

Basin Classification

Oil and natural gas (as well as groundwater) are all found in sedimentary basins. Basin classification based on tectonic settings provides a framework not only for understanding the genesis and evolution of petroleum basins and their sedimentary fill but also process-based analogs for the exploration of frontier basins.

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Basin: What's in a Name?

The term 'basin' has different meanings depending on its location and containment. Groundwater basin is for aquifers; drainage basin delineates a river system; oceanic basin refers to the abyss; and sedimentary basin is a depression in the earth's crust filled with sediments.

Sedimentary basins are on the scale of tens to hundreds of kilometers in length and width, and thousands of meters in depth. As such they are usually tectonic basins formed by plate tectonic processes. A. G. Fisher distinguishes between 'starved' (partially filled with sediments), 'stuffed' (fully filled), and 'overfilled' basins. Gerhard Einsele distinguishes between 'active' (still subsiding and receiving sediments), 'inactive' (with no deposition), and 'deformed' (uplifted, eroded, and structurally deformed) basins. Basins may be 'closed' (e.g., a lake) or 'open' (e.g., marine shelf); they may be located

onshore, offshore or deepwater (below the shelf-slope break).

Basins may also be described in terms of depositional environment (fluvial, eolian, deltaic, lacustrine, continental, marine, reefal, abyssal) or sedimentary fill (clastic, carbonate, evaporate, turbidite) or what economic resource they contain (petroleum, natural gas or coal). A vast majority of sedimentary basins are also petroleum basins, which may be 'mature' (well explored and produced) or 'frontier' (little explored or drilled). Sometimes we refer to basins in terms of their geographic location, e.g., North American or Southeast

"Classifications are theories about the basis of natural order, not dull catalogues compiled only to avoid chaos."

Stephen Jay Gould

Wonderful Life: The Burgess Shale and the Nature of History (1989)

A view of the Grand Canyon in Arizona incised by the Colorado River.



Asian basins; or the particular stratigraphic period when they formed, such as Silurian or Jurassic basins.

