reflect control by lineaments trending north-south, northwest, and northeast. In central South Dakota, erosion and deposition of chalk and calcareous shale on a west-sloping carbonate ramp were controlled by lineaments that generally trend northeast and northwest.

Paleotectonism on lineament-bound blocks characterized four tectonic zones located in the Late Cretaceous seaway: the western foredeep, the west-median trough, the east-median hinge, and the eastern platform. The regional geometry of all four tectonic zones appears to be related to the geometry of the convergent plate margin on the west. Paleotectonic activity on lineament-bound blocks may have been the result of horizontal forces related to the convergent margin and to vertical forces related to the movement of the North American plate.

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Geologic Setting and Natural Gas Potential of Niobrara Formation, Williston Basin

Chalk units in the Niobrara Formation (Upper Cretaceous) have potential for generation and accumulation of shallow, biogenic gas in the central and eastern Williston basin. Similar to areas of Niobrara gas production in the eastern Denver basin, Niobrara chalks in South and North Dakota were deposited on carbonate ramps sloping westward off the stable eastern platform of the Western Interior seaway. Within the Williston basin, the Niobrara of the western Dakotas, eastern North Dakota, and central South Dakota has different stratigraphic relationships. These three areas can be further subdivided and ranked into six areas that have different exploration potential. The south margin of the Williston basin in central South Dakota is the most attractive exploration area.

Niobrara chalk reservoirs, source rocks, and structural traps in the southern Williston basin are similar to those in the eastern Denver basin. Chalk porosities are probably adequate for gas production, although porosity is controlled by burial depth. Organic carbon content of the chalk is high and shows of biogenic gas are reported. Large, low-relief structural features, which could serve as traps, are present.

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Stratigraphy and Petroleum Potential of Trout Creek and Twentymile Sandstones (Upper Cretaceous), Sand Wash Basin, Colorado

The Trout Creek and Twentymile Sandstones (Mesaverde Group) in Moffat and Routt Counties, Colorado, are thick, upward-coarsening sequences that were deposited along the western margin of the Western Interior basin during Campanian time. These units trend northeast-southwest and undergo a facies change to coal-bearing strata on the northwest. Surface data collected along the southeastern rim of the Sand Wash basin were combined with well-log data from approximately 100 drill holes that have penetrated the Trout Creek or Twentymile in the subsurface. The sandstones exhibit distinctive vertical profiles with regard to grain size, sedimentary structures, and biogenic structures. A depositional model that incorporates the key elements of the modern Nile River (northeast Africa) and Nayarit (west-central Mexico) coastal systems is proposed for the Trout Creek and Twentymile Sandstones and associated strata. The model depicts a wave-dominated deltaic, strand-plain, and barrier-island system. Depositional cycles are asymmetrical in cross section as they are largely progradational and lack significant transgressive deposits. Source rock–reservoir rock relationships are ideal as marine shales underlie, and coal-bearing strata overlie sheetlike reservoir sandstones. Humic coal, the dominant source of Mesaverde gas, generates major quantities of methane upon reaching thermal maturity. Existing Mesaverde gas fields are largely structural traps, but stratigraphic and combination traps may prove to be equally important. The sparsely drilled deeper part of the basin warrants testing as large, overpressured-gas accumulations in tight-sandstone reservoirs are likely to be found.

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Williston in the Family of Cratonic Basins

The Williston basin is one of a clan of subcircular to elliptical elements in the interiors of all cratons; such basins are distinguished by characteristics common to all. In each, the basement consists of continental crust and each basin is surrounded by areas of continental crust. Subsidence rates are typically low, so that conditions near depositional base level prevailed during much of the history of sediment accumulation. Episodic subsidence occurred over time spans of 10^7-10^8 years; major episodes of subsidence are broadly concurrent on all cratons. Tectonic tempo and mode of subsidence evolved synchronously on all cratons; therefore, similar isopach and facies patterns (and similar oil or gas maturation, migration, and trap potentials) occur on all cratons.

All members of the clan exhibit a range of individual variations imposed by latitude and climate. Intraplate tectonism and volcanism, approach to or distance from source areas, and distribution paths of detrital sediment. Nevertheless, facts and concepts developed by intensive study of basins with high-density documentation (outcrop and subsurface) are commonly applicable to basins such as the Williston, which is in a less mature stage of exploration.

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Hummingbird Structure in Southeastern Saskatchewan

Saskatchewan's first Devonian oil pool was discovered September 1966, at Hummingbird, 45 mi (72 km) southwest of Weyburn, Saskatchewan. The Hummingbird structure, located on the northwest flank of the Williston basin, is domal in nature and covers approximately 1 mi^2 (2.6 km^2). Oil production is from two zones. The Ratcliffe Member of the Mississippian Charles Formation produces from an algal and bioclastic limestone averaging 49 ft (15 m) thick. The Devonian Birdbear Formation produces from a finely crystalline vuggy dolomite averaging 56 ft (17 m) thick.

