Aspects of the Regional Geological Framework of Low-Permeability Shallow Gas Reservoirs in Upper Cretaceous Strata (Colorado and Montana Groups), Southwestern Saskatchewan

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The Upper Colorado Group of southwestern Saskatchewan comprises predominantly dark grey marine shales, in part calcareous, which contain northeastward-thinning bands of fine-grained sandstone and siltstone up to several metres in thickness, as well as rare bentonite layers. The basal member, the Second White-Speckled Shale (upper Cenomanian and lower Turonian) is separated from the stratigraphically highest member, the First White-Speckled Shale (upper Coniacian and lower part of the Santonian), by an unnamed unit (upper Turonian and lower Coniacian) of noncalcareous shales.

Shaly fine-grained sandstones and siltstones of the Milk River Formation (upper Santonian and lower Campanian) overlie Upper Colorado strata, forming the basal stratigraphic unit of the Montana Group.

In southwestern Saskatchewan, these Upper Cretaceous rocks are economically important because they contain some $46.4 \times 10^9\ m^3$ of nonassociated gas, more than half of the province's initial established reserves (Saskatchewan Energy and Mines, 1986). The three main gas pools in this part of Saskatchewan, namely Hatton, Bigstick and Liebenthal, lie at the southeastern limits of the very large Southeast Alberta Gas System which, in Alberta, contains initial established reserves of nonassociated gas in Upper Colorado - lowermost Montana Group rocks of $286 \times 10^9\ m^3$ (Energy Resources Conservation Board, 1985). These pools are currently being rapidly developed, and extensive exploration is in progress to try to maintain high reserves.

The Upper Cretaceous rocks belonging to the same stratigraphic interval in northern Montana host productive gas pools such as East Keith (some 180 km southwest of Hatton), Tiger Ridge, Bowes and Bull Hook (approximately 200 km south of Hatton with reserves estimated at more than $21 \times 10^9\ m^3$ (Maher, 1969)), and Bowdoin (approximately 250 km southeast of the Hatton Pool with cumulative production of $0.19 \times 10^9 m^3$ to the end of 1978, [Nyedegger et al, 1979]). Farther south and east, gas pools such as Hardin, Liscom Creek, Pumpkin Creek, Cedar Creek, West Short Pine Hills and Cady Creek (southeastern Montana and northwestern South Dakota) are further evidence of the widespread occurrence of Upper Cretaceous shallow gas reservoirs in the northern Great Plains of North America. Rice and Shurr (1980) and Rice and Claypool (1981) have suggested that the northern Great Plains might contain about $3.25 \times 10^{12}\ m^3$ of shallow gas, with recovery volumes dependent upon well-completion technology and revenue-to-cost ratio of the gas.

The author's preliminary study area in southwest Saskatchewan covers Townships 1 to 23 and Ranges 21W3 to 30W3, inclusive. A grid of northeast-southwest and northwest-southeast stratigraphic cross-sections will be constructed to trace, as far as possible, lithostratigraphic units between the base of the Lower Colorado Group and the top of the Milk River Formation currently recognized in southeastern Alberta and northern Montana into southwestern Saskatchewan. Revisions to Saskatchewan's Upper Colorado stratigraphic nomenclature are likely to be recommended. Also, updated isopach, structure and net-pay maps will be prepared. These, supplemented by petrologic examination of cored intervals and by investigation of geothermal gradient and hydrodynamic regime patterns, will be used to reappraise the geometry, sedimentology and economic potential of Upper Colorado - lower Montana Group strata. Subsequently, the study-area will be expanded eastwards and northwards.

Previous Work

Pioneer geological studies of Cretaceous strata of the northern Great Plains region were largely carried out by the Geological Survey of Canada (e.g., Dawson, 1875, 1882; Dowling, 1917; Dowling et al., 1919; Dyer, 1926a; Williams and Dyer, 1930; McLearn et al., 1935) and the United States Geological Survey (e.g., Stanton and Hatcher, 1905; Bowen, 1914; Stebinger, 1914).

Geological publications about oil and gas accumulations in Alberta and adjoining areas began to appear in the 1920s and 1930s. They ranged in scope from description of individual fields in various stages of discovery and development (e.g., Clark, 1923; Hume, 1924; Perry, 1928) to regional assessments (Dyer, 1926b; Ross, 1926; Hume, 1933). These and subsequent similar works enabled important contributions towards present understanding of Cretaceous depositional environments, facies distribution, chronology and paleogeography of the North American Western Interior Seaway to be presented by, amongst others, Williams and Burk (1964), Kauffman (1969), Obradovich and Cobban (1975), Stelck (1975), Williams and Stelck (1975) and Caldwell (1982). These, in turn, provided useful regional settings for detailed geological research of Upper Cretaceous strata in the northern Great Plains, such as has been published by Suffield Block Study Committee (1972), Last, Kloepfer Ltd. (1973), Suffield Evaluation Committee (1974), Meijer Drees (1973, 1975), Myhr and Meijer Drees (1976), Meijer Drees and Myhr (1981), Male and Pacholko (1982) and Warren (1985), mainly from southeastern Alberta; by Christopher et al. (1971), Simpson (1975, 1979a, 1979b, 1980, 1981a, 1981b, 1981c, 1982, 1983, 1984a, 1984b), Simpson and Katham (1980), Simpson and Singh (1980) and Singh (1982), mainly from southwestern Saskatchewan; and by Rice (1976a, 1977, 1980, 1981), Shurr (1979, 1984a, 1984b), Nydegger et al. (1979), Rice and Claypool (1981), Rice and Shurr (1980, 1983), Gautier (1981), Gautier and Rice (1982), Gautier et al. (1983), Shurr and Reiskind (1984), and Shurr and Rice (1986, 1987), mainly from Montana and adjacent states.

