

Chapter 2

Sedimentary Basins and Plate Tectonics

2.1 Scope

The outer part of the earth's crust, the lithosphere, is constructed predominantly of sedimentary rocks of Mesozoic, Tertiary, and Quaternary deposits extending to a depth of about 12 km on land and only 1 km or less on the ocean floors.

The crust itself is the bedrock of the outer layer of the earth and is relatively thin, 20–40 km thick under the continents, composed mainly of acidic igneous rocks (granites, granodiorites, etc.); but is much thinner, about 8 km thick or less, under the oceans, where it is composed mainly of basaltic rock. The crust differs in composition and thickness depending on whether it underlies the continents or the oceans. The crust is floating generally on a **solid mantle** about 3,000 km in thickness, and is composed of very dense rocks surrounded by outer shell layers of the ultradense and highly viscous liquid rock of the asthenosphere. The **core**, which is the innermost solid iron mass, with a radius of about 3,500 km, is surrounded by the mantle.

During the past three decades (since 1967), the theory of plate tectonics has dominated geological thinking. According to this theory, the surface of the earth's crust (under both continents and oceans) is made up of rigid, aseismic lithospheric blocks which are slowly and intermittently in motion. There are major and minor plates, together with more complex smaller units. The plates are separated by linear “active bands,” in which volcanicity and seismic activity seem to be concentrated (Fig. 2.1; Komatina 2004).

The plate tectonic theory of continental displacement replaced the geosynclinal theory of the development of the folded mountain ranges of the earth's crust; the term “geosyncline” was originally used to describe

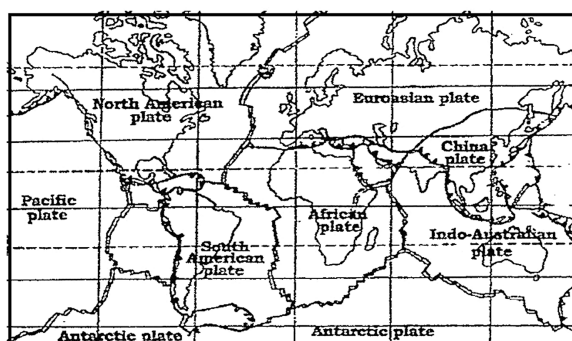


Fig. 2.1 Position of main tectonic plates (Komatina, 2004)

the long, narrow, subsiding depressions in which thick sediments accumulated and were affected by orogenesis (violent folding and uplift accompanied by volcanic activity). In general, the average rate of recent plate movements is usually from 1 to 2 mm/yr (Komatina 2004). There are two forms of tectonic movements:

- (a) **Active tectonic movements** consist of epeirogenic movements (uplifts and downwellings) and orogenic movements (mountain formation on “geosynclinal” areas), which have led to Alpine and Mesozoic mountain ranges where tectonic activity was manifested in powerful seismicity and the development of volcanism, e.g., in the Alpine-Mediterranean zone in Eurasia.
- (b) A **passive tectonic system** is characteristic of a large part of the Precambrian platforms, and applies to the entire territory of North American and Russia, and the large central zone of Africa, e.g., the Algerian Saharan platform, where the relief is level, low-lying in some areas and elevated in others.

2.2 Continental Shelves

The earth's crust consists of two types, continental and oceanic, below which lie the vastly more bulky and heavier mantle and core. The continental crust, which is three to four times as thick as the oceanic crust, includes all the major land masses with submerged borders, known as continental shelves. The boundary zones between the continents and the oceans form the continental margins, which are made up of three components: (1) the continental rises, which largely comprise the "fans" of continental sediments; (2) the gently dipping shelves 5–250 miles in width, which constitute the submerged edges of the continents; and (3) the steeper slopes, about 10–30 miles wide, the bases of which mark the transition zone between the continental-type crust and the oceanic-type crust.

Under the 1958 Geneva Convention, the continental shelf is legally defined as "the sea bed and subsoil of the submarine areas adjacent to but outside the area of the territorial sea to a depth of 200 m or, beyond that limit, to where the depth of the superjacent waters admits the exploitation of the natural resources of such areas."

