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Abstracts

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Development and Distribution of Rift Systems

Rifts are elongate depressions overlying places where the lithosphere has ruptured in extension. Rift basins are rifts filled with sedimentary and (to a lesser extent) volcanic rocks and are becoming recognized as containing a substantial proportion of hydrocarbon resources. Rifts occurring at slowly spreading oceanic centers are not considered here.

Intraplate earthquakes and in-situ stress measurements indicate that plate interiors are generally in compression. Rifts form within those, relatively unusual, environments in which intraplate stresses result in extension rather than compression. Various tectonic conditions can lead to local extension within plates. A simple treatment relates these to the stages of the Wilson cycle of ocean opening and closing. A distinction has also been drawn between "passive rifts" in which stresses applied at plate boundaries establish the environment, and "active rifts" in which stresses applied to the plate from above or below (perhaps by uplift over a mantle plume) lead to extension. The Neogene and Quaternary rifts of Africa are examples of active rifts while rifts formed at continental collision, e.g., Upper Rhine, Baikal, Aegean rifts, and the rifts underlying the West Siberian basin are examples of passive rifts. Interpretation of these collisional rift systems commonly requires determination of the direction of "continental escape."

In whatever way rifts originate, their development is similar because the processes of rift extension are similar. Recent studies have emphasized the importance of listric and other types of normal faulting in the lithosphere during rifting. The base of the lithosphere is often within the crust during rifting and the lower continental crust, forming part of the asthenosphere, deforms by high temperature creep. By analogy with oceanic rifts the base of the lithosphere during rifting may have been close to the lower limit of ground-water circulation.

Rift subsidence and thermal history have been simply analyzed by assuming that the lithosphere thins vertically beneath the rift in proportion to the amount of horizontal rift extension. Refinements of this type of treatment involve assessing the relative importance of dike injection and thinning by flow beneath the rift as well as considering the possible effects of pre-rift lithospheric thinning and conduction sideways from the rift.

The sedimentary development of rifts is complex and varied. Many rifts contain subaerial and lacustrine deposits especially near the base of the rift-fill. Evaporites are common where climatic conditions are appropriate, and marine sediments show the influence of such factors as global sea level change and the interaction of subsidence and sediment-supply rates. Sediment-starved rifts are rare.

A common property of rifts is that potential reservoir rocks lie near the base of the sediment fill and that possible source rocks lie higher up the sequence. Migration of oil and gas into places where basal reservoir rocks occupy structurally high areas is common. Many rifts are overlain by broader basins in what is often called "the steer's head condition." In some places, though not all, this relationship can be accounted for by post-rift cooling. Although rifts are numerous and varied, they have features in common largely because of the uniformity of extensional processes that makes them worth treating as a class.

Rifts are widespread within continents ranging in age back to three billion years, and the older the continent the more rifts it is likely to contain. Rift structures are commonly reactivated and rift reactivation is a major process in intraplate tectonism.

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Comparative Cenozoic Petroleum Geology of Major Deltas—Mississippi, Niger, and MacKenzie

Oil and gas are produced from Tertiary sandstone reservoirs in deltaic and related depositional systems in the United States Gulf Coast, Niger, and MacKenzie-Beaufort basins. In each area there is an orderly, predictable interrelationship of sedimentation, stratigraphy, depositional environment, and structure, with the characteristics, ages, and distribution of producing trends.

In comparing and contrasting the three areas, it is apparent that they have many aspects in common, resulting from the fact that they are relatively young, subsiding paralic basins on "Atlantic-type" margins. They contain thick accumulations of deltaic sediments that have prograded in regressive basin-filling sequences as the basins subsided. Therefore each has a vertical gross lithologic sequence that has shale at the base, overlain by interbedded sandstones and shales, overlain by massive sandstones. The vertical sequence is repeated laterally from basin to land. In each basin the stratigraphic units thicken basinward across a series of normal, listric, down-to-the-basin syndepositional faults, with which are associated "rollover" anticlines that form traps. Trapping associated with diapiric structures is also characteristic.

Significant differences are related to the different geologic settings and geologic histories of the basins. For example, the presence of salt in the Gulf Coast basin has resulted in a wide variety of salt-dome-related trapping mechanisms in addition to the shale diapirs and rollover anticlines common to all three areas. Pre-Tertiary tectonic settings, different in each case, control basin configurations and affect structural trends. Vertical and lateral differences in depositional systems and sequences, and in sandstone geometries, result from variations in ratios of rates of sedimentation to rates of subsidence that are, in part, tectonically controlled.

The framework for the occurrence of oil and gas is well understood in the maturely explored and intensively studied Gulf Coast Tertiary basin. Concepts developed there can be applied to developing the less-explored Niger basin and to exploring the frontier Mackenzie-Beaufort basin.

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Character of Ancient Petroliferous Lake Basins of the World

The principal oil- and gas-bearing lacustrine rocks in the world were formed from sediments deposited in or peripheral to ancient stratified lakes, of a variety of ages, which for millions of years maintained a size comparable to that of modern inland seas. In these lake systems, both lipid and woody organic matter were developed and preserved in large quantities. The lacustrine rock system commonly constitutes a depositional complex that includes indigenous hydrocarbon source, reservoir, and trap units.

Lacustrine strata of China consist primarily of siliciclastic rocks; those of Brazil, Angola, and Cabinda are principally of siliciclastic rocks with abundant carbonate units; those of the

United States consist of at least 50% carbonate rock. Hydrocarbon resources of lacustrine depositional systems are greatest in the People's Republic of China (several billion barrels of recoverable oil). Hydrocarbon resources are also significant in the ancient lake basins of Brazil, Angola, Cabinda, and United States. Currently developed Chinese oil fields in nonmarine rocks are primarily in structural traps, those of South America and Africa are in combination structural and stratigraphic traps, whereas those of the United States are principally in stratigraphic traps.