The Hummingbird structure is a sedimentary structure resulting from multiple-stage salt solution and collapse. Recurring local solution of Middle Devonian Prairie Evaporite during Late Devonian and Early Mississippian time resulted in collapse of overlying strata and deposition of compensating thicknesses of Souris River, Duperow, and Bakken sediments. Between Mississippian and Cretaceous time, solution of Prairie Evaporite in the surrounding area caused collapse of all super-Prairie Evaporite beds. The extra Souris River, Duperow, and Bakken strata at Hummingbird created the structure. Vertical migration of formation waters along a high-angle fault is suggested as the cause of the local salt solution at Hummingbird.

SONNENBERG, S.A., Bass Enterprises, Denver, CO

Tectonic and Sedimentation Model for Morrow Sandstone Deposition, Sorrento Field Area, Denver Basin, Colorado

Pennsylvanian Morrow sandstones are oil and gas productive through a large area in southeastern Colorado. The Sorrento field is a recent Morrow discovery with reserves estimated at over 10 million bbl of oil over an area of 3,200 ac at depths of 5,400-5,600 ft (1,646-1,707 m). Minor production also occurs from the Mississippian Spergen and Saint Louis and the Pennsylvanian Marmaton.

Productive Morrow sandstones are interpreted on the basis of subsurface mapping to be fluvial valley-fill deposits, consisting mainly of channel sandstone. These deposits are encased in marine shale and range in thickness from 5 to 55 ft (1.5 to 16.7 m). Net pay ranges from 5 to 30 ft (1.5 to 9.1 m). Porosities average 19% and permeabilities range from 1 to 4,000 md.

STEVENSON, G. M.,* Consultant, Denver, CO, and D. L. BAARS,* Consultant, Evergreen, CO

Paradox—Pull-Apart Basin of Pennsylvanian Age

The Paradox basin (Colorado Plateau province) is an intracratonic depression developed on continental crust. The elongate northwest-trending rhombic-shaped basin of Middle Pennsylvanian age is bounded on the northeast by the Uncompahgre-San Luis segments of the Ancestral Rocky Mountains and on the southwest by the less prominent Four Corners lineament. The basin sagged along intersecting basement fractures by strong east-west extension during Middle Pennsylvanian time. The master fracture system was the northwest-trending Olympic-Wichita structural lane.

Oblique divergent strike-slip faulting along the Uncompahgre-San Luis segment created a tension-releasing bend where the Paradox pull-apart basin nucleated and subsequently developed throughout Middle Pennsylvanian time. Smaller subbasins developed by orthogonal spreading along intersecting northeast-trending transform faults, where the rate of basin-floor subsidence was related to combinations of normal and strike-slip faulting. The greater Paradox basin was episodically deepened during Middle Pennsylvanian time by rejuvenated extensional basement faulting. Vertical displacement was greatest along the Uncompahgre front, which caused tilting of the basin and deposition of an asymmetrically thick sedimentary sequence.

By mid-Desmoinesian time, the rate of divergent strike-slip faulting slowed considerably. Folds caused by minor wrench movements provided shoaling conditions along the southwest shallow carbonate shelf where porous algal mounds developed. Meanwhile, continued tectonic movement and space-reduction of the basin floor may have triggered salt flowage and diapirism in the deep eastern pull-apart trough. As wrench tectonism diminished from late Desmoinesian through Early Permian time, the eastern portion of the basin continued to subside and was filled with marine and continental sediments.

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Geologic Interpretation of a Seismic Profile Across Oregon Basin Thrust, West Flank of Big Horn Basin, Wyoming

A seismic profile across the central western rim of the Big Horn basin, Wyoming, provides evidence of major flank thrusting beneath the Oregon Basin anticline. Vertical separation at the Precambrian basement level on this westerly dipping thrust zone is at least 6 km (20,500 ft), as verified by a deep footwall test of a spurious subthrust structural closure. The displacement on the Oregon Basin thrust is the same order of magnitude as that measured on the Casper Arch thrust and about half of that on the Wind River thrust. Actual fault plane dip cannot be accurately determined on the seismic profile because of poor seismic returns from the subthrust block, but based on data from other seismic line crossings of the thrust it appears that the fault plane dips west at about 45°. Under this assumption the amount of overhang at the Precambrian-sediment contact is at least 3 mi (4.8 km), and could be as much as 5 mi (8.0 km) if the fault plane is listric. Forward seismic modeling has helped in the selection of the most likely fault-plane solution and in understanding the attenuation of footwall seismic data.

The seismic profile traverses three major thrust-fold trends in the hanging-wall block (all with westerly asymmetry), each of which contains an important oil accumulation. From east to west, these are: Oregon Basin, Horse Center, and Half Moon.