From the edge of the continental shelf, the surface of the continental crust slopes gradually downwards to the deep oceanic basins, which are underlain by the thinner oceanic-type crust. The thickness of the continental crust decreases gradually below the continental slope until the thinner oceanic crust is reached (Fig. 2.2).

Fig. 2.2—The world's continental shelves include the major seas, lakes, and some marine platforms within the 200-m depth range (Petroleum Press Service 1951).

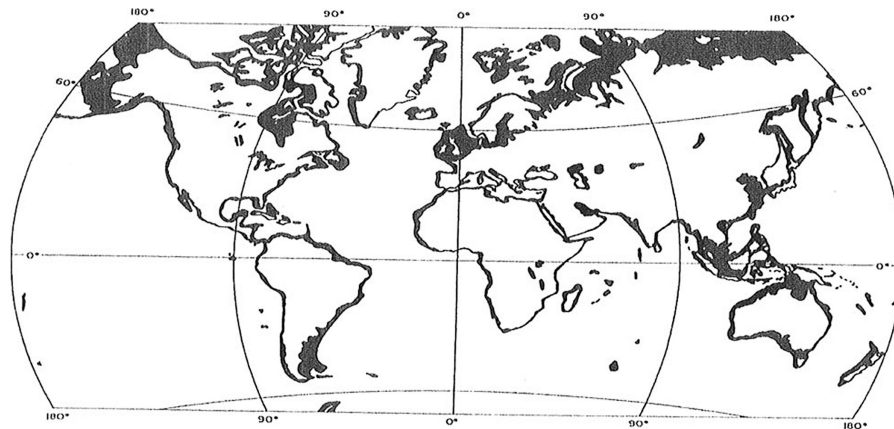


Fig. 2.2 World continental shelves (Petrol. Pres Service, 1951)

In some oil field provinces, a broad "geosynclinal belt" of much sedimentation, which typically evolves to a large asymmetrical structural basin by being subjected to orogenesis, is the consequence of developments that have taken place over a long period of time. Sedimentary basins of such type are termed active when the floors have continued to sink and the depressions thus formed due to gravitational forces have filled with sediments. On the gentler side, older rocks underlying the sediments may outcrop on a part of one of the major shields where faulting is common in some belts, especially along the hinge line. On the more disturbed side (of the mobile belt side), there are foothills and mountain ranges; strong folds and overthrusting occur. The thickness of the sediments formed is less on the shelf or platform side than elsewhere.

Fig. 2.3—An asymmetrical structural basin "geosyncline trough" showing a maximum thickness that lies between the shelf side and the mobile rim where strong structures have developed; examples of this broad pattern are the Arabian shield of Saudi Arabia and the area of the Tigris-Euphrates valley of Iraq (Hobson 1975)

2.3 Plate Interactions

In plate tectonic theory, composite continents are assembled by crustal collisions that occur when the consumption of oceanic lithosphere beneath arc-trench systems results in the closure of an oceanic basin. The arrival of a continental block at a subduction zone where the intervening oceanic lithosphere was consumed, will thus throttle subduction, and the

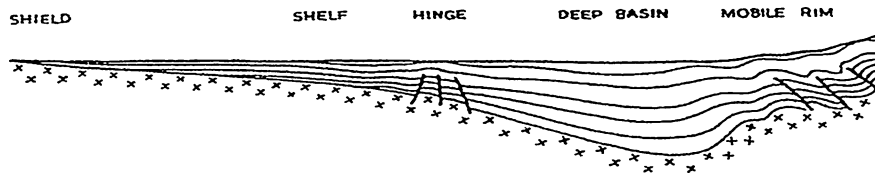


Fig. 2.3 A cross section of sedimentary basin its length of several hundred miles, and the thickness of the sediments overlying the basement could be a maximum of 10 miles. It lies between a stable shield (foreland) and a mobile belt. (Modified from Hobson, 1975)

position of the previous subduction zone will be taken by a crustal suture belt marking the line of tectonic juxtaposition of the two continental blocks involved in the crustal collision (Fig. 2.4). Examples of continental collisions in which one of the continental margins has a marginal arc-trench system and the other has a rifted-margin sediment prism (Dickinson 1974).

