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Depositional and Diagenetic Models for Devonian Birdbear (Nisku) Reservoirs, Northeastern Montana

Carbonates comprising the approximately correlative Upper Devonian Birdbear and Nisku Formations were deposited over an immensely broad, shallow shelf that extended from eastern North Dakota over an immensely broad, shallow shelf that extended from eastern North Dakota to central Alberta. Major oil production is concentrated in Nisku pinnacle reefs bordering the central Alberta basin and Birdbear stromatoporoid banks and biostromes bordering the Williston basin in northeastern Montana. Birdbear fields are located on structures coincident with favorable reservoir facies. Birdbear porosity, formed upon dolomitization, is dominated by interconnected intercrystalline and microvugular voids, skeletal molds, and leaching-enhanced intraskeletal voids. Fractures and vugs are relatively unimportant. Diagenesis and the distribution of reservoir facies, in turn, were controlled by the sequence and local geography of depositional settings and early burial conditions. Accordingly, depositional and diagenetic models are fundamental to geological exploration for Birdbear reservoirs.

Depositional models over the region are varied, but all have in common early marine inundation of a nearly featureless shelf and coastal plain, followed by universal gradual shoaling by vertical sediment accretion culminating in an extremely restricted depositional setting. Mud-rich depositional textures and contained fossil assemblages demonstrate the predominance of low-energy, shallow subtidal to supratidal waters of more or less elevated salinities. Normal marine shelf conditions were exceptional. Depositional models are constructed as vertical facies sequences, each subject to local and regional facies changes. One such model sequence, from the base upward, progresses from restricted intertidal mud flats (commonly brecciated mudstone), semirestricted *Amphipora* banks (wackestone and current-bedded packstone), normal marine lagoons (nodular-bedded mudstone and wackestone), semirestricted stromatoporoid biostromes (in-situ laminar and tabular stromatoporoid boundstone), restricted intertidal mudflats (laminated, stromatolitic mudstone), to supratidal flats and evaporitc ponds (nodular-mosaic anhydrite and mudstone). *Amphipora* bank and stromatoporoid biostrome facies, which bear the highest porosity values, are especially prone to lateral facies change.

Principal events of a generalized Birdbear diagenetic model include desiccation, brecciation, and caliche development in mudstone; displacive growth of nodular and nodular-mosaic gypsum; and lithification by pervasive dolomitization. These early events were accompanied throughout by physical compaction and loss of nearly all primary porosity. Development of most secondary porosity occurred during dolomitization. Deep-burial diagenesis encompassed fracturing; gypsum-to-anhydrite transformation accompanied by fracture and pore filling and replacement by anhydrite; hydrocarbon generation and migration; and pressure-solution formation of stylolites and microstylolites. These latter events are characterized by chemical compaction, cementation, and reduction of secondary porosity. Any specific diagenetic model and resultant reservoir characteristics, however, are valid only for that particular set of rock fabrics and burial settings embodied in any given depositional model.

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Poncho Field—Cretaceous "J" Sandstone Stratigraphic Traps—Denver Basin, Colorado

Distributary channel and delta destructional sandstones of Early Cretaceous age are important reservoirs for stratigraphic traps in the "J" sandstone at Poncho field, Adams and Arapahoe Counties, Colorado.

Cores and logs from the field area reveal a lowermost, nonproductive, northeast-trending delta front sandstone (J-3); a middle complex of southeast- and east-trending, productive distributary channel sandstones (J-2) that grade into tightly cemented delta fringe marine sediments to the southeast and northeast; and an upper, northeast trending, productive delta destructional sandstone (J-1). Vertical and lateral sequences of sedimentary structures, textures, trace fossil assemblages, and geometry and trend of sandstone bodies suggest that these units were part of a wave-dominated delta complex that prograded to the east and southeast from the area of Lonetree field.

Thin section and SEM analyses reveal that the principal cements in both reservoir sandstones are quartz overgrowths, kaolinite, and chlorite, and that the bulk of the porosity is secondary and related to dissolution of carbonate cement and feldspar grains. Porosities and permeabilities are most variable and lowest in the nonproductive delta front sandstones, averaging 15% and 7 md; variable and intermediate in the productive distributary channel sandstones, averaging 16% and 28 md; and most uniform and highest in the overlying delta destructional sandstones, averaging 21% and 88 md.

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Application of Geological Studies to Overburden Collapse at Underground Coal Gasification Experiments

Detailed geologic and mineralogic studies were conducted on the Hanna, Wyoming, and Hoe Creek, Wyoming, underground coal gasification sites. These studies demonstrate the importance geologic factors have on controlling overburden collapse into the reactor cavity during and after coal gasification and on subsequent environmental problems. Parameters that control the collapse of overburden material into the reactor cavity include: duration of the burn; maximum span of unsupported roof rock; lateral and vertical homogeneity, permeability and rock strength; and thickness of overburden materials. The duration of the burn, maximum span of unsupported roof rock, and total thickness of overburden rock are, in large part, determined by the technical engineering aspects of the burn. The remaining parameters are determined by geological factors including original composition, depositional environment, diagenesis, and structural deformation.

