by tides in the shallow ocean/big land-locked water bodies because of decreasing diurnal rotation rate.

(b) The over isostatic compensation of the Indo-Gangetic plain can be explained from the following diagrams. The Indo-Gangetic plain is evolved due to down-buckling of the converging Indian lithosphere vis-à-vis its subduction beneath the Eurasian plate. The down-buckling effect has facilitated movements of more lithospheric materials in the deeper level which the anti-root (real root) becomes more deeper than expected, which causes the Bouguer anomaly more negative than its computed part. In the figure, Δg_I, Δg_B and Δg_R are isostatic anomaly, observed Bouguer anomaly and computed anomaly of the root zone.



7. **(a)** What are those factors found in structure and rock type in support of the continental drift theory? (b) How the Paleozoic glaciation records explain the continental drift theory?

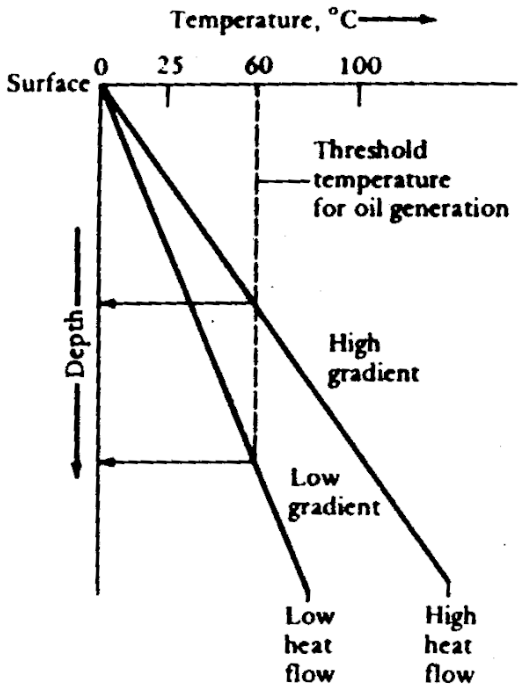
Seafloor Spreading

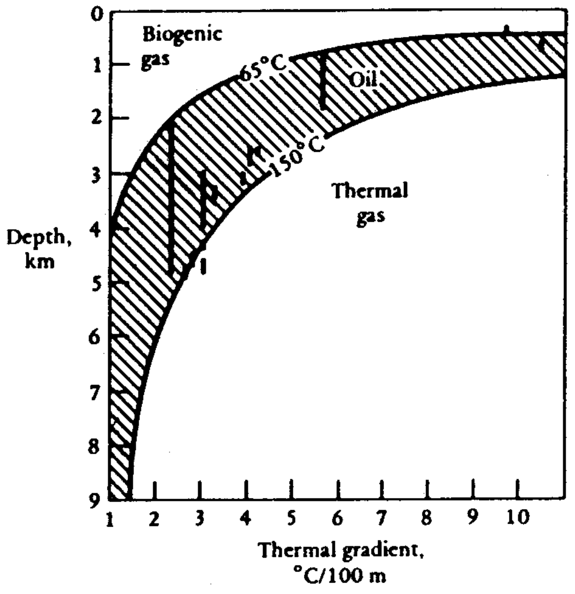
Ans. **(a)** Several geologic features ended abruptly at the coast of one continent and reappeared on the facing continent across the Atlantic. The folded Appalachian Mountains are an excellent example. The deformed structures of the mountain belt extend northeastward across the eastern United States and through Newfoundland, terminating abruptly at the ocean. The mountain belt with a similar age, rock sequence, fossils, and structural style, reappears on the coasts of Ireland, Scotland, and Norway. Folded mountain ranges at the Cape of Good Hope, at the southern tip of Africa, are another example of a similar geologic feature. Here, the ranges trend from east to west and terminate sharply at the coast. An equivalent structure, of the same age and style of deformation, appears near Buenos Aires, Argentina. The source of the 1 Ga old Roraima Formation sediments of Guyana lies to the east and appears to be situated in northwest Africa. These evidences support the drifting of continents.