All plate interactions that involve construction of new lithosphere or consumption of old lithosphere as a result of large horizontal motions of plates, involve significant vertical motions of the lithosphere. There are three basic causes of subsidence or uplift as a result of plate interactions: (1) changes in crustal thickness; (2) thermal expansion or contraction of the lithosphere; and (3) broad flexure of plates of the lithosphere in response to local tectonic or sedimentary loading.

From a kinetic point of view, there are three kinds of plate junctures, analogous to the three classes of faults as defined by relative displacements:

(a) **Divergent plate junctures** (analogous to normal faults)—A separation of two plates (sea-floor spreading) occurs and causes rupture of the intact old lithosphere, which in turn results in intercontinental rifting when an incipient rift crosses a continental block. The rate of spreading may average several centimeters per year and might produce over geologic time the continental drift that represents the separation of Africa and South America and the associated growth of the Atlantic Ocean.

The plates diverge or move relatively apart and result in sea-floor spreading, in which magmatic material from the underlying lithosphere wells up in between to form linear lava ridges—parallel, linear “mid-ocean ridges”—which are found in the Atlantic, Pacific, and Indian Oceans.

(b) **Transform plate junctures** (analogous to strike-slip faults)—One plate slides laterally past the other along a transform or deep fault, without

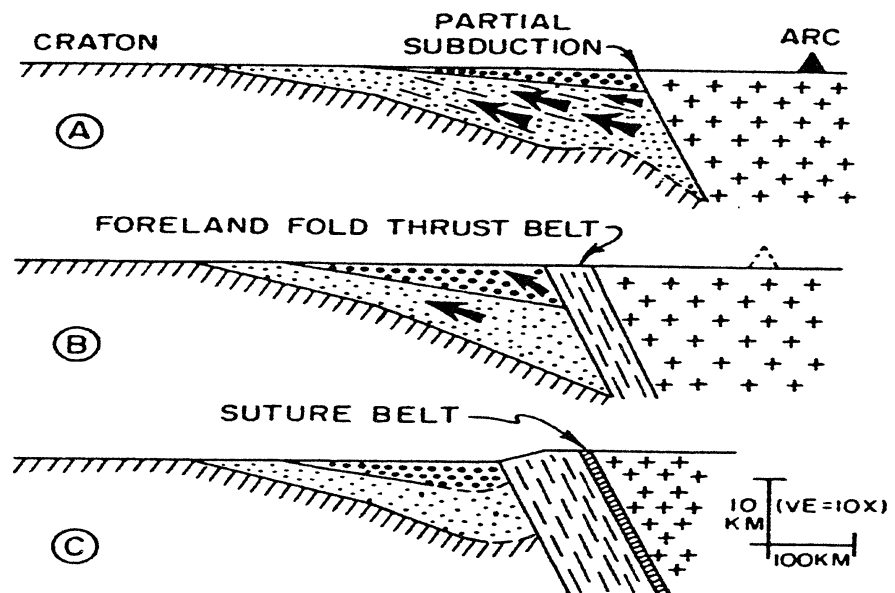


Fig. 2.4 Development (schematic) of foreland basin (heavy stipples) and suture belt from continental collision between arc-trench system (crosses) and rifted-margin sediment prism (light stipples). A, early stage of encounter; B, full collision; C, postcollision uplift of foreland fold-thrust belt. Heavy arrows show induced migration of hydrocarbons. (Dickinson, 1974)

accretion or consumption. However, hybrid plate boundaries also occur in some areas, as in oblique-slip faults, where some component of extensional or contractional motion occurs along a transform, and hence the two terms *transtension* and *transpression* are used to describe the interaction.

In accordance with the transform movements of the plates, the mid-ocean ridges in the Atlantic and Pacific Oceans, which run roughly north/south, are broken into a series of segments, each about 200 miles long, together with their related offsets, at the points of which are “transform fault zones,” formed roughly at right angles to the mid-ocean ridges, and projecting above the deep ocean floors; these become earthquake and volcano zones.

- (c) **Convergent plate junctures** (analogous to thrust faults)—When two oceanic plates collide, one plate is thrust at an angle beneath the other, and dives down into the mantle where it is partially destroyed by heat. Convergent junctures are sites of plate consumption where oceanic lithosphere formed previously at a divergent plate juncture, descends into the mantle. Part of the slab continues to sink to a depth of about 700 km, where it comes to rest; the part which rises to merge with the upper plate is converted to low-density magma.

