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1. Learning outcomes

After studying this module, you shall be able to:

- Learn about sedimentary basins and mechanisms of sedimentary basin subsidence.
- Know about types of sedimentary basins in relation to their plate tectonic settings, including Indian examples of most basin types.
- Learn about sedimentary basin analysis and basin mapping methods in brief.

2. Introduction to sedimentary basins

Sedimentary basins are morphotectonic depressions on Earth's crust, which accumulate considerable amount of sediments over geological time. Sedimentary basins are the repositories of a great volume of economic deposits, including hydrocarbons, coals, ground water and many of the mineral and metal deposits. Study of basin analysis covers the basin formation mechanisms, sedimentation style of the basin, evolution of a basin with time due to the changing tectonic regime and its ultimate destruction. Detailed study of sedimentary basins is necessary for the successful exploitation of different types of deposits of economic deposits.

3. Mechanism of basin subsidence

Subsidence in a sedimentary basin may be explained by three basic mechanisms, which include mechanical stretching, thermal subsidence and flexure loading.

3.1. Mechanical stretching: This mechanism is very important in divergent settings characterized by extensional stress conditions. Mechanical stretching results in thinning of the crust (Fig. 1). The effect is believed to be two fold. The lower, hotter part of the lithosphere flows away from the locus of extension, and an upper, cooler and more brittle crust produces extensional fault-bounded sedimentary basins. This process satisfactorily explains the formations of terrestrial rift valleys like the east African rift.

3.2. Thermal subsidence: Thermal subsidence is related to increase in density of crustal material because of cooling. Cooling is possible if a portion of the earth's crust is initially heated. The lithosphere gets heated up quickly (e.g., via magmatic intrusions or pervasive dike intrusions) but it cools down very slowly by conduction. As the lithosphere cools down, it subsides. Thermal subsidence explains subsidence in ocean basins. Magnitude of subsidence increases away from the mid-oceanic ridge (Fig. 1).

3.3. Loading: This mechanism involves subsidence of any region in the earth's crust by the loading effect caused by excess mass. The loading may be of two types, namely tectonic loading and sediment loading. A common example of tectonic loading involves subsidence of the earth's crust caused by the formation of thrust belts. The crust is over-thickened because of the formation of thrust sheets. The basin forms close to the thrust belts (Fig. 1). Sediment loading amplifies the original subsidence of a basin. If the original basin is filled with sediment, or water or water sediment mixture instead of air, the additional load acts as a driving force in amplifying the thermo-tectonic subsidence (Fig. 1).