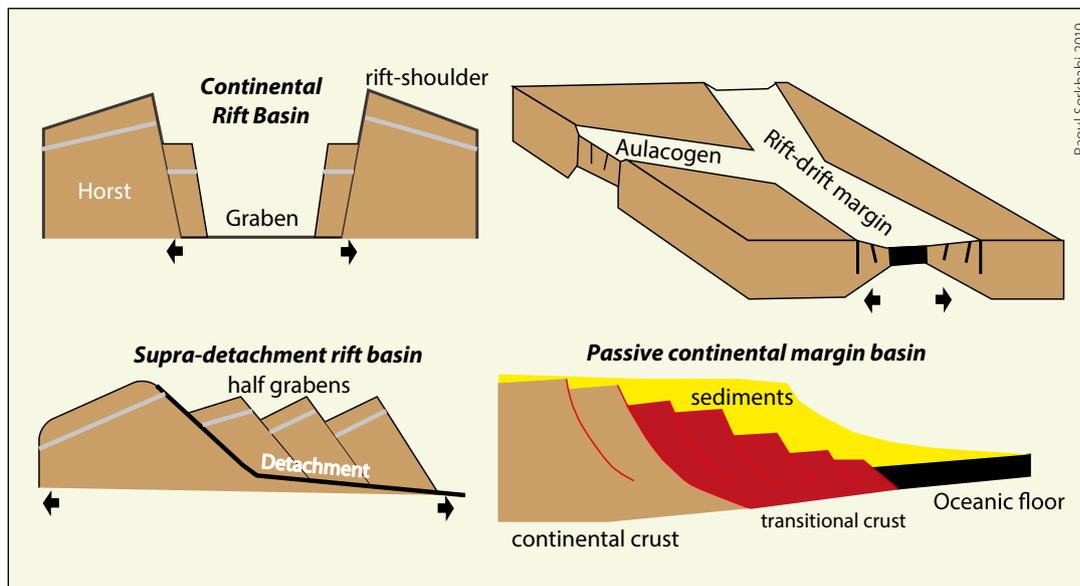
Plate Tectonics and Sedimentary Basins

Only a tectonic classification explains the origin and evolution of sedimentary basins and their sediment fill. Before the plate tectonic revolution of the 1960s, sedimentary basins were viewed as 'geosynclines' and were described by a terminology that was sometimes confusing and misleading. In the mid-1970s and early 1980s, thanks to the efforts of William Dickinson, Albert Bally, Doug Klemme and others, plate tectonic approaches to classify sedimentary basins were developed (see references online *Geoexpro.com*).

A plate tectonic approach considers five main factors:

1. Nature of the crustal basement underlying the sedimentary basin. The basement may be continental (with a granitic composition, density of 2.7 g/cm³, and an average thickness of 30–40 km), oceanic (with a basaltic composition, density of 2.9 g/cm³, and average thickness of 6 km), or transitional, as typically found along the rifted continental margins.
2. Position of the basin in the plate interior, plate edge or continental margin (intra-cratonic, passive margin, active margin or suture zone).
3. Plate tectonic setting, i.e. the nature of plate boundary associated with the basin. This may be divergent, convergent or transform.
4. Orientation (parallel or perpendicular to the tectonic plate boundary) and shape of the basin (wide or narrow, elongated, circular, triangular or quadrilateral).
5. Mechanism of basin subsidence including crustal stretching (extension), compressional tectonic loading, crustal bending by sediment overload, and thermal (cooling) subsidence of the crust.

It is important to note that sedimentary basins are composite in their nature and complex in their histories. A basin may start as a



Basins of divergent plates.

continental rift and then proceed over tens to hundreds of millions of years to become a foreland basin in front of a lofty mountain. In other words, a tectonic and facies analysis of the sedimentary record of a basin may reveal various types of tectonic settings. Usually the latest tectonic setting is used to categorize a basin.

The following is a brief description of sedimentary basins based on plate tectonic settings and with emphasis on petroleum prospectivity.

Cratonic Basins

A craton includes an igneous-metamorphic core or a stable basement, called the 'Precambrian shield' covered by a **continental platform** with sediments deposited over hundreds of millions of years. Within a craton there may also be **intra-cratonic basins**. Examples include the Illinois, Michigan and Williston Basins of the North American craton.

A Google Earth image of the Basin-and-Range in south-west USA, formed by tectonic extension since the Oligocene.



Intra-cratonic basins initially formed in proximity to plate margins (rifting or convergent) but are currently far from plate boundaries. These long-lived basins are sustained by a low degree of crustal stretching and thermal subsidence affecting the plate interior over geological time.