Fig. 2.5—A diagram of a subduction of an oceanic plate, with evolution of volcanic island and trench (Hobson 1975)

Fig. 2.6—Two principal kinds of plate interactions at divergent and convergent plate junctures (Dickinson 1981)

Hobson (1975) discussed the convergence of plates according to a different approach, depending on whether oceanic- or continental-type plates are involved.

- (1) A **coastal mountain range** is formed along the leading edge of the continental plate, when it is advancing towards and overriding a relatively stationary oceanic plate.
- (2) **Island arcs and subduction zone trenches** are formed when an oceanic plate is advancing and passing beneath a relatively stationary continental plate.
- (3) **Major mountain ranges** are formed when two continental-type plates slowly converge, as a result of the squeezing of the sediments carried on the underthrust plate (e.g., the Himalayas in India).

2.4 Development of Sedimentary Basins

Plate tectonics theory is generally related to lateral and vertical motions of plates that form sedimentary basins. A sedimentary basin develops as an accumulated prism of strata, resulting either from subsidence of the basin floor, or from uplift of confining basin margins. Each basin has its own unique history connected to a particular sequence and combination of plate interactions and depositional conditions. During basin evolution, the stratigraphic fill of the basin took place because of the activity of the depositional systems. Folded and faulted structures within the basin were formed because of either tectonic or sedimentary

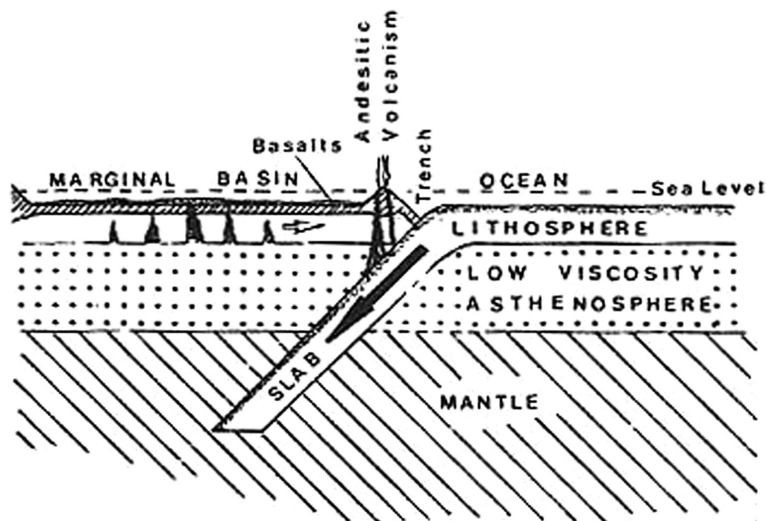
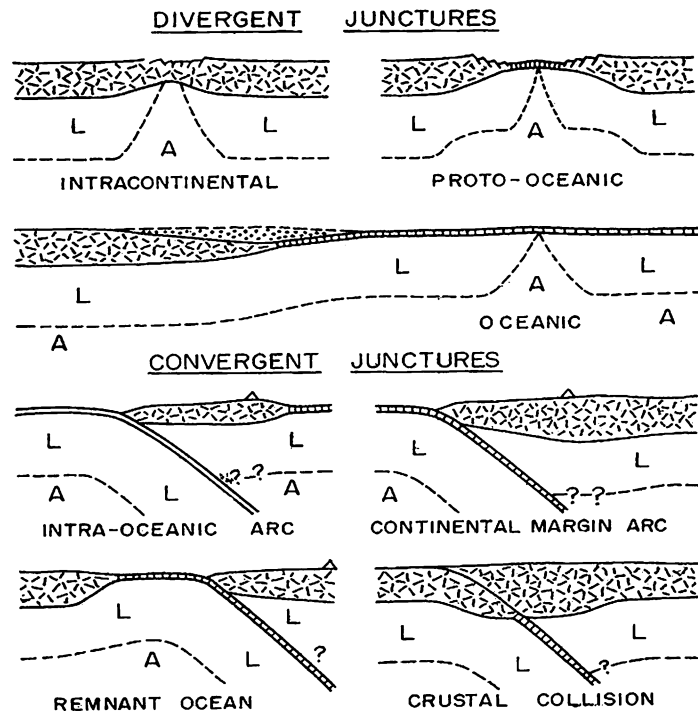