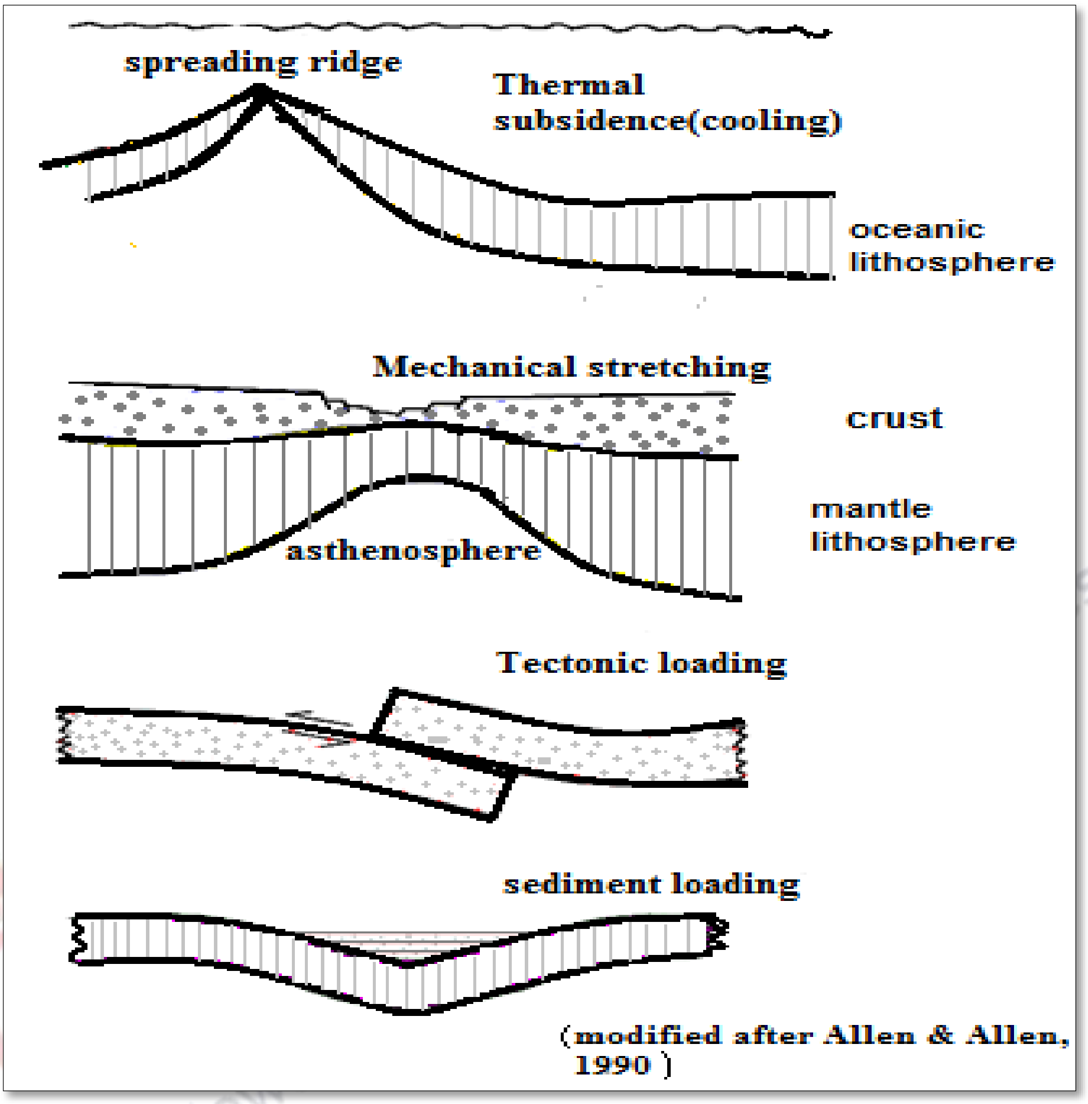

Fig. 1 Sketches showing three basic mechanisms for basin subsidence.

4. Classification of sedimentary basins

Basins were earlier known as geosynclines. Sedimentary basins are classified considering its plate tectonic context. Primary aspects of classification and evolution of basins are, a) whether a basin is formed on an oceanic crust or on a continental crust, b) proximity of the basin to a plate boundary and c) the nature of the nearest plate boundary.

Basins form in all three types of crustal stress environments i.e. extensional, compressional and strike-slip settings. In extensional regimes the axis of maximum stress is vertical and in both compressional and strike slip regimes the axis of maximum stress is horizontal. Five broad categories of sedimentary basins are recognized which are as follows (Busby and Ingersoll, 1995).

a) Basins in divergent setting
b) Basins in intraplate setting
c) Basins in convergent setting
d) Basins in transform and transcurrent fault setting
e) Basins in hybrid setting

4.1. Basins in divergent setting

These basins form because of extensions and these are broadly divided into two types, a) terrestrial rift valley basins and b) Proto-oceanic rift troughs.

4.1.1. Terrestrial rift valley basins: Rifts within the continental crust bounded between high angle normal faults are known as terrestrial rift valley basins. These are broadly classified into two types- passive rift and active rift. In case of a passive rift, extension causes the basin to form, which is unrelated to the mantle plume and triple junction. Active rift involves crustal extension caused by the upward movement of a mantle plume and formation of triple junction. The proportion of bimodal volcanics is significant in case of active rifts. Terrestrial rift valley basins may evolve into an ocean basin with continued rifting and drifting over a period of a few millions of years.

A common example of terrestrial rift valley basin is a half graben, which is flanked by a high-angle extensional fault in one side and hanging wall dip slope on the other side (Fig. 2). Most of the sediments are supplied by the hanging wall dip slope. The footwall scarps supply localized fan-shaped conglomeratic deposits. The basin may be a few tens of km wide and a few hundred km in length.

