

the ideal situation in which enhanced porosity is created immediately before migration. Later in the burial history, after thermal decarboxylation of organic fluids produces CO<sub>2</sub>, a second opportunity exists to create enhanced porosity. Using these diagenetic concepts, it may be possible to predict enhanced reservoir porosity within tripolitic chert.

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Lithofacies and Diagenetic Controls on Reservoir Development and Production, Goose Lake Field, Eastern Montana

Goose Lake field is located on a north-northwest-oriented structural nose on the western side of the Williston basin and produces from carbonate island facies in the Mississippian Ratcliffe zone. Island facies are concentrated on the structural nose and include low-energy, fenestral, pisolite-algal lime boundstones (supratidal) and high-energy, evenly laminated, pellet-oolite lime grainstones (beach and storm deposits). These beach grainstones occur preferentially along a narrow zone on the western side of the field, suggesting that major wave and wind approach was from the west.

Development of distinct porosity systems within these rocks and in encasing offshore facies accounts for variations in permeability, oil and water production ratios, and overall cumulative production. Both reservoir facies contain porosity as high as 20%, whereas permeability is highly variable. In wells with high cumulative production (i.e., above 200,000 bbl), permeability is normally 10-20 md. Grainstones are typified by primary intergranular, oomoldic, and microvuggy porosity, whereas algal boundstones have micro-intercrystalline, fenestral, and microvuggy to mesovuggy porosity. Porosity occlusion in these facies is due to a variety of early calcite cements, late-stage anhydrite, and baroque dolomite. The encasing offshore marine facies may contain high micro-intercrystalline porosity but lack effective permeability and serve as the updip seal. Porosity in these fine-grained facies and supratidal units is probably due to an early freshwater leaching episode that affected islands situated on paleohighs during rising sea level and less arid climatic conditions.

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Hydrocarbon Potential in Paradox Basin: an Overview

The petroleum-rich Paradox basin of southeastern Utah and southwestern Colorado remains an exploration frontier. With current production and exploration programs focusing on "algal mound" limestones in the Pennsylvanian Paradox Formation and deeper Mississippian structures, numerous other zones with hydrocarbon potential exist. Floored by a complexly faulted Precambrian basement, there is ample evidence suggesting that both source beds and reservoir rocks comprise much of the Cambrian section underlying the region. Although successfully developed at Lisbon field, Devonian sandstones and Mississippian carbonates have only been peripherally explored in other parts of the basin and much remains to be learned about deeper evaporite sequences in the Paradox Formation where turbidite deposits are known or inferred to exist between source bed shales and dolomites. Migration reservoirs exist in the Laramide structures that rim and occupy parts of the basin. Permian tar sand deposits estimated to hold 4-8 billion bbl of oil in place remain to be developed where an exhumed stratigraphic trap in the White Rim Sandstone is exposed west of the confluence of the Colorado and Green Rivers. Additionally, carbon dioxide gas deposits associated with Tertiary intrusives in the region require further delineation and development for coal slurry and enhanced oil recovery projects. Accordingly, the basin is expected to continue being developed for its resources for several decades.

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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, south-central Montana, is represented by the Sauk sequence, a transgressive-regressive package of fine-grained clastic sand carbonates. In ascending order, the sequence

consists of the Flathead Sandstone, Wolsey Shale, Meagher Limestone, Park Shale, Pilgrim Limestone, and Snowy Range Formation.

Regionally, the Park is a green, micaceous shale with interbedded siltstone at the base and intercalated limestone at the top. However, in the northern Bridger Range, the lower 30 m (98 ft) is a prominent interval of interbedded arkosic sandstone and shale. A quartz- and/or orthoclase-rich facies and a biomicritic, arkosic, glauconite-rich facies comprise this interval. Individual sandstone beds, 5-17 cm (2-7 in.) thick, are characterized by sharp contacts, scoured surfaces, load structures, and weakly developed cross-stratification. Gneissic, quartzofeldspathic pebbles and biomicritic cobbles occur in sharp contrast to adjacent shales. The arkosic sandstones were deposited in a nearshore island environment adjacent to an areally restricted source of clastic detritus. Variations in environmental energy regime and tectonic stability resulted in the two facies.

The abundance of basement-generated grains in the basal Park Shale, their absence in the upper Wolsey Shale and Meagher Limestone, and the localized occurrence of arkose indicate late Middle Cambrian tectonism and exposure of Precambrian crystalline basement. Subsequent weathering resulted in an easily erodible source of coarse-grained clastics.

Due to its unique mineralogy and stratigraphic setting, the Park arkosic interval may provide a key stratigraphic marker for refining estimates of displacement along Laramide structures within the study area.