Fig. 2.5 Diagram illustrating subduction of an oceanic plate, with evolution of volcanic island arc, marginal basin and trench. (after Sleep and Toksoz. Nature. 547, Oct. 22, 1971, in Hobson, 1975)

Fig. 2.6 Principal kinds of plate interactions at divergent (above) and convergent (below) plate junctures showing relations of lithosphere (L) and asthenosphere (A) as well as crust (ornamented) (Dickinson, 1981)



evolution. Extensional deformation usually produces normal faults and tilted blocks, whereas contractional deformation produces folds and thrust faults.

Plate movements have lately been considered to result from the presence of “hot spots,” which represent a number of thermal centers, and are fixed in the upper mantle, from which “plumes” of hot material rise intermittently to burn holes in the overlying crust. Consequently, the continental plates are pushed away from these “hot spots” by the creation of new ocean floor; and when the movement of the lithosphere above the plume occurs by the process of sea-floor spreading, a “plume scar” is left on the crust in the form of a line of volcanic cones.

2.4.1 Geodynamic Settings of Sedimentary Basins

Sedimentary basins can occur in two general kinds of geodynamic settings.

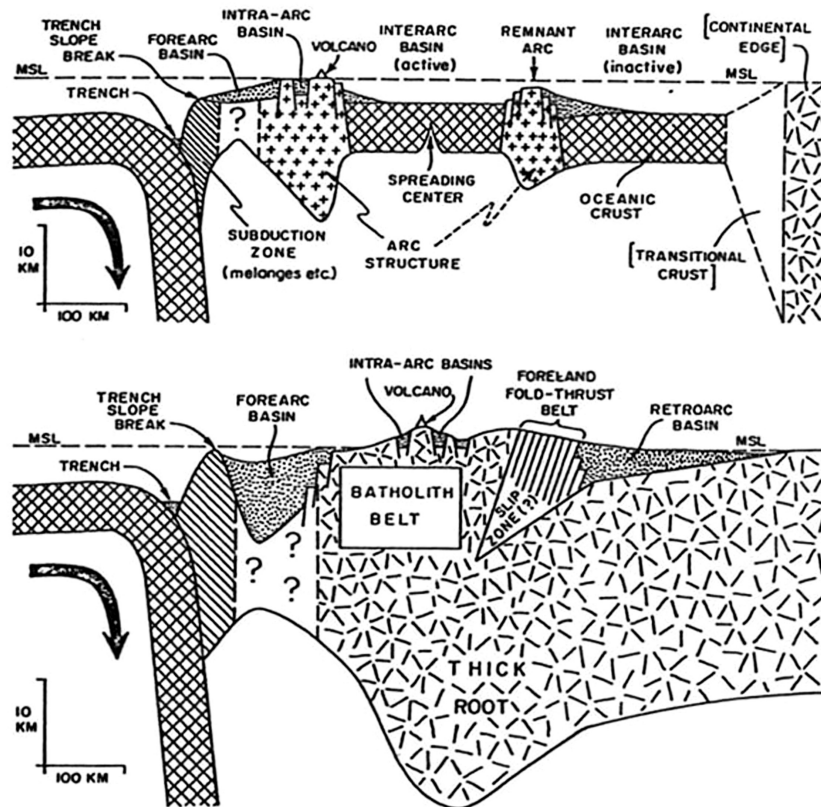
- (1) **Rifted settings occur** where divergent plate motions and extensional structures dominate and are later enhanced by thermal decay as time passes and

may be augmented mostly by flexures in response to sedimentary loading.

- (2) **Orogenic settings** occur initially where convergent plate motions and contractional structures dominate; subsidence occurs initially by plate flexures, either because of plate consumption or because of local tectonic thickening of crustal profiles, possibly augmented by sedimentary loading and other thermotectonic effects. The lithosphere may exchange locations between rifted and orogenic settings, and hence the name composite basins, in terms of plate tectonic settings. Basins of rifted settings, in which tectonic evolution is dominated by extensional plate motions and crustal rifting, and those of orogenic settings, in which tectonic evolution is dominated by contractional plate motions and orogenic deformation, include several idealized subgroups.