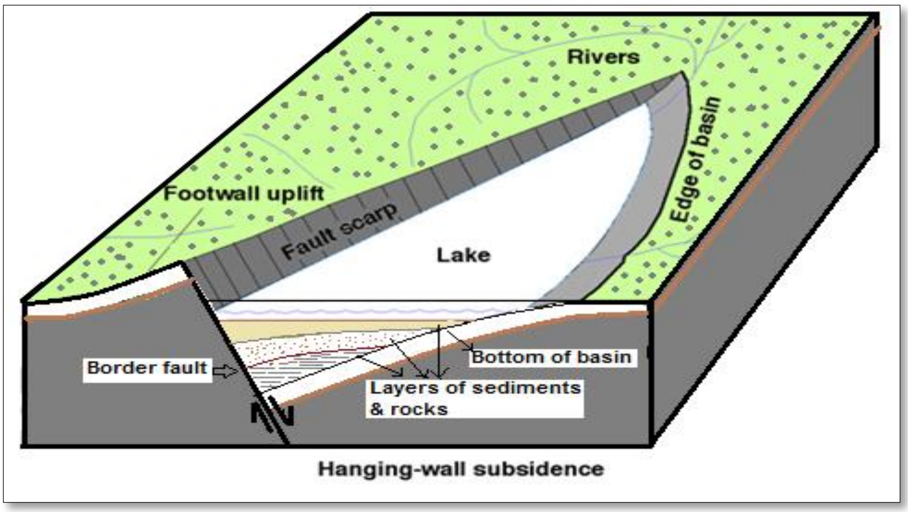

Fig. 2 Sketch of a half-graben basin (modified from Schlische, 1995).

Terrestrial rift valley basin may also involve a series of horst and graben structures, bounded by normal faults on both sides (Fig. 3). Horsts or highs indicate the elevated portions of the basin, while the grabens indicate depressions. The 'Bombay High' represents a horst-like structure on the basement. The thickness of Cenozoic sediments is much higher within the grabens compared to the horsts.

At present, there is no active terrestrial rift valley basin in India. Modern rift basins are found in East Africa.

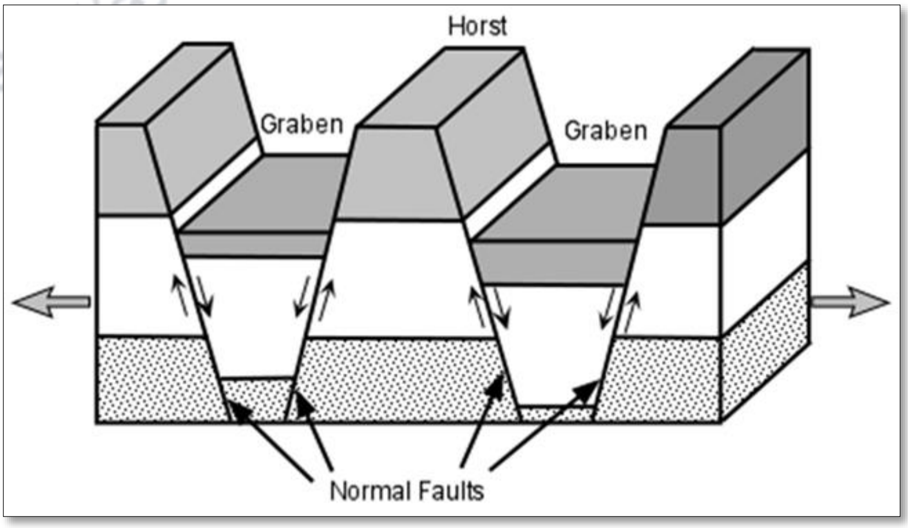

Fig. 3 Three-dimensional view showing horst and graben structures in a terrestrial rift valley basin (modified after Slische, 1995).

4.1.2. Proto-oceanic rift troughs: These are incipient oceanic basins floored by a new oceanic crust and flanked by young rifted continental margins (Fig. 4). This type of basin indicates a transitional stage between terrestrial rift valley basins and passive margin basins. They form because of the continued extension of the rift basin. They are characterized by the presence incipiently developed oceanic crust in the axial portion. Red Sea is an example of proto-oceanic rift trough.

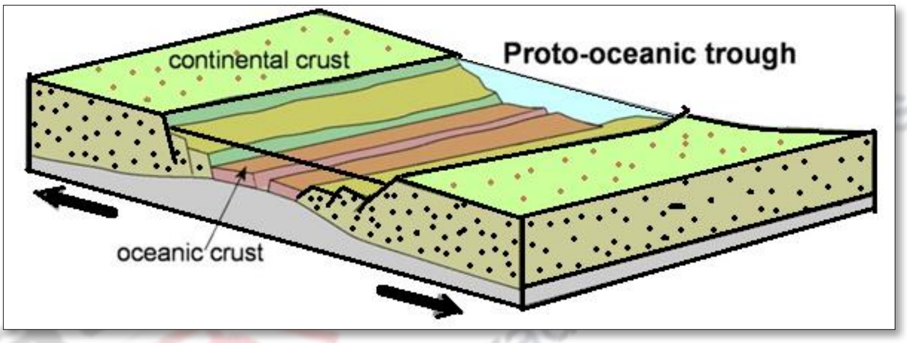

Fig. 4 Sketch showing a proto-oceanic basin (sketch modified after Nichols, 2009).

4.2. Basins in intraplate setting

These basins occur inside a plate and are situated away from plate boundaries.

