Sandstone at the base, this sequence is composed of three shale-limestone couplets, possible products of the complex interaction of sea level fluctuations and gentle tectonism along reactivated Precambrian structural elements. In ascending order, these couplets are the Wolsey Shale and Meagher Limestone, the Park Shale and Pilgrim Limestone, and the Dry Creek Shale and Sage Pebble members of the Snowy Range Formation.

In south-central Montana, the Park Shale is 50 m (165 ft) of 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 (100 ft) is a prominent interval of interbedded arkosic sandstone and micaceous shale. Here, thin sandstone beds are characterized by sharp, commonly graded bases, weakly developed cross-stratification, load structures, and a distinctive suite of glauconite, quartz, orthoclase, and plagioclase grains. Quartzofeldspathic gneiss pebbles and biomicrite intraclast pebbles and cobbles occur in these beds, in striking contrast to the fine to medium sand that composes most of the sandstone beds of the interval. These arkosic sandstone beds are localized in the northern Bridger Range and are unknown in the southern Bridgers and in Cambrian outcrops of surrounding areas.

The occurrence of Park sandstone beds that contain orthoclase and plagioclase grains and pebbles of quartzofeldspathic gneiss requires (1) the presence of a localized island of Precambrian crystalline rock, an erosional remnant that must have risen at least 200 m (650 ft) above the surrounding Cambrian/Precambrian erosion surface and was exposed above the depositional interface through most of the Middle Cambrian, or (2) an island of Precambrian crystalline rock that was exposed by late Middle Cambrian reactivation of zones of Precambrian structural weakness. Probably the strongest argument favoring the second alternative is the paucity of conspicuous feldspar grains and gneiss clasts in the middle and upper Wolsey Shale and Meagher Limestone of the Bridger Range. This evidence, coupled with the abundance of these basement-generated grains in the basal part of the overlying Park Shale, strongly suggests that the arkosic interval of the Park is the product of weathering and erosion of a nearby island. This island was tectonically activated during the late Middle Cambrian and was available as a source of coarse clastic sediment principally during that time.

The location, size, and shape of this island are unknown: no abbreviated Cambrian section is known in the area, and the arkose beds show no strong paleocurrent or paleosource directions. However, because the arkose beds are restricted to the northern Bridger Range and because a relatively local source is required for this type of sediment, the sediment-producing island must be close by. The most spatially and lithologically feasible tectonic feature along which late Middle Cambrian movement might have produced an island or series of islands is the Willow Creek-Jefferson Canyon fault zone, along which significant movement occurred during deposition of the LaHood Formation (Precambrian Y); the fault zone structurally divides the northern and southern parts of the Bridger Range, and later Paleozoic movement has been documented along this zone.

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Gas Reservoirs in Composite Shale-Sandstone Lithologies: A Rocky Mountain Energy Frontier

Thick sequences of marine rocks consisting of thin (1 to 5 cm) composite bedsets of sandstone and shale constitute a major part of the Cretaceous sedimentary prism that accumulated in the Western Interior. Today, these rocks include significant source beds and are locally important reservoirs for natural gas. Because of their large areal extent, immense volume, and ubiquitous gas content, sequences of composite sand-shale bedsets constitute an important potential resource of hydrocarbons throughout the Rocky Mountains region—an energy frontier.

The composite bedsets contain the reservoirs, source beds, and seals. The shale layers serve as both source beds and seals, and very thin (1 to few cm) wavy and lenticular beds of sandstone make up the reservoir rocks. Because these lithologies are associated generally with marine regressions, most of the constituent organic matter is terrigenous and the strata are gas-prone. The composition of the gas varies, depending on the degree of thermal maturity, from biogenic methane in Upper Cretaceous strata of the northern Great Plains of the United States and Canada, to supermature dry gas in the Mancos Shale in parts of the Piceance Creek basin in Colorado.

The reservoirs in these rocks do not require structural closure for gas entrapment, but successful commercial production generally requires fracture stimulation. In general, the reservoirs are characterized by high irreducible water saturation, high ratios of horizontal to vertical permeability, and sensitivity to water-based fluids. Field boundaries are determined by economic factors. The maximum depth of production is determined ultimately by reservoir porosity which, in turn, is the product of two distinct porosity loss trends. The shale component undergoes almost complete loss of effective porosity during early compaction, although products of organic matter transformations, shale dewatering, and clay diagenesis continue to be expelled into adjacent sandstone layers throughout most of the subsidence history of the basin. The porosity trend in the sandstone layers is controlled mainly by cementation by-products of shale diagenesis and by the original sand composition. The overall reservoir porosity reflects the ratio of sandstone to shale in the sequence and the extent of porosity loss in the sandstone layers. Generally, porosity loss increases with increasing depth and maturity and is irreversible and predictable.

