pattern from the Jurassic onward. Subduction zones formed on the southern and eastern margins of the accreting Asian continent, but the eastern arcs were of an extensional nature. The timing of this back-arc extension varied from place to place, i.e., Late Jurassic in the Songliao basin of northeast China, Cretaceous in the basin-and-range-type extension in southeast China, and middle to late Tertiary in the Japan Sea, Bohai, Subei, East China Sea, and South China Sea basins of the entire eastern perimeter of the continent.

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Evolution of the Arctic-North Atlantic Rift System

The Arctic-North Atlantic rift system is superimposed on the Caledonian and Hercynian sutures of Laurentia-Greenland, Fennosarmatia, and Africa.

Devonian to Early Carboniferous wrench movements along the axis of the Arctic-North Atlantic Caledonides preceded the late Visean onset of crustal extension on the Barents Shelf and in the Norwegian-Greenland Sea. These rifts remained intermittently active for about 270 m.y. until crustal separation between Greenland and Fennosarmatia was achieved during the early Eocene. The Carboniferous rifts of the British Isles and the Canadian Maritime Provinces became inactive during the late Hercynian diastrophism, during which they were deformed to varying degrees by transpressional movements.

The Triassic development of the Tethys-Central Atlantic-Gulf of Mexico rift-transform system was accompanied by rift propagation into the North Atlantic and west European domain, whereby the reactivation of late Hercynian wrench faults probably was an important factor in the localization of individual grabens. The development of the North Sea and West Shetland-Rockall-Lusitania-Grand Banks rift system is probably related to the Late Permian and Triassic southward propagation of the Norwegian-Greenland Sea rift system.

Following crustal separation in the Tethys during the Middle Jurassic and in the North Atlantic during the Early Cretaceous, the rifts on the respective continental margins became inactive, while crustal extension continued in areas north of the Charlie-Gibbs fracture zone. Particularly in the Norwegian-Greenland Sea area, a gradual concentration of rifting activity toward the future zone of crustal separation can be observed. This activity was accompanied by a decrease of rifting in marginal graben systems, such as those of the North Sea and the Barents Shelf. After the early Eocene crustal separation in the Iceland and Norwegian-Greenland Seas, grabens on the adjacent shelves became inactive.

The duration of the rifting stage preceding crustal separation is highly variable (Central Atlantic ± 50 m.y., Norwegian-Greenland Sea ± 270 m.y.). Volcanic activity in the Arctic-North Atlantic rift was generally at a very low level during its Paleozoic and Mesozoic evolution, but increased prior to crustal separation. Evidence shows that intermittent local thermal doming is possibly related to the implacement of hot asthenospheric material in the upper mantle, at the crust-mantle boundary, and/or within the lower crust.

The hydrocarbon potential of the various branches of the Arctic-North Atlantic rift system is highly variable. Source rock and reservoir developments are controlled by the paleogeographic setting of the respective basin, whereas their preservation and the development of effective hydrocarbon kitchens are largely related to the geodynamic process governing the subsidence-uplift of the respective basin.

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Smectite Dehydration—Its Relation to Structural Development and Hydrocarbon Accumulation

A comparison of clay diagenesis data obtained from a study of Tertiary shales from wells drilled in the Brazos-Colorado River system of Texas, the Mississippi River system of Louisiana, and the Niger River system of Nigeria illustrates significant differences in temperature intervals over which smectite (expandable clay) diagenesis occurs.

The age of the shales studied ranges from 1 to 50 m.y., and the threshold temperature required to initiate diagenesis ranges from about 160°F (71°C) in Mississippi River sediments to more than 300°F (150°C) in the Niger delta. Water expelled from smectite into the pore system of the host shale during the process of diagenesis may migrate out of the shale early, or it may be totally or partially trapped and released slowly through time. In either situation, the water can act as a vehicle for hydrocarbon migration provided hydrocarbons are present in a form and in sufficient quantities to be transported.

Observations from the northern Gulf of Mexico basin indicate a close relation between buildup of high fluid pressure and the smectite-illite transformation process. Abnormal pressures exert partial control on the type and quantity of hydrocarbons accumulated because pressure potential determines the direction of fluid flow, and overpressuring partly controls the geometry of growth faults and other related faults and folds in the basin.

The depths to which growth faults can penetrate and the angle of dip that these faults assume at depth are largely dependent on fluid pressure in the sedimentary section at the time of faulting. Dips of some faults in Texas have been observed to change abruptly within the interval of smectite diagenesis, and some faults formed in the overpressured Miocene and younger sections become bedding-plane types at depths above the temperature level required for thermal generation of petroleum. Although these faults are important for fluid redistribution in the shallow sandstone-shale section, they play a minor role in moving hydrocarbons out of shales below the faults in much of the Texas offshore area.

Fluid movement upward along fault systems in the lower Tertiary section, which overlies fault trends in the sub-Tertiary section, is proposed as a mechanism for flushing hydrocarbons from the deeper portion of the northern Gulf of Mexico basin. These fault systems would have maximum development immediately above the "basement faults," with displacement decreasing progressively upward. Seismic data indicate that, in the upper (younger) Tertiary section, these deep fault systems are represented by near-vertical (high-angle) fracture systems that cut across the low-angle growth faults. Fluid movement within these deep fault and fracture systems would be enhanced by smectite diagenesis because water derived from smectite that was trapped during basin subsidence would cause the flushing process to continue for longer periods of time and to extend to greater depths than could be attained if only remnants of original pore water were present.

Based on data obtained from both the Brazos-Colorado and Mississippi River systems, it is concluded that smectite dehydration in shale is a major factor in both hydrocarbon migration and accumulation in basins where expandable clays are present. Concepts developed here can be applied to any basin that has had or now contains expandable clay shales. The effect of smectite diagenesis and the time of fluid release out of the shales must be considered with all other stratigraphic, structural, and geochemical parameters considered in basin evaluation.

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Theoretical Aspects of Cap-Rock and Fault Seals for Single- and Two-Phase Hydrocarbon Columns

Cap-rock seals can be divided genetically into those that fail by capillary leakage (membrane seals) and those that fail due to fracturing or wedging open of faults (hydraulic seals).

A given membrane seal can trap a larger column of oil than gas at shallow depths, but at greater depths, gas is more easily sealed than oil. Where a gas cap overlies on oil rim, however, the maximum-allowable two-phase column is always greater than if only oil or gas occurs below the seal.

This trap contrasts with the hydraulic seal, where the seal capacity to oil always exceeds that for gas. Moreover, a trapped two-phase column, at hydraulic seal capacity, will be less than the maximum-allowable oil-only column, but more than the maximum gas-only column.