earth's water surface that faces the moon (T in fig. 12.4) at zenith, with the result high tidal bulge (high tide) is created at the zenith. This is called **zenith tide or direct tide.** Simultaneously high tide is also created at the opposite side (A in fig. 12.4, nadir) of the earth at nadir. Please remember this opposite side of the earth does not face moon but is opposite to that side of the earth (zenith) which faces the moon. This **nadir lunar tidal bulge** (high tide) is called **nadir tide or indirect tide** because it is not generated by the gravitational attraction of the moon, but is generated by the centrifugal force resulting from the rotation of the earth and the moon.

12.6 THEORIES OF THE ORIGIN OF TIDES

Numerous theories have been propounded from time to time to explain the origin of tides in the oceans. Since the origin of ocean tides depends upon the tide generating force resulting from the interactions between the earth and the moon, and between the earth and the sun i.e. the gravitational attraction of the sun and the moon, the rotation of the earth-moon system, it requires the understanding of principles and laws of astrophysics, physics, geophysics, mathematics, hydrodynamics etc. The spatial variations in tidal waves complicate the problem of the origin of tides. In the beginning Bernoulli, Laplace, Airy, Poincare etc. ventured in this precarious field and based their hypotheses and explanation on hypothetically conceived oceans. This is why their concepts could not hold on for long time because they could not explain actual tides in real ocean basins of heterogeneous character. Basically, the following 2 models of the origin of tides in the oceans have been postulated :

- **equilibrium model** of tides, and
- **dynamic model** of tides.

The basic difference between these models of the origin of tides in the oceans is related with the movement or no movement of **lunar tidal bulges.** The equilibrium model of tides assumes continuous ocean water surface on the earth's surface with infinite depth and no movement of tidal bulges with the rotating earth. On the other hand, dynamic model of tides assumes both land and ocean surfaces on the earth, and movement of tidal bulges as **rotary waves.** Most of the theories of the origin of tides revolve around these models of tides. These theories include the following :

1. equilibrium theory of Newton (1687)
2. dynamical theory of Laplace (1755)
3. progressive wave theory by William Whewell (1833)
4. canal theory by G.B. Airy (1842)
5. stationary wave theory by R.A. Harris

1. Equilibrium Model of Tides

The equilibrium model of the origin of tides is based on the following assumptions, say axioms:

- That the hypothetical earth's surface is covered by only water surface with infinite depth,
- That there is no land surface and there is no obstruction from the ocean bottoms due to their infinite depth in the movement of tidal waves.
- That the waves generated by tidal bulges are progressive waves.
- The water is always in equilibrium state with respect to gravitational attraction of the moon and centrifugal effect of the rotation of the earth-moon system.

According to this model the gravitational attraction of the moon is greatest at the water surface of the earth facing the moon because there is shortest distance between the moon and the earth, say the moon is closest to the earth. This greatest pull of the moon causes **lunar bulge** of water at the surface of the earth (zenith) facing the moon. On the other hand, the other side of the earth which is opposite to the moon (nadir) is farthest from the moon and hence gravitational pull of the moon is minimum and thus centrifugal force dominates over gravitational attraction of the moon, with the result water again bulges outward at the side opposite to the moon because of outward centrifugal force resulting from the rotation of the earth-moon system. Thus, we have two bulges (tides) at the same time on the earth's surface, one is **zenith lunar bulge** on the side of the earth that faces the moon, the second one is **nadir lunar bulge** on the other side of the earth, that is opposite to the moon (fig. 12.4).

According to this equilibrium model the tidal bulges do not move along with the rotation of the earth but remain stationary. Since the earth rotates on its axis, a place on the earth's surface passes in and out of the tidal bulges. When the place passes through the bulge water rises causing tides and when that place goes out from the bulge, the water falls causing ebbs. The different places of earth's surface pass through different parts of the tidal bulges. This is why there is variation in the periods of tides on the earth's surface from low latitudes to the higher latitudes. For example, there are **diurnal tides** in high latitudes (polar region), **mixed tides** in the middle latitudes, and **semidiurnal tides** in the low latitudes.

