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Depositional Environments and Reservoir Morphologies of Channel Sandstones

Channel sandstones are deposited in fluvial channels, fluvial-dominated deltas, submarine channels, and channel-dominated submarine fans on shelves and slopes of many basins. Excellent models of these channel-sandstone depositional environments and reservoirs are in Upper Pennsylvanian and Lower Permian sediments of the eastern shelves and slopes of the west Texas Permian basin. In dip-trending paleodrainage systems on superimposed alluvial plains, sandstone reservoirs are in single and multiple strike-oriented point bars in meander belts, and longitudinal and transverse bars in braided belts. By differential compaction these sandstone belts may produce oil where they drape over buried paleotopographic features such as reefs, structures, and sandstone bodies. Conversely, reservoirs may be found in these buried features by recognizing diversions in the trend of overlying sandstone belts. Oil and gas in sediments adjacent to channels may be trapped by nonpermeable channel-fill barriers. Seismic cross sections of meander belts can clearly show convex-downward bases.

Stratigraphic traps are in thin distributary-channel and delta-plain sandstone facies of shelf-elongate deltas on shelves. Shelf-margin lobate deltas have reservoirs in thick distributary-channel, delta-plain, and delta-front sandstone deposits.

"Packages" of fine-grained, lenticular turbidites can be correlated in submarine channels and fans. Stratigraphic cross sections reveal levees that trap oil in turbidites. Many slope-sandstone facies have been stratigraphically miscorrelated by hundreds of feet with lower sandstone formations.

Regional and local models of shelf and slope channel-sandstone systems and reservoirs and the subsurface methods that reveal them should aid research, production, and exploration geologists. This paper is an attempt to bridge the gap between research and applied geology by describing how the depositional environments of channel sandstones are recognized in the subsurface and how oil and gas are trapped in these sandstones.

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Intraslope Basins on Active Diapiric Continental Slope: A Key to Sand-Body Geometry in Ancient Submarine Canyons and Fans

The hummocky bathymetry of the continental slope off Texas and Louisiana is the result of active diapirism. Most of the diapirs originated from Louann Salt (Middle to Upper Jurassic) mantled by Tertiary shale; some may be completely shale. Except for the local outcrops of the shale, the diapirs are covered by younger sediments. The irregular bottom topography directly influences the path of bottom-hugging transport such as debris flows and turbidity currents.

Three types of intraslope basins have been recognized in this area of hillocks and depressions. The blocked-canyon intraslope basin, for example, Gyre Basin, was formed when an upward-moving diapir blocked a canyon at the time it had little or no active bottom transport, thus preventing the canyon from maintaining a continuous thalweg. The thalweg could be reactivated when the upcurrent part of the canyon filled to the level of a spill point. Seismic reflection profiles over such a basin show sets of onlapping reflections on the diapir flanks alternating with draping sets of reflections. The former reflections are interpreted as deposits from debris flows and turbidity currents; the latter represent mainly hemipelagic sedimentation.

Interdomal basins, for example, Orca Basin, were formed where upward-moving, coalescing diapirs surrounded a section of sea bottom that remained at or near its original depositional depth. In these basins, only draping seismic reflections resulting from pelagic and hemipelagic deposition are present.

The third type of intraslope basin—collapse basin—was formed by tensional collapse due to an extension of sediments over the top of a diapir. Solution of near-surface salt may also have been a forming mechanism. Continuous draping reflections, interrupted by faults and graben structures, are present on seismic records.

The sequences of sets of semitransparent reflections overlain by parallel reflections, as present in blocked-canyon basins, are interpreted to reflect variations in sediment input on the basis of sea-level variations. A rapid lowering of sea level enabled rivers to transport large volumes of coarse silt and sand over the shelf to the heads of submarine canyon systems on the upper continental slope. This rapidly deposited sediment was highly underconsolidated and unstable and was easily removed by slumping, debris flows, and turbidity currents. The bottom-hugging gravity flows transported sediment across the continental slope onto deep-sea fans on the rise. The material deposited in the canyons by these processes is recognized on reflection records as a set of semitransparent reflections. When the sand and silt supply ended, transport by mud-carrying turbidity currents may have continued for a time and may be present on the seismic records as less distinct, onlapping parallel reflections. During the succeeding rise and high stand of sea level, bottom transport completely ceased and pelagic and hemipelagic deposits slowly blanketed the sea floor, producing more distinct parallel reflections.

