

and most apparent, production trend, results from the Opeche Shale infilling of northwest-southeast-oriented stream valleys. Most production to date has been from sandstones following this alignment juxtaposed downdip of these impermeable shales.

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Origin and Significance of Surface Occurrences of Natural Gas, Northern Denver Basin, Colorado

Natural gas commonly occurs in ground water and has been venting to the surface from abandoned water wells in the northern part of the Denver basin near urban areas of LaSalle and Greeley. Because these gases pose an explosion and fire hazard, our studies are aimed at determining their origin and source in an effort to help prevent these dangers.

Two types of gases have been distinguished on the basis of chemical and isotopic composition. Some of the gases are chemically dry ($C_1/C_{1.5} > 0.99$) and enriched in the light isotope ^{12}C ($\delta^{13}C$ values range from -73 to -67 ppt). These gases are interpreted to be of biogenic origin; they are being, or have been, generated in an anoxic, sulfate-free environment by decomposition of organic matter within Upper Cretaceous Laramie-Fox Hills aquifer.

Other gases contain significant amounts of heavier hydrocarbons ($C_1/C_{1.5}$ values range from 0.76 to 0.88) and are isotopically heavier ($\delta^{13}C_1$ values range from -49 to -44 ppt). The chemical and isotopic compositions of these gases suggest that they are of thermogenic origin and were generated during intermediate stages of thermal maturity in the deeper part of the Denver basin. In addition, these thermogenic gases are almost identical in both chemical and isotopic composition to those produced from the underlying Cretaceous "J" sandstone and Codell Sandstone Member of the Carlile Shale at depths ranging from about 2,100 to 2,300 m (6,888 to 7,544 ft). The surface gases of thermogenic origin have probably migrated from these deeper reservoirs, and this migration may be related to recent drilling activity in the area.

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Evidence for Extension of Lake Basin Fault Zone from Coal Bed Correlations in South-Central Montana and Implications for Hydrocarbon Exploration

The Lake Basin fault zone is a structural lineament that extends west-northwest across central Montana. The lineament consists mainly of an echelon northeast-striking normal faults that are surface expressions of left-lateral movement along a basement wrench fault. Information gathered from the recent field mapping of coal beds and from shallow, closely spaced drill holes in the northwest part of the Powder River basin, Montana, permit detailed coal bed correlations, which revealed another linear zone of an echelon faulting directly on the extended trend of the Lake Basin fault zone. The faulted area, herein named the Sarpy Creek area, is located 48 km (30 mi) east of Hardin, Montana. It is about 13 km (8 mi) long and 10 km (6 mi) wide and contains 20 en echelon normal faults that have an average strike of $N65^\circ E$. The Lake Basin fault zone is therefore extended 32 km (20 mi) farther southeast than previously mapped to include the Sarpy Creek area.

The Lake Basin oil field, Montana, and the Ash Creek oil field, Montana and Wyoming, produce from faulted anticlinal structures that have been interpreted to be genetically related to primary wrench-fault systems—the Lake Basin fault zone and Nye-Bowler fault zone, respectively. Therefore, the faulted area of Sarpy Creek (as yet unexplored), and areas southeastward from there along the trend of the Lake Basin fault zone are possible sites for hydrocarbon accumulation.

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High-Resolution Stratigraphic Correlations and Geochemical Analyses, Cretaceous Niobrara Formation, Northwestern Denver-Julesburg Basin

The middle Santonian-lower Campanian part of the Smoky Hill Member of the Niobrara Formation represents a fourth-order regressive-transgressive cyclothem. Studies of this interval have improved our understanding of the influence of depositional environments and struc-

tural setting on distributions of organic matter in epicontinental marine strata. Geochemical analyses of fresh quarried sections at Lyons and LaPorte, Colorado, show that, in general, C_{org} (organic carbon) levels are highest between mid-regression and mid-transgression. Rhythmic fluctuations of C_{carb} (carbonate carbon) and C_{org} correspond to limestone-marlstone bedding couplets at a scale of 15-20 cm (6-8 in.). Pronounced lateral variations between Lyons and LaPorte exist in C_{org} , HI (pyrolytic hydrogen index), sediment accumulation rates, and T_{max} (temperature of maximum pyrolytic yield). Comparisons of geochemical averages at Lyons ($C_{org} = 2.5\%$, $C_{carb} = 9\%$, HI = 100, $T_{max} = 445^\circ C$) and LaPorte ($C_{org} = 4\%$, $C_{carb} = 9.5\%$, HI = 450, $T_{max} = 422^\circ C$) indicate an elevated thermal maturity at Lyons and depositional conditions more favorable for preservation of marine organic matter at LaPorte. In both sections, C_{org} and C_{carb} show strong negative correlations, possibly reflecting cyclic climatic controls on the development of bedding couplets. High-resolution stratigraphic correlations of 100,000-year or smaller intervals between Boulder and Owl Canyon, Colorado, based on widespread bentonites and bedding couplets, reveal a paleostructural high near Lyons. Shallow-water conditions and increased turbulence over this high are reflected in sediment accumulation rates only 60% of those at LaPorte. Increased amounts and hydrogen richness of organic matter at LaPorte may reflect a deeper water, more quiescent depositional setting.

