powered by subductive closing of the Ural–Proto-Atlantic ocean system, but distinct styles and kinematic sequences are imposed through gravity spreading by synorogenic topography, and by 1.5 to 4.5 km of foreland subsidence succeeding 2.5 to 6 km of cratonic shelf subsidence. Traditional exploration prospects are surface folds and frontal thrusts within a Silurian to Mississippian clastic wedge thinning southward from 6.5 to 0.5 km. Future prospects are in lower Paleozoic carbonate rocks involved in subthrust structures and, perhaps, in rift fill below the regional decollement. Risk is related to porosity distribution and to surface-water invasion. Overthrust styles include: detached folds and bed-parallel decollements; sled-runner thrusts, folded-fault structures, and polyphase thrusts; and fold-discordant thrust sheets. Some styles predominate regionally: folded-fault structures in the north and the south, imbricate stacks in the middle, and fold-discordant thrusts in the south. There is no hard evidence of eastward migration of thrusting. Kinematic sequences suggest that a frontal subbelt of detached folds or decollement always was located west of a subbelt of thrust imbrication. Basement subsidence, thrust pileup, erosion, and foredeep sedimentation caused the subbelts to shift position and width, thereby generating kinematic sequences essential for the definition of prospects.

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Zenith Field—Significant Dakota (Muddy) "D" Sandstone Discovery, Adams County, Colorado (Secs. 17-20, T3S, R62W)

Zenith field is located on the moderately-dipping, eastern flank of the Denver-Julesburg basin, approximately 43.4 km east of Denver. The field was discovered in March 1979, with the completion of Empire Drilling Company 1 Hilton for 1,285 bbl of oil per day and 750 Mcf of gas per day from the Lower Cretaceous (Muddy) "D" sandstone from 2,222 to 2,234 m. Development drilling by Empire, Champlin Petroleum Inc., and Amoco Production Co. has increased the number of producing wells in the field to five "D" sandstone wells and one Muddy "J" sandstone well. The initial potentials of the additional wells range from 50 to 500 bbl of oil per day with 1,000 Mcf of gas per day. Cumulative production for the field to November 1, 1979, was estimated at 96 thousand bbl of oil and 64 MMcf of gas. Several other wells are in the process of being drilled and completed. Six wells in the field have been plugged and abanonded.

The "D" sandstone throughout the D-J basin is developed as marine-bar and distributary channel sandstones, and hydrocarbon accumulations are found primarily in stratigraphic traps. Zenith field is part of an east-west trending distributary channel which is also productive at Strasburg field, 3.2 km to the east, and Bennett field, 5.6 km to the west. The channel averages less than 1.6 km in width. The productive limits of all three fields are controlled by the pinch-out of porosity and permeability associated with facies changes within the channel. At least three distinct facies can be identified from well logs in Zenith field.

The "D" sandstone of Zenith field is predominantly fine grained, poorly sorted, and very shaly. The sandstone ranges in thickness from less than 6 m to greater than 15 m. The "D" sandstone thickness in producing wells is usually greater than 12 m. The average porosity and permeability in the "D" sandstone are low.

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Oil-to-Source Correlation—Pineview Field, Overthrust Belt, Utah

The Pineview field, discovered in 1975, started the recent expansion of exploration in the Overthrust belt and produces mainly from the Jurassic Nugget and Twin Creek formations. Mass spectra, gas chromatographs, and carbon isotopes show that oils from the two formations are geochemically similar, which suggests that they were generated in the same or similar source rock. Source evaluation data indicate that Cretaceous shales and the Phosphoria Formation are the best potential source rocks in this part of the Overthrust belt. An oil-to-source correlation shows that the Pineview oils are related to the Cretaceous source rocks rather than the Phosphoria. A Cretaceous source is geologically reasonable at Pineview because Cretaceous shales of the subthrust section underlie the Jurassic reservoirs. The geochemistry of the different Cretaceous formations is quite similar, probably because of their generally similar depositional environments. Therefore, it is not possible to determine which Cretaceous formation is actually the source of the Pineview oils.

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Facies Control on Bitumen Saturation, Peace River Oil Sands Deposit, Alberta, Canada

In the Peace River oil sands deposit an estimated 75 billion bbl of heavy oil are trapped at the updip pinchout of the Lower Cretaceous Bluesky and Gething Formations, at depths of 1,500 to 2,500 ft (457 to 762 m). The principal oil-saturated sand body occurs near the updip edge of the reservoir and averages 80 to 100 ft (24 to 31 m) in thickness. Downdip, the Gething Formation thickens to over 250 ft (76 m) but becomes mainly shale with a few thin sands. Throughout the area it is capped by thin marine sands of the Bluesky Formation. Based upon palynology and sedimentary structures, this sequence grades upward from continental through brackish to marine.

Sedimentary structures of a channel sequence are clearly displayed in the main sand body. From bottom to top the sequence is: a channel lag deposit containing abundant disoriented detrital carbonaceous fragments, plane-bedded or structureless sand, large scale cross-bedded sand, smaller scale cross-bedded sand, and structureless or bioturbated sand containing abundant glauconite. Laterally this sequence commonly grades into thinly interbedded oil-saturated sand and shale.