The weight of the sediment deposited on the flanks of diapirs causes a loading effect which, in turn, influences the movement of salt. In blocked-canyon basins, this diapiric movement has permitted the sediment facies to be repeated. Several examples of recent upward motion of salt are known, for example, protruding basalt on Alderdiche Bank and sand overlying caprock atop a diapir directly southwest of Gyre Basin.

Identification of these types of intraslope basins and an attempt to map the distribution of blocked-canyon basins may reveal the major canyon systems that were opertive on this continental slope. Probably only a few such canyon systems were opertional; therefore, a better understanding of all processes involved must be obtained prior to further studies of sand-body geometry and reservoir characteristics in an area strongly influenced by diapirism.

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Petroleum Source Beds: Environment of Deposition and Stratigraphy

Measurement of organic carbon content, alone, is insufficient to identify potential oil source beds because terrestrial OM (Organic Matter), oxidixzed planktonic OM, or reworked OM from a previous sedimentary cycle can create misleadingly high levels of organic carbon in marine sediments. Consequently, the presence of an oil-prone organic facies, as identified by kerogen typing, is essential to establish oil source rock character. Kerogen type is mainly dependent on the origin of the precursor plant remains (whether planktonic or terrestrial) and on the oxidizing (oxic) or reducing (anoxic) character of the early depositional environment.

Oxygen depletion, sufficient to arrest or minimize bioturbation at the benthic boundary, enhances oil source bed deposition, because it leads to almost entirely anaerobic microbial reworking of planktonic remains. This type of bacterial reworking favors the preservation and concentration of lipids in the residual OM, leading to the formation of "oil-prone" koergens (types I and II).

Marine oil source bed deposition and occurrence are controlled mainly by factors relevant to qualitative organic matter preservation during early sedimentation, rather than by planktonic productivity in the shallow euphotic zone. Many areas of high planktonic productivity, today, do *not* correspond with zones of high organic enrichment in bottom sediments (e.g., Grand Banks of Newfoundland, Antarctica, Australia, Northwest Shelf, Northeast Brazilian Shelf) because of oxic conditions, commonly in combination with low sedimentation rates. Conversely, whenever zones of high productivity, such as those present in some coastal upwellings, are underlain by anoxic water layers, then prolific oil source bed deposition does occur.

Zones where deep ventilation and thus oxic conditions prevail at sea bottom are much more common than zones of oxygen depletion. Persistent oxic conditions at the benthic boundary lead to deposition of "gas-prone," "type III," to "non-source," "type IV" organic facies, depending on sedimentation rate and amount of terrestrial organic matter input. Such unfavorable organic facies, resulting from past oxic conditions, have been commonly recognized as stratigraphically widespread under continental margins and in cratonic basins, regardless of past water depth. Thus, prolific oil source beds, in terms of relative rock volumes, are the exception in most sedimentary basins.

These observations are compatible with the functioning of the carbon cycle: efficient organic matter recycling through mineralization, rather than enhanced preservation, is the most common and most probable fate of dead organic matter in the environment.

Geochemical-sedimentologic evidence suggests that potential oil source beds are and have been deposited in the geologic past in four main anoxic settings as follows:

1. *Large anoxic lakes*—Permanent stratification promotes development of anoxic bottom water, particularly in large lakes which are not subject to seasonal overturn, such as Lake Tanganyika. Warm equable climatic conditions favor lacustrine anoxia and nonmarine oil source bed deposition.

