chlorite is common as initial pore filling in marine rocks, whereas kaolinite and illite initiate pore filling in nonmarine rocks.

Spindle field, second largest oil field in Colorado, produces oil and gas from Hygiene and Terry sandstones deposited as offshore marine bars. Upward-coarsening lithofacies in both sandstones are: (1) bioturbated muddy sandstones (shelf and interbar); (2) very fine-grained, poorly sorted, weakly cross-stratified sandstone (bar margin); (3) fine-grained to medium-grained, moderately sorted, cross-stratified sandstone (central bar).

On the basis of known fabrics and environments, Hygiene and Terry sandstones were predicted by use of the reported diagenesis model to show a $\Delta G°_f$-related diagenesis in interbar and bar-margin facies, and an initial chlorite diagenesis in the central-bar facies. Preliminary thin-section and SEM investigations tend to confirm the prediction for the finer grained facies. The origin of kaolinite-rich pore filling in the central-bar facies is not clearly understood, but it may be related to abundant argillaceous clasts which provide in-situ material for continuous alteration of pore-fluid composition during diagenesis.

Modification of predicted diagenesis in the coarser grained facies provides an additional basis for anticipation of diagenetic sequences in other offshore-bar deposits.

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Resource Appraisal Predictions and Exploration Performance—Case Studies for Onshore United States

Geologic estimates of undiscovered recoverable oil and gas resources in the United States were published in U.S. Geological Survey Circular 725 in mid-1975, based on data through 1974. In the 1975 study, 47 onshore provinces included within 11 regions, were evaluated. Three of these geologic provinces, (1) West Texas–Eastern New Mexico, (2) North Slope, Alaska, and (3) the Overthrust belt of Idaho-Utah-Wyoming, were selected as case studies to show the relation between the 1975 resource assessments and subsequent exploration results.

U.S. Geological Survey resource estimates for the maturely explored West Texas–Eastern New Mexico province range from 4 to 14.4 billion bbl of oil and 35 to 100 Tcf of gas, based on the 95 and 5% probability percentiles. Exploration wildcat drilling from 1974 through 1977 resulted in more than 840 oil and gas discoveries, mainly of small field or pool size. Exploration results in this province, based on finding rates and the amounts of oil and gas discovered, do not appear to have met the resource predictions.

Resource estimates for the immaturely drilled North Slope province range from 3 to 10 billion bbl of oil and 7 to 25 Tcf of gas. About 40 wildcats were drilled from 1974 through 1977, resulting in 15 successful oil wells and 1 gas well. Two of the oil discoveries appear to be in the >50 million-bbl field size ("A" class). Resource predictions appear to have been met, or exceeded for the North Slope, based on this recent exploration performance.

Estimates of resources for the Overthrust belt, the most recently successful of the three provinces, range from 0 to 0.2 billion bbl of oil and 0 to 1.1 Tcf of gas. Three gas and five oil fields were discovered out of 89 total wildcats drilled from 1974 through 1977, at least four of which are estimated to be of "A" field-size class or greater. Exploratory performance to date has exceeded the earlier resource estimates in the Overthrust belt.

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Palo Duro Basin Analysis

A comprehensive stratigraphic analysis of the Palo Duro basin, emphasizing facies and depositional systems, provides a framework for resource analysis and exploration. A pre-Pennsylvanian section consists of thin, basal, Cambrian sandstone overlain by Ordovician and Mississippian shallow-shelf carbonate rocks. Pennsylvanian and Lower Permian rocks consist of 1,000 m of basin and slope shales, massive shelf-margin carbonate rocks, and deltaic sandstones. Facies distributions define a major episode of basin subsidence and transgression (Pennsylvanian) with shelf-margin retreat, followed by regression (southward), and basin filling (Early Permian). In Late Permian time, the basin was an extensive sabkha-shelf platform on which salt (upper sabkha), anhydrite-gypsum (lower sabkha), dolomite (subtidal to intertidal shelf), and red beds were deposited. Two continuous 1,220-m cores drilled to the base of the evaporites provide a unique opportunity for calibration of well logs with petrographic studies, and for resource evaluation (fluid tests, uranium and copper analyses, etc).

The subsurface analysis has been coordinated with geomorphic and hydrologic studies in the same area (climate, slope, stream, and eolian process monitoring and field surveys of selected drainage basins) to demonstrate surface and subsurface interrelations. For example, locations of salt solution zones in the evaporite section coincide with surface erosional features, suggesting control of solution rate and position by drainage. High solute loads of area streams are probably derived from subsurface evaporite solution and result from regional surface discharge of groundwater circulation systems.

Lack of proven oil and gas reserves in the basin may be attributable to a limited volume of thermally mature source rocks.

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Upper Permian Evaporites and Red Beds of Palo Duro Basin, Texas—Facies Patterns Through Time

Subsurface facies analysis of Upper Permian evaporites and red beds of the Palo Duro basin, Texas, provides information important in evaluations for potential hydrocarbons, uranium, copper, and evaporite minerals. Cores, cuttings, and well logs were used for analysis. Stratigraphic units include the Clear Fork Group, Glorieta and San Andres Formations, and post-San Andres Guadalupian and Ochoan strata.