Thus far, production from these rocks has been mainly a result of accidental discovery during exploration for more conventional reservoirs and subsequent field development. Successful exploitation of the enormous gas resources in these strata will require intentional exploration programs.

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Shannon Sandstone, Powder River Basin: Hydrodynamic Control of Sand Body Geometry and Facies Sequences in Western Interior Cretaceous Seaway

The Campanian Shannon Sandstone Member of the Cody Shale forms the reservoir for several significant oil fields in the western Powder River basin of Wyoming. Linear Shannon sand bodies were deposited on the muddy shelf of the Cretaceous Interior Seaway up to 200 km (125 mi) east of the paleoshoreline. The sandstone bodies are asymmetric in transverse section: northeastern flanks are shorter and steeper than the gentle accretion surfaces on the southwest flanks. The long axes of these bodies are aligned northwest-southeast to north-northwest-south-southeast. Paleocurrent direction is generally southerly, hence the sandstone bodies are aligned at a small angle to the prevailing transport direction, as required by hydrodynamic theory.

Three major facies types are recognized in cores, in subsurface wireline logs, and in outcrop. In a typical coarsening-upward vertical sequence, a large-scale cross-bedded facies overlies a thin-bedded facies which in turn overlies a bioturbated facies. These facies are genetically related lateral equivalents.

The large-scale cross-bedded facies lies on the upcurrent flank and crest of the sandstone body, and grades down the down-current flank into a thin-bedded facies, which grades in turn into bioturbated facies. The cross-bedded facies is typified by current-rippled surfaces, and by trough to tabular cross-bed sets. The sandstone is glauconitic, very fine to medium-grained, and commonly contains sideritic and shale intraclasts. The thin-bedded facies consists of sand and shale in flaser-, wavy-, and lenticular-bedded associations which may exhibit significant burrowing. Thin-bedded sandstones are generally very fine to fine-grained with a significant silt and clay component. The bioturbated facies is a shaly fine sandstone to siltstone interpreted as a distal thin-bedded facies extensively reworked by burrowing.

The Shannon appears to have been deposited by intermittent storm flows in an outer shelf environment where the water was deep enough for sharp-crested rather than hummocky megaripples to develop. Numerical modeling of geostrophic circulation due to wind stress forcing of Campanian shelf waters demonstrates a good correlation between measured paleotransport indicators and model results. The time-averaged bottom circulation induced by a typical mid-latitude storm is southerly. However, a significant onshore or offshore component of bottom flow may be present due to interaction of storm setup and resultant geostrophic currents with a varying coastal and bathymetric configuration.

In this model, storm currents decelerating across the crests of subtle topographic highs on the shelf surface would deposit preferentially the coarser fraction of their transported load, so that the aggrading sea floor would become enriched in sand. When a portion of the Campanian shelf attained a critical sand content, large-scale linear sand bodies were triggered, which were dynamically analogous to the sand ridges of modern storm-dominated shelves. These features tended to migrate southward across the aggrading shelf surface by means of the accumulation of successive facies packages on their down-current slopes.

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Imaging Beneath Complex Structure: A Case History

Migration is recognized as the essential step in converting seismic data into a representation of the earth's subsurface structure. Ironically, conventional migration often fails where migration is needed most—when the data are recorded over complex structures. Processing field data shot in Central America and synthetic data derived for that section, demonstrates that time migration actually degrades the image of the deep structure that lies below a complicated overburden.

In the Central American example, velocities increase nearly two-fold across an arched and thrust-faulted interface. Wave-front distortion introduced by this feature gives rise to distorted reflections from depth. Even with interval velocity known perfectly, no velocity is proper for time migrating the data here; time migration is the wrong process because it does not honor Snell's law. Depth migration of the stacked data, on the other hand, produces a reasonable image of the deeper section. The depth migration, however, leaves artifacts that could be attributed to problems that are common in structurally complicated areas: (1) departures of the stacked section from the ideal, a zero-offset section, (2) incorrect specification of velocities, and (3) loss of energy transmitted through the complex zone.

For such an inhomogeneous velocity structure, shortcomings in CDP stacking are related directly to highly nonhyperbolic moveout. As with migration velocity, no proper stacking velocity can be developed for these data, even from the known interval-velocity model. Proper treatment of nonzero-offset reflection data could be accomplished by depth migration before stacking. Simple ray-theoretical correction of the complex moveouts, however, can produce a stack that is similar to the desired zero-offset section.

Overall, the choice of velocity model most strongly influences the results of depth migration. Processing the data with a range of plausible velocity models, however, leads to an important conclusion: although the velocities can never be known exactly, depth migration is essential for clarifying structure beneath complex overburden.