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Radiometrics for the Petroleum Explorationist

Ground radiometrics provide the petroleum explorationist with an economical means of gathering large volumes of data in a short time. Profiles generated by a radiometric survey delineate prospective acreage and permit judicious use of the exploration dollar. Observations and techniques presented in this paper represent the acquisition and interpretation of over 100,000 mi (160,000 km) of radiometric data.

Radiometric and geochemical anomalies reflect surface and near-surface alteration by vertically migrating hydrocarbons. The observed decrease in natural radiation background over a petroleum reservoir is the result of several interactive factors: (1) the adsorptive capacity of hydrocarbons for radioactive particles, (2) the decrease of surface and near-surface porosity and permeability due to secondary mineralization, and (3) the increase of relatively low-radiation, secondary carbonates in the soil. High radiometric anomalies can be associated with faults, fracture systems, unconformable surfaces, or radioactive deposits that terminate in the near-surface.

Radiometric survey design and acquisition require a thorough knowledge of instrumentation, calibration, window aperture, integration time, background level, temperature drift, survey accessibility and positioning, and targeted anomaly size and shape. The advent of data processing and the need for repeatable data necessitate proper annotation of surface changes and development of production analogs. Processing permits quantitative analysis and enhancement of radiometric data. Normalization and Rad-Stack processes correct profiles to an average-background level and enhance the signal-to-noise ratio by attenuating random events (e.g., cosmic radiation). The science of radiometrics is applicable in a fully integrated exploration program.

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Geologic Development, Origin, and Energy Mineral Resources of Williston Basin, North Dakota

The Williston basin is a major producer of oil and gas, lignite, and potash. Located on the western periphery of the Phanerozoic North American craton, the Williston basin has undergone only relatively mild tectonic distortion during Phanerozoic time. This distortion is largely related to movement of Precambrian basement blocks.

Sedimentary rocks of cratonic sequences Sauk through Tejas are present in the basin. Sauk, Tippecanoe, and Kaskaskia sequence rocks are largely carbonate, as are the major oil- and gas-producing forma-

tions. Absaroka and Zuni rocks have more clastic content, but carbonates are locally important. Clastics of the Zuni sequence contain abundant lignite. Tejas sequence rocks are not significant in the production of minerals or energy, although glacial sediments cover much of the region.

Depositional environments throughout Sauk, Tippecanoe, and Kaskaskia deposition were largely shallow marine. Clastic sediments were transported into the southern part of the basin during Absaroka sequence deposition, a product of erosion of Ancestral Rocky Mountain orogenic structures. Continental and shallow-marine clastic sediments were deposited during Zuni sedimentation until Cretaceous deeper marine environments were established. Laramide orogenesis to the west provided detritus that was deposited in fluvial, deltaic, and marginal-marine environments, regressing to the east.

Major structures in the basin, and the basin itself, may result from left-lateral shear along the Colorado-Wyoming and Fromberg zones during pre-Phanerozoic time. Most structures probably resulted from renewed movement or "tensing" of pre-Phanerozoic faults.

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#### Heat Flow in Geophysical Exploration of Sedimentary Basins

In continental heat-flow studies, sedimentary basins are usually avoided because of difficulties in obtaining thermal conductivity measurements and because temperature gradients may contain advective signals caused by moving ground water. These problems are superimposed in the Denver and Williston basins where complex geothermal gradients derive both from large contrasts among thermal conductivities of strata and from regional ground-water flow. Detailed heat-flow studies may solve these problems and provide data relevant to basin hydrology: the occurrence and nature of geothermal resources, oil source rock maturation and secondary migration of petroleum, and formation and deposition of strata-bound ores.

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#### Diagenetic Destruction of Primary Reservoir Porosity in Viola Limestone, South-Central Oklahoma

The Viola Limestone in south-central Oklahoma is a Middle and Upper Ordovician carbonate unit interpreted as being deposited on a carbonate ramp within and peripheral to the southern Oklahoma aulacogen. Depositional environments within the study area ranged from anaerobic deep ramp through aerobic middle and shallow-ramp environments. Total organic carbon analyses of the lower anaerobic deep-ramp facies suggest that, at least locally, the Viola is a potential hydrocarbon source rock. Detailed petrographic examination of the Viola indicates that primary porosity in the shallow-ramp skeletal packstones and grainstones was initially quite high. This combination of source potential and original porosity should make the Viola an attractive target for hydrocarbons in southern Oklahoma. The Viola, however, has been subjected to a complex sequence of diagenetic events that have extensively altered the sediments and occluded much of the primary porosity. A thorough understanding of the timing and nature of these events can be critical in evaluating the economic potential of the Viola.

