northeastern part of the state (Williston basin). The ratio of sodium plus potassium plus chloride to dissolved-solids concentration is greatest in northeastern Montana where the Madison contains salt beds, and decreases toward recharge areas. The ratio of sulfate to total anions is greatest in north-central and southeastern Montana where anhydrite probably is the source of the sulfate. The ratio is smallest in northeastern and northwestern Montana; however, the concentration of sulfate, in milligrams per liter, can be greater in northeastern Montana than in other areas because of the greater concentration of all dissolved solids.

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Depositional Framework for Lower Member of Metaline Formation (Cambrian), Northeastern Washington

The Metaline Formation is a Cambrian unit that crops out in Stevens and Pend Oreille Counties, northeastern Washington. The 985 to 1,250-m (3,200 to 4,100-ft) thick formation has been divided into lower, middle, and upper members, although structural complications and numerous covered intervals have made measurement of complete stratigraphic sections impossible. Based mainly on trilobite studies, early workers assigned a Middle Cambrian age to the 120 to 290-m (390 to 950-ft) thick lower member. The present study divides the lower member into the following five lithofacies: (1) gray mudstone, (2) ooid-arenite, (3) gray packstone-wackestone, (4) black packstone-wackestone, and (5) black mudstone facies.

The gray mudstone facies grades upward from underlying fine-grained siliciclastics, and it is composed of bioturbated lime mudstones with a small admixture of thin-shelled trilobite fragments, chitinophosphatic inarticulate brachiopods, and disarticulate echnioderms. The ooid-arenite facies occurs as pods within the gray mudstone facies, and is composed of spherical quartz grains and ooids developed around quartz cores in a neomorphic spar matrix. The facies is extremely well-sorted. The gray packstone-wackestone facies is composed of ooid-oncoid packstones alternating with argillaceous, fossiliferous wackestones. Rounded intraclasts and peloids are secondary components. Fossil allochems include robust trilobite fragments, echinoderm plates, and rare (?) *Epiphyton* algae. The black packstone-wackestone facies contains the same components as underlying rocks but is characterized by an increase in carbonaceous material and pyrite causing the black color. Fossils are less robust than in the underlying facies. The black mudstone facies is characterized by bioturbated lime mudstones with rare fossil fragments. The top of the member is marked by a red-stained, well-cemented zone below a disconformable contact with the middle member.

The lower member of the Metaline Formation represents the first carbonates deposited on a ramp-type shelf margin during a major Middle Cambrian transgression. The observed lithologies suggest deposition under conditions of changing water depth, agitation, and oxygenation in the shallow subtidal zone. The mudstones and wackestones in all facies were deposited under low-energy conditions. Shallowing allowed increased agitation, and oxygenation suitable for the local development of ooids and oncoids. Periodic storms produced high-energy packstone deposits composed of concentrations of the components found in the typically low-energy subtidal zone.

Along with the transgression of marine environments, oxygen-starved waters migrated shoreward from an offshore, lower shelf basin. This transgression of the pycnocline caused dysaerobic and anaerobic conditions in shallow subtidal waters of the upper shelf. Aerobic and dysaerobic conditions produced gray rocks, and anaerobic conditions produced black rocks rich in organic material. Biofacies were also affected by the low oxygen levels. Thin-shelled and chitinophosphatic forms dominated the epifauna when dysaerobic conditions occurred. With decreasing oxygen content, the epifauna was progressively excluded from the shallow subtidal zone. The result of maximum anoxia was the cessation of carbonate sedimentation and the formation of a submarine hardground at the end of "lower Metaline deposition."

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Origins of Oil in Railroad Valley, Nye County, Nevada

Trap Spring field was discovered in 1976, becoming the second commercial oil field in Nevada. The first, Eagle Springs, was discovered in 1955 and is about 6 mi east of Trap Spring. Currant, a third, noncommercial, one-well field, was found in 1978 and is about 7 mi north of Eagle Springs. Trap Spring field is productive from Oligocene welded ash-flow tuffs, and Currant produced from the Eocene Sheep Pass Formation. Production at Eagle Springs is from both of these units plus some production from the Ely Limestone (Pennsylvanian). Possible sources of oil for these fields are beds within the nonmarine Sheep Pass Formation and the marine black shales of the Chainman Formation (Mississippian). Prior to discovery of Currant field, the origin of the Eagle Springs and Trap Spring oils was problematical, and a wide range of source rock and post-generation alteration possibilities were considered. The n-C_{15+} chromatograph of the Currant oil shows unusually high peaks of pristane and phytane and a slight even-carbon preference in the n-C_{18} to n-C_{26} range. These factors are indicative of a recently generated oil from a source rock in a carbonate-evaporative sequence. The geochemical data and geologic conditions support the hypothesis that the oil produced at the Currant well was generated in the Sheep Pass Formation. The n-C_{15+} distribution of Trap Spring oil differs significantly from that of the Currant oil and is more typical of oil generated in source rock deposited in a marine environment. The most likely source of this oil is the Chainman Formation. The origin of the oil from Eagle Springs remains unclear as it has chemical affinities to both Trap Spring and Currant oils. It is possible that the Eagle Springs oil is a mixture of oil generated in the Sheep Pass Formation and Chainman Shale.

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Differential Vertical Tectonics: Insights from Models Composed of Sandstone and Limestone Deformed at Confining Pressure

Rock models ($12 \times 3 \times 3$ cm, $4 \times 1 \times 1$ in.) composed of a precut forcing block of sandstone beneath a 1-cm thick, multilithologic layered veneer of sandstone and limestone or of uncemented sand, have been deformed room-dry, at 100-MPa confining pressure, room temperature, and a strain rate of 10^{-4} sec^{-1}. Upon frictional sliding along the lubricated precut (inclined at 30° to 90° to the intact veneer) the forcing blocks deform the layered veneer into a faulted drape fold. Thin sections cut parallel to the dip and to the strike of the precut and major fault in the veneer are studied to provide detailed maps of the induced deformation (microfractures, faults, intragranular strains, "bedding" thickness changes, brittle versus ductile behavior, and nature of the folding and hinge formation). In addition, dynamic fabric analyses of faults, microfractures, and calcite twin lamellae yield stress trajectory diagrams that serve to test the applicability of corresponding numerical or analytical solutions.

Insights gained from the models primarily deal with (a) brittle or ductile behavior of the limestone depending upon location within the faulted drape fold; (b) nature of the deformation concentrated in the leading edge of the "upthrown" forcing block; (c) configuration and sequence of faulting associated with the major "upthrust" in the veneer; (d) location and significance of associated precursive microfracturing; (e) cataclastic thinning of veneers to the point where discrete layers are "tectonically eliminated" in the major fault zones; (f) hinge formation within the veneer; and (g) the role of "bedding-plane slip" in the folding process.

Deformation features in these models are used to interpret the geometry and genesis of the large scale structures at the Clark's Fork Corner of the Beartooth Block and at Rattlesnake Mountain near Cody, Wyoming; at Colorado National Monument near Grand Junction, Colorado; at the Yampa drape fold, Dinosaur National Monument; and in the subsurface along the Oak Ridge fault, Ventura basin, California. Collectively, these features are criteria for, and hence help define, the differential-vertical-tectonic style.

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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 of south-central Montana is part of a 450 to 500-m (1,475 to 1,640-ft) thick transgressive-regressive sequence of fine-grained clastic and carbonate rocks. Above the Flathead

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