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Structural Development and Oil Occurrence on Northeast Flank of Uinta Mountains near Irish Canyon, Northwestern Colorado

The study area is located along Vermillion Creek, 1-3 mi (1.6-5 km) east of Irish Canyon, in northwestern Colorado. The exposed stratigraphic section consists of steeply dipping to vertical Upper Cretaceous Almond Formation, Ericson Sandstone, and Mancos Shale along the toe of the Sparks Ranch thrust fault, and of lesser dipping older Mesozoic and Paleozoic formations in distant parts of the thrust plate. In most places, the Almond Formation is in contact across the thrust fault with the Eocene Wasatch and Green River Formations, and all of these formations are unconformably overlain by the Oligocene Bishop Conglomerate and the Miocene Browns Park Formation. The structural development of the area has involved three major events: (1) Late Cretaceous uplift of the Uinta Mountains; (2) Paleocene and Eocene thrust movements of the Sparks Ranch fault; and (3) late Tertiary normal faulting associated with a collapse of the eastern Uinta Mountains. Oil-saturated sandstones are present in outcrops of 10 Paleozoic, Mesozoic, and Tertiary formations adjacent to several of the late Tertiary normal faults. Oil is escaping to the surface along these faults, probably from a large, deep-seated reservoir located below the Sparks Ranch thrust fault.

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Solution of Devonian Prairie Formation Salts: Implication, Seismic Recognition, and Interpretation

Evaporite deposits of the Devonian Prairie Formation in the Williston basin have undergone episodic dissolution, creating many types of hydrocarbon traps. Removal of the salt has resulted in collapse breccias, drape structures, local thickening of potential reservoir rock by sink infill, and enhanced migration paths. Recognition of the presence and absence of the salt section assists an interpreter in avoiding the pitfall, of salt-related velocity phenomena. Keys to recognizing salt solution on seismic data include abrupt terminations of salt reflectors, rootless structures, and isochron thickening and thinning. Comparisons of sets of isochron maps, to identify areas of superimposed thicks and thins, help determine the timing of solution.

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Paleozoic Paleotectonics and Sedimentation in Southern Rocky Mountain Region

During the Paleozoic, the southern Rocky Mountain region included most of New Mexico and Arizona and at least the northern parts of adjacent Chihuahua and Sonora. It was particularly stable part of the North American craton during the Cambrian through Middle Devonian. Slow

deposition of shelf clastics and dolomitic carbonates was interrupted by several long erosional hiatuses. Major recognizable tectonism first appeared in the Devonian with at least one depositional basin formed west of the Defiance-Zuni uplift. Thin Early Mississippian shelf carbonates and evaporites covered nearly the entire region.

The most significant tectonic activities started in the late Chesterian and extended with increasing magnitude until the end of Wolfcampian time. Local basins and uplifts date from this interval and occurred in two belts. One belt was about 80 mi (130 km) wide along the western sides of the Hueco and Pederal uplifts and along both sides of the Uncompahgre uplift. Another belt extended northwest from the Pedregosa basin into southeastern Arizona. Major tectonic events initiated the Morrowan, Atokan, and Missourian Epochs and occurred twice within the Wolfcampian Epoch. Leonardian, Guadalupian, and Ochoan Epochs were times of tectonic stability. During the Leonardian, sediments from the Uncompahgre uplift gradually covered all the other uplifts.

The timing of these Paleozoic tectonic events suggests a cause-effect relationship with plate-tectonic histories that brought North American and northern Europe together in the Late Devonian (Acadian orogeny) and Euramerica and northwestern Gondwana together in the Late Mississippian through Early Permian (Appalachian orogeny).

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Lemhi Arch, a Late Proterozoic and Early Paleozoic Landmass, Central Idaho

The northwest-trending Lemhi arch of central Idaho first formed in late middle Proterozoic time, and as much as 4,500 m (14,760 ft) of middle Proterozoic clastic rocks were eroded in later Proterozoic time. The west flank of the arch was partly covered in late Proterozoic(?) and Early Cambrian time by the Wilbert Formation. On the east flank, westward-thinning marine sedimentation began with deposition of the Middle Cambrian Flathead Formation, and continued through the Late Cambrian. During Ordovician and Silurian times, the east flank of the arch was dry. The west flank was submerged in the Ordovician, and the Summerhouse Formation, Kinnikinnic Quartzite, and Saturday Mountain Formation were deposited. The west flank of the arch was briefly exposed after deposition of the Saturday Mountain Formation, but was partly submerged later in the Silurian, when the Laketown Dolomite was deposited. During the Middle and Late Devonian, deposition was renewed on the west flank of the arch, where the Jefferson Formation indicates eastward transgression. The east flank was exposed until the Late Devonian, when a thin sequence of the Jefferson and Three Forks Formations was deposited across the top of the arch, and marine sedimentation was continuous from the miogeocline far onto the craton.