Regional Stratigraphy and Related Nomenclature Problems

The stratigraphic nomenclature currently in common usage for correlating Upper Cretaceous strata in southeastern Alberta, southwestern Saskatchewan, and north- and east-central Montana is shown in Fig. 1.

Units that make up the Upper Colorado Group in southwestern Saskatchewan and southeastern Alberta are, for the most part, informally defined (First White-Speckled Shale, "unnamed noncalcareous shale", Second White-Speckled Shale) and appear to lack type localities. North and Caldwell (1975, p. 306) noted the unsatisfactory nomenclature applied to the Cretaceous rocks of Saskatchewan, and pointed out that sequences of this age are closely similar to those in Montana and in North and South Dakota, so that many stratigraphic names originating and used in these states "could be applied with advantage north of the International Boundary". The author concurs with their statements.

Rice (1981) has published a 511 km long, 12-well subsurface cross-section of Cretaceous (mostly Upper Cretaceous) strata from close to the northwest end of the Southeast Alberta Gas System to the southeast end of the Bowdoin Gas Field, and has shown that formation-top picks are clearly traceable over this distance. Simpson (1981a) used selected U.S. stratigraphic terminology in core descriptions of Upper Colorado strata and on a cross-section in extreme southwestern Saskatchewan.

North and Caldwell (1975, Fig. 2) showed two hiatuses in the Colorado Group, one above and the other below an unnamed shale which rests upon the Fish-Scale Sandstone. Simpson (1982b) recognized no stratigraphic break within the Big River Formation, which he described as lying both above (the unnamed shale of North and Caldwell) and below the "Fish-Scale Marker". However, he noted the presence of a disconformity above the Big River Formation, most pronounced in central Saskatchewan where the uppermost beds appear to have been removed by erosion and where, in an eastward direction, successively younger strata rest upon Big River shales and mudstone. North and Caldwell recognized another hiatus between the First White-Speckled Shale and the Milk River - Lea Park Formations.

Meijer Drees and Myhr (1981) proposed that the predominantly subtidal and intertidal nearshore deposits which form highly productive natural gas reservoir rock in the Southeastern Alberta Gas System (Milk River Gas Pool) be termed the Alderson Member of the Lea Park Formation. They selected the type section in the ARCO Alderson well (Lsd. 10-4-15-10W4) between depths 253.5 and 338.3 m. Other authors (e.g., Rice, 1981) have used the term "Milk River Equivalent" for these rocks. In Saskatchewan, Simpson and Singh (1980) adopted unqualified use of the term "Milk River Formation", largely because this name is so deeply entrenched in the oil and gas industry and related literature.

Both the stratigraphy and the nomenclature of Upper Colorado Group rocks will be further reviewed in course of this study.

Lithology and Sedimentology of Reservoir Rocks

Second White-Speckled Shale/Greenhorn Formation

Simpson (1981a) examined and described ten cored intervals collected from this unit in the study area; since this work was done, core has been recovered from a further 19 wells. Simpson assigned rocks of the Second White-Speckled Shale, which is up to 61 m thick in southern Saskatchewan, to the Greenhorn Lime with a maximum core thickness of 3.5 m, and/or to the stratigraphically lower Phillips Sandstone with a maximum cored thickness of 20.6 m.

The Phillips Sandstone is made up of interbedded, fine-grained, pale olive-grey to grey sandstone and siltstone, along with generally subordinate dark grey mudstone which is bituminous in places. Lithologic layers mostly range in thickness from a few millimetres to several centimetres. They are commonly horizontally laminated, but some thicker siliciclastic layers are cross-laminated. Sandstone layers are quartzose and micaceous, and in many places have sharp bases and indistinct siltstone and/or mudstone tops. Horizontal to subhorizontal sand-filled burrows are locally abundant - sufficiently so in places to destroy primary layering across thicknesses up to 0.6 m. Some siltstone layers contain mud-filled Chondrites. Pale grey bioclastic limestone and chalk are sporadically