Basins of Divergent Plates

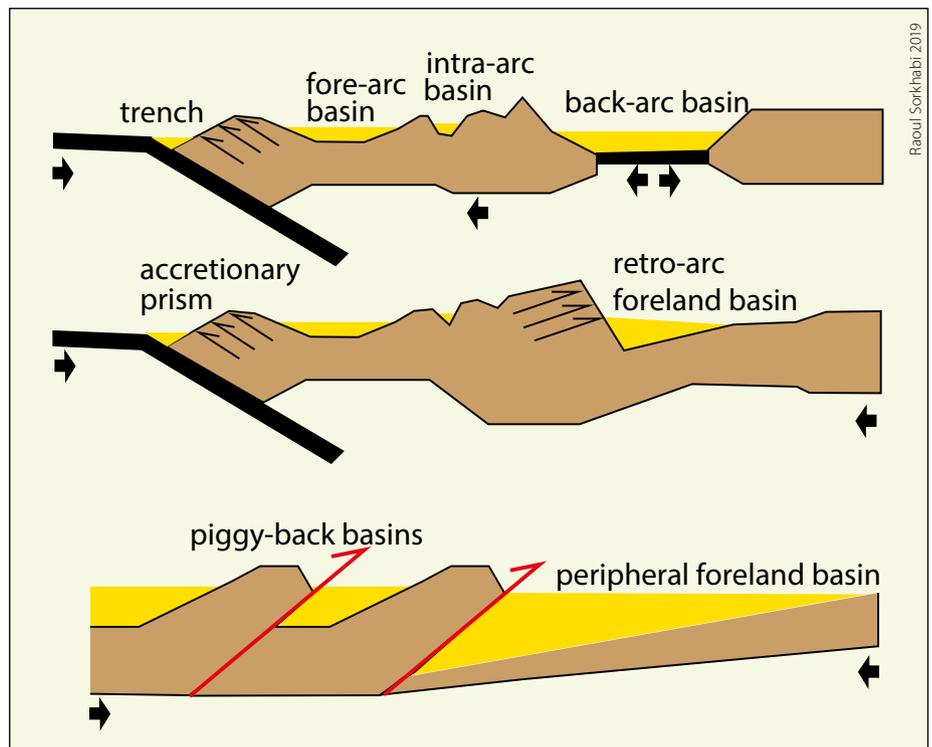
The extension and thinning of continental lithosphere leads to continental rifting, which involves volcanic eruptions and normal faults. High-angle normal faults produce horsts and grabens (basins) parallel to the rifting. Modern examples of **continental rift basins** include the East African lakes and the Rio Grande in New Mexico. In low-angle normal faulting, the basin lies above a major detachment fault at mid-crustal depths; this **supra-detachment basin** is characterized by a series of elongated ranges and half-grabens. The Great Basin in south-west USA is a well-studied example of this type of continental extension.

As the extension progresses and mantle asthenosphere rises, a juvenile oceanic crust splits the continent into two divergent plates. The Red Sea between Africa and Arabia is a typical example of this **proto-oceanic** (or **nascent ocean**) basin.

In continental rift settings, three rift faults at 120° form a triple junction. Of these, two rift arms continue to extend and separate the continent while the third arm fails to do so. These **failed** (or **fossil**) **rift basins** are usually perpendicular to the rifted continental margin. Also called **aulacogens** (from the Greek *aulax*, 'furrow') by the Russian geologist Nikolay Shatsky, failed rift basins are well recorded along the East and West Africa margins. They are often overlain by major river deltas and are excellent basins for oil and gas exploration.

Continental rift basins may eventually evolve into ocean basins with a mid-ocean ridge forming the boundary of the two divergent plates. In this case, the **passive continental margin** in the interior of the plate develops a shelf-slope-rise configuration with a wedge of sediments thinning toward the ocean floor. Passive continental margin sits on top of the initial continental rift structures and thinned crust, and its sedimentary history is largely controlled by sea level transgressions and regressions as well as thermal subsidence (cooling and sagging) and sediment overloading (bending) of the thinned continental crust. Passive continental margins have very long, wide and thick shelves made up of sandstone, carbonate and mudstone as well as slope turbidites and rises as observed along the Atlantic margins.

Oceanic sag basins are floored by oceanic basalt and lie at deep waters between the mid-oceanic ridge and the continental margins (either passive continental margins like the Atlantic or active continental margins like the Pacific). As the oceanic floor



Basins of convergent plates.

spreads, cools and subsides with age the oceanic basin deepens and receives pelagic sediments as well as carbonate oozes. Despite covering vast parts of the world's ocean, these oceanic basins are not favorable for conventional petroleum exploration for a variety of reasons, including deep waters, thin sedimentary cover, relatively cold oceanic crust, and lack of traps.