In the footwall block of the thrust, Mesozoic and Paleozoic rocks beneath the Tertiary unconformity dip uniformly west at low angles, and this regional homoclinal dip continues for about 30 mi (48 km) across the Big Horn basin to the first line of thrust-folding (e.g., Garland trend) on the eastern basin flank.

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Pre-Laramide Tectonics—Possible Control on Locus of Turonian-Coniacian Paralic Coal Basins, West-Central New Mexico

Published evidence indicates that Late Cretaceous shorelines trended northwest through west-central New Mexico and adjacent Arizona. Our investigations delineate these shorelines through time and relate them to the prominent northwest-trending monoclinal flexures in the Zuni and southwestern San Juan basins. We related the transgressive (T)-regressive (R) marine cycles (T2-R2, T3-R3, T4-R4) of C. M. Molenaar to deep-rooted monoclinal or asymmetric anticlinal structures. The T2-R2 turnaround is coincident with the Pinon Springs anticline in the northern part of the Zuni basin and appears to be controlled by the Atarque and Gallestina monoclines in the southern part of this basin. Shoreline configurations during the T3 and T4 transgressive maximums coincide with the axis of the Nutria monocline and relate to some subtle pre-Laramide movements along this structure. The R2 regression is unique to New Mexico, suggesting local tectonic control on the configuration of the seaway. The subsequent T3 transgression, which was a major widespread event elsewhere in the Western Interior, was abbreviated in west-central New Mexico near the location of the Nutria monocline.

The T2-R2 through T4-R4 shoreline turnarounds produced numerous paralic basins favorable for the accumulation of organic detritus. A turnaround probably represents a period of slow rates of shoreline migration which allowed a thicker, more extensive accumulation of plant material and hence thicker coals. The present and most of the past coal production in the Zuni and southwestern San Juan basins is from coals formed in paralic basins just landward of the turnarounds caused by pre-Laramide tectonics.

SUMMERS, W. K., W. K. Summers and Assoc., Inc., Socorro, NM

Continental-Scale Ground-Water Flow Systems and Occurrence of Oil and Gas

Physical processes in continental-scale ground-water flow systems account for the migration and accumulation of oil and gas. Conceptualized discharge areas correlate well with existing fields, and flow-system dynamics offer explanations for discrepancies in physical and chemical properties of hydrocarbons for the observed pressure-temperature regimes.

Quantification of continental-scale ground-water systems demands that we apply Darcy's law and fluid-continuum mechanics to all rocks regardless of geologic and petrologic character. However, difficulties arise in quantifying continental flow systems because data have not been generalized for the purpose. For example, a lot of potentially useful data contain transient components which diminish their utility. In-situ data for rocks with low intrinsic permeabilities are virtually nonexistent.

Slice or slab maps offer a partial solution to overcoming the most difficult problem: how to represent three-dimensional (time-dependent) phenomena adequately using maps and cross sections.

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Time-Temperature Reconstructions of Diagenetic Systems

Predicting the distribution of porosity and permeability enhancement in hydrocarbon reservoirs can be achieved by integrating the generation of carboxylic acids, phenols, mineral oxidants, and liquid hydrocarbons in time-temperature space. Such predictive models can be constructed by linking data from oil-field water chemistry, source rock geochemistry, clay mineralogy, clastic diagenesis, thermal modeling and basin analysis.

The detailed organic and inorganic geochemistry and the thermal scenarios used in the time-temperature analysis must be basin specific. Predictive time-temperature models using kerogen-specific kinetic parameters have been developed for two tectonic settings: rift or "pull-apart" basins, and intermontane or "Laramide" basins. From these integrated reconstructions, the optimum conditions and capacity for porosity and permeability enhancement can be predicted.

The optimum conditions for porosity and/or permeability enhancement are: (1) short migration distances, (2) rapid evolution from organic solvent generation to the liquid hydrocarbon window (thermal environments associated with crustal attenuation or overpressuring could cause such perturbations), (3) adequate fluid flux (organic acids are highly water soluble), and (4) available conduits in potential reservoir rocks (fractures, unconformities, or preserved original porosity).

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Echo Springs Upper Almond Field, Washakie Basin: Study of a Successful Tight Gas Reservoir

The Echo Springs (upper Almond) field is an economically successful tight gas reservoir. A study of the upper Almond reservoir petrophysics and performance was undertaken to explain reservoir and production anomalies between the upper Almond "sweetspot" and "non-sweetspot" areas of the field, and to develop a geologic and economic model of the field that could be used to evaluate other areas for tight gas potential. Well performance in the upper Almond is a unique function of depth of burial and reservoir overpressuring, pore size and pore throat radius, and connate water saturation. The sweetspot and non-sweetspot production profiles correspond to two distinct upper Almond rock types. Variations