Though this equilibrium model appears at first sight to offer right explanation to solve the problem of origin of ocean tides but since it is based on hypothetical earth having water surface all around it, it cannot be applicable in real world because the real world has both ocean basins as well as continents. Further more, it is not palatable to accept the stationary position of tidal bulges on a rotating earth.

2. Equilibrium Theory of Newton

Sir Issac Newton propounded his theory of gravitation in his Principia in the year 1687 wherein he stated that every celestial body of the universe possesses gravitational force. The celestial bodies attract each other through their gravitational force in such a way that they remain in equilibrium. Thus, the sun, the earth and the moon are also in equilibrium due to their respective pull towards each other. Though the gravitational force of the sun is far greater than that of the moon but the lunar gravitational force has more effect on the earth than the sun because of its nearness to the earth. The earth and the moon while attracting each other revolve around their common centre of gravity and thus two types of force are produced *e.g.* (i) **centrifugal force** which works outward from the centre, and (ii) **centripetal force** which works towards the centre.

Centrifugal force is similar at all points on the earth's surface. The earth's surface under the moon is 6,400 km (4,000 miles) nearer to the moon's surface than its (earth's) centre so that the centripetal or gravitational force (attractive force) is greater than the centrifugal force at the earth's surface. Consequently, the water of the earth's surface under the moon is attracted and pulled and high tide is caused. The opposite side of the earth's surface also experiences tide because the reactionary force (centrifugal force) of the gravitational force (centripetal force) of the moon is more effective. In other words, the centrifugal force of the moon is greater than the attractive force at the opposite side of the surface of the earth and thus a bulge of water is caused.

Gravitational and centrifugal forces balance each other along the line joining both the poles resulting in a resultant force which is directed towards the centre of the earth. This forces causes lowering of sea level and depression *i.e.* low tide. It is apparent that each place experiences two high tides every day. Similarly, there are two tides on the earth's water surface at the same time, one is caused due to gravitational (centripetal) force being greeter than the centrifugal force while the second one is caused due to centrifugal (outward) force being greater than the gravitational force so that both may balance each other. It may be stated that the highest points of rise of water or say high tides lie nearest to and farthest away from the moon while the lowest points of water surface or say lowest tides lie at places perpendicular to the above places. These four phenomena viz. two high tides and two low tides occur simultaneously at one time on the earth's surface.

Evaluation of Newton's Theory of Tides

- Since the earth's surface is comprised of land and water and hence the gravitational force of the moon will not be so effective as it would have been if the earth's surface would have been composed of only water.

- Secondly, the bulge of water may not be possible unless some sort of horizontal movement of tide is involved. In other words, changes in the position of water masses in the form of horizontal movement is essential for the bulging of sea water outward. In order to overcome this short-coming the theory was subsequently amended. The theory envisages that waves are generated during the occurrence of tides and these waves move westward with their crests directly under the moon.
- Thirdly, the time of high tide should be the same at all places along each meridian but this never happens. For example, Liver-pool and Leith, both are situated on 8^0W longitude (meridian) but the time differ-ence of high tides of these two places is of three hours.
- Fourthly, the proposed theoretical time by this theory for a tidal wave to move round the earth would be slightly more because there is vast variation in the configuration of the coasts of different oceans and their depths and thus the tidal waves have to move under internal as well as external frictions. In fact, the tidal waves are not free but are forced waves which are very often obstructed by continental and oce-anic barriers (bottom reliefs). G.B. Airy regarded this equilibrium theory as an erroneous approach to explain ocean tides. According to him it is erroneous to explain the origin of tides on the basis of gravita-tional force.
- The tidal bulges are seldom stationary but they move as **rotary waves** within an ocean basin as envisaged in **dynamic theory** of ocean tides.
- The equilibrium theory ignores the presence of continents and their obstructions in the free movement of tidal bulges. This hypothetical consideration is far from reality.