4.2.1. Intra-cratonic basin: Intracratonic basin occurs within the cratonic areas. Origin of this type of basin is controversial because of the stable nature of the craton. It may be associated with a fossil axial rift in cases. Broad convex-downward basins are also known as sag basins. Thermal subsidence is significant in case of sag basins. Vindhyan, Kaladgi, Cuddapah, Chhattisgarh and Bastar basins belong to this category.

4.2.2. Passive margin: A passive margin represents the transition between a continent and an ocean, which is not an active plate boundary. It represents a mature rifted continental margin at continent-oceanic interface. Passive margin occurs at every ocean-continent boundary that is not marked a subduction zone or strike-slip fault. The subsidence of this basin increases gradually toward the deep ocean side. Passive margins define the east and west coast of India, which are further classified depending on the occurrence of basinal highs.

4.2.3. Active ocean basin: These are oceanic basins whose volume either increases or decreases with time. Atlantic is an example of active growing ocean basin since it has passive margins on both sides. The Pacific is an example of active shrinking ocean basin as subduction zones occur on both sides.

4.2.4. Dormant ocean basin: These are ocean basins floored by non-spreading and non-subducting oceanic crust. These basins are floored by oceanic crusts, which neither spread nor subducts and therefore they maintain their volume. Gulf of Mexico is the largest dormant ocean basin.

4.3. Basins in convergent setting

Basins in convergent margins may be of various types depending on the nature of plates involved in the subduction, i.e. ocean-ocean, continent-continent and ocean-continent. Variation in the angle of subduction is also an important factor.

4.3.1. Trench: A trench is an elongated deep trough formed on the subducting oceanic plate. It represents the deepest sedimentary basin. This type of basin occurs in the Andaman area.

4.3.2. Trench slope basin: Local structural depression formed on the subduction complex is known as trench slope basin. This type of basin occurs in the Andaman area.

4.3.3. Fore-arc basin: This basin occurs within the arc-trench gap. Sediments are supplied to this basin mostly from the magmatic arc (Fig. 5).

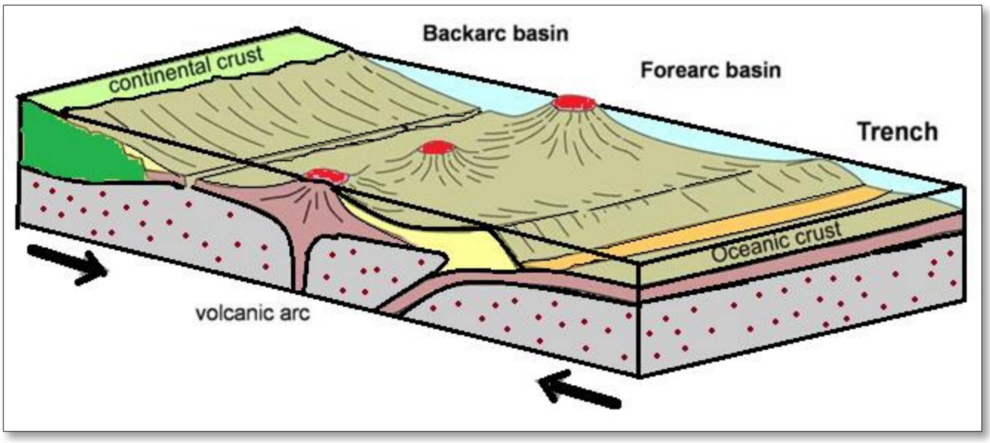

Fig. 5 Cross section showing trench, fore-arc and back-arc basin (modified from Nichols, 2009).

4.3.4. Intra-arc basin: Extensional back-arc basins form where the angle of subduction of the down-going slab is steep and the rate of subduction is greater than the rate of plate convergence.

4.3.5. Back-arc basin: The oceanic basin behind intra-oceanic magmatic arc and continental basin behind continental magmatic arc, without foreland fold thrust belts are fore-arc basins. This type of basin forms in case of the steep angle of subduction, so the rate of subduction exceeds the plate convergence rate. This type of basin occurs in the Andaman area.