Oceanic basins evolve regularly from nascent phases dominated by extensional tectonics into remnant phases dominated by contractional tectonics. Similarly, the sedimentary assemblages along rifted continental margins include phases deposited within protooceanic rifts underlying the younger miogeoclinal prism, which may in turn be covered and flanked by the

Fig. 2.7 Schematic diagrams (vertical exaggeration 10X) to illustrate sedimentary basins associated with intraoceanic (above) and continental margin (below) magmatic arcs. (Dickinson, 1981)



deposits of a progradational continental embankment. These rifted-margin sedimentary associations may later be covered in part, with the onset of orogeny, by the foreland deposits of retroarc, or peripheral basins as arc (Fig. 2.7) or as collision (Fig. 2.8, Dickinson 1981).

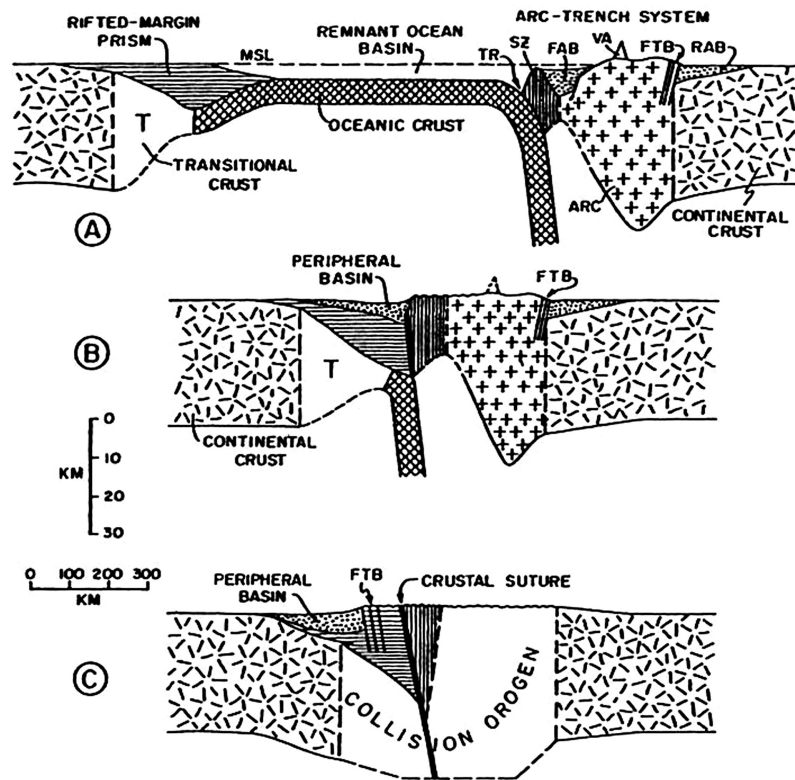
2.4.2 Sedimentary Basins and Hydrocarbon Occurrences

Dickinson (1981) discussed the accumulation of oil and gas within the thick prisms of sediment deposited along many rifted continental margins. The plates apparently rest upon a mobile layer called the asthenosphere, within which the geothermal gradient across the plates is controlled mainly by the conductivity between the basal temperature (that of the asthenosphere) and the surficial temperature (that of the troposphere [atmosphere and hydrosphere]). The rigid blocks of plates are spherical caps, or arcuate slabs, of the earth's lithosphere that extend down to the so-called low velocity zone of the upper mantle. The amount, nature,

and location of fluid hydrocarbons within the basin is governed by the geometric shape and size of the basin, the nature of the stratigraphic fill and the types of structures, and most importantly by the thermal history of the basin.