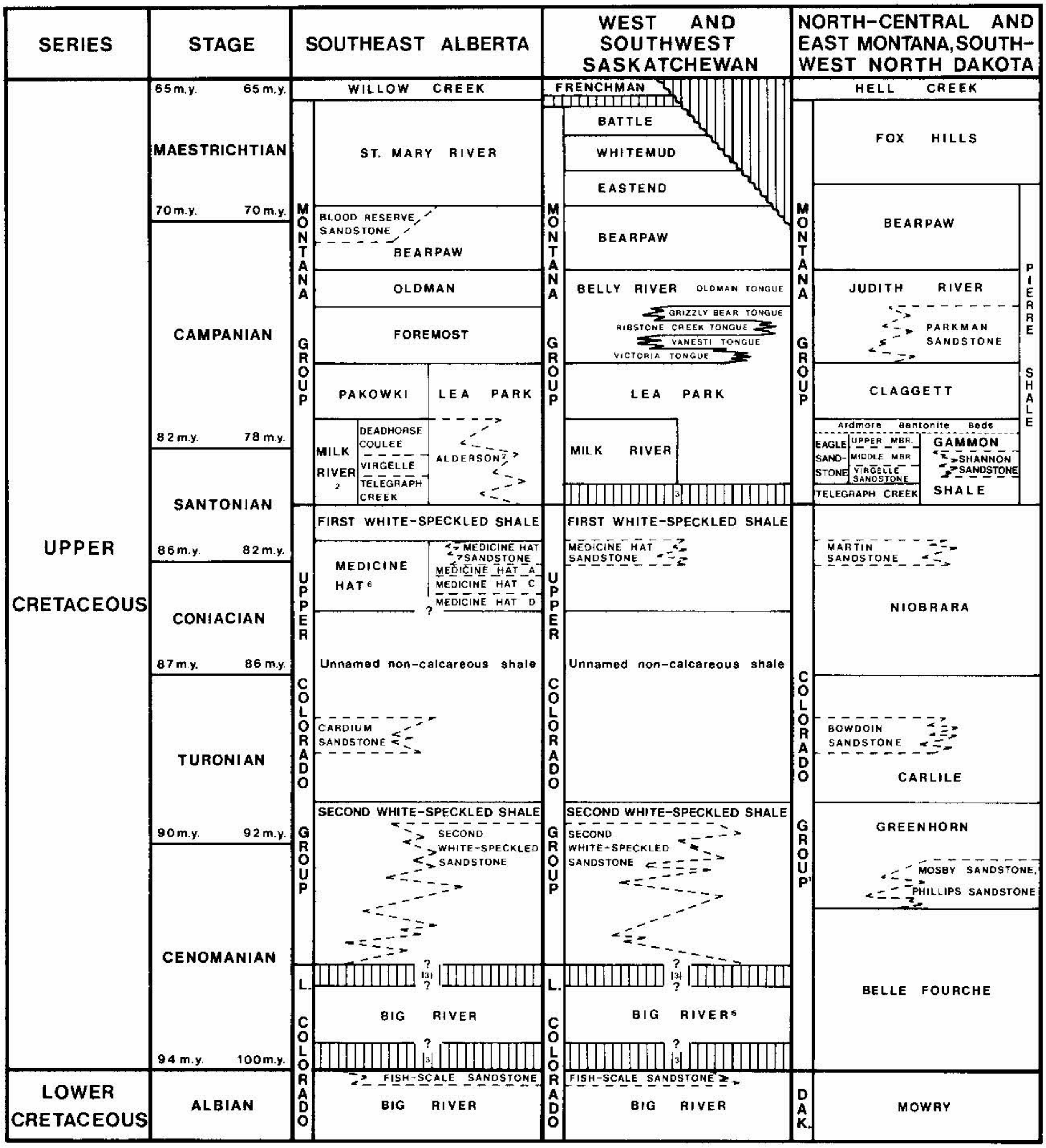


Figure 1 - Correlation chart of Upper Cretaceous rocks of the northern Great Plains (adapted from Bluemle et al., 1981[1]; Meijer Drees and Myhr, 1981[2]; North and Caldwell, 1975[3]; Rice, 1976b[4]; Simpson, 1982[5] and Warren, 1985[6]). Ages down the left side of the "stage" column are from Obradovich and Cobban (1975), those down the right side are from Van Hinte (1976).

distributed as layers 1 mm to 5 cm thick, especially in the uppermost 3 m where scarce calcite concretionary layers up to 20 cm thick are also found. Pelecypod, coccolith and fish debris are sporadically present and locally abundant, as are plant-fragment occurrences in some sandstone beds.