(b) During the latter part of the Paleozoic Era, glaciers covered large portions of the continents in the Southern Hemisphere. The deposits left by these ancient glaciers are distinct and can be readily reorganized, and they cannot be mistaken for other types of sediment. In addition, striations and grooves on the underlying rock show the direction in which the ice moved. Except for Antarctica, all of the continents in the Southern Hemisphere now lie close to the equator, far removed from a latitude that could produce glaciation. In contrast, the present-day continents in the Northern Hemisphere show no trace of glaciation during this time. In fact, fossil plants in North America and Europe indicate a tropical climate in those areas. This evidence is difficult to explain in the context of immovable continents because the climate belts are determined by latitude. Even more difficult to explain is the direction in which the glaciers moved. Regional mapping of striations and grooves indicates that in South America, India and Australia, the ice accumulated in the oceans and moved inland. Such movement of ice would be impossible unless there was a land-mass where the oceans now exist. The pattern of glaciation was considered strong evidence of continental drift.

8. (a) How the geothermal gradient affects the depth of thermal window for hydrocarbon generation? Explain with neat diagrams. (b) The heat flow and heat production at a location for a heat flow province is 49 mWm^{-2} and 2.0 μWm^{-3}. The heat flow and heat production at another location for the same heat flow province is 81 mWm^{-2} and 6 μWm^{-3}. Calculate the reduced heat flow and the characteristics thickness of the crust involved in the radiogenic heat production.

Ans. (a) Low conductive formations with their high geothermal gradients raise the depth at which the oil window is entered. Thus, oil generation begins at greater depths in subductive troughs than in rift basins as explained in the following figures. Layers of low-conductivity rock may raise the depth at which oil generation begins. For a higher conductive salt dome, the isotherm above it is elevated and depressed beneath it. While for a mud diapirs of low thermal conductivity, the isotherms are depressed over it.

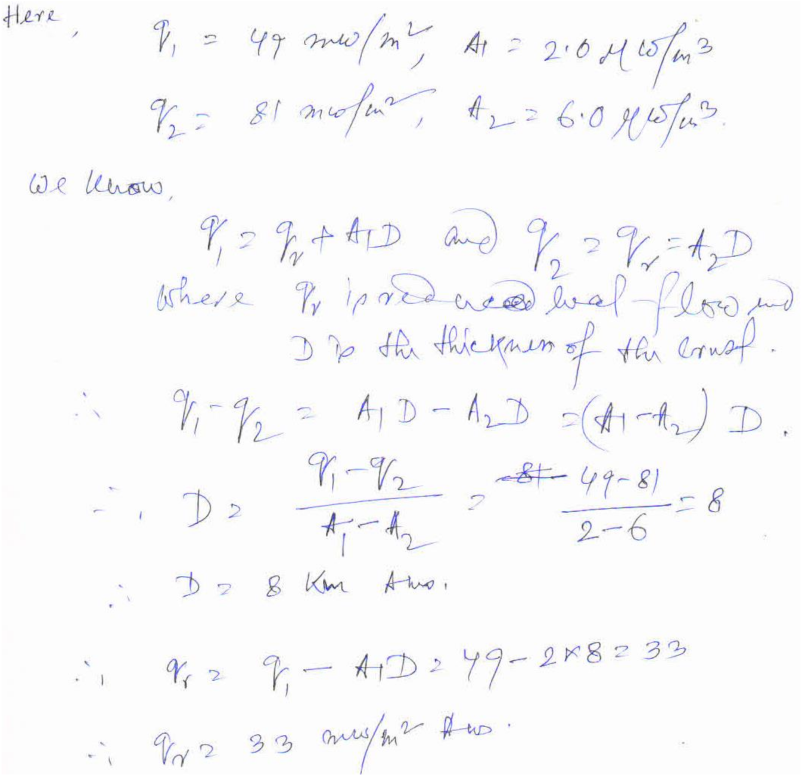




B. Plot illustrates that how oil occurs in a liquid window between 65 and 150°C, which extends

A. Plot illustrating the variation of depth for different thermal gradients. Oil is occurring in a liquid window between 65 and 150°C, which extends from shallow depths with high thermal gradients to deep basins with lower gradients.	from shallow depths with high thermal gradients to deep basins with lower gradients.