Analysis of the plate tectonics of sedimentary basins should identify styles and times of basin evolution and trends that embody favorable combinations of the following four important attributes for hydrocarbon occurrence. (1) Organic-rich source beds within the sedimentary sequence are generally fine-grained sediments deposited in black-bottom areas where oxidation by aerobic decay during early diagenesis is limited, and rapid burial enhances the likelihood of preservation. Basins in which sedimentary fill includes the favorable sites that harbor the largest sources of potential hydrocarbons exist in oxygen-minimum zones on open slopes and in low-oxygen zones within saline nonmarine or marginal marine environments. (2) Fluid hydrocarbons are normally generated by appropriated heat for thermal maturation of liquid hydrocarbons or thermal gas. (3) Permeable migration paths for the concentration of fluid hydrocarbons should have access

Fig. 2.8 Schematic diagrams (vertical exaggeration 10X) to illustrate sedimentary basins associated with crustal collision to form intercontinental suture belt with collision orogen. Symbols: TR, trench; SZ, subduction zone; FAB, forearc basin; RAB, retroarc basin; FTB, foreland fold-thrust belt. Diagrams A-B-C represent a sequence of events in time at one place along a collision orogen marked by diachronous closure; hence, erosion in one segment (C) of the orogen where the sutured intercontinental join is complete could disperse sediment longitudinally past a migrating tectonic transition point (B) to feed subsea turbidite fans of flysch in a remnant ocean basin (A) along tectonic strike. (Dickinson, 1981)



to gather any hydrocarbons produced. The most effective carriers are tilted conduit beds of well-sorted sandy strata contained beneath impermeable sealing beds of shales or eruptive rocks. (4) Petroleum and petroleum hydrocarbons can be contained in porous reservoir beds (whether clastic or carbonate), and are confined by impermeable capping beds or traps that may be formed either by stratigraphic enclosures or by structural features of tectonic or sedimentary origin.

Conceivably, plate tectonics may lead to a comprehensive theory of hydrocarbon genesis. Plate interactions fully explain the causes of subsidence, the sequencing of depositional events, the development of structural features, and the timing of thermal flux—all of which in turn can explain conditions in the geologic record of sedimentary basins (Dickenson 1981).

prisms are drawn down against and beneath the suture belts formed by crustal collisions that assemble composite continents. During such partial subduction, fluid hydrocarbons may be driven updip away from the subduction zones to accumulate in reservoirs along adjacent platform margins and within growing foreland fold-thrust belts, e.g., the immense petroleum accumulations of the Persian Gulf southwest of the Zagros suture belt. Similar oil migration in response to partial subduction may have influenced the distribution of petroleum in foreland basins in general; if so, strategies for exploration can perhaps be improved by taking this factor into account. Dickinson (1974) assumed that there were possible direct relations between plate movements accompanying subduction and the opening of migration paths for petroleum.

2.5 Oil Migration and Subduction

Petroleum and natural gas pools are abundant within the thick prisms of sediment deposited along many rifted continental margins. The rifted-margin sediment

2.6 Rifted-Margin Sediment Prisms

In plate tectonic theory, ocean basins are initiated by continental separations that begin with **intracontinental rifting**. When complete separation of continental

fragments is achieved, the raw edges of continental blocks along rifted continental margins are in preferred positions to receive thick prisms of sediment, composed both of debris washed off the adjacent continental blocks and of biogenic calcareous materials that were deposited in shoal areas at the flanks of the adjacent oceans.

The growing rifted-margin sediment prism imposes sufficient load on the lithosphere near the interface between old continental and new oceanic crust to induce downbowing of the lithosphere by flexure (Fig. 2.9, Walcott 1972). The flexure tilts the surface of the continental block seaward to allow landward parts of the rifted-margin sediment prism to encroach as much as 100–250 km beyond the initial continental edge, which may be depressed as much as 2.5–5 km. Continued growth of the rifted-margin sediment prism may in time allow its oceanward edge to advance well into the adjacent oceanic basin until the continental shelf, and perhaps even part of an accretionary coastal plain, come to stand fully above the oceanic basement. The type of rifted-margin sediment prism developed by wholesale sedimentary progradation of the continental edge has been aptly termed a continental embankment (Dietz 1963).

Accumulations of petroleum in rifted-margin sediment prisms are well known. The natural association of offshore source beds and nearshore reservoir beds of various kinds is inherent. The following two factors combine to exert a pumping action that drives fluid hydrocarbons updip from offshore source beds into favorable reservoir beds. (1) The **progressive loading** of

offshore source beds because of depositional growth of the rifted-margin prism; and (2) The **progressive seaward tilting** of the continental edge and the successive layers of the rifted-margin prism because of flexural bending of the lithosphere under the growing sedimentary load offshore. These factors are probably most influential within fully developed continental embankments, where potential conduit beds, intercalated with sealing beds, connect offshore source beds with inshore facies suitable as reservoir beds without interruption by thin slope facies (Dickenson 1974).

