stratification, variation within layers, heterogeneity, and performance of reservoir examples.

An appreciation of facies variability and depositional processes for carbonates can come from examination of modern environments of deposition. Common patterns in structural, textural, and diagenetic trends can be summarized from several modern settings for reefs and mounds, sand shoals, and lagoons and tidal flats. The lessons learned from detailed studies of modern examples center on several important points: (1) the trend and continuity of facies belts vary, but the patterns are orderly when the setting is understood; (2) typically, carbonate deposits form in localized ovoid or elongate thicks, not in widespread sheets; (3) the depositional systems contain complex, highly variable facies patterns in map view; (4) a predictable sequence of sediments, although not fully developed throughout the depositional environment, typifies the setting; (5) the stratigraphy as revealed by sediment coring is highly variable, recording a short-lived, but exceedingly complex geologic history; and (6) early diagenesis related to evolving depositional environments can significantly alter the porosity and permeability of the sediments.

Carbonate depositional systems, as shown by modern examples, are complex from the scale of a producing field right down to that of a pore throat. This fact, coupled with frequent control by facies over subsequent diagenesis, imparts the great heterogeneity to carbonate reservoirs. Log response and reservoir quality are directly related to facies and diagenesis, with varying grain size a major control over permeability amounts in porous intervals. Permeability affects recovery efficiency and thereby links the depositional facies through sediment texture to reservoir performance.

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Depositional Environments and Petroleum Geology of Jurassic Eolian Deposits (Norphlet Formation), Eastern Gulf of Mexico Area

Jurassic Norphlet sediments in the eastern Gulf of Mexico area accumulated under arid climatic conditions. The accumulation of thick Jurassic salt deposits, anhydrites, and red beds in association with Norphlet sandstones indicates that arid climatic conditions were prevalent during Norphlet deposition. Usually an association of salt deposits, anhydrites, and red beds is characteristic of arid climatic conditions, and eolian sands can be expected to accumulate under such depositional conditions.

The Appalachian Mountains of the eastern United States extended into southwestern Alabama and provided a barrier for air and water circulation during the deposition of the Norphlet Formation. These mountains produced the topographic conditions that contributed to the arid climate. In the region, Appalachian structural features are recognized as basement ridges and arches, such as the Conecuh and Pensacola ridges and associated Wiggins arch. These paleohighs affected Norphlet sedimentation and acted as local sediment sources.

Norphlet paleogeography in the eastern Gulf coastal plain was dominated by a broad desert plain, rimmed to the north and east by the Appalachians, and to the south by a developing shallow sea. The desert plain extended westward into eastern and central Mississippi.

Norphlet sedimentation began as a result of basin subsidence accompanied by erosion of the southern Appalachians. Norphlet conglomerates were deposited in coalescing alluvial fans near an Appalachian source. The conglomeratic sandstones grade downdip into red beds that accumulated in distal portions of alluvial fan and wadi systems. Quartz-rich sandstones were deposited as dune and interdune sediments on a broad desert plain. The principal source of the sand was updip alluvial fan and plain and wadi deposits. Wadi and playa lake sediments also accumulated in the interdune areas. A marine transgression during the late phase of deposition of the Norphlet Formation resulted in the reworking of previously deposited Norphlet sediments.

To date, 35 Norphlet oil and gas fields have been established in the region. Petroleum traps discovered are principally structural traps involving salt anticlines, faulted salt anticlines, and extensional fault traps associated with salt movement. Although basement highs also have potential as petroleum traps in the area, salt movement is the critical factor in forming a petroleum trap. Numerous Norphlet fields are located along the regional peripheral fault trend, particularly in association with the Pollard-Foshee fault system in southern Alabama and the Florida panhandle. Other onshore Norphlet petroleum traps include salt anticlines, such as Copeland, and salt grabens, such as the Mobile graben. In Mississippi, several Norphlet fields are located near the Jackson dome, a Cretaceous igneous intrusion. The Norphlet fields discovered in offshore Alabama are along the Lower Mobile Bay fault trend. The petroleum traps in the offshore area include a series of generally east-west-trending salt anticlines.

Reservoir rocks consist primarily of quartz-rich sandstones of eolian, wadi, and marine origin. The average composition of these quartz-rich sandstones is 72.5% quartz, 15.0% feldspar (plagioclase, microcline, and orthoclase), 4.4% rock fragments (chert, shale, phyllite, schist, and quartzite), 3.8% cement (carbonate, quartz, and anhydrite), 3.2% authigenic clay, and 1.1% accessory minerals. Porosity includes primary intergranular and secondary intergranular, and intragranular developed as a result of decementation and grain dissolution. Porosity in Norphlet reservoirs can exceed 25%.

The primary source of hydrocarbons in the Norphlet reservoirs is Smackover carbonate mudstones. Norphlet shale samples analyzed were found to be low in total organic carbon (0.1-0.2%). Smackover carbonate mudstones are locally rich in algal and amorphous kerogen. The geochemical and carbon isotopic composition of Norphlet crude oils compares favorably with the composition of Smackover crude oils and Smackover carbonate mudstones.