The coals and overburden units at both sites are Eocene in age and are virtually flat lying. The three burn cavities studied at the Hoe Creek site are directly overlain by laterally discontinuous, poorly indurated, kaolinite-cemented sandstones, siltstones, and mudstones of channel and overbank origin. At the Hoe Creek I experiment, a small reactor cavity and a correspondingly short maximum span of unsupported roof rock consisting of fine-grained, low permeability overbank deposits resulted in minimal collapse. At the Hoe Creek II experiment, a significant amount of collapse occurred due to an increased span of unsupported roof rock comprised of poorly consolidated, more permeable channel sandstones and a limited amount of overburden mudstones and siltstones. Roof rock collapse extended to the surface at the Hoe Creek III experiment where the maximum span of unsupported roof rock was largest and where the roof rock consisted of highly permeable, poorly consolidated channel sandstones.

The unit comprising the reactor cavity roof rock at the Hanna II experimental site is a laterally continuous lacustrine delta deposit, which primarily consists of sandstones with lesser amounts of interbedded siltstones and claystones. The overall strength, specifically the bridging capacity, of this unit is enhanced by abundant calcite cement. This cement reduced permeability and interstitial waters which probably kept spalling of the roof rock to a minimum. Consequently, roof rock collapse at the Hanna II experiment was much less extensive than at the Hoe Creek II and III experiments.

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Potentiometric Surface and Quality of the Water of Madison Group, Montana

The potentiometric surface map of the Madison Group of Mississippian age in Montana indicates that water in this aquifer generally moves northward. The principal recharge areas of the Madison are the Little Belt and Big Snowy Mountains of central Montana, the Pryor and Bighorn Mountains of south-central Montana and northern Wyoming, and the Black Hills uplift of Wyoming and South Dakota. The dissolved-solids concentration of the water ranges from a few hundred milligrams per liter near mountainous recharge areas to about 300,000 mg/L in the northeastern part of the state (Williston basin). The ratio of sodium plus potassium plus chloride to dissolved-solids concentration is greatest in northeastern Montana where the Madison contains salt beds, and decreases toward recharge areas. The ratio of sulfate to total anions is greatest in north-central and southeastern Montana where anhydrite probably is the source of the sulfate. The ratio is smallest in northeastern and northwestern Montana; however, the concentration of sulfate, in milligrams per liter, can be greater in northeastern Montana than in other areas because of the greater concentration of all dissolved solids.

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Depositional Framework for Lower Member of Metaline Formation (Cambrian), Northeastern Washington

The Metaline Formation is a Cambrian unit that crops out in Stevens and Pend Oreille Counties, northeastern Washington. The 985 to 1,250-m (3,200 to 4,100-ft) thick formation has been divided into lower, middle, and upper members, although structural complications and numerous covered intervals have made measurement of complete stratigraphic sections impossible. Based mainly on trilobite studies, early workers assigned a Middle Cambrian age to the 120 to 290-m (390 to 950-ft) thick lower member. The present study divides the lower member into the following five lithofacies: (1) gray mudstone, (2) ooid-arenite, (3) gray packstone-wackestone, (4) black packstone-wackestone, and (5) black mudstone facies.

The gray mudstone facies grades upward from underlying fine-grained siliciclastics, and it is composed of bioturbated lime mudstones with a small admixture of thin-shelled trilobite fragments, chitinophosphatic inarticulate brachiopods, and disarticulate echnioderms. The ooid-arenite facies occurs as pods within the gray mudstone facies, and is composed of spherical quartz grains and ooids developed around quartz cores in a neomorphic spar matrix. The facies is extremely well-sorted. The gray packstone-wackestone facies is composed of ooid-oncoid packstones alternating with argillaceous, fossiliferous wackestones. Rounded intraclasts and peloids are secondary components. Fossil allochems include robust trilobite fragments, echinoderm plates, and rare (?) *Epiphyton* algae. The black packstone-wackestone facies contains the same components as underlying rocks but is characterized by an increase in carbonaceous material and pyrite causing the black color. Fossils are less robust than in the underlying facies. The black mudstone facies is characterized by bioturbated lime mudstones with rare fossil fragments. The top of the member is marked by a red-stained, well-cemented zone below a disconformable contact with the middle member.

The lower member of the Metaline Formation represents the first carbonates deposited on a ramp-type shelf margin during a major Middle Cambrian transgression. The observed lithologies suggest deposition under conditions of changing water depth, agitation, and oxygenation in the shallow subtidal zone. The mudstones and wackestones in all facies were deposited under low-energy conditions. Shallowing allowed increased agitation, and oxygenation suitable for the local development of ooids and oncoids. Periodic storms produced high-energy packstone deposits composed of concentrations of the components found in the typically low-energy subtidal zone.