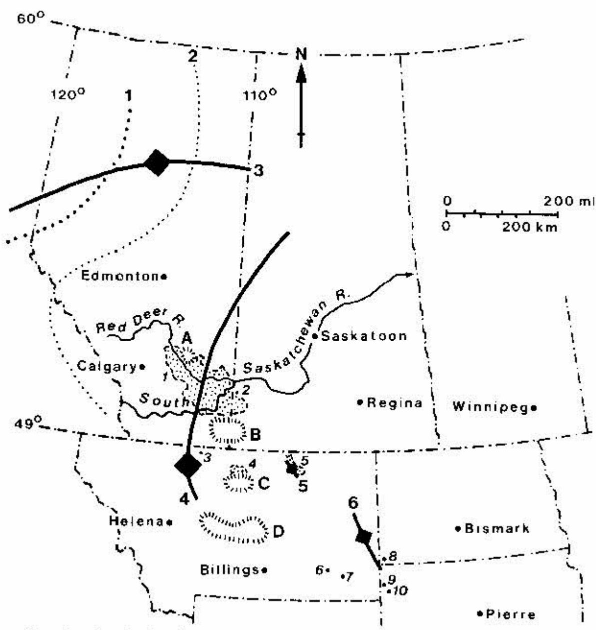
Within the Phillips Sandstone, upward-coarsening sequences defined by upward decrease in the proportion of intercalated mudstone are common, and an overall northward decrease in grain size has been noted (Simpson, 1982a), along with attenuation of the lowermost sand of the Phillips Sandstone. A transition from thick (in the southwest) to thin (in the northeast) Phillips Sandstone development trends northwesterly from about Twp. 3 Rge. 13W3 to Twp. 12 Rge. 24W3 and possibly farther (Simpson and Katham, 1980). In Saskatchewan's Bigstick Gas Pool, which is situated at a depth of about 692 m, the average thickness of pay sand totals 3.73 m and the porosity is 20 percent. Westwards, in Alberta, gas reservoirs at this stratigraphic level are mostly 600 to 630 m deep, 0.75 to 2 m thick and have a porosity of almost 22 percent.

The Greenhorn Lime, up to about 6.5 m thick in southern Saskatchewan, is predominantly dark grey, coccolithic, silty mudstone which is bituminous in millimetre-thick layers and contains pale grey limestone and chalk layers ranging in thickness from less than 1 mm to about 2 cm. Horizontal lamination is well developed, cross-lamination less so. Inoceramus and fish skeletal debris are common. Pyrite concentrations, where present, are usually elongate in the plane of bedding in carbonate layers. Bioturbation is rare.

A bentonite layer 0.3 to 0.7 m thick at the base of the Greenhorn Lime appears to be ubiquitous in the study area. It is horizontally laminated, biotite-rich and medium grey to pale bluish grey.

In the Bowdoin Dome area of north-central Montana, the Phillips Sandstone consists of three coarsening-upward cycles, individually up to 23 m thick, and identifiable on gamma-ray, density and resistivity logs (Nydegger et al., 1979). Cycles are shaly at the base and finely sandy at the top. Commercial production is from the tops of the upper two cycles where sandstones have estimated average porosities of 15 to 17 percent and permeability values of 2 to 3 md. The Greenhorn Lime in this region is dominantly a carbonate, the reservoir rock being finely crystalline limestone containing shell fragments and discontinuous laminae of organic-rich shale which are barriers to vertical permeability. The unit is brittle, and fractures readily in response to both natural and induced forces. Its porosity is 6 to 13 percent, and permeability ranges from less than 0.1 to 6 md. The base of the Greenhorn Lime here is a highly radioactive impure bentonite zone up to 12 m thick. It forms an impermeable barrier between reservoirs in the Phillips Sandstone and the Greenhorn Lime, and acts as a seal for gas entrapment. Nydegger et al. (1979) point out that, although the bentonite is composed of smectite and so is highly susceptible to swelling, production in adjacent reservoirs should not be affected because, at the shallow depths involved, fracturing in them should move horizontally.

Rice and Shurr (1980) considered the Phillips Sandstone to be an "offshore bar" shelf sandstone of a type that generally forms narrow elongate bodies and that Walker (1984), from a study of ridges developed in modern shelf and shallow marine sands, showed as having ranges in height, length and width of 3 to 12 m, 3.7 to 18.5 km, and 0.9 to 2.8 km, respectively. Referring to paleogeographic maps published by Williams and Burk (1964), Rice and Shurr further considered that the Dunvegan delta, located in northwestern Alberta and adjacent British Columbia, was the source for these clastics, even though Stelck (1975) pointed out that this delta complex seems to have been restricted to an area northwest of the Peace River Arch (Fig. 2). Rice (1984) showed that the Phillips Sandstone in the Bowdoin Dome area and the stratigraphically equivalent Mosby Sandstone of the Central Montana Uplift were deposited in higher energy environments than contemporaneous sediments in intervening areas where relatively low-energy conditions prevailed.



Geological features

1 Southeastern limit of freshwater Dunvegan delta (Stelck, 1975)

2 Southeastern limit of Dunvegan delta (Williams and Burk, 1964)

3 Peace River Arch

4 Sweetgrass Arch

5 Bowdoin Dome

6 Cedar Creek Anticline

Topographic features

A Hand Hills

B Cypress Hills

C Bearpaw Mountains

D Central Montana Uplift

U. Cretaceous shallow gas fields : *1,* Southeast Alberta Gas System; *2,* Burstall; *3,* East Keith; *4,* Tiger Ridge - Bowes - Bull Hook; *5,* Bowdoin; *6,* Liscom Creek; *7,* Pumpkin Creek; *8,* Little Missouri; *9,* West Short Pine Hills; *10,* Cady Creek

Figure 2 - Map showing locations of major geological structures and topographic features quoted in the text.