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Capitan Reef Complex (Permian), Guadalupe Mountains, Southwestern United States: A Classic Sedimentologic Model in Flux

The Capitan reef complex of west Texas and New Mexico has been an important sedimentologic model since a reef origin was proposed for the Capitan Limestone in 1929. The Capitan's magnificent exposures in the Guadalupe Mountain area; its large scale; its variety of carbonate, sandstone, and evaporite facies; and its relationship to major petroleum resources of the Permian basin have made it a justly famous sedimentary geologic model for academic and industrial geologists alike. Since 1950, extensive research has yielded markedly contrasting sedimentologic interpretations of key features, such as the nature and origin of the Capitan massive ("reef wall"); the back-reef pisolite, sandstone, and evaporite facies; the depositional profile of the shelf and shelf edge; the importance and magnitude of sea level fluctuations; and the role of submarine, vadose, and phreatic diagenesis.

Early views of a barrier reef depositional profile have been replaced by a shelftop marginal mound profile, in which the mound's gentle crest coincided with the backreef pisolite and tepee facies. The Capitan massive, earlier considered an ecologic barrier reef, is now interpreted as an outstanding example of massive limestone formed at a submerged shelf edge where extensive submarine cementation lithified sponge wackestones and formed massive cement boundstones. Permian vadose diagenesis, earlier accorded much importance and inferred as being related to major sea level falls, appears negligible. Phreatic diagenesis by mixed meteoric and marine fluids was at least locally important in the Capitan massive and foreslope strata. The famous Guadalupe pisolite, interpreted until the mid-1960s as lagoonal, and then widely accepted as Permian caliche of vadose origin, is now reinterpreted as largely synsedimentary, formed by subaqueous precipitation from hypersaline waters of a peritidal shelf crest; associated vadose fabrics are minor, overprint isopachous pisolite fabrics and are unrelated to major intraformational erosion surfaces.

Subaerial erosion surfaces within the reef complex are largely localized high on the shelf marginal mound. Unequivocal evidence of emergence of the Capitan massive or its underlying foreslope has not been recognized, suggesting that any sea level lowering during Capitan deposition did not exceed a few tens of meters. Although a sabkha origin of the back-reef evaporites and eolian transportation of sand across a sabkha surface has conceptual appeal, a lagoonal origin of the evaporites and subaqueous deposition of the back-reef sandstone sheets better fits the available field evidence. Vast amounts of siliciclastic sand had to bypass the Capitan massive and upper foreslope facies, but neither channels nor scoured erosion surfaces have been identified.

The Capitan reef complex can serve not only as a "world class" sedimentologic model, but also as a much studied model not yet well understood. The model is one whose scientific investigators have frequently been afflicted by over-reliance on Holocene models ("modern model mesmerism"), by overthrust of established authorities or dogma ("dogma reverence"), by uncritical acceptance of new concepts ("bandwagonitis"), by overuse of superficial "look-alike" features for genetic analogies, and by just not discerning what was available for viewing in the field or laboratory. Capitan remains a model "in flux" awaiting more critical field and laboratory research.

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Extensional Models for Formation of Sedimentary Basins and Continental Shelves

Two kilometers of sediment cover more than 70% of the continents. The major accumulations occur in sedimentary basins and at continental shelves. The areas of maximum subsidence are generally associated with thin crust and evidence of extension. Of the concepts advanced to explain this subsidence, uniform extension has proved the most useful.

Models based on uniform extension account for the gross features of the basins and shelves, and provide a quantitative method for examining the history of subsidence. Modifications, however, are needed to explain the detailed subsidence of most areas and to account for regions with early uplift. Problems associated with the sum of the heave on the faults underestimating the amount of extension appear resolved.

The problems and modifications lead to limitations in the use of the models. The advantage, however, that they require a quantitative evaluation of all the data more than offsets these limitations. Because of this requirement for quantitative evaluation, the models have great value as tools in the design of data-acquisition programs.

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A Spectrum of Late Paleozoic and Cretaceous Shelf Bars, Western United States

Shelf-bar sandstones of the Cretaceous Western interior seaway of North America form excellent stratigraphic traps for hydrocarbons. Modern shelf sands occur in a variety of settings and are affected by such processes as storms and tidal, longshore, and shelf currents. Case studies of several Cretaceous and late Paleozoic sandstones document a spectrum of ancient shelf-bar types analogous with modern shelf systems.

Several shelf bars deposited in nearshore environments (8-10 mi offshore) were associated with deltaic axes. Sands were reworked from these axes by currents moving along the shoreline that were diverted by a headland. Such shelf-plume sandstones were subsequently reworked by storms and other shelf processes. The relative effects of storm and shelf or coastal currents greatly influenced the geometry and characteristics of the nearshore shelf bars, of which several variations can be documented.

Tidal currents are an important factor in forming and modifying modern shelf bars in the North Sea. Examination of primary structures and directional features suggests tidal currents were relatively unimportant in nearshore shelf bars of the Cretaceous Interior seaway. Examples of Pennsylvanian shelf-bar sandstones from the Sacramento Mountains of New Mexico have features characteristic of both storm and tidal processes.

