

completed. The Missourian and Virgilian sequence includes about 132 m of carbonate rocks divided into 46 units for collection and description. Eighteen of these units yielded a silicified brachiopod assemblage totaling 21 strophomenids and 17 taxa of other orders. Fossil abundance is greatest in the lower part of the Missourian and from the topmost Missourian through the middle Virgilian. Correlation with the middle Virgilian of North Texas and, perhaps, the lower Missourian of the southwest is especially strong. Notable range extensions include: (1) *Paeckelmanella?* n. sp., an otherwise Arctic Permian taxon, in the Virgilian; (2) *Mesolobus euampygus* in the Early Missourian, an extension of generic range from the Desmoinesian; (3) *Paucispinifer* n. sp., a Permian genus occurring in the Missourian; and (4) *Neospirifer latus lateralis*, a Missourian species occurring in the Virgilian. In addition, *Calliprotonia* n. sp. is reported the second occurrence of this genus in the North American Virgilian.

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Kinematic Model for Evolution of Cordilleran Fold/Thrust Belt, Canada to Mexico

Cretaceous to early Tertiary shortening of the foreland region occurred along listric thrust faults bounded by conjugate wrench faults that cut through and ductilely deformed the underlying Precambrian basement. Oblique convergence on east-dipping B-type subduction along the western edge of the North American plate coupled with west-dipping A-type subduction along a zone east of the plate margin and marked by muscovite-bearing two-mica granites produced conjugate WNW-trending left-slip and NE-trending right-slip faults and the foreshortening evinced by the decollement faults of the Western Overthrust. Many left-slip faults split into right-turning splays that join other left-lateral faults, creating thrust systems with a regional Z-shaped bend (e.g., thrusts of the Sawtooth Range, Montana). Conversely, right-slip faults split into left-turning splays that join other right-slip faults creating S-shaped thrust systems. Conjugate pairs of strike-slip faults bound concave-westward zones of decollement thrust faults (e.g., thrusts of the Belt graben, Montana). Complex flower structures mark the loci of many wrench faults (e.g., Arizona and southwestern New Mexico). Late Tertiary to Holocene extensional deformation of western North America produced the north-trending listric normal faults of the Great Basin and reversed the sense of movement on many preexisting strike-slip and thrust faults. These regional relationships are clearly visible on digitally processed Landsat imagery.

This model also accounts for the synchronous intrusion of both two-mica (muscovite) and one-mica (copper porphyry type) granitic rocks in the region. This geologic paradigm will assist the exploration for hydrocarbons and minerals.

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Lithology and Depositional Environment of Ashern Formation (Middle Devonian), North Dakota

The Ashern Formation (Middle Devonian) is the basal unit of the Kaskaskia Sequence in North Dakota. It is unconformably underlain by the Silurian Interlake Formation, and overlain, generally conformably, by the Winnipegosis Formation of Middle Devonian age. The Ashern is present in the northwestern one-third to one-half of North Dakota. Beyond the limits of the overlying Winnipegosis Formation, the Ashern is in-

distinguishable on electric logs from the basal argillaceous members of the Dawson Bay and Souris River formations and, together with these, must be considered undifferentiated basal Devonian.

The Ashern Formation is composed of two members. The lower red member is predominantly an argillaceous microcrystalline dolostone, containing nodular anhydrite and thin shale partings. The upper dark gray member is predominantly a featureless microcrystalline limestone. Together, these two members range in thickness from about 10 m near the limit of the Ashern Formation to about 50 m near the center of the Williston basin.

The red member owes its color to a reworking of a lateritic soil on top of the Late Silurian/Early Devonian erosional surface. The fine-grained dolostone and its nodular anhydrite imply supratidal deposition in a sabkha environment. The featureless gray member was deposited in a low intertidal to subtidal environment. There is an occasional suggestion of bioturbation, though no fossils have been found. No porosity is evident in the formation, except for some partly anhydrite-filled fractures near the top in one core.

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Depositional Environment and Rock Fabric, Birdbear ("Nisku") Formation (Upper Devonian), Williston Basin, North Dakota

The Birdbear Formation was deposited as the upper part of a widespread marine carbonate and evaporite system prevalent in the Williston basin during the Middle and Late Devonian. Rock facies representing shallow-water and associated carbonate sub-environments are present in the Birdbear. Stillstands of sub-environments and frequency of transitions between sub-environments are similar to those in the underlying Duperow Formation. Evaporites are dominant in the uppermost part of the Birdbear.