Petrographic evidence combined with the use of cathodoluminescence indicates that several generations of calcite cementation occurred within the shallow-ramp packstones and grainstones. An initial phase of very early, possible syndepositional marine cementation is evidenced by cloudy, inclusion-rich syntaxial cements on echinoderm fragments. This early phase of cementation was followed by several generations of clear syntaxial calcite, prismatic calcite, blocky mosaic calcite, and bladed mosaic calcite, all of which indicate changes in the pore-water chemistry from the inclusion-rich cements. This phase of meteoric phreatic cementation occurred soon after the marine cementation and occluded virtually all remaining primary reservoir porosity.

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#### Oil-Bearing Sediments Beneath San Juan Volcanics—Colorado's Newest Frontier

During the Tertiary, the western part of the northern Sangre de Cristo Range dropped 16,000 ft (4,877 m) to become what is now known as the San Luis basin. The foreland basin formerly adjacent to and west of the range remained intact but was subsequently concealed by 10,000 ft (3,048 m) of volcanic deposits. The existence of this concealed basin, a north-eastern arm of the San Juan basin, was first suggested by Vincent Kelly who named it the San Juan sag.

Oil, which was generated in the underlying Mancos Shale, migrated upward into vesicles and fractures in volcanic rocks. In at least two places, oil is currently seeping onto the volcanic surface or into overlying soil. These oil occurrences encouraged geologic and geophysical exploration and have led to confirmation by drilling that the basin exists.

Porous reservoirs in both Tertiary sedimentary rocks and volcanic rocks overlie a 2,000 ft (610 m) Cretaceous Mancos Shale source rock. Within the Mancos Shale are fractured reservoirs, volcanic sills that have reservoir potential where fractured or porous, and stray sandstones. The Dakota Formation underlies the Mancos Shale and is about 200 ft (61 m) thick in this area. In addition, the Jurassic section has potential for source rocks in the Todilto Formation and reservoir rocks in the Entrada and Junction Creek Sandstones.

The San Juan sag, a newly discovered basin of 2,600 mi<sup>2</sup> (6,734 km<sup>2</sup>) is a frontier for Colorado oil and gas exploration.

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#### Seismic Exploration in Rocky Mountain Region

Structurally and stratigraphically, modern exploration in the Rocky Mountain region depends increasingly on seismic delineation of prospective targets. In many areas an integration of geology and geophysics is required for a viable prospect today.

Structurally, the unique Rocky Mountain foreland deformation would have remained an enigma without modern seismic efforts and its pursuit drilling. This recent work resulted in several dramatic discoveries beneath thrust Precambrian rocks. Continual drilling success in the Overthrust belt (where structure is largely masked by Tertiary sediments) has been the result of integrating new subsurface data with improved seismic work. Basin and range deformation, in many places superimposed on the complexities of low-angle thrusts or hidden by volcanic cover is severely testing seismic acquisition technology and interpretation skills. The challenge to acquire good seismic data from beneath thick volcanic fields has been successful in Colorado and Wyoming.

Angular unconformities are often clearly visible on seismic sections where they were difficult or impossible to recognize because of the absence of paleontologic data or because the strata above and below the erosional surface are too similar. Detection of angular discordance not only sets up the potential for locating truncation or pinch-out traps, but also enlarges our understanding of the tectonics and timing of Rocky Mountain deformation. Pennsylvanian deformation was as consequential in the Rocky Mountains as Laramide deformation, but is commonly masked by undisturbed Mesozoic rocks. Detection of these faults and folds has been greatly enhanced by seismic data, as well as deep-seated basement faults whose recurrent movement has controlled overlying stratigraphy.

Stratigraphic exploration in Rocky Mountain basins has challenged both geologists and geophysicists and they have joined in an increasingly sophisticated search for traps in sand dunes, fluvial channels, incised valley, delta fans, salt-solution structures, carbonate banks and reefs, karst topography, and sometimes in poorly understood, but equally prolific, simple porosity and/or permeability barriers.

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#### Exploration Tectonics and Vitrinite Reflectance, South Park Basin, Colorado

The southernmost of three intermontane basins was reevaluated in the late 1970s by Amoco. Geophysical data indicated a deeper and more structurally complex basin than expected. Reinecker Ridge is a large anticlinal structure in the center of the basin, which was unsuccessfully drilled in 1978. The well deviated away from the structure and the Dakota Sandstone objective. Vitrinite reflectance data indicate the structure is unlikely to be oil productive because it was formed after oil generation; therefore this portion of the basin has low exploration potential.