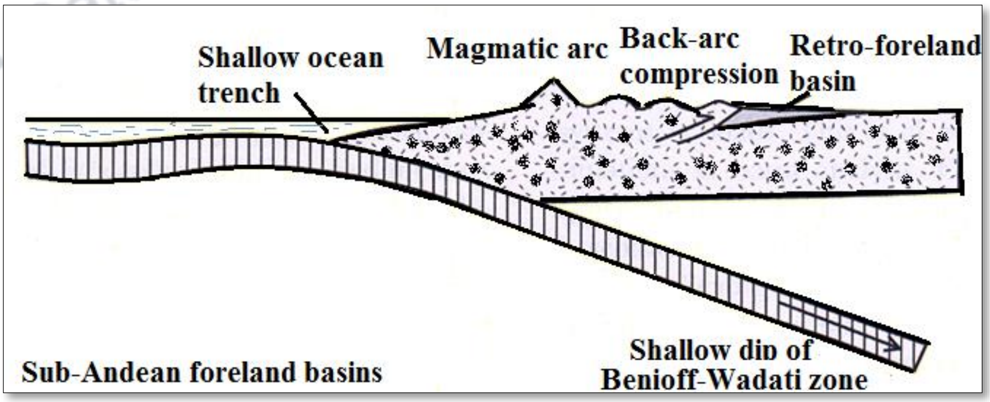

Fig. 6 Retro-arc foreland basin (modified from Decelles and Giles, 1996).

4.3.6. Retro–arc foreland basin: A foreland basin develops parallel to a mountain belt. This type of basin forms in case of gentle angle of subduction (Fig.6) so that plate convergence is larger than the subduction, which causes compression. This type of basin occurs in the Andes region of South America. This type of basins is called retro-arc foreland basin because of its position behind the arc. In case of retro-arc foreland basin, the tectonic load of the thrust belt is responsible for its origin, while fore-arc basin involves thinning of the crust. The angle of subduction zone is much gentler in this case compared to that involved in a fore-arc basin.

4.3.7. Peripheral foreland basin: Peripheral foreland basins occur on the plate that is subducted (Fig. 7). Tectonic loading of the thrust belt forms this type of basin. The amount of load and the flexural rigidity of the foreland lithosphere determine the width and depth of this basin. The basin is deep if the flexural rigidity of lithosphere is less and the amount is load. The basin is shallow if the flexural rigidity of the lithosphere is high and the amount of load is less. The deepest part of the basin is known as the foredeep. Examples of this type of basin include Ganga and Punjab basins.

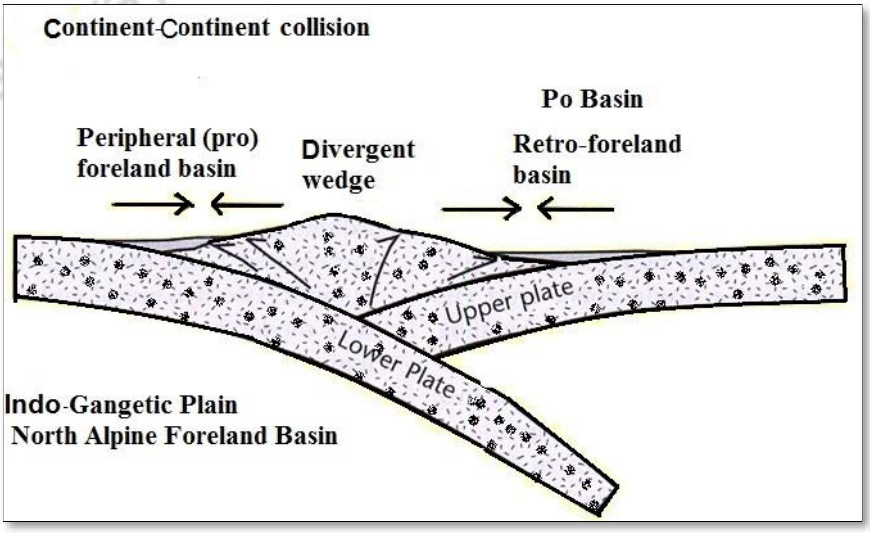

Fig. 7 Idealized model for peripheral foreland basin (modified after Decelles and Giles, 1996).

4.3.8. **Piggyback basin:** It is a type of minor depression developed on top of a thrust sheet as part of a foreland basin system. The basin is separated from the fore deep by an anticline or syn-depositional growth structures.

4.3.9. **Remnant ocean basin:** It is a type of shrinking ocean basin caught between a colliding continental margin and/or arc-trench system, and ultimately subducted or deformed with suture belt e.g. Bay of Bengal.

4.3.10. **Foreland intermontanne basin:** It is a type of basin formed within basement uplifts in foreland settings.

4.4. Basins in transform and transcurrent fault setting

4.4.1. **Transtensional basin:** The overlap of two separate strike-slip faults may create regions of extension, which forms pull-apart basin (Fig. 8). This type of basin is typically rectangular or rhombic in plan and is deep in nature.

4.4.2. **Transpressional basin:** This type of basin forms in the localized zones of compression along a strike slip fault system.