2. *Anoxic silled basins*—Only those landlocked silled basins with positive water balance tend to become anoxic. The Baltic and Black Seas are examples. In arid-region seas (Red and Mediterranean Seas), evaporation exceeds river inflow, causing negative water balance and well-oxygenated bottom waters. Silled basins should be prone to oil source bed deposition at times of worldwide transgression, at high and low paleolatitudes. Silled-basin geometry, however, does not automatically imply the presence of oil source beds.

3. *Anoxic layers caused by upwelling*—These develop only when the oxygen supply in deep water cannot match demand owing to high surface biologic productivity. Examples are the Benguela Current and Peru coastal upwelling. No systematic correlation exists between upwelling and anoxic conditions because deep oxygen supply is commonly sufficient to match strongest demand. Oil source beds and phosphorites resulting from upwelling are present preferentially at low paleolatitudes and at times of worldwide transgression.

4. *Open-ocean anoxic layers*—These are present in the oxygen-minimum layers of the northeastern Pacific and northern Indian Oceans, far from deep, oxygenated polar water sources. They are analogous, on a smaller scale, to worldwide "oceanic anoxic events" which occurred at global climatic warmups and major transgressions, as in Late Jurassic and middle Cretaceous times. Known marine oil source bed systems are not randomly distributed in time but tend to coincide with periods of worldwide transgression and oceanic anoxia.

Recognition of the proposed anoxic models in ancient sedimentary basins helps in regional stratigraphic mapping of oil shale and oil source beds. Furthermore, explanation and prediction of the most favorable zones for widespread and prolific oil source bed occurrence can be achieved by paleogeographic reconstructions (plate tectonics, paleoclimate, and paleo-oceanography) conducted in conjunction with seismic stratigraphy and regional geochemical studies.

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Evolution of Carbonate Porosity During Burial—Bahamas, Florida, and Gulf Coast: Holocene to Jurassic

Modern carbonate sediments are deposited with large amounts of porosity; commonly they contain more pore space than grain volume. In contrast, ancient carbonate rocks usually retain only a few percent porosity. Although the details of porosity loss may be complex, estimates of porosity in large samples on the scale of aquifers and reservoirs reveal several relations that may be obscured by the detail of petrographic and geochemical studies.

Early diagenesis in carbonate sediments, with the exception of marine cementation, does not significantly reduce porosity. Examples from the Quaternary and Tertiary of the Bahamas and Florida demonstrate that porosity reduction by early freshwater diagenesis at shallow depths, less than 1,500 ft (500 m) for example, is quite inefficient. Although freshwater alteration efficiently stabilizes carbonate mineralogy and drastically alters permeability patterns, it leaves total porosity relatively unaffected. Thus large volumes of carbonate pore space are carried deeper into the subsurface during continued burial.

In the South Florida basin, carbonate porosity decreases persistently with depth from 0 to 18,000 ft (0 to 5,500 m) in rocks ranging in age from Pleistocene to Jurassic(?). Although this decrease is irregular in detail, on a broad scale both the average porosity and the range of measured porosity at any interval decrease with depth. A porosity basement (below which porosity is 5% or less) is encountered at about 14,000 ft (4,300 m). A south Florida standard curve defining porosity decrease with depth helps define an optimal exploration window bounded by thermal maturation criteria at the top and porosity criteria at the bottom.

Upper Jurassic hydrocarbon reservoirs in the Smackover Formation of southern Arkansas and northern Louisiana occur at depths ranging from 4,500 to 11,000 ft (1,400 to 3,350 m), and average porosity values for these reservoirs closely approximate the south Florida standard curve for the same depth range. In contrast, deeper Smackover reservoirs in Mississippi, Alabama, and Florida, which occur between 11,000 ft (3,350 m) and 22,000 ft (6,700 m), have considerably higher porosity than would be expected for their depth. Although these occurrences of porosity at considerable depth are poorly understood, this porosity development is in part the result of interactions of reservoir rocks with acidic brines, the occur-