Medicine Hat Sandstone/Martin Sandstone

In southwestern Saskatchewan, the Medicine Hat Sandstone occurs about 25 to 30 m below the top of the First White-Speckled Shale, at a depth of approximately 500 m in the Hatton area and 520 m in the Burstall area. Rocks of this unit in the study area have been described by Simpson (1981a) from 11 cores from Twps. 12 to 18, Rges. 28 to 30W3. Since publication of Simpson's report, five cores containing Medicine Hat Sandstone have been taken from within the study area, the most southeasterly being from Twp. 5 Rge. 26W3 in a region where the Medicine Hat Sandstone is barely distinguishable on geophysical logs. Where completely represented by core sections, the Medicine Hat Sandstone ranges in thickness from 7.3 to 9.6 m; geophysical logs show it attains a maximum thickness of about 13.7 m.

This rock unit is made up of fine-grained, medium grey to pale olive-grey speckled sandstone interbanded with medium dark grey speckled muddy siltstone and dark grey mudstone. Bands occur as lenses and continuous layers up to a few centimetres thick, with numerous but discontinuous mudstone partings a few millimetres thick. Sandstone layers are quartzose, micaceous and cross-laminated or horizontally laminated. They incorporate moderately abundant pelecypod (especially Inoceramus) and fish skeletal debris.

The top of the Medicine Hat Sandstone is generally strongly indurated across a thickness of 0.05 to 0.5 m, providing an effective cap rock to underlying gas-bearing strata. Indurated horizons of similar thickness also occur at lower levels in the unit, having formed where calcite cemented and partially or completely plugged siliciclastic layers of relatively high original porosity and permeability below bentonitic permeability barriers. Cone-in-cone structures commonly occupy the top 2 cm of indurated zones, which have polygonal patterns ornamenting their uppermost surfaces (Kendall and Simpson, 1974).

Simpson (1981b) describes an informal three-fold subdivision of the Medicine Hat Sandstone with a 1.5 to 3.5 m thick zone of predominant, upward-coarsening, fine-grained sandstone (the main reservoir rock) sandwiched between zones of muddy siltstone and subordinate fine-grained sandstone (0.5 to 4.0 m thick above the main sandstone, 3 to 4 m thick below). Rare granules and small pebbles of nodular siderite are present in all three subdivisions.

Thin, laminated bentonites (mostly about 2 cm thick) occur at several levels in the Medicine Hat Sandstone, especially the uppermost 0.3 m, as well as in the overlying First White-Speckled Shale.

The lower contact between the Medicine Hat Sandstone and the First White-Speckled Shale is gradational, while the upper contact (which is below 25 to 30 m of First White-Speckled Shale) is generally sharp. East and north of the Hatton area, the Medicine Hat Sandstone is increasingly fine-grained and shaly. In the Hatton area, the average net thickness of pay zones in the Medicine Hat Sandstone is about 3 m and, in the Burstall area, about 2.8 m (Saskatchewan Energy and Mines, 1986); respective porosities are 21 and 16 percent, and the permeability ranges from 0.1 to more than 250 md (Simpson, 1981b).

In the Medicine Hat area of southeastern Alberta, this unit forms the reservoir for the Medicine Hat A Gas Pool, contains a higher proportion of relatively well-washed fine-grained sandstone, and has a net-pay thickness of 3.88 m and an average porosity of 17 percent. Elsewhere in this gas pool in Alberta, pay thickness ranges between 0.48 m (Johnson Field) and 3.45 m (Cassils Field). Warren (1985) provided a type log showing gamma, neutron and density porosity, and resistivity curves for the Milk River, Medicine Hat and Second White Specks Formations. He showed the Medicine Hat Formation to be a 60 m thick unit. Earlier ERCB reference logs (attachments to Decision 77-9 respecting Application No. 770202; attachment to examiners' report on Application No. 8981) show the Medicine Hat Formation to comprise three upward-coarsening sequences which are, from bottom to top, reservoirs for designated gas pools Medicine Hat D (about 40 m thick), Medicine Hat C (some 20 m thick) and Medicine Hat A (about 12 m thick).

The Medicine Hat C Gas Pool (0.36×10^6 hectares) is smaller in area than the Medicine Hat A Pool (1.73×10^6 hectares), has an average pay thickness in the range of 0.53 m (Atlee Buffalo Field) to 1.17 m (Cassils Field) and only rarely exceeding one metre, and has an average porosity of 14 percent. The Medicine Hat D Gas Pool is smaller (0.27×10^6 hectares), has thinner pay (0.4 m in Bindloss Field to 1.12 m in Suffield but mostly less than 0.75 m) and an average porosity of 14 percent (Energy Resources Conservation Board, 1985).