3. Progressive Wave Theory of Tides

W. Whewell propounded his **progressive wave theory** in the year 1833 to explain various problems of the occurrences of tides in the oceans such as origin of tides, times of tides, propagation of tidal waves etc. Whewell prepared a map of cotidal lines of the world oceans which he himself revoked after he was convinced by the concepts of ocean tides as forwarded by G.B. Airy in the year 1842. The theory of ocean tides propounded by Airy is known as '**canal theory**'. The 'progressive wave theory' and 'canal theory' of ocean tides is based on the following facts :

- The earth is a heterogeneous body and not a homogenerous perfect fluid as was conceived in equilibrium model of ocean tides. In other words, the earth consists of both continents (lithosphere) and oceans (hydrosphere).
- Tide occurs at different points of location at different times on the same longitude.
- There is time-lag of tides away from the source of origin i.e. the time of the occurrence of tides varies (is delayed) as we go away from the source.
- There is variation in the magnitude and amplitude of tides at different places.
- Tide is in the form of tidal wave which travels from east to west.

The crests and troughs of such tidal waves become tides and ebbs respectively. These waves are originated in the oceans under the influence of tidal force of the moon. The length and velocity of tidal waves depend on the depth of seas and oceans. In a globe completely surrounded by water the tidal waves would travel freely from east to west but the position of land and water hinders the velocity and direction of these waves.

Since the continents roughly stretch from north to south and hence they hamper the free movement of tidal waves. These waves are least hampered in the oceans surrounding the Antarctic continent.

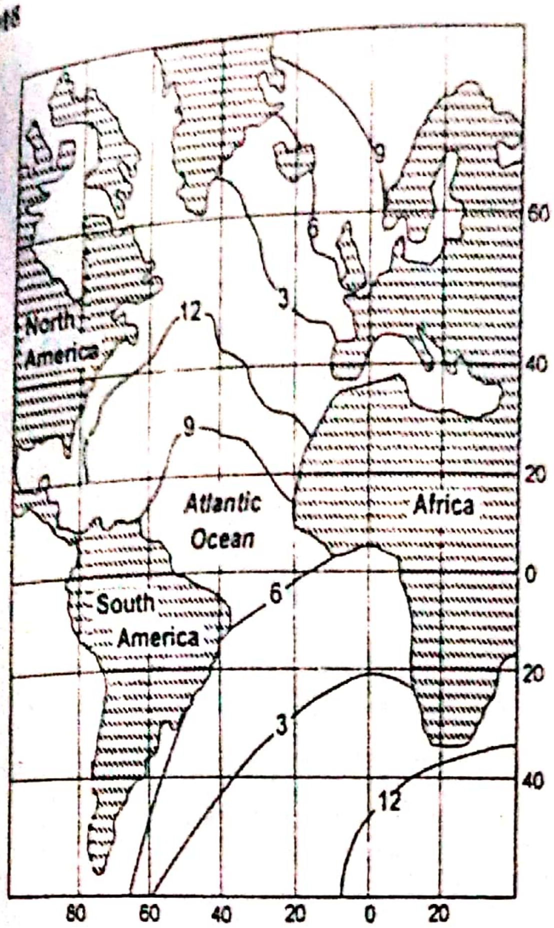

Fig. 12.9 : Co-tidal lines of the Atlantic Ocean, based on progressive wave theory.

Thus, tidal waves are generated in the southern ocean in the southern hemisphere under the influence of tide-producing force of the moon. These waves are called **primary waves** which move from east to west in the form of **forced waves**. These waves are obstructed by the continents and are consequently refracted northward. **Secondary waves** are generated when the westward movement of primary waves is obstructed by land masses. These northward moving waves are called secondary waves or **derived waves** which also move from east to west.

Further minor waves are generated from these secondary waves. These secondary and minor waves progressively move northward though there is gradual decrease in their magnitude and amplitude but these waves generate tides every where. It may be pointed out that the primary waves are influenced by the moon but the minor waves move freely. It is, thus, apparent that the tidal waves after being originated in the southern ocean progressively move northward with continuous lag of time and dissipation of wave energy. In other words, the arrival of these progressive waves at successive places northward along the same longitude is also progressively delayed. This is why there is difference of time of tide at different places on the same longitude. In other words, the time of tides is progressively delayed northward along the longitude. These progressive waves become ineffective after reaching north pole. The crests and troughs of these waves after reaching the coasts cause tides and ebbs respectively. Fig. 12.9 depicts the **co-tidal lines** (the lines joining the points of high waters occurring at the same hour are called co-tidal lines) of the Atlantic Ocean.