Original depositional environments are recognized with subsequent diagenetic events evaluated. The development of interparticle and moldic porosity is outlined, in particular, with reference to dolomite.

Dolomites are prevalent in the upper section of the Birdbear Formation. Evidence suggests shallow intertidal and supratidal conditions with porosity development associated with the dolomites. Overlying limestones and anhydrites act as caprock.

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Origin of Dolomite, Red River Formation, Richland County, Montana

Distribution of limestone, dolomite, and anhydrite as determined from compensated neutron-density logs and core studies of the Ordovician Red River Formation in Richland County indicates that: (1) virtually all deposition, including the B and C zone anhydrites, occurred subtidally (contrary to previous interpretations invoking localized tidal flats on paleo-highs); (2) various rock units such as the anhydrites and B and C "laminated" zones have remarkable uniformity and lateral continuity over many tens of miles; and (3) dolomitization occurred in subtidal stromatolites, by primary precipitation, or by gravitational seepage of Mg-rich brines into normal marine subtidal carbonates. The lateral persistence of the A and B zone dolomites indicates they formed mainly by primary precipitation and/or dolomitization of subtidal stromatolites whereas the localized replacement dolomites of the C and D zones formed by gravitational seepage of dense brines.

The C zone dolomite of the Red River is the major oil-producing zone in Richland County. This dolomite occurs immediately beneath the "C" zone anhydrite as concentrated lenses of: (1) tight cryptocrystalline anhydritic dolomite, (2) porous fine to very fine-grained dolomite, and (3) relatively tight partly dolomitized limestone. The dolomitized lenses are typically one to two km in diameter and up to 50 m thick. They apparently formed beneath "holes" in the C anhydrite through which dense Mg-rich brines (formed during precipitation of the subtidal anhydrite) seeped. These "holes" formed almost randomly, probably by hydraulic fracturing as interstitial waters from compacting sediments beneath the anhydrite escaped upward, but minor faulting may have created more linear "holes" locally.

The D zone dolomite along the eastern edge of Richland County also formed by gravitational seepage, but the absence of a D zone anhydrite allowed for relatively laterally persistent dolomitization. Distribution of D zone dolomite was controlled mainly by paleo-topography of the basin floor; the brines filled in lows whereas dolomitization was minor or nonexistent over paleo-highs.

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#### Low- $^{18}\text{O}$ Authigenic Clays and Calcite in Shallow Cretaceous Sandstones of Alberta

$\delta^{18}\text{O}$  values of authigenic minerals in shallow (<1,500 m) Cretaceous rocks from Alberta suggest that ground water exerts an important control upon the diagenesis of sandstones. In Alberta, ground waters are significantly depleted in  $^{18}\text{O}$  relative to seawater.

Minerals precipitated in equilibrium with ground water should have  $\delta^{18}\text{O}$  values predictably lower than similar phases formed from more  $^{18}\text{O}$ -rich fluids. The  $\delta^{18}\text{O}$  values of 150 clay samples from the Milk River, Belly River, and Viking formations range from 6 to 20‰ (SMOW). An equally large variation in  $\delta^{18}\text{O}$  (+11 to +28‰, SMOW) and  $\delta^{13}\text{C}$  (-10 to +2‰, PDB) is shown by over 125 carbonate samples. Detrital clays from the Milk River have  $\delta^{18}\text{O}$  values of +16 to +20‰ (SMOW). The  $\delta^{18}\text{O}$  (+24 to +28‰, SMOW) and  $\delta^{13}\text{C}$  (-3 to +1‰, PDB) values of dolomite clasts are typical of platform carbonates. The much lower  $\delta^{18}\text{O}$  values of the authigenic kaolinite, smectite (+10 to +15‰, SMOW), and calcite (+15 to +19‰, SMOW) in the sandstone aquifer reflect neof ormation from low- $^{18}\text{O}$  ground waters at temperatures as low as 5°C. Involvement of organically derived  $\text{CO}_2$  during calcite formation is indicated by low  $\delta^{13}\text{C}$  values (-10 to -3‰, PDB). In sandstone of the Belly River Formation, early pore-lining chlorite and later pore-filling kaolinite and calcite have quite low average  $\delta^{18}\text{O}$  values of 6.3, 12.0, and 13.1‰ (SMOW) respectively. The kaolinite and calcite approach oxygen isotope equilibrium at a temperature of  $55 \pm 10^\circ\text{C}$  with ground waters of about -8 to -10‰ (SMOW). The chlorite is out of isotopic equilibrium and formed either at lower temperatures and/or from more  $^{18}\text{O}$ -rich fluids. The  $\delta^{18}\text{O}$  values of <2 $\mu\text{m}$  clays from the Viking Formation (18-20‰ SMOW) may reflect a detrital origin. Illite-smectite, however, which is concentrated in the <0.2 $\mu\text{m}$  fraction, has lower  $\delta^{18}\text{O}$  values (+12 to 16‰), perhaps suggesting ground-water involvement in its genesis.

