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Depositional Models, Intrabasin Tectonics, and Sea Level Changes in Petroleum Exploration

Recurrent movement on Precambrian-age basement-fault systems has influenced the origin, thickness, and distribution of Phanerozoic strata in the interior of the North American continent. In this structural setting, tectonic and sedimentation patterns are well known for major orogenies of the late Paleozoic, late Mesozoic-early Cenozoic (Laramide orogeny), and post-Oligocene. The influence of basement-fault movement on sedimentation and erosion during anorogenic times is generally not as well known. Subtle structural movement controlled topography in the depositional basins, which in turn influenced the distribution of high energy (reservoir) and low energy (nonreservoir) deposits. In addition, extensional fractures in strata overlying basement faults provided pathways for petroleum migration, either vertically or horizontally. Inversions of structural movement along fault zones are commonly observed, and they sometimes mask the recognition of exact time of sporadic fault movement.

The most common petroleum reservoirs are deposited during rising or high sea level stands and are fluvial-deltaic, estuarine, shoreline, shelf, and lacustrine sandstones, and shallow marine and tidal-dominated carbonates. Depositional topography, which formed within the depositional basin during highstands, controls the distribution of unconformities during lowstands. Associated lowstand reservoirs are either base of slope or shelf sandstones, or secondary porosity in carbonates associated with paleokarst or dolomitization. Porosity in sandstones deposited during highstands may be infilled with diagenetic clays because of subaerial exposure during lowstands. Thus, recognition of the lowstand unconformity is of vital importance in exploration.

All rock systems record sea level changes, but those most important to petroleum exploration in western cratonic basins are in the Ordovician, Devonian, Permian-Pennsylvanian, Jurassic, Cretaceous, and Tertiary. A major problem is to determine whether structural topography, or depositional topography and eustatic changes, exerted the primary control on sedimentation. Petroleum occurrences in well-documented sequences related to sea level changes are discussed for the Rocky Mountain and Mid-Continent regions.

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Rift-Related Structures and Their Seismic Expression

Normal faults and associated secondary structures are common features in continental rifts. Fault dip and displacement, stratal dip, and fold position and size vary considerably. Synthetic seismic-reflection profiles show that each of these structural variables, as well as rock velocity, influences the seismic expression of rift-related structures.

The observed dip and curvature of any fault on an unmigrated seismic section depend, not only on the dip and curvature of the actual fault surface, but also on the velocity and dip of the overlying strata. The observed dip of a fault decreases as the velocity of the strata directly overlying the fault increases. Thus, planar normal faults in rocks whose velocities increase with depth may appear to flatten with depth on seismic sections. The observed dip of a fault decreases as the acute angle between the fault surface and the overlying strata decreases. Consequently, on unmigrated seismic sections, normal faults dipping in the opposite direction as the strata may appear to have steeper dips than identical normal faults dipping in the same direction as the strata; planar normal faults active during deposition may appear to steepen with depth.

The appearance of secondary structures associated with normal faulting on unmigrated seismic sections depends on the position and size of the secondary structures. A greater thickness of low-velocity rocks on the downthrown side of a normal fault may disrupt and bend the reflections on the upthrown side. Depth, rock-velocity distribution, and fault displacement affect the severity of the distortion. This distortion may obscure secondary structures on the upthrown side of faults, and can be interpreted erroneously as secondary faulting and folding. Synclines produced by drag on the downthrown sides of normal faults generally have small radii of curvature relative to their burial depths. This relationship makes them difficult to identify on unmigrated seismic sections. In contrast, forced folds in rifts are gentle, shallow structures overlying normal faults. These folds are easier to identify because they are unaffected by the distortion beneath faults, and their synclines have large radii of curvature compared to their burial depths.

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Rift Deformation Produced by Combined Extension and Shearing

Continental rifts form when lithospheric segments move apart. In response, the brittle, upper lithosphere faults and the ductile, lower lithosphere flows. Clay and analytical models suggest that rift-fault patterns depend on the angle between the rift axis and the relative displacement direction between the divergent lithospheric segments. If the axis and displacement direction are not orthogonal, both extension and shearing contribute to the rift deformation.

In clay models of combined regional extension and right-lateral shearing, steeply dipping, planar, conjugate strike-slip faults form if the angle between the rift axis and the displacement direction is less than 30°. The dextral strike-slip faults trend subparallel to and the sinistral strike-slip faults trend at large angles to the rift axis. If the angle equals 30°, oblique-slip and normal faults form. The dextral oblique-slip faults trend subparallel to, the sinistral oblique-slip faults trend at large angles to, and the normal faults trend about 30° clockwise to the rift axis. The oblique-slip and normal faults have steep to moderate dips and are relatively planar. If the angle exceeds 30°, normal faults form. These faults strike obliquely to the rift axis and to the relative displacement direction between lithospheric segments, except if the rift axis and the displacement direction are orthogonal. In cross-sectional view, the moderately dipping, relatively planar normal faults commonly die out into other faults or splay out near gently dipping horizons within the clay. Analytical models support these experimental results.

The models apply to the Gulf of California and Gulf of Aden, two continental rift systems produced by combined regional extension and right-lateral shearing. The modeling results can explain the presence of north-trending normal faults (striking obliquely to the Gulf of California trend and to the displacement direction between Baja California and mainland Mexico); northwest-trending, dextral strike-slip faults; and northeast-trending, sinistral strike-slip faults formed during the late Miocene/early Pliocene opening of the Gulf of California. The modeling results can also explain why many normal faults, which formed during the opening of the Gulf of Aden, trend west-northwest to west, obliquely to the Gulf of Aden trend and to the displacement direction between the Arabian Peninsula and the Horn of Africa.