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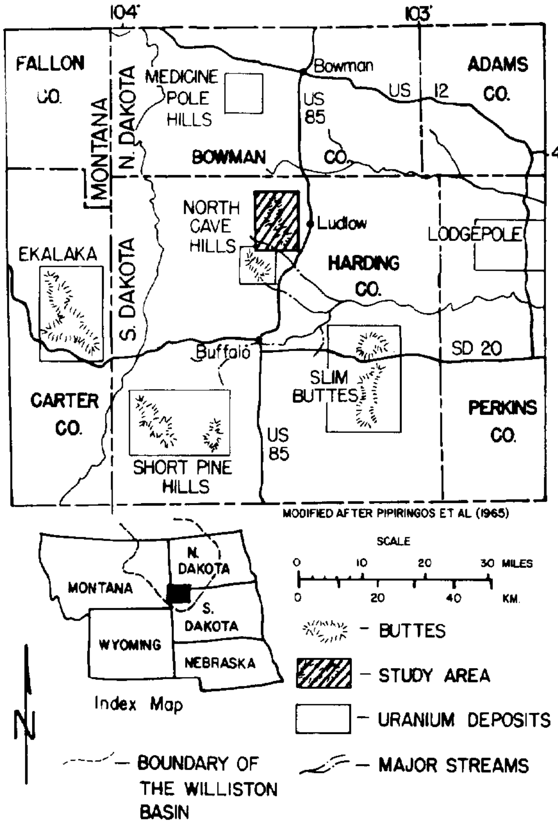
Paleoenvironment of Fort Union Formation, South Dakota

Rocks of Paleocene age are represented in the Cave Hills of northwestern South Dakota by the Ludlow, Cannonball, and Tongue River members of the Fort Union Formation. The Cave Hills are situated within the southern margin of the Williston basin, 80 mi (130 km) north of the Black Hills, South Dakota.

Numerous fine-grained, fining-upward sedimentary sequences comprise the Ludlow Member and are attributed to meandering streams occupying a low-gradient lower alluvial to upper deltaic plain. Major channel sandstones measuring up to 40 ft (12 m) in thickness, crop out and trend markedly to the northeast. Thinner sandstones adjacent to the large channel sandstones vary considerably in geometry and paleocurrent direction and are commonly associated with alternating siltstone, mudstone, claystone, and lignite deposits of levee, overbank, swamp, and possibly lacustrine origin.

The Cannonball Member is 130 ft (40 m) thick in the North Cave Hills and is represented by two fine-grained, coarsening-upward sandstone-mudstone sequences. A distinct vertical succession of sedimentary facies occur within each sequence representing offshore/lower shoreface through upper shoreface/foreshore depositional environments. A north to northeast depositional strike for the Cannonball shoreline is inferred from ripple crest and cross-bed orientations.

Numerous tree stumps in growth position are preserved along the upper surface of the Cannonball Member in the North and South Riley Pass mining districts. These stumps probably represent remnants of a cypress (*Metasequoia*) forest or swamp that stabilized the uppermost sands of the Cannonball shoreline.



The basal part of the Tongue River consists of approximately 40 to 50 ft (12 to 15 m) of lenticular sandstone, siltstone, mudstone, thin-bedded lignite, and kaolinite beds representing thin broad channels, point-bar, levee, overbank, and nearshore swamp depositional environments. Massive fluvial channel sandstones measuring several tens of ft in thickness overlie the fine-grained basal Tongue River lithologies. These channel sandstones represent the continued progradation of continental/fluvial/coastal plain depositional environments eastward over the marine sandstones of the Cannonball Member.

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Petroleum Exploration Contributes to Structural Knowledge of Rocky Mountain Foreland Deformation

The structural configuration and causal interpretation of foreland uplifts in the Rocky Mountain region have gained some clarity through recent petroleum exploration efforts. The most enlightening procedures have continued to be drilling, seismic recording, and surface mapping.

Drilling has confirmed the presence of an overturned limb of Paleozoic rocks beneath many foreland thrusts and a 20° to 30° angle of dip on most fault planes, two characteristics predicted by Berg in 1961 in his fold-thrust theory. Drilling has also revealed that some foreland thrusts do not have an overturned limb of Paleozoic rocks, and instead Precambrian rocks have been thrust directly over Eocene or Cretaceous rocks.

Seismic records have shown a relatively planar fault zone that does not appear to steepen at depth, and, in fact, frequently appears more horizontal, even with velocity corrections to depth. These records have also demonstrated thrust traces at angles ranging from 20° to 35°. Synthetic seismograms made from sonic logs recorded in wells that penetrated Precambrian rocks show zones of intense fracturing in both crystalline and metasedimentary rocks.

Surface mapping and biostratigraphic work on and adjacent to these