environment because of the rapid facies changes in the Teapot. The Teapot Sandstone has a complex diagenetic history and diagenetic patterns are facies controlled.

Lithofacies of the Teapot Sandstone are analogous to the modern Nile delta. The Teapot Sandstone is interpreted as a regressive, wave/fluvial-dominated deltaic sequence which prograded eastward into the Cretaceous seaway. Marine lithofacies coarsen upward from bioturbated offshore siltstone to nearshore sandstone with large, pellet-lined ophiomorpha and overlying well-sorted, horizontally laminated foreshore sandstone exhibiting ridge and runnel topography. Marine foreshore sandstone is overlain by complexly interbedded sandstone and carbonaceous shale in stacked fining-upward sequences of the delta plain. Rootlets and contorted beds are common. Fining-upward units are interpreted as abandoned channels, whereas coarsening-upward sequences are interpreted as interdistributary bay or lagoonal deposits. Capping the sequence is a thick, cross-bedded fluvial section consisting of levee, point bar, and channel sand deposits. Slumped beds, intraformational basal conglomerates, and minor eolian ripple laminations are present in fluvial sandstone.

The Teapot Sandstone has a complex diagenetic history. Siderite and framboidal pyrite formed early in the diagenetic sequence at shallow depths of burial under anaerobic conditions. Pore-filling kaolinite, chlorite, and quartz overgrowths formed coevally following dissolution of relatively unstable framework grains. Poikilotopic calcite cement is locally abundant and extensively replaces framework grains. Depositional facies exert strong control on diagenetic patterns. Kaolinite occurs predominantly in fluvial sandstone. Chlorite is restricted to marine facies, and calcite is further restricted to well-sorted foreshore marine sandstone. Quartz overgrowths occur only in relatively well-sorted sandstone, whereas pyrite and siderite are common in shaly sandstone and siltstone.

Nearshore marine and fluvial sandstone are potentially hydrocarbon reservoirs, although authigenic clays have significantly reduced permeability. Reservoir potential of well-sorted foreshore marine sandstone was destroyed by pore-filling calcite cement. However, tightly cemented sandstone forms a potential diagenetic trapping mechanism.

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Tectonic Significance of Ross Pass Fault Zone, Central Bridger Range, Montana

The Ross Pass fault zone (RPFZ) in the central Bridger Range marks the boundary between Proterozoic Belt Supergroup rocks to the north and Archean metamorphic rocks to the south, and may represent the overlap of two Laramide styles of deformation: thin-skinned fold and thrust deformation to the north and basement-involved foreland deformation to the south.

The fault zone consists of three northwest-trending, northeast-dipping, oblique-slip thrust faults with varying amounts of displacement. The middle thrust, the Pass fault, is the most extensive within the zone; to the west, the Proterozoic LaHood Formation is faulted against Archean quartzo-feldspathic gneisses and amphibolites and overlying Middle and Upper Cambrian strata. Displacement decreases eastward as the fault offsets the lower Paleozoic section and dies out within the upper Paleozoic strata. This variation in displacement is caused by folding within the hanging wall strata along the fault plane during thrusting. The folded strata are again offset by another smaller thrust to the northeast, the Peak fault, which may have originated as an out-of-the-syncline thrust. The Dry Fork fault, southwest of the Pass fault, is largely an intraformational thrust within the Middle Cambrian Meagher Limestone which formed in response to buttressing against the Archean foreland block to the south.

South of the RPFZ, both the Archean and the overlying Phanerozoic strata have been deformed into a large asymmetric, steeply dipping, eastward verging fold typical of basement-involved foreland structures.

The structural relationships along the RPFZ developed as the southeast margin of the Montana salient of the Cordilleran fold and thrust belt impinged on the northern margin of the Laramide foreland province. The relatively small displacement within the thrusts indicates that the RPFZ is within or near the leading edge of the Montana salient. The RPFZ may be an extension of the inferred ancestral Willow Creek fault zone to the west, which was the southern margin of the Proterozoic Belt basin. Laramide compressional stresses exploited this long active zone of weakness and resulted in the impingement of fold and thrust structures upon a foreland uplift.

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Paleotectonics of Frontier Formation in Wyoming

The most intense and widespread pre-Laramide structural deformation of Cretaceous sedimentary rocks in Wyoming is associated with the Wall Creek sandstone of the Frontier Formation. Most of the evidence of structural deformation is found immediately below the regional unconformity at the base of this sandstone.

Regionally, an isopach map from the top of the Frontier Formation to the top of the Mowry Formation shows strong and persistent thinning onto a north-trending arch in western Wyoming and thickening into a northwest trending basin in eastern Wyoming.