Subduction-related Basins

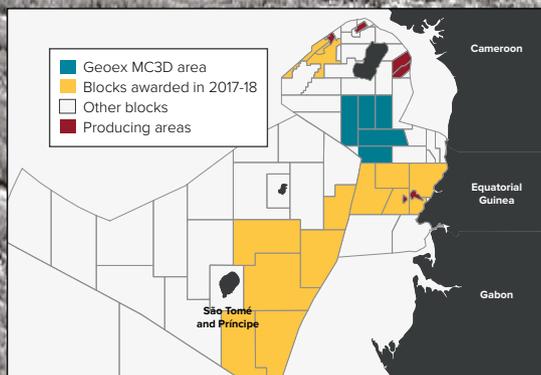
As the dense oceanic plate converges with a continental plate, it eventually subducts beneath the continental plate along a trench. The partial melting and dehydration of the subducting slab produces molten buoyant magmas which rise and create a volcanic arc on the overriding plate. The subduction is also associated with various types of sedimentation.

These include **trench-slope basins** on the downbent oceanic floor and **accretionary wedges**, which are a thrust mixture of ocean floor basalt and deep-sea sediments scraped off from the downgoing oceanic slab. Other examples include **forearc basins** lying in front of the magmatic arc, and **intra-arc basins** (within the magmatic arc) lying on the continental plate. Although DSDP-ODP drillings have detected hydrocarbons shows in the arc-trench gap basins, these basins have not proved favorable for petroleum exploration because of their deep water environments, low geothermal gradients (cold crust), and intense tectonic activities that are destructive of petroleum systems. Arc-trench gap basins are well developed along the Pacific.

Back-arc basins form behind the magmatic arc, either in intra-oceanic island arcs or continental magmatic arcs not associated with retro-arc thrust belts. Many back-arc basins are actually extensional rifts due to tensile stresses in the back of the magmatic arc arising from 'roll-back' (seaward retreat) of the subducting trench and slab. Back-arc basins are commonly

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found in the western Pacific; for example, Japan Sea. Back-arc basins formed on Sunda Shelf in South East Asia are significant hydrocarbon basins with high-heat flow.

Another type of continental sedimentary basin related to subduction that is an important habitat for petroleum is the **retro-arc foreland basin**. These basins form in front of a fold-and-thrust belt which develops as the old, cold continental crust is juxtaposed against the young, hot magmatic arc, and therefore underthrusts as a result of compression between the converging plates building up. The Cordilleras of North and South America formed in this manner, and the retro-art foreland basins associated with these mountains (the Rockies and Sub-Andean basins) are classic petroleum provinces.

Basins of Continental Collisions

As the intervening ocean between two converging continents completely subducts and closes, the two continents collide directly along a suture zone. If a part of the ocean on either side of the collided continent is not closed it is called a **remnant basin**, such as the Bay of Bengal on the east side of the Indian continental plate.