(b)



Here, $q_1 = 49$ mW/m², $A_1 = 2.0\ \mu W/m^3$

$q_2 = 81$ mW/m², $A_2 = 6.0\ \mu W/m^3$.

We know,

$q_1 = q_r + A_1 D$ and $q_2 = q_r = A_2 D$

Where q_r is reduced heat-flow and D is the thickness of the crust.

∴ $q_1 - q_2 = A_1 D - A_2 D = (A_1 - A_2) D$.

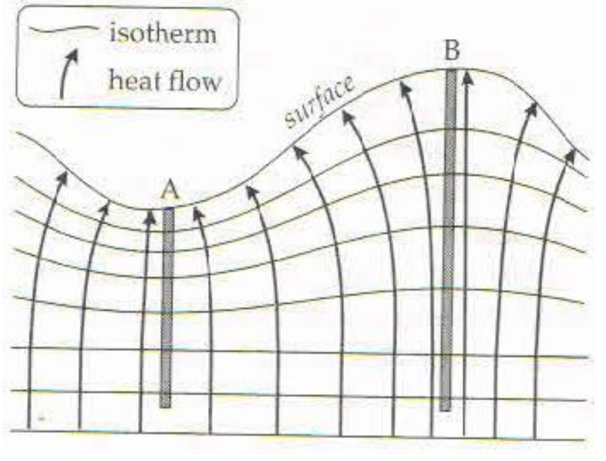
∴ $D = \frac{q_1 - q_2}{A_1 - A_2} = \cancel{81}\ \frac{49-81}{2-6} = 8$

∴ D = 8 Km Ans.

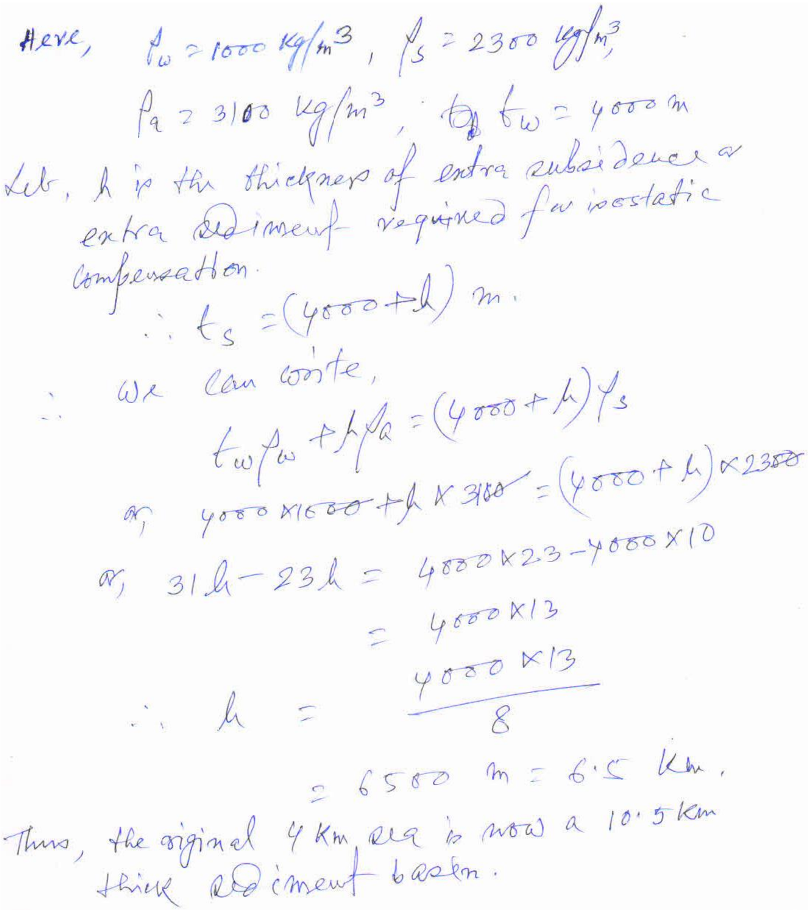
∴ $q_r = q_1 - A_1 D = 49 - 2 \times 8 = 33$

∴ $q_r = 33$ mW/m² Ans.