Evaluation of the Theory

According to the progressive wave theory the age of tides increases northward. In other words, if tide is generated in the south on a particular longitude it reaches quite late at the points located further north on the same longitude. On the other hand, the data available so far about the time of tides denote that the time of spring tides is almost the same from Cape Horn to Greenland in the Atlantic Ocean. Normally, the tides are local or regional phenomena rather than phenomena originating in the southern ocean and moving progressively northward. At some latitudes daily and semi-diurnal, both types of tides are observed. Further, there is spatial variation in the irregularity of tides in different oceans. These variations cannot be explained on the basis of progressive wave theory.

4. Stationary Wave Theory

R.A. Harris of the U.S. Coast and Geodetic Survey propounded the concept of stationary waves as opposed to the progressive waves. This theory offers almost satisfactory explanation for local differences in tides, their types and their age. According to Harris tide phenomena are not due to progressive waves which originate in the southern oceans as claimed by William Whewell but are due to stationary waves which originate independently in each ocean. In other words, tide phenomena are regional phenomena. The stationary wave theory can be explained with the help of an experiment. If a rectangular tank of 'developing tray' containing water is rocked from one side to the other or is simply tilted, the water level rises along one side of the tray but falls along the other side. This generates oscillation in the water contained in the tray. Such oscillations in the water are called stationary waves. There is such a centre in the middle of the tray where there is no change in the level of water. This point is called **nodal point** (fig. 12.10). The water level moves rhythmically from one end of the tray to the other end along a line which is called **nodal line**. The period of oscillation of water in the tray depends on the length and depth of the tray and the force of shocks applied to the tray. The aforesaid example is the case of uninodal system (fig. 12.10 A) but there may also be binodal oscillation system (fig. 12.10 B).

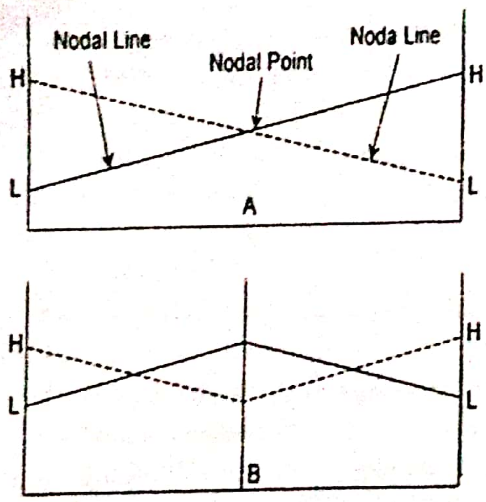

Fig. 12.10 : Uninodal (A) and binodal (B) oscillation systems.

Based on above analogy, different oceans of the earth are like giant water containing trays. The tidal forces of the sun and the moon cause oscillations in the oceanic waters but the oscillations do not occur along straight limes as in the case of the tray rather they occur around central point because of the rotational force of the earth, with the result several **amphidromic points** are generated. The **tidal bulges** lag behind the rotational speed of the earth and hence these break into numerous cells in the open ocean. The crests and troughs of the tidal wave rotate around a point located in the center of each cell. This central point is called **amphidromic point**. The oceanic water remains calm and stationary at these points whereas water level changes around them. This mechanism results in the formation of waves which move in anti-clockwise direction around these amphidromic points. Such oscillatory mechanism of water occurs in every ocean and is collectively called as **oscillation system**. Numerous stationary waves are generated from these amphidromic points. Every stationary wave has a definite time of its oscillation. The oscillation system and mechanism are affected by the depth, configuration and length of the ocean basins and the rotational speed of the earth. The stationary waves after being originated from the amphidromic centres move towards the coasts. The forward movement of these waves is hampered by the continental peninsulas, islands, bays etc. When these waves reach the coasts, their crests and troughs cause tides and ebbs respectively. There is positive correlation between the depth of the oceans and the height of tides. In other words, if the depth of the ocean becomes greeter, higher stationary waves are generated and high waves generate high or spring tides. Low tides are generated in shallow seas because of lower height of stationary waves.