Part of the thinning onto the western arch is caused by progressively deeper erosion of a regional unconformity at the base of the Wall Creek sandstone, and regional onlap of the Wall Creek sandstone above the unconformity. There is also some westward thinning of the lower Frontier interval, however, which is not related to the Wall Creek unconformity.

Of the more specific paleostructures discussed, the north-trending anticlines in the vicinity of the Moxa arch in southwestern Wyoming are particularly well developed. An east-west anticline in the Bison basin area appears to have been faulted on the south flank, and a broad arch on the west side of the Powder River basin may have influenced paleocurrents and sandstone depositional trends of the productive "First Frontier Sandstone" of that area.

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Vitrinite Reflectance of Coals from the Heath Formation, Central Montana

The Heath Formation (Mississippian) in central Montana is a black calcareous shale containing low to moderate amounts of oil (Fischer assay) and is considered a petroleum source rock for the overlying Tyler Sandstone.

Seven core holes were drilled in the summer of 1982 by the Montana Bureau of Mines and Geology in cooperation with the Mineral Management Service. Thin coal seams from the core samples were studied using vitrinite reflectance analysis. Since vitrinite reflectance is a method of determining thermal maturation of organic material in sediments (in this case, a thin coal seam near the base of the Heath Formation), it was possible to construct an iso-reflectance map of the Heath Shale in this area, and estimate the minimum temperature of heating undergone by the organic constituents.

Reflectance values show a regional trend caused by burial and the geothermal gradient. Little variation is present in these reflectance values (0.49% to 0.55%). The lowest reflectance values are in the central portion of the study area, and increase to the east and west. However, substantially higher vitrinite reflectances were recorded in the far eastern portion of the area. These high reflectances probably are the result of heating by an igneous intrusion, which was cored during drilling.

The sediments heated by the normal geothermal gradient have immature vitrinite which is below the limits of the petroleum generation window. In the small area where the intrusive was discovered, the vitrinite is mature and there is a good possibility of oil generation.

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Influence of Transcontinental Arch on Cretaceous Listric-Normal Faulting, West Flank, Denver Basin

Seismic studies along the west flank of the Denver basin near Boulder and Greeley, Colorado illustrate the interrelationship between shallow listric-normal faulting in the Cretaceous and deeper basement-controlled faulting. Deeper fault systems, primarily associated with the Transcontinental arch, control the styles and causative mechanisms of listric-normal faulting that developed in the Cretaceous. Three major stratigraphic levels of listric-normal faulting occur in the Boulder-Greeley area. These tectonic sensitive intervals are present in the following Cretaceous formations: Laramie-Fox Hills-upper Pierre, middle Pierre Hygiene zone, and the Niobrara-Carlile-Greenhorn. Documentation of the listric-normal fault style reveals a Wattenberg high, a horst block or positive feature of the greater Transcontinental arch, was active in the east Boulder-Greeley area during Cretaceous time. Paleotectonic events associated with the Wattenberg high are traced through analysis of the listric-normal fault systems that occur in the area. These styles are important to recognize because of their stratigraphic and structural influence on Cretaceous petroleum reservoir systems in the Denver basin. Similar styles of listric-normal faulting occur in the Cretaceous in many Rocky Mountain foreland basins.

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Use of Seismic Stratigraphy for Minnelusa Exploration, Northeastern Wyoming

The Powder River basin in northeastern Wyoming has long been a productive oil province. Abrupt lithology changes of the Upper Pennsylvanian-Permian Minnelusa Formation have provided a variety of hydrocarbon traps. However, these same abrupt changes have also yielded many surprises to the hopeful explorationist.

The upper Minnelusa is composed mainly of sands, dolomites, and anhydrites, and was deposited in sabkha environment. Unconformably overlying the Minnelusa is the supratidal Opeche shale. Hydrocarbon traps in the upper Minnelusa sands are usually stratigraphic in nature, and are of two common types. In one, a porous sand is trapped by an updip facies change; in the other, thick Opeche deposits in interdunal areas provide an updip seal for the porous sands.

The C-H field area, located in Campbell County, Wyoming, was chosen for initial study. Abrupt updip termination of the thick productive upper Minnelusa sand appeared to provide an ideal situation for a stratigraphic-seismic study. Sonic logs used to construct a geologic cross section showed a significant difference in the sonic response of porous upper Minnelusa sand versus no sand. Synthetic seismograms were then produced from these wells and, when organized in cross-section form, they again showed an obvious difference in response from sand to no sand conditions.

A "pilot" seismic line tying these wells was acquired. From this data, a good correlation between synthetic and actual seismic data was achieved. The updip termination of the productive Minnelusa sand was clearly identifiable on the seismic data.