Last, Kloepfer Ltd. (1973) constructed net-pay isopach maps for the Medicine Hat Sandstone using contours of 0 m (0 ft.), 3.0 m (10 ft.), 6.1 m (20 ft.) and 9.1 m (30 ft.). The producing unit was found to be delta-shaped, its apex (in Twp. 10 Rge. 8W4) pointing to the southwest, and made up of northwest-trending sand ridges averaging about 30 km in length, 3 km in width and attaining about 10 m in height. The authors concluded that the Medicine Hat Sandstone was deposited as a delta that was reshaped by wave-action and longshore currents. The 130 km long delta front is oriented northwest-southeast and is situated about 110 km from the apex, which lies close to the crest of the Sweetgrass Arch so that the delta sands fan away on both the northwestern and southeastern flanks of the rch. Sandstone thicknesses exceeding 6.1 m are concentrated along a northeast-trending zone which, though affected by sand-ridge development, extends from close to the delta apex to the delta front. This zone of maximum sand thickness may represent deposits of the main distributary channel.

In a more recent study (Martin Petroleum Consulting Ltd., 1985), the Medicine Hat Sandstone was interpreted to be a nearshore marine deposit with its source area to the south and southwest. Alternatively, it may be a shelf sandstone similar in origin to the Phillips Sandstone (Rice and Shurr, 1980).

In the northern Great Plains region of the U.S., the Niobrara Formation consists predominantly of chalk and chalky shale (Shurr, 1984b; Shurr and Rice, 1986), which are southerly counterparts of the First White-Speckled Shale that, in Saskatchewan, lies below, to the northeast of, and above, the Medicine Hat Sandstone. Sandy horizons appear to be rare except in north-central Montana, where the Martin Sandstone forms a 7.5 to 12 m thick unit in the Bowdoin Dome area (Rice, 1981). Although gas-bearing, the Martin Sandstone had not yielded commercial quantities of gas to 1979 (Nydegger et al., 1979). Shurr and Rice (1987) state that, in the Dakotas, chalk units in the Niobrara Formation are potential gas reservoirs that might contain in excess of 1700 x 10^9 m^3 of gas in place.

Milk River Formation/Alderson Member/Eagle Sandstone/Gammon Shale (and Shannon Sandstone)

The Milk River Formation is about 115 m thick in southwestern Saskatchewan, with the top of the unit approximately 350 m deep in the Hatton area. Simpson (1981a) published brief descriptions of two of the three Milk River core sections then available from wells drilled in the study area; the longer core represented only one-fifth of the complete Milk River section. Subsequent natural gas development in the area has resulted in the current availability of another thirteen core sections from this unit. As stated earlier, unqualified use of the name Milk River Formation has been retained in Saskatchewan because it is so deeply entrenched in petroleum literature (Simpson, 1980).

In southwestern Saskatchewan, Milk River rocks in core comprise weakly consolidated, medium dark grey to medium grey muddy siltstone and pale olive-grey fine-grained silty sandstone. One or other of these two lithologies is alternately dominant in bands that grade into one another and are generally a few metres thick. Within the bands, the dominant rock type is mixed with subordinate amounts of the other main type. Relatively clean, coarser grained, better sorted salt-and-pepper sandstone makes up 10 to 15 percent of most Milk River core in the form of irregularly shaped, discontinuous, subhorizontal lenses and stringers which are up to about 5 mm thick and several centimetres across. Very rare conglomeratic bands, ranging in thickness from a single pebble to about 15 cm, being poorly sorted and containing matrix-supported angular to subangular clasts of chert and fine-grained felsite, are also present, as are pale green, finely laminated bentonite layers a few centimetres thick. Siderite and rare chert nodules 2 to 8 cm thick and up to more than 8 cm in maximum diameter occur at intervals a few metres apart.

Milk River rocks are made up mostly of sand-, silt- and clay-sized particles. Sand- and silt-sized particles are predominantly angular to subrounded quartz grains 0.05 to 0.15 mm (rarely up to 1.5 mm) in diameter. Clay-sized particles, by analogy with the Gammon Shale clay suite in southwestern North Dakota described by Gautier et al. (1983), comprise mixed-layer illite/smectite, discrete illite and mica, kaolinite and chlorite (see also Longstaffe, 1984). Biotite and white mica are ubiquitous and randomly distributed as subhorizontal flakes about 0.4 to 1.0 mm across, but make up less than 1 percent of either siltstone or sandstone. Dark-coloured equidimensional sand- and silt-sized particles have not, for the most part, been compositionally identified, but many are lignitic. Pyrite (and possibly some chalcopyrite) is commonly present as disseminated euhedra approximately 0.1 mm across, subhedral crystalline aggregates partially infilling shelly debris, or rare framboids (less than 0.05 mm diameter).

Primary lamination is only rarely preserved, most Milk River rocks in cored intervals appearing to have been thoroughly bioturbated. Recognizable subhorizontal burrows are moderately abundant. Most are mud-filled, flattened, 1 to 2 mm in diameter, slightly sinuous and rarely bifurcated; many of these have an iridescent dark blue-gold colouration, possibly due to lining or partial infilling by bornite or related sulphides. Some burrows are sand-filled.