12.7 TIDAL BORES

Tidal bores are steep wall of seawater moving upstreams from their mouths when the tidal waves enter the low-lying rivers. "A tidal bore (bore = crest or wave) is a wall of water that moves up certain low-lying rivers due to an incoming tide. Because it is a wave created by the tides, it may be considered to be true tidal wave" (H.V. Thurman and A.P. Trujillo, 1999). Tidal bores are formed when tidal waves with great height i.e. high tidal range (here tidal range means height of the crests of tidal waves), enters a narrow and low-lying river, which debauches in the sea or bay, and rushes upstream and is obstructed by the flow of the river. Consequently, the tide water is forced to have a steep wall-like crest. The following conditions are conducive for the occurrence of tidal bore :

- Narrow and low-lying coastal river with gentle channel gradient,
- A bay with narrow opening and tappering head,
- Large tidal range (wave height), usually more than 5 meters,
- Upward decreasing water depth, meaning thereby decreasing depth of water in upriver section, etc.

When tide water enters the coastal river with high tidal range, the seaward flow of the river obstructs the incoming tide, with the result the front of tidal wave crest is forced to assume high tidal range. Thus, the tidal wave with steep tidal wall of more than 5 m in height rushes upstream or upbay. This wall-like high tidal waves are called tidal bores which move upstream with average speed of 20-22 kilometers per hour. As the tidal bores move upstream, their effects continue to decrease. The Amazon river of South America has 800 km long estuary which is travelled by tidal bores. The estuary of the Chientang river of China is known to have the highest tidal bore, measuring more than 8 meters in height, in the world. Large tidal bores are noticed in Petitcodiac river of New Brunswick of Canada, the Seine river of France etc. Tidal bores also occur in Hooghly river of India.

It may be mentioned that it is not the tidal range which always determines the height of tidal bores. For example, the Bay of Fundy of Nova Scotia has the largest tidal range in the world (17 meters) but the tidal bore has the height of about one meter or so. This is because the Bay of Fundy has quite wide mouth at its opening. Thus, it is evident that large tidal bore can occur only in those coastal rivers and bays which have narrow and constricted openings in the sea.

12.8 TIDAL CURRENTS

Water currents are generated by tides due to upward and downward movement of sea level in the open and nearshore regions. The coastward movement of tides causes **flood currents** which pile up seawater against the sea coast. The currents caused by returning tides are called **ebb currents.** Thus, flood currents move coastward while ebb currents move away from the coasts.

The currents associated with tides in the open ocean are called **rotary currents** which turn in counterclockwise direction in the northern hemisphere and clockwise in the southern hemisphere. When the rotary currents enter the shallow water of nearshore areas they suffer from friction and ultimately they change to **alternating** or **reversing currents.** The velocity of rotary currents in the open sea is very slow, around one kilometer per hour, but the reversing currents move very fast with the velocity of 44 kilometers per hour. The reversing tidal currents assume greater velocities in the region of irregular coastlines, in narrow and constricted bays, and in narrow coastal rivers.

The rise and fall of tides, and flood currents and ebb currents have great potentials for the generation of electricity wherever there are bays with narrow openings and constricted tidal inlets or narrow estuaries. This aspect will be discussed in the chapter 'marine resources.'

12.9 IMPORTANT DEFINITIONS

Ambphidromic point : The central point or nodal point in an amphidromic system, is called amphidromic point from where the co-tidal lines radiate in all directions.

Apogean tides : The low tides, caused at the time when the moon is at the farthest distance from the earth, are called apogean tides, which are 20 percent lower than normal tides.

Centrifugal force : is the force that works outward on a body rotating about an axis.

Centripetal force : is force that works toward the center of a rotating body.