In conclusion, the largest reserves of petroleum are inferred to accumulate where conditions are most favorable for long-distance updip migration of oil from offshore source beds into attractive reservoirs in nearshore deposits along or near platform margins. The requisite regional dips and overburden loads are attained within the sediment prisms deposited along rifted continental margins, and also beneath foreland basins associated with foreland fold-thrust belts adjacent to major orogens. Apparently, optimum relations for oil concentration thus occur in the Middle East where a rifted-margin sediment prism was drawn partly into a subduction zone, now a suture belt marking the site of continental collision, and was partly buried beneath a foreland basin sequence (Dickenson 1979).

See Glossary—Plate tectonics—Definitions; and examples of plate junctures.

Appendix 2-A.1

Davis and Elderfield (2004) submitted a concise review of the relatively brief history of hydrogeology, which began shortly after the revival of plate tectonic theory little more than thirty years ago. It describes the nature and important consequences of fluid flow in the sub-seafloor, ending with a summary of how the oceans are affected by the surprisingly rapid exchange of water between the crust and the water column overhead.

The importance of fluid circulation below the seafloor and the exchange of water between the crust and the oceans can be easily appreciated by considering that the oceanic crust constitutes the most extensive geological formation on earth, and that hydrologic activity within it extends from mid-ocean ridges to subduction-zone accretionary prisms. The

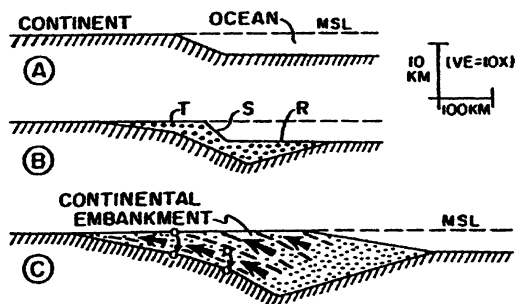


Fig. 2.9 Growth (schematic) of rifted-margin sediment prism (stippled). A, rifted continental margin without sedimentation; B, continental terrace (T)-slope (S)-rise (R) configuration; C, progradational continental embankment; small arrows show rotational tilt of basement along continental margin downward toward ocean basin; heavy arrows show updip migration of hydrocarbons parallel to bedding (dashes). (Walcott, 1972)

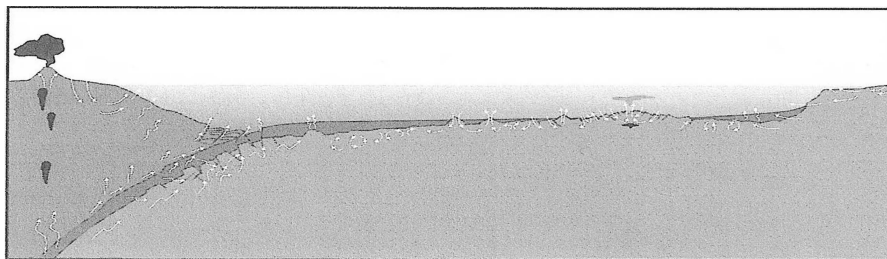


Fig. 2.10 Schematic cross-section depicting various types of sub-seafloor fluid flow, ranging from topographically driven flow through continental margins and consolidation-driven flow at subduction zones to thermal buoyancy driven flow at mid-ocean ridge axes and in the oceanic crust beneath broad regions of the oceans. Oceanic igneous crust and sediments are shown light gray and darker gray, respectively, and magma is shown in black: flow is depicted by white arrows. The figure was originally prepared for the Integrated Ocean Drilling Program Initial Science Plan, 2003–2013, and is reproduced courtesy of JOI, Inc. (Davis and Elderfield, 2004)

upper part of the crust is characterized by very high permeability, and it is host to huge fluxes of water. At the ridge axes occur the most spectacular and directly observable manifestations of flow; and at the seafloor, heat from magmatic intrusions drives high-temperature springs (Fig. 2.10).

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