4.4.3. **Transrotational basin:** This type of basin is formed by rotation of crustal blocks about vertical axis.

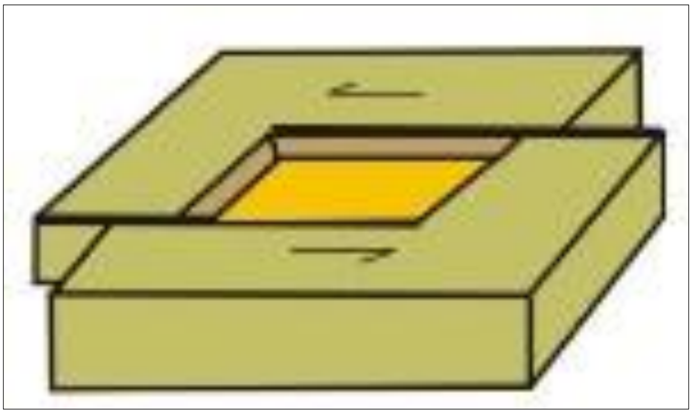

Fig. 8 Sketch of a pull apart basins showing strike-slip faults.

4.5. Basins in hybrid setting

4.5.1. Aulacogen: It is a failed arm of a three-armed rift system, two of whose arms continued to evolve to form ocean basins (Fig. 9). The basin extends from the margins toward the interiors of cratons. The basin is wider near the sea and narrows down towards the land. Cambay basin is an example of Aulacogen.

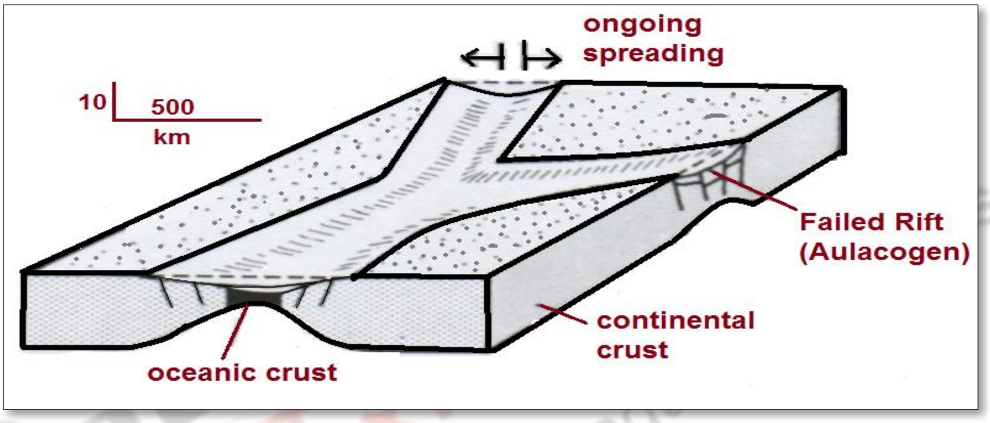

Fig. 9 Failed rift and aulacogen in RRR (rift-rift-rift settings) (modified after Einsele, 2000)

4.5.2. Intra-continental wrench basin: It is a complex type of basin formed within continental crust due to distant collisional process.

4.5.3. Impactogen: It is a type of rift basin formed at high angles to orogenic belts without pre-orogenic history e.g. Baikal Rift.

4.5.4. Successor basins: Formed in intermontanne settings following the cessation of local orogenic taphrogenic activity e.g. Southern Basin and Range Province.

5. Sedimentary basin analysis and basin mapping methods

Basin analysis involves a comprehensive analysis of sedimentology, stratigraphy and tectonic context of a study area. It considers all possible controls on the formation of a sedimentary succession for a model for sedimentary basin evolution. Study of basin analysis involves understanding origin of sedimentary basins, its subsequent evolution and ultimate destruction. Geological cross-section, structure and contour mapping is done for this purpose. All this helps to identify basin fill, basin geometry in three-dimensional scenarios.

5.1. Basin mapping methods:

- **Isopach maps:** Isopachs are the loci along which the total sediment thickness of a sedimentary succession remains same. An isopach map shows the areal variation in the thickness of a stratigraphic unit.

- **Paleogeological maps or sub crop maps:** These are maps showing the geological units outcropping at an unconformity surface. They can be constructed from extensive outcrop or subsurface data.

- **Worm's-eye-view maps:** These maps show the distribution of geological units that show onlapping relationship with an unconformity (Miall, 1984). Their main use is to illustrate the pattern of basin fill, shifting shorelines or gradual burial of a pre-existing erosional topography.