9. (a) How the topography affects the isotherms and the direction of heat flow? Explain with a neat diagram. **(b)** 4 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 (2300), and basement (3100).

Ans. (a) It is generally accepted that the heat-flow is only vertical. Well below the surface the isotherms (surfaces of same temperature) are horizontal and the flow of heat (orthogonal to the isotherms) is vertical. However, with undulating surface (as shown by the figure below), the isotherms follow the topography. Thus, the heat-flow lines are deviated from the higher topography and focused towards the lower topography.	

(b)



Here, $\rho_w = 1000\ kg/m^3$, $\rho_s = 2300\ kg/m^3$,

$\rho_a = 3100\ kg/m^3$, ~~t_f~~ $t_w = 4000\ m$

Let, h is the thickness of extra subsidence or extra sediment required for isostatic compensation.

$\therefore t_s = (4000+h)\ m.$

We can write,

$$\therefore t_w\rho_w + h\rho_a = (4000+h)\rho_s$$

$$\text{or, } 4000\times 1\cancel{000} + h\times 31\cancel{00} = (4000+h)\times 23\cancel{00}$$

$$\text{or, } 31h - 23h = 4000\times 23 - 4000\times 10$$

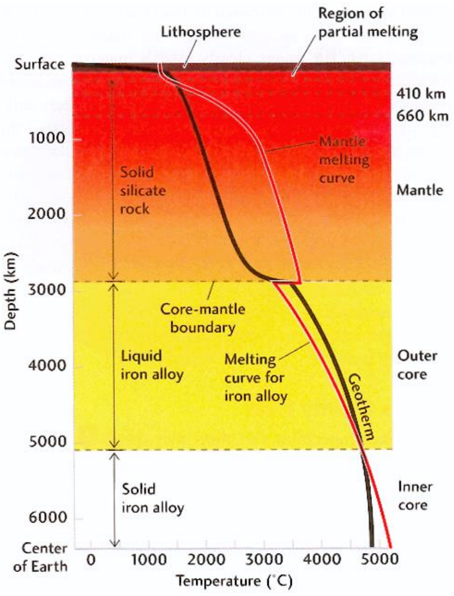
$$= 4000\times 13$$

$$\therefore h = \frac{4000\times 13}{8}$$

$$= 6500\ m = 6.5\ km.$$

Thus, the original 4 km sea is now a 10.5 km thick sediment basin.

10. (a) How the geotherm and melting temperature control the level of solidity of materials at different depth-level inside the Earth? **(b)** Derive the expressions of densities beneath mean sea level of water-depth ‘d’ and water-density ρ_w and beneath a mountain of height ‘h’ using Pratt’s isostatic model. Take the normal thickness of the continental crust as T. Isostacy



(a) It is apparent from the plot below that the real temperature in the lithosphere is sharply increased, and the melting point is higher in this solid rigid layer. In the partially melted layer, called asthenosphere, the meting point is little reduced to less than the real temperature, and make the medium at these levels semi-solid. Both increase further beyond the layer of asthenosphere, however the melting point curve increases more sharply up to certain depth (say ~ 1000 km), and both are increased gradually afterwards. Near the lower mantle-outer core boundary, the real temperature increases sharply, and exceeds the values of melting point, which facilitated the transformation of the semi-solid materials into liquid in the outer core-lower mantle boundary. The melting point temperature remains less the real temperature throughout the outer core, and keep the medium in this layer in liquid state. Subsequently, at the outer core-inner core boundary, the melting point increases more sharply, and exceeds the value of real temperature, and the materials inside the core becomes solid.

Ans. (b) Pratt assumed that the depth of the base of the upper layer is levelled and that isostatic equilibrium is achieved by allowing this upper layer to be composed of columns of constant density. Taking the base of the upper layer as the compensation depth and equating the masses above this level in each column of unit cross-sectional area gives:

$$\rho_u T = (h + T)\rho_1$$
$$= \rho_w d + \rho_d (T - d)$$

Thus, in this model, compensation is achieved by mountain consisting of and being underlain by material of low density,

$$\rho_1 = \rho_u\left(\frac{T}{h + T}\right)$$

and the ocean being underlain by material of higher density,

$$\rho_d = \frac{\rho_u T - \rho_w d}{T - d}$$