Along with the transgression of marine environments, oxygen-starved waters migrated shoreward from an offshore, lower shelf basin. This transgression of the pycnocline caused dysaerobic and anaerobic conditions in shallow subtidal waters of the upper shelf. Aerobic and dysaerobic conditions produced gray rocks, and anaerobic conditions produced black rocks rich in organic material. Biofacies were also affected by the low oxygen levels. Thin-shelled and chitinophosphatic forms dominated the epifauna when dysaerobic conditions occurred. With decreasing oxygen content, the epifauna was progressively excluded from the shallow subtidal zone. The result of maximum anoxia was the cessation of carbonate sedimentation and the formation of a submarine hardground at the end of "lower Metaline deposition."

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Origins of Oil in Railroad Valley, Nye County, Nevada

Trap Spring field was discovered in 1976, becoming the second commercial oil field in Nevada. The first, Eagle Springs, was discovered in 1955 and is about 6 mi east of Trap Spring. Currant, a third, noncommercial, one-well field, was found in 1978 and is about 7 mi north of Eagle Springs. Trap Spring field is productive from Oligocene welded ash-flow tuffs, and Currant produced from the Eocene Sheep Pass Formation. Production at Eagle Springs is from both of these units plus some production from the Ely Limestone (Pennsylvanian). Possible sources of oil for these fields are beds within the nonmarine Sheep Pass Formation and the marine black shales of the Chainman Formation (Mississippian). Prior to discovery of Currant field, the origin of the Eagle Springs and Trap Spring oils was problematical, and a wide range of source rock and post-generation alteration possibilities were considered. The n-C_{15+} chromatograph of the Currant oil shows unusually high peaks of pristane and phytane and a slight even-carbon preference in the n-C_{18} to n-C_{26} range. These factors are indicative of a recently generated oil from a source rock in a carbonate-evaporative sequence. The geochemical data and geologic conditions support the hypothesis that the oil produced at the Currant well was generated in the Sheep Pass Formation. The n-C_{15+} distribution of Trap Spring oil differs significantly from that of the Currant oil and is more typical of oil generated in source rock deposited in a marine environment. The most likely source of this oil is the Chainman Formation. The origin of the oil from Eagle Springs remains unclear as it has chemical affinities to both Trap Spring and Currant oils. It is possible that the Eagle Springs oil is a mixture of oil generated in the Sheep Pass Formation and Chainman Shale.

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Differential Vertical Tectonics: Insights from Models Composed of Sandstone and Limestone Deformed at Confining Pressure

Rock models (12 × 3 × 3 cm, 4 × 1 × 1 in.) composed of a precut forcing block of sandstone beneath a 1-cm thick, multilithologic layered veneer of sandstone and limestone or of uncemented sand, have been deformed room-dry, at 100-MPa confining pressure, room temperature, and a strain rate of 10^{-4} sec^{-1}. Upon frictional sliding along the lubricated precut (inclined at 30° to 90° to the intact veneer) the forcing blocks deform the layered veneer into a faulted drape fold. Thin sections cut parallel to the dip and to the strike of the precut and major fault in the veneer are studied to provide detailed maps of the induced deformation (microfractures, faults, intragranular strains, "bedding" thickness changes, brittle versus ductile behavior, and nature of the folding and hinge formation). In addition, dynamic fabric analyses of faults, microfractures, and calcite twin lamellae yield stress trajectory diagrams that serve to test the applicability of corresponding numerical or analytical solutions.

Insights gained from the models primarily deal with (a) brittle or ductile behavior of the limestone depending upon location within the faulted drape fold; (b) nature of the deformation concentrated in the leading edge of the "upthrown" forcing block; (c) configuration and sequence of faulting associated with the major "upthrust" in the veneer; (d) location and significance of associated precursive microfracturing; (e) cataclastic thinning of veneers to the point where discrete layers are "tectonically eliminated" in the major fault zones; (f) hinge formation within the veneer; and (g) the role of "bedding-plane slip" in the folding process.

Deformation features in these models are used to interpret the geometry and genesis of the large scale structures at the Clark's Fork Corner of the Beartooth Block and at Rattlesnake Mountain near Cody, Wyoming; at Colorado National Monument near Grand Junction, Colorado; at the Yampa drape fold, Dinosaur National Monument; and in the subsurface along the Oak Ridge fault, Ventura basin, California. Collectively, these features are criteria for, and hence help define, the differential-vertical-tectonic style.

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Paleotectonic Implications of Arkose Beds in Park Shale (Middle Cambrian), Bridger Range, South-Central Montana

The Cambrian System in the Bridger Range of south-central Montana is part of a 450 to 500-m (1,475 to 1,640-ft) thick transgressive-regressive sequence of fine-grained clastic and carbonate rocks. Above the Flathead