The Lemhi arch continued to influence marine deposition even after it was submerged, separating shelf deposits in southwest Montana and east-central Idaho from miogeoclinal deposits in central Idaho. The arch was overridden by the Medicine Lodge thrust in late Early and Late Cretaceous times.

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Stratigraphy and Depositional History of Coyote Creek–Miller Creek Trend, Lower Cretaceous Fall River Formation, Powder River Basin, Wyoming

The Coyote Creek–Miller Creek trend produces high-gravity, low-sulfur oil from a series of Fall River fields in an area generally characterized by west-southwestward monoclinal dip. The trend includes, from south to north, the Coyote Creek South, Coyote Creek, Donkey Creek, Kummerfeld, and Miller Creek fields. The Wood and West Moorcroft fields produce oil from very similar Fall River traps located several miles east and northeast, respectively, of Miller Creek. Only Donkey Creek includes structural closure; all of the other fields produce from purely stratigraphic traps. The reservoir sandstones are characterized by upward-fining sequences. These sequences locally replace and are generally easily distinguishable from two regionally correlative upward-coarsening sequences. Analyses of cores and nearby outcrops indicate that the upward-fining sequences accumulated on point bars of a meandering river; the upward-coarsening sequences were deposited on the

fronts of northwestward-prograding deltas. Detailed mapping of the fluvial and delta-front facies demonstrates that the Coyote Creek–Miller Creek trend, together with the Wood and West Moorcroft fields, represents a meander-belt system that was contemporaneous with the younger of the two delta-front units. Each of the stratigraphic-type fields occurs at a convexity along the eastern edge of the irregularly shaped meander belt; each consists of numerous point bars. Clay plugs, which resulted from infilling of abandoned meander loops, were preferentially preserved along the margins of the meander belt, where they now serve as updip permeability barriers between the oil-bearing fluvial and water-wet delta-front sandstones.

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Stratigraphy, Depositional History, and Petroleum Geology of Lower Cretaceous Fall River Formation, Powder River Basin, Wyoming

The middle Albian Fall River Formation, better known to petroleum geologists as the "Dakota Sandstone," constitutes a northwestward-thinning wedge of predominantly sandy strata under and overlain by marine shale. Two major episodes of deltaic progradation can be recognized in the formation, permitting mapping of lower and upper deltaic members. Study of outcrops, cores, and subsurface relationships indicates that the Fall River consists predominantly of fluvial strata in the southeastern part of the Powder River basin; delta-front and delta-plain facies, which are cut out and replaced locally by northwest-trending meander belts, predominate in an area that trends northeastward across the central part of the basin; the delta-front facies pinches out into offshore marine shale in the northwestern part of the basin. The large majority of Fall River stratigraphic trap-type fields produce oil and gas from sandy meander-belt deposits. The largest accumulations of hydrocarbons in traps of this type, as exemplified by the Powell-Mexican Springs trend (lower member) and the Coyote Creek–Miller Creek trend (upper member), occur in the more seaward parts of the deltaic members, near the seaward termini of meander-belt systems. Mapping of meander belts and of the surrounding deltaic deposits constitutes a necessary first step in exploration for stratigraphic traps within the Fall River Formation.

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Upper Cretaceous Vernal Delta of Utah—Depositional or Paleotectonic Feature?

A conspicuous seaward bulge of the middle to late Turonian shoreline of the Cretaceous seaway in northeastern Utah and southwestern Wyoming has been identified by previous authors as the Vernal delta. Strata of the Frontier Formation and the Ferron Sandstone Member of the Mancos Shale that form the Vernal delta consist largely of fluviodeltaic facies. The delta, however, is not recognizable as a locus of Turonian sedimentation; there is no isopach thick associated with it.

The Vernal delta is a large feature, encompassing an area of at least 6,250 mi² (16,187 km²). A comparison between the depositional setting and paleogeography of northeastern Utah during the Late Cretaceous and a present-day area on the east flank of the Andes in Colombia indicates strong similarities. Further comparison suggests that a feature the size of the Vernal delta could not have been produced by a single river.

The Vernal delta overlies the ancestral Uinta Mountain uplift, an area where Cenomanian marine shales were entirely removed by what appears to have been submarine erosion during early Turonian time. When the shoreline prograded eastward across this area during middle Turonian time, the sediment load caused the area to subside, but at a rate slower than rates of subsidence to the north and south. This differential subsidence is the cause of the shoreline bulge. Although it includes deltaic facies, the Vernal delta is not a delta per se, but a feature produced as the result of interaction between sedimentation and gentle tectonic movement of the ancestral Uinta Mountain uplift.

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Models for Hydrocarbon Accumulation and Maturation in Deep Dysaerobic Basins