- **Lithofacies maps:** A map showing the distribution of sediment types being deposited at that time. For construction of lithofacies maps thin stratigraphic units are preferred.

- **Multicomponent ratio maps**: These maps record computation of sand/shale ratio and clastic ratio. Ratio maps are constructed based on the variations between two or three lithofacies end members, which are representative of the whole basin. The clastic ratio is defined as the ratio of total cumulative thickness of clastic deposits to thickness of nonclastics: (conglomerate + sandstone + mudstone)/ (limestone + dolomite + evaporite + coal) (Miall, 1984).

- **Paleocurrent maps:** These are maps showing the direction of paleocurrents in the basin at that time.

- **Grain-size maps**: These are maps showing the areal distribution of sediment grain size. This is especially useful for basins dominated by conglomerates.

5.2. Cross Sections

Cross sections are of two types, a) master cross sections and b) stratigraphic sections.

a) **Master cross sections**: These are cross sections showing detailed geometry and sediment fill.

b) **Stratigraphic sections:** These are cross sections showing the time correlations of all the major rock units along some generalized traverse across the basin. Such a section includes hiatuses, during which there was non-deposition or erosion.

In a true scale most basins record relatively thin accumulations, hundreds to thousands of meters of sediment spread over distances of tens to hundreds of kilometers. Thus, horizontal and vertical scale does not match. Cross sections are almost always drawn with great vertical exaggeration 10:1 and 100:1.

6. Summary

Sedimentary basins are the tectonic depression on the earth crust where sediment gets deposited. These are formed due to the mechanical thinning of the crust and are accompanied by extensional fault-controlled subsidence. Thermal effects change the density of the lithosphere so that the isostatic balance is disturbed and therefore subsidence. The sediment loading amplifies these primary mechanisms. The tectonic settings of basin formation are divergent, convergent, transform and transcurrent, and hybrid. Basins in divergent settings associated with terrestrial rift valley; basins in intraplate settings associated with crustal sagging, thermal subsidence, flexuring due to sediment load; basins in convergent settings associated with folds, fault and thrust belts; basins in transform and transcurrent fault settings associated with strike-slip faults, and basins in hybrid settings. Basin analysis is usually comprises study of sedimentary succession at the surface and subsurface with respect to sedimentary facies, sedimentary structures. Isopatch, isochore, lithofacies, ratio, sub crop, and paleocurrent geological maps are constructed on the surface to delineate the

sedimentary formations. Master cross section through the basin to show its geometry and sediment fill and stratigraphic section shows the time correlations of all the major rock units along some generalized traverse across the basin.

The different basins are summarized in Table 1 (modified after Busby and Ingersoll, 1995).

Table 1: Sedimentary basins, their tectonic settings and examples

Tectonic setting	**Name of the basin**	**Definition and modern example**
Divergent settings	1. Terrestrial Rift valleys	Rifts within continental crust bounded between high angle normal faults, commonly associated with bimodal volcanism e.g. East African rifts.
	2. Proto-Oceanic Rift Troughs	Incipient oceanic basins floored by new oceanic crust and flanked by young rifted continental margins e.g. Red Sea.
Intraplate settings	1. Intracratonic basins	Broad cratonic basins floored by fossil rifts in axial zones e.g. Vindhyan basin
	2. Passive margins	Mature rifted continental margins at continent-oceanic interfaces e.g. Krishna-Godavari basin.
	3. Active ocean basins	Basins floored by oceanic crust formed at divergent plate boundaries not related to arc-trench system e.g. Indian ocean
	4. Dormant ocean basins	Basins floored by non-spreading and non-subsiding oceanic crust
Convergent settings	1. Trenches	Elongate, deep troughs formed by subducting oceanic plate e.g. Andaman Trench
	2. Trench-slope basins	Local structural depressions developed on subduction complexes e.g. Andaman trench
	3. Fore-arc basins	Basins within arc-trench gap e.g. Andaman sea
	4.Intra-arc basins	Basins along arc platform that include superposed and overlap volcanoes
	5.Back-arc basins	Oceanic basins behind intra-oceanic magmatic arc and continental basin behind continental magmatic arc without foreland fold thrust belts e.g. Mariana basins.