Pelecypod, gastropod and Baculites debris are common, generally as shell fragments or Inoceramus prisms. However, complete Inoceramus valves up to about 6 cm long are preserved in places, as are open or closed articulated valves of unidentified pelecypods and complete gastropod (also unidentified) shells 1 to 5 mm long. Baculites shells are thin and delicate, and generally retain a beautiful mother-of-pearl iridescence. They attain lengths in excess of 8 cm and widths of 1.5 cm, and most have been completely flattened. Sutures have not been described to date. Chitinous fish remains have been seen, but are extremely rare.

Permeability of the Milk River Formation is mostly less than 0.23 md, and porosity values range from 13.6 percent to 17.8 percent (Simpson and Singh, 1980; Singh, 1982). Pay thickness ranges from close to 2 m (Liebenthal) through to 2.6 m (Burstall) to 6.8 m (Hatton) (Saskatchewan Energy and Mines, 1986).

In southeastern Alberta, the stratigraphic equivalent of that province's type Milk River Formation (as developed farther to the south and southwest) and of southwestern Saskatchewan's Milk River Formation, the Alderson Member of the Lea Park Formation, has been defined and described by Meijer Drees and Myhr (1981). These authors considered that the rocks of the Alderson Member had initially been deposited in nearshore subtidal to subtidal and intertidal environments, and were thus transitional between a sandy nearshore, foreshore, shore and backshore facies (the Eagle and Milk River Formations) and a marine, offshore shale facies (the Lea Park Formation). The member is about 85 m thick and consists of thinly and lenticularly interbedded, bioturbated silty shale and laminated, in places bioturbated, very fine grained sandstone. The two lithologies form a sedimentological unit which resembles the "parallel laminated to burrowed sets" found in Recent sublittoral sediments. Thin, laminated and thin lenticular sandstone beds scattered through the lower part of the Alderson Member are the most porous and permeable rock types. Discontinuous zones of partly silicified siderite nodules, pebbly bands and bentonitic shale beds are also present. At the top of the member is a thin widespread sideritic claystone bed containing round black chert pebbles. It is overlain by Claggett (or Pakowki) Shale.

Previous to the study by Meijer Drees and Myhr (1981), Last, Kloepfer Ltd. (1973) had suggested that the sediments which now make up the reservoir rocks of the Milk River Formation were originally chenier deposits, composed of coarse silts, wood, shells and minor sand. They were laid down as northwest-trending, 3 to 6 m high, approximately 1500 m long beaches developed by longshore current and wave activity along the seaward margin of a delta during periods of marine stillstand and consequent slow deposition. Such periods alternated with those of rapid deposition of clays and finer grained silts as mudflats offshore from the delta.

Sea-level fluctuations produced vertical stacking of at least six reworked chenier-ridge complexes. A major episode of marine offlap, followed by onlap of the Pakowki (Lea Park) sea, gave the Milk River Formation reservoir rocks their present regional configuration (i.e., shaling out on all sides except the southwest). Last, Kloepfer Ltd. (1973) pointed out that here, northeast-trending channel sands were developed with a sequence of coals, carbonaceous sands and silts, the continental facies of the Milk River Formation. Bentonite beds, some of which are regionally correlatable, are numerous. In southwestern Saskatchewan, Singh (1982) used two such regionally recognizable markers to subdivide the Milk River Formation into Lower (poorly prospective for gas), Middle (containing the most prospective gas-bearing strata) and Upper (a few gas occurrences present) units.

The Milk River Formation, as recognized by Meijer Drees and Myhr (1981), is a northwestern continuation of Montana's Telegraph Creek and Eagle Formations and has been subdivided into three members named, from bottom to top, Telegraph Creek, Virgelle and Deadhorse Coulee. Because of this direct correlation, Milk River Formation geology in the type area (McCrory and Walker, 1986) is here inherently included with the geological summary of the Eagle Sandstone/ Gammon Shale (and Shannon Sandstone).

The 1.55 x 10^6 hectare Milk River Gas Pool in Alberta has an average depth of 355 m. Its pay thickness ranges from 1.88 m (Bow Island Field) to 10.32 m (Cassils Field), with most fields containing 3 to 6 m; and its average porosity is 15.4 percent (Energy Resources Conservation Board 1985).

In Montana, the Eagle Sandstone formed as a coastal blanket deposited in wave-dominated deltaic and interdeltaic environments along the western shoreline of the Western Interior Seaway (Rice and Shurr, 1983). In the east, it comprises elongated sand ridges of the inner shelf, up to 15 m thick and reworked by storm waves, and thin, discontinuous storm-generated beds that display parallel or ripple laminations and sharp bases or are extensively bioturbated and that are intercalated with shale. In the west, the Eagle Sandstone conformably overlies the Telegraph Creek Formation, which consists of offshore marine siltstones and shales interbedded with thin shelf sandstones. These increase in number and thickness upward, and the formation is transitional between calcareous shale of the underlying Niobrara Formation and interdeltaic coastal sandstone of the overlying Virgelle Sandstone Member (the 25 to 40 m thick basal unit of the Eagle Sandstone). The 20 to 50 m thick Middle Member of the Eagle Sandstone overlies the Virgelle Sandstone Member, and is made up of a lower unit of predominant mudstone which alternates with siltstone, sandstone and some coal beds, and an upper unit of fine- to medium-grained sheet-like sandstone. The lower unit probably represents coastal-plain deposits which formed behind the Virgelle strandline, whereas the upper unit was probably deposited in a deltaic environment. The lithologically variable 10 to 30 m thick Upper Member of the Eagle Sandstone rests disconformably upon the Middle Member. More northerly outcrops are made up of interbedded sandstone, siltstone and shale. More southerly outcrops consist of one or two upward-coarsening sequences which grade from interbedded sandstone to resistant sandstone ledges. In both areas, chert gravel containing a few shark teeth is scattered or concentrated into laminae or beds and appears to be a lag deposit.