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#### Channels and Chimeras: Coastal vs. Fluvial Deposition of Mannville Group, Lloydminster Area, Saskatchewan

Examination of nearly 4,000 m of core from more than 180 wells clearly demonstrates that fluvial processes were insignificant in deposition of the Mannville Group (Lloydminster member and above) in the Lloydminster area of Saskatchewan (R18W3-28W3, T44-54). Previous fluvial models are based primarily on the presence and geometry of channels interpreted from geophysical well logs. With rare exceptions, however, well spacing and core data are inadequate to prove a fluvial origin of such features, if they exist at all. A notable exception is an unequivocal channel deposit in the Waseca Formation in the Pikes Peak-Lashburn area. However, the nature of adjacent strata, the presence of numerous clay drapes within the deposit and its dimensions ( $\leq 40$  m thick, 1.6 to 2.7 km wide, but only 30 km long) are inconsistent with fluvial deposition in a terrestrial setting. The most compelling argument against a fluvial origin of the Mannville is the presence in every core studied of numerous sedimentary structures that are extremely difficult to reconcile with fluvial deposition and the paucity of possible fluvial structures or sequences of structures. The former include swash-zone cross lamination; oscillation ripples; and hummocky cross-stratification; and flaser, wavy, lenticular, and pin-stripe bedding. Cored intervals of strata which can be equivocally interpreted to represent fluvial or other channels (such as massive or ripple cross-laminated sands) are nearly everywhere less than 5 m thick. Even if such an interpretation is applied in every example, channel deposits are volumetrically insignificant. Finally, many undoubtedly marine or brackish assemblages of foraminifera and dinoflagellates have been recovered in the study area. Ubiquitous wave-generated sedimentary structures, essentially tabular geometries of sand bodies, and microfossils in the Mannville Group clearly demonstrate deposition in a coastal, rather than fluvial, setting.

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#### Subsurface-Derived Secondary Oomoldic Porosity, Smackover Formation (Upper Jurassic), South Texas

Subsurface-derived secondary oomoldic porosity is an important factor in reservoir development in the south Texas Smackover Formation. Much of the section penetrated is impermeable; however, reservoirs as thick as 33 ft (10 m), with porosity ranging from 4 to 26% and permeabilities ranging from 0.1 to 6.5 md, have been cored at depths below 18,000 ft (9,486 m).

In the grainstone facies, four general stages of diagenesis affected porosity: Stage 1 (marine-phreatic environment), precipitation of an isopachous carbonate cement and extensive grain micritization; Stage 2 (shallow-meteoric environment), precipitation of very coarse-crystalline syntaxial calcite and fine-crystalline equant calcite, dissolution of aragonitic skeletal grains, and incipient solution-compaction; Stage 3 (regional fluid-mixing environment), intrapore precipitation of and grain/matrix replacement by fine to medium-crystalline rhombic dolomite; and Stage 4 (subsurface environment associated with basinal fluid expulsion), dissolution of ooids and dolomite resulting from decarboxylation of kerogen, microstylolitization by solution compaction, and precipitation of coarse-crystalline calcite and baroque dolomite. The magnitude of each general diagenetic stage varies regionally.

Oomoldic porosity is present only in the updip, highly dolomitized grainstone facies. The dolomite formed a chemically rigid matrix that allowed the calcite ooids to be dissolved without solution compaction between grains. In the downdip, poorly dolomitized facies there was no chemically rigid framework, and dissolution proceeded by solution compaction resulting in loss of