Detailed examinations of primary sedimentary structures and facies relationships are useful in recognizing the various shelf-bar types and predicting the occurrence and distribution of similar potential reservoirs.

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Depositional Systems and Cycles, Eocene Yegua Formation, Texas, Gulf Coastal Plain

Tertiary Gulf Coast stratigraphy is characterized by a series of large-scale progradational wedges. Fluvial-deltaic and deep-water sandstones in several progradational units have proven to be prolific hydrocarbon-bearing reservoirs. The Eocene Yegua Formation is considered a relatively minor wedge compared to the Wilcox, Vicksburg, and Frio progradations. Prior to the late 1970s, Yegua exploration, and thus stratigraphic control, were confined to areas overlying the relatively stable submerged Wilcox deltaic platform.

Basinward, the Yegua thickens significantly beyond the margin of the Wilcox platform. In the few wells penetrating this thickened Yegua section, thick sandstones were unexpectedly encountered several miles beyond presumed Yegua shorelines. The discovery of Black Owl and Toro Grande fields in the early 1980s triggered an exploration play in the expanded Yegua. Several depositional models were proposed to explain the occurrence of sandstones in this downdip setting. Deep water, shelf, and deltaic origins all had their proponents.

The Yegua has numerous thin, laterally persistent, high-resistivity shales. These shales, inferred to be deposited during transgressive (non-progradational) episodes, have been used to subdivide the Yegua Formation into 12 genetic units. Correlation of these marker beds in more than 4,000 wells has resulted in a series of detailed regional maps delineating and documenting Yegua depositional systems and cycles.

The Yegua in the central Texas coastal plain is characterized by a series of narrow (1-3 mi wide) dip-oriented depositional axes. These axes represent meanderbelt and distributary channel deposits associated with fluvial and deltaic systems. The scale of these features is comparable to modern Texas coastal plain systems. The distribution and direction of the narrow axes are strongly influenced by syndepositional growth faults. Reworking of sands by shoreline processes are only a minor factor influencing reservoir distribution in the Yegua.

Regional mapping also documents shifts in depositional axes and depocenters of the various Yegua genetic units. Several minor Yegua depositional cycles are the result of these shifts rather than eustatic sea level fluctuations. However, a eustatically controlled cycle within the Yegua has been documented, and provides a mechanism for deposition of sand in the downdip Yegua trend. Several other sands in this trend are associated with dip-oriented fluvial and deltaic axes deposited during progradational episodes. As these axes extended beyond the margin of the subjacent Wilcox platform, they reactivated, or initiated, a series of growth faults. Sand deposition was thickened and confined to localized depocenters along these faults.

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Seismic Prediction of Porosity and Hydrocarbon Traps in Carbonate Rocks

Seismic stratigraphy has been used in many areas to identify stratigraphic carbonate traps such as shelf margins, pinnacle reefs, mounds, and updip porosity pinch-outs. Many large oil fields are the result of oil entrapment in these types of stratigraphic traps. Examples include fields from the Gulf Coast, Permian basin, Mid-Continent, and Rocky Mountain provinces in the United States, as well as fields in the Middle East, Canada, North Sea, and the Far East.

Where the trap shows geomorphological relief, evidence such as draping, pull-ups, dim spots, data dispersion, and other criteria can be used. Stratigraphic carbonate traps can be localized with some precision using these criteria. However, the specific definition and measurement of porosity in carbonate rocks are much more difficult. With very careful integration of geologic (rock data from cores and petrophysical data from logs) and geophysical (high resolution seismic) data, it is possible to estimate both the thickness and, in a qualitative way, the amount of porosity in a potential carbonate reservoir.

During the Carboniferous in the Mid-Continent, a sequence of depositional and diagenetic events created irregular pods of porosity in otherwise tight limestones. The areal extent, thickness, and quality of this porosity are the primary factors that determine the location, geometry, and productivity of major oil fields in the area. A twenty-million-barrel oil field has been studied in detail, and the initial production rates and overall production richness correspond closely to measurable seismic phenomena. A seismic line shot through the producing interval at a depth of 4,000 ft, using 30-fold, broad band (20-120 hertz) data has allowed the recovery of frequencies over 100 hertz. These data confirm (1) the presence of porosity and (2) field limits that correspond to the field limits known from subsurface information.

The Geoquest System work station was used to model (1) the key porous interval as known from core and petrophysical data in the analog field and (2) evaluate similar phenomena in the surrounding play area and measure both porosity thickness and quality in prospective stratigraphic traps. Two specific trap types occur regionally. The first type evidences porosity that developed locally and has an acoustically recognizable event over it (and between it and an overlying shale). The second type shows evidence of local porosity extending vertically to the shale seal. In both types, the lateral limits can be mapped seismically. The trap types have very different characteristics; both trap types and variations of them can be modeled successfully.

The trap types discussed are very subtle and have historically been