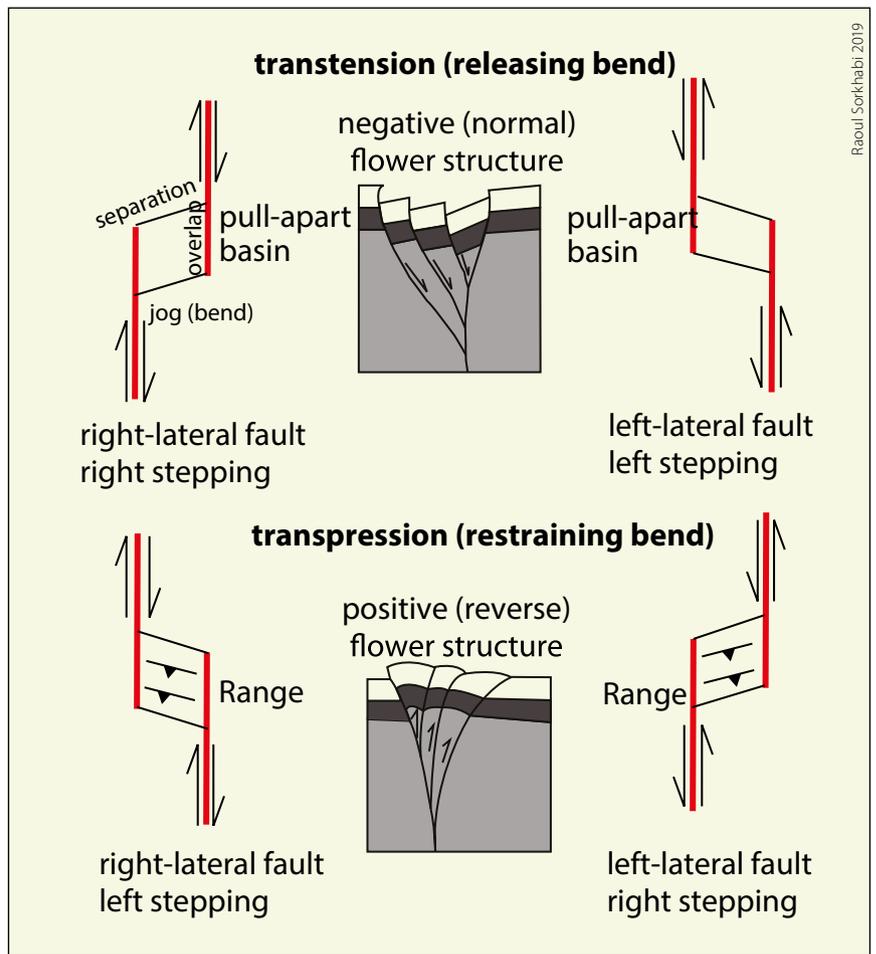
Continued tectonic compression between the continents shortens and thickens the crust and gives rise to mountain belts such as the Alps and the Himalaya. (Some geologists have called this ‘A-type subduction’ to distinguish it from the ‘B-type subduction’ of oceanic plate. However, continents, having low density, do not subduct into the mantle and it is better to use the term ‘underthrusting’ in continental collision.) Continental collision produces its own types of sedimentary basins. The largest is the **peripheral foreland basin** that develops in front of the rising mountain range and is filled with sediments shed from the range. The Zagros Basin is the world’s most petroliferous foreland basin.

Collisional mountains form in a series of thrust sheets that sequentially move (younging) toward the foreland. Sedimentary basins may develop on top of the moving thrust sheets. Such basins are called **piggy-back** or **thrust-sheet-top basins**. An example is the Peshavar Basin in the Himalaya of Pakistan.

As the collided crust thickens over time, a rift basin perpendicular to the collision line may form. This is called **impactogen** and examples include the Rhine Graben in Europe, and north-south trending grabens in Tibet.

Basins of Transform Plate Boundaries

Transform or strike-slip faults displace the blocks horizontally (not vertically), and as such they do not create depressions (basins) or ranges. The San Andreas Fault in California is a textbook example of a strike-slip fault along



Basins of transform boundaries.

which the North American and Pacific plates pass by each other. However, as can be observed along that fault, if the strike-slip fault steps sideways (jogs to right or left), localized stress will build up in the step-over or bend zones, and **transtensional (pull-apart) basins** or transpressional highs thus develop. The former shows a negative flower structure (normal faulting) and the latter a positive flower structure (reverse faulting) on seismic images. Pull-apart basins in California (for example, the Los Angeles Basin) although localized and relatively small in size, are nevertheless important petroleum-bearing basins.

Basins and Petroleum: A Sum-up

With increased knowledge, basin classification schemes have improved. Petroleum exploration has contributed a wealth of subsurface imaging and well data to our understanding of sedimentary basins. Since the oceans cover 72% of the earth’s surface, three-quarters of sedimentary basins have formed by tectonic extension. Moreover, 70% of sedimentary basins available for exploration formed during the Phanerozoic Eon (the past 540 million years) as the records of the Precambrian basins have been obliterated by erosion and tectonic activities. Of all the basins explored, rift basins and passive margins provide the largest reserves of oil and gas. Even the petroliferous Zagros Foreland Basin was superimposed on the passive margin of the colliding Arabian plate.

References available online. ■