	6. Retro-arc foreland basins	Foreland basins on continental sides of continental margins e.g. Andes foothills.
	7. Remnant ocean basins	Shrinking ocean basins caught between colliding continental margin and/or arc-trench system, and ultimately subducted or deformed with suture belt e.g. Bay of Bengal.
	8. Peripheral foreland basin	Basins above rifted continental margins that have been pulled into subduction zones during crustal collision e.g. Ganga basin
	9. Piggyback basins (satellite basin)	Basins formed and carried atop moving thrust sheets e.g. Peshawar basin
	10. Foreland intermontanne basins	Basins formed in basement-cored uplifts in foreland settings.
Transform settings	1. Transtensional basins	Basins formed by extension along strike slip fault system e.g. Salton Sea.
	2. Transpressional basins	Formed by compression along the strike slip fault system e.g. Santa Barbara basin
	3. Transrotational basins	Formed by rotation of crustal blocks about a vertical axis.
Hybrid settings	1. Intra-continental wrench basins	Formed within and an continental crust due to distant collisional process
	2. Aulacogens	Failed rifts at high angles to continental margins that have been reactivated during convergent tectonics so that they are at high angles to orogenic belts. e.g. Cambay basin
	3. Impactogens	Rifts formed at high angles to orogenic belts without pre-orogenic history e.g. Baikal rift
	4. Successor basins	Formed in intermontanne settings following cessation of local orogenic taphrogenic activity. e.g. southern basin and range province

Frequently Asked Questions-

Q1. What determines the depth of a rift basin?

Ans: The depth of a rift basin is directly related to the extensional stress involved in its formation; more is the stress deeper is the basin. It also depends on the thickness of crust, the thicker the crust deeper is the basin

Q2. Compare source of sediments in fore-arc basin and half graben?

Ans: In a fore-arc basin, most of the sediment is supplied by the magmatic arc. In a half graben most of the sediment is supplied from the hanging wall side. Footwall side supplies coarse and immature alluvial fans.

Q3. What is a piggyback basin?

Ans: These are small-scale sedimentary basins developed on top of a moving thrust sheet as part of a foreland basin system. Piggyback basins form in the wedge-top depositional zone of a foreland basin system as new thrusts in the foreland cut up through the existing footwall containing the eroded wedge-top basins in the old thrust sheet.

Q4. What are the different tectonic settings of sedimentary basins?

Ans: Basins form in three types of tectonic settings i.e. extensional, compressional and strike-slip settings. In extensional regimes the axis of maximum stress is vertical and in both compressional and strike slip regimes the axis of maximum stress is horizontal. Five broad categories of sedimentary basins are recognized on the basis of their plate tectonic setting and basin forming mechanisms. Basins in divergent settings associated with terrestrial rift valleys; basins in intraplate settings are associated with crustal sagging, thermal subsidence, flexuring due to sediment load; basins in convergent settings associated with folds, thrust belts; basins in transform and transcurrent fault settings associated with strike-slip faults; basins in hybrid setting involves change in tectonic settings.

Q5. Briefly describe the basins associated with divergent settings?

Ans: The crustal lithosphere gets stretched to form terrestrial rift valley basins, which may further evolve into proto-oceanic rift troughs. Two types of basin occurs. i. Terrestrial rift valley basins: In the zones of extension continental crust subsides to produce rifts, which are extensional fault bounded basins. The axis of the rift lies more-or-less perpendicular to the direction of stress. ii. Proto-oceanic rift troughs: Continued extension of the rift basin may lead to the formation of proto-oceanic rift troughs. Basaltic magmas rise to the surface in the axis of the rift and start to form quasi-oceanic crust. Where there is a thin strip of basaltic crust in between the two halves of a rift system the basin is called a proto-oceanic trough.

Q6. What are basinal 'highs' and 'lows'?

Ans: Basinal highs represent original basement highs above which sediment thickness is considerably reduced. Basinal 'lows' are characterized by huge thickness of sediments. In a divergent setting grabens are the sites of 'basinal lows' while the horsts are the sites of 'basinal highs'.

Multiple Choice Questions-

1. Which one of the following basins is caused by stretching

(a) Fore-arc basin
(b) Half-graben
(c) Piggy-back basin

Ans: b

2. Ganga basin belongs to which category

(a) Peripheral foreland basin
(b) Passive margin basin
(c) Aulacogen

Ans: a

3. Krishna-Godavari basin belongs to which category

(a) Trench-slope basin
(b) Passive margin
(c) Fore-arc basin

Ans: b

4. Which is the deepest sedimentary basin

(a) Back-arc basin
(b) Trench basin
(c) Proto-ocean

Ans: b

5. “The map which represents the loci along which the total sediment thickness of a succession is constant” is called

(a) Isochore map
(b) Isopach map
(c) Structure contour map

Ans: b

6. A cross section of a sedimentary basin is drawn with a vertical exaggeration 100:1. What will be the true thickness of the bed, which shows 993m in cross section

(a) 99300 m
(b) 9.93 m
(c) None of the above

Ans: b

Suggested Readings:

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