The drilling phase of our exploratory program yielded mixed results. Some excellent development wells were drilled, one being completed for 625 BOPD. Although we were 70 to 80% successful in predicting the presence or absence of porous upper Minnelusa sand, only 20% of our extension or wildcat wells were productive.

Two major problems were soon discovered: (1) the seismic response from a thick, relatively low velocity Opeche shale is very difficult to distinguish from an upper Minnelusa sand; and (2) thin, porous Minnelusa sands are difficult to identify seismically, thus updip trap limits are not easily defined.

A variety of seismic trace attributes were examined in hopes that subtle amplitude and frequency differences would help distinguish thick Opeche shale from Minnelusa sand. This approach produced very limited success. Better results were achieved on the second problem, that of thin bed resolution. Accentuating the upper portion of the seismic frequency spectrum (40 to 80 Hz) did allow better mapping of thin Minnelusa sands.

In conclusion, through a closely coordinated geologic-geophysical effort, a useful methodology was developed which can be applied to a variety of stratigraphic-seismic exploration projects. The basic steps involved are as follows. First, determine if known lithologic changes can be seen on sonic or density logs. If successful, can the changes on logs be seen on synthetic seismograms? If successful, can the change be seen on a pilot seismic line? Finally, prepare for some complications and failures.

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Evaluation of Low-Temperature Geothermal Potential of Cache Valley, Utah

This research is a continuation of the assessment of low-temperature geothermal resources of Cache Valley, Utah, initiated by the Utah Geological and Mineral Survey. The study area is the southern part of a narrow, north-trending graben located in north-central Utah and southern Idaho.

Tools used for evaluating the low-temperature geothermal resources are ground-water temperatures, thermal gradients, silica and Na-K-Ca geothermometers, and mixing models for estimating reservoir temperatures.

Ground-water temperatures range from 9.9 to 50.0°C, with a background temperature of about 13.0°C. The three areas in the study area with anomalous water temperatures are: (1) North Logan, 16.0 to 25.1°C; (2) Benson, 13.5 to 23.0°C; and (3) Trenton, which has evidence for past and present warm spring activity, with temperatures ranging from 22.9 to 50.1°C.

Thermal gradients generally range from 15° to 52°C/km, approximately the same as the average thermal gradient for the Basin and Range province, 35°C/km.

The silica and Na-K-Ca geothermometers, when applied to the groundwater of Cache Valley, Utah, show varying degrees of agreement, with estimated reservoir temperatures averaging 50 to 100°C. When the mixing models are applied to the water in the Trenton area, estimated reservoir temperatures are 30 to 200°C.

The function, $F(T) = \log(Na/K) + B \log(\sqrt{Ca/K})$, is used as an exploration tool to indicate a possible geothermal anomaly when the value is less than 2.00. The Trenton area is a possible geothermal anomaly located using this method.

Warm water in Cache Valley, Utah, appears to be the result of groundwater which has migrated from depth, is warmed by the normal thermal gradient, rises quickly along permeable fault zones, and either mixes with near surface recharge water or is forced to flow horizontally because of a less permeable confining layer. Both of these models mask the higher temperatures at depth.

Considering measured surface temperatures, calculated reservoir temperatures, thermal gradients, and the local geology, most of the Cache Valley, Utah, area is unsuitable for geothermal development. However, the areas of North Logan, Benson, and Trenton have anomalously warm ground water in comparison to the background temperature of 13.0°C for the study area. The warm water has potential for isolated energy development but is not warm enough for major commercial development.

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Regional Structural Synthesis, Wyoming Salient of Western Overthrust Belt

Surface geologic mapping, regional and high-density reflection seismic data and information from approximately 370 wells are combined to describe geometrically that area of the western Overthrust belt between the Snake River Plain and the Uinta uplift. Particular care has been taken to two-dimensionally verify interpretations of multiple thrust sheets by linear restoration. By establishing equivalence of pre-thrust lengths of affected beds, one can gain confidence in interpreted structural geometrics as well as generate data in regard to internal shortening and deformation intensity. Due to irresolvable geometric problems within sections, 47 cross sections were developed at roughly 6-mi (10 km) spacing to help verify changes in displacement or placement of key structural elements. Displacements of 0 to 32 mi (51 km) have been demonstrated, and both structure of faults and subcrop relations of Absaroka and younger thrusts are described. Jurassic to Paleocene (Sevier) thrusts were active across a previously deformed cratonic shelf terrane and interacted with active structural elements such as the Uinta uplift, Gros Ventre Range, and Moxa arch. Thrusts are progressively younger to the east, except for the Darby-Prospect pair in which the Darby system is younger.

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Depositional Environments of Upper Cretaceous Fox Hills Formation, Niobrara and Weston Counties, East-Central Wyoming