Reservoir properties vary between the facies. The channel lag deposits have coarser grain size, less interstitial clay, and generally lower oil saturations than the thinly interbedded sand and shale. The cross-bedded sands contain the highest oil saturations and form the largest and most continuous reservoir. Oil saturations are commonly lower in the marine sands of the Bluesky Formation where glauconite, clastic carbonate, and local carbonate cement combine to reduce porosity and permeability.

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Paleocene (Midway) Continental Shelf Deposits, Rio Grande Embayment, Texas

The Midway Group has been considered a monotonous section of marine shale which was deposited on the continental shelf during the initial Cenozoic transgression. However, recent studies show the Midway to be a complex group of sediments deposited in environments ranging from deltaic to bathyal.

Sedimentary rocks of the Midway Group crop out along the northern and western edges of the Rio Grand embayment. Siltstones deposited as a beach occur in the northwest corner of the Rio Grande embayment in Uvalde County, Texas. To the east and south, richly fossiliferous carbonate rocks indicate a nearshore shallow-marine environment. Basinward, the Midway Group grades into shale deposited on the shallow continental shelf. Sandstones, up to 10 ft (3 m) thick, occur intermittently throughout the shale. These shallow-marine sands are most likely derived by longshore currents paralleling the coast.

Sandstone in the Midway is increasingly abundant toward the shelf edge near Laredo, Texas. The sand was probably deposited as barrier islands and shallow-marine shelf sands. The source of the sand was probably to the east. Significant quantities of gas have been discovered in these sandstones near Laredo in both the United States and Mexico.

Recent gas discoveries have been made in the Midway rocks of eastern Texas which were deposited in deltaic to bathyal environments. It appears that a delta prograded over the shallow continental shelf, and sediments were deposited on the shelf edge and upper slope. Sands from the delta complex were probably carried by longshore currents to the south and deposited near the shelf edge in the vicinity of Laredo.

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Two Controls of Sand-Wave Size: Dynamic Equilibrium Processes and Kinematic Depositional-Erosional Processes

Studies in flumes and estuaries have shown that the average size of dunes or sand waves in equilibrium with the flow that generated them is controlled primarily by flow velocity, depth, and sediment size. Equilibrium sand-wave height and wavelength increases with flow velocity, for a constant depth and sediment size, until flows become transitional with the upper flat-bed phase.

Additional non-equilibrium processes operate at a site of deposition. Sand is deposited on lee slopes of sand waves more rapidly than it is eroded from stoss slopes. The balance of the sand, that part deposited at the base of lee slopes but not subsequently eroded at the upstream stoss slopes, is left behind. Bed forms decrease in size as sand is thus removed from circulation unless either (1) sediment transported in suspension from outside the depositional area is trapped by sand waves as rapidly as sediment is removed, or (2) sand waves merge to form larger ones.

Sand waves in nonequilibrium flows, where neither of these two processes operates, should show a change in cross-sectional area proportional to the change in the sediment-transport rate. Sand-wave cross-sectional area is observed to be proportional to the sediment-transport rate raised to a power of 0.5 to 2 in equilibrium flows that are not transitional with upper flat beds, and where depth and sediment size are constant. Consequently, where depth is constant, both equilibrium and nonequilibrium processes tend to keep sand-wave cross-sectional area approximately proportional to sediment-transport rates. Where depth changes downcurrent, the two processes may conflict, and the response of the bed will have to be determined experimentally.

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Mechanisms Controlling Porosity in Red River (Upper Ordovician) Carbonate Reservoir, Cabin Creek Field, Montana

Cabin Creek field, on the Cedar Creek anticline in southeastern Montana, produces oil from Mississippian, Silurian, and Ordovician carbonate rocks. The major producing reservoir is the Upper Ordovician Red River Formation.

The Red River of Cabin Creek field is a 500-ft (152 m) thick limestone-dolomite sequence; the upper Red River consists of several cycles of uniformly thick peritidal shelf carbonate rocks. Favorable porosity is restricted to the dolomites; the limestones are nonporous and serve as cap rocks. Porosity and permeability are controlled both by dolomitization and by silica and anhydrite cements. Lateral and vertical variations of dolomitization are mainly responsible for variations in reservoir properties and effective pay thickness. Average porosity is 13%, with a maximum of 25%. Production is from porosity zones in the upper 150 ft (45 m) of the Red River.

Upper Red River limestones consist of biomicrite-wackestones which contain diverse faunal assemblages, and are interpreted as shallow, open-marine shelf deposits. The limestones are pelletal in part, poorly bedded, burrowed, stylolitic, with widespread dolomitic mottling. Producing dolomite zones consist of two distinct facies. The lower facies, interpreted as subtidal, consists of biomicrite-wackestone and skeletal dolomite with moldic porosity. The upper facies, interpreted as intertidal, consists of wavy-laminated, unfossiliferous, microcrystalline dolomite with intercrystalline porosity. The upper facies is abruptly truncated by overlying pelletal limestone and (locally) thin black shale. Con-