Evaporites and associated carbonate rocks show ba-

sinward (southerly) facies changes from supratidal to subtidal; facies exhibit many features of modern, low-relief, coastal sabkhas. Lithofacies include (1) salt formed in upper sabkha evaporating ponds, (2) lower sabkha anhydrite in bedded units, (3) supratidal to subtidal dolomite with nodular and bedded anhydrite, and (4) highly burrowed subtidal-shelf carbonates. Red beds occur as sheets (up to 300 ft or 100 m thick) of shale and fine sandstone, which intertongue basinward with evaporites and dolomite. It is suggested that these formed largely in tidal mudflats grading basinward into tidal sandflats. Clastic input was by eolian and/or low-energy alluvial processes. The genetic aspect of the stratigraphy is a general southerly facies shift through time.

Potential for potash minerals is best in the upper sabkha facies associated with salt, whereas anhydrite is abundant in the lower sabkha deposits. Copper may be present in the tidal-flat systems. Lack of large gamma ray anomalies suggests that ore-grade uranium concentrations are unlikely. Hydrocarbons are present in Guadalupian facies equivalents on the southern basin margin, and knowledge of facies relations will aid exploration.

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Active Submarine Landslide Processes, Mississippi Delta

A major project is in progress to map the entire submarine portion of the modern Mississippi delta using precision depth recorders, side-scan sonar, and subbottom profiling. The survey network is composed of north-south lines spaced at 140-m intervals and east-west crosstie lines 600 m apart. The object is a detailed documentation of seafloor changes resulting from bottom sediment and slope instability. Subaqueous slope failures are widespread and active, occurring on slopes with very low inclinations, ranging from 0.2 to 1.5°. They have resulted in damage and loss to offshore oil and gas structures. The types of features include collapse depressions, bottleneck slides, elongate slides and slumps, mudflow gullies, and overlapping mudflow lobes. The basic mechanism can be approximated as downslope translation of shallow slabs of debris. Stability calculations based on measured shear-strength properties and failure geometry indicate that very high excess pore-water pressures are needed to initiate failure, and there is some empirical evidence to suggest that such pressures exist and are related to rapid sedimentation, surface wave perturbation of bottom sediments, and in-situ methane gas generation.

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Cyclic Sedimentation of Cretaceous-Paleocene Reservoir Sandstones in West-Central Pakistan

The Upper Cretaceous and Paleocene sequence in the eastern Sulaiman Range of west-central Pakistan records continuous cyclic sedimentation in shallow-marine, shelf environments. These rocks are 800 m thick and are representative of at least 50 cycles of shoreface and fluvial to fluviotidal origin. Lithogenetic studies using sedimentary structures, trace fossils, and vertical sequences indicate that the shoreline orientation was northwest-southeast with the open shelf on the northeast. Shallow-marine carbonate rocks of the Cretaceous Mughalkot Formation grade abruptly into 26 shoreface cycles and 10 fluvial to fluviotidal cycles of the Cretaceous Pab Sandstone. Gradationally above this are 14 shoreface cycles of the Paleocene Khadro Formation, distinguished from the underlying Pab Sandstone by the increased amounts of argillaceous matrix and lower-shoreface shales.

The Mughalkot carbonate rocks and the lower-shoreface shale interbeds of the Pab and Khadro Formations may serve as hydrocarbon source beds for the Pab and Khadro sandstone reservoir beds.

This sequence suggests a rather uniform rate of subsidence with episodic transgressions and controlled-sediment-supply progradation. The abrupt increase in the amount of argillaceous detritus during the early Paleocene suggests a significant change in the source-area character.

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Carbonate Replacement of Sulfate—New Mechanism for Porosity Generation in Carbonate Rocks Marginal to Evaporite Basins

Production of macropores by gypsum replacement of carbonate, and of intergranular porosity by pervasive dolomitization constitute two important mechanisms for generating high porosity in carbonate rocks in and adjacent to evaporite basins.

Exposures of Upper Permian Capitan Group carbonate beds in Carlsbad Caverns and other caves of the Guadalupe Mountains, New Mexico, indicate that one of the earliest stages of speleogenesis was the massive replacement of carbonate by sulfate. Field relations indicate that replacement took place in a mixing zone between a meteoric freshwater lens and gypsum-saturated brines. Replacement is most pronounced along joints, indicating a possible correlation with the rate of freshwater input. Replacement probably began with the development of the lens following orogenic uplift of the Guadalupe Mountains, or solutional deflation of basinal evaporites. As uplift and deflation continued, hydrologic base level fell with respect to replacement gypsum pods, exposing them first to freshwater phreatic conditions, and later to vadose conditions, causing their partial or complete recrystallization or dissolution and creating enormous voids. These underwent limited enlargement in the freshwater phreatic zone, and collapsed following draining of the caves.

Replacement of the gypsum may be recognized by primary carbonate structures preserved as remnant inclusions. Replacement gypsum crystals are generally equant with complex boundaries, but may derive their size and shape from carbonate macrostructures re-