Available data suggest that hydrocarbons in the more deeply buried strata are contained in secondary pores which received oil or gas subsequent to significant episodes of cementation and/or compaction, and dissolution of minerals. Reservoir rocks with abundant primary porosity are most commonly preserved at relatively shallow burial depths, and many are intercalated with immature source units. Primary pores contain hydrocarbons that have migrated to reservoirs from mature source rocks (more deeply buried?). In China, oil is recovered in great quantities from sandstones with abundant primary porosity, particularly in those basins with high geothermal gradients. The oil apparently migrated to the primary pores from nearby source beds which reached thermochemical maturation at relatively shallow depths of burial and before significant early cementation and compaction of the sandstone units. Matrix porosity and permeability in sandstone units are best developed and preserved in those rocks composed of chemically stable minerals and few labile grains.

Fluid-pressure gradients may be abnormally high in those lacustrine systems that have reached the stage of thermochemical maturation. In these cases, oil and/or gas are generated and expelled in quantities great enough to locally increase fluid pressures faster than pressure is released to adjoining rocks. Abnormally high fluid-pressure gradients in lacustrine units also occur in those impermeable hydrocarbon-bearing strata that have apparently been elevated at a rapid rate. In such a system, equilibration between fluid pressures in beds of low matrix permeability in the deep subsurface and permeable beds near the surface is restricted. In both cases, fractured overpressured rocks of low matrix permeability may yield oil and/or gas from pools whose boundaries are not restricted to local structures. Rather, they are restricted by relatively permeable beds that have provided access to the surface for pressure and fluid release (and invasion of water). Local avenues of permeability in overpressured rocks are greatest along natural, open fractures.

Although reservoir rocks for fields developed in lake basins are commonly described as being of a lacustrine origin, others were formed from sediment deposited at the edge of a lake or in settings well removed from a lake. Principal reservoir rocks in the Uinta basin, Utah, represent the basal parts of coalesced fluvial channels formed at the fluctuating margin of lake Uinta. Red-colored oil-bearing strata in some Chinese fields whose reservoir rocks are channel-fill sandstones formed from sediment deposited on an alluvial plain several kilometers from the lacustrine shoreline. Lacustrine turbidite, bar, and deltaic rocks are important reservoirs in Brazil, Africa, United States, and China. Petroliferous sedimentary rocks formed in lake basins are known over much of the world where they contain many billion barrels of recoverable oil and offer the promise of more.

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Geologic History of Reefs

A reef, whether fossil or modern, is the physical expression of a community of calcium carbonate-secreting organisms which grew in one place for an extended period of time, forming either isolated structures or cores of complex buildups. These sea-floor highs are not only sites of rapid carbonate fixation and accretion but also locales of internal sedimentation, synsedimentary lithification, and active bioerosion—attributes which set them apart from most other sedimentary deposits.

The core facies of large and complex fossil reefs generally illustrate a succession of growth stages, each of which is characterized by specific lithologies and invertebrate taxa. These stages, now recognized in reefs throughout the geologic record, are generally referred to as the pioneer (stabilization), colonization, diversification, and domination (climax) phases of reef growth. They record the transition from shoals of skeletal sand populated by small, rooted invertebrates and/or algae to thickets of branching or lamellar organisms to complexes made up of many different taxa with varied growth forms and life habits to a cap comprising only a few, generally lamellar to encrusting skeletons.

Just as the development of any one reef is dependent upon inherently biological factors so the history of reefs in general reflects the evolution of Phanerozoic marine invertebrates. For a reef illustrating all stages to develop, a prerequisite is the existence of metazoans capable of secreting large skeletons of variable growth form. At those times in geologic history when only small, prone, branching sessile invertebrates occur, buildups called reef mounds are present that illustrate only the first two stages of growth. Thus there are times when no reefs occur, periods when reef mounds are the norm, and periods when complex reefs dominate.

Although the attributes that characterize all reefs are present in the very earliest Cambrian bioherms, against the backdrop of geologic time, there are two general cycles of reef growth. Each begins with reef mounds which are subsequently populated by sponges and then gradually transformed into complex reefs by the appearance of corals and/or stromatoporoids. The first cycle begins in Early Cambrian time and culminates in the Late Devonian (240 m.y.); the second cycle begins in the Mississippian and has continued to the present (340 m.y.). During the early phases of these cycles reef mounds occur on or around shoal-rimmed platforms; in the latter stages reefs commonly form the rim facies, and control platform evolution.

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Geological Evaluation of Fractured Reservoirs

Effective evaluation of fractured reservoirs involves both qualitative and quantitative data of various levels of complexity. This paper attempts to describe those geological and petrophysical data necessary in making an early evaluation of a fractured reservoir, during either exploration or early development phases. As such, prediction rather than detection will be emphasized.

Early in the evaluation of a fractured reservoir the majority of predictions are based on direct observations of a combination of geological and rock data. Those observations are generally made by geologists and/or petrophysicists, and are used to determine: (1) fracture origin and distribution, (2) the reservoir characteristics of the fracture system, (3) the interaction of the fracture and matrix porosity systems, and (4) the type of fractured reservoir, based on the contribution of the fracture system to overall reservoir quality. Each of these determinations is discussed, including the general types of geological interpretations