The coastal sandstones and nonmarine rocks of the Eagle Sandstone grade eastwards into offshore marine siltstones and shales of the Gammon Shale, which is about 100 m thick at its western boundary in Central Montana, increasing to about 300 m at the North Dakota - Montana border (Gautier, 1981). Farther eastward, it thins and disappears. In the upper part of the Gammon Shale, upward-coarsening sandstone sequences, the Shannon Sandstone Member, have been deposited near the edge of a broad shelf more than 320 km from the western shoreline of the Western Interior Seaway (Shurr, 1984). Genetic processes leading to the development of the Shannon Sandstone, a ridge field of complex linear sand ridges, are not presently clearly understood, but probably involve tectonic as well as sedimentation events (Shurr, 1984a). The top of the Gammon Shale is a strict time line at the base of the Ardmore Bentonite Beds, a widespread stratigraphic marker in the northern Great Plains (Gautier, 1981).

The Eagle Sandstone is a gas reservoir in the Tiger Ridge Field north of the Bearpaw Mountains, where most production is from the Middle and Upper Members. The sandstones are generally highly porous (20 to 30 percent) and permeable (100 to 300 md), though these properties are strongly controlled by diagenetic processes, especially those related to chemically enriched waters resulting from igneous activity (Gautier and Rice, 1982). The Gammon Shale contains gas in thin (less than 1 cm thick) discontinuous lenses and laminae of siltstone and very fine grained sandstone and, because of its immense volume and potential for biogenic gas generation, is considered by Gautier and Rice (1982) to hold the greatest potential for shallow gas production in the northern Great Plains. Gas is produced from the upper 80 to 100 m of the 300 m thick Gammon Shale in the Little Missouri Field, southwestern North Dakota. Porosity averages about 21 percent, and permeability less than 1 md.

Natural Gas: Its Origin, Accumulation and Development

A biogenic origin has been convincingly argued for natural gas in shallow Upper Cretaceous reservoirs in the northern Great Plains of the U.S. and Canada (Rice and Claypool, 1981). Not only is this gas composed almost entirely of methane (C_1/C_{1-5} ratio greater than 0.98), but it is isotopically light ($\delta^{13}C_1$ generally in the range -65 to -70 ppt). Moreover, the various requirements for the commencement and maintenance of biogenic methane production appear to have prevailed in the host rocks. These requirements include an anoxic, sulphate-deficient environment, suitable temperatures (0 to 75^{o}C), space in which methanogenic micro-organisms can function (not a problem until muds have been buried to about 2000 m), and the presence of organic matter (in excess of about 0.5 percent organic carbon). Jones et al. (1986) concur with Rice and Claypool's (1981) findings.

Accumulation of biogenic gas requires that certain physicochemical and sedimentological conditions for concentration and entrapment be met. Rice and Claypool (1981) pointed out that, in nonmarine and brackish-water environments that are generally low in sulphate, methane production begins close to the surface, but most is lost by aerobic bacterial oxidation or escape to the atmosphere because of low hydrostatic pressures. In marine sediments, biogenic methane can be retained in solution in interstitial water because of higher hydrostatic pressure due to the overlying water column. This methane can be held until traps and seals are formed through sediment compaction (depths of burial greater than 500 m generally necessary) and other processes. Continued biogenic methane production in excess of solubility, or exsolution of gas due to hydrostatic pressure reduction (e.g., lowering of sea level, uplift and erosion, upward migration of gas-bearing waters to zones of lower hydrostatic pressure) leads to the formation of a free gas phase which, in the northern Great Plains area, was probably stratigraphically trapped in discontinuous, relatively impermeable silt and sand enveloped by organic-rich mud.

Porous and permeable reservoirs are often flushed with fresh water, and natural gas accumulates only in closed structural traps. In the northern Great Plains, numerous bentonite beds and carbonate-cemented layers also acted as excellent seals enabling gas accumulations to form. Rice and Claypool (1981) noted that most biogenic gas pools are at shallow depth and so have low reservoir pressure. In fact, many are underpressured in relation to prevailing hydrostatic pressure gradients, perhaps because of dilation of pore volume and decrease of reservoir temperature associated with uplift and erosion, thus helping to trap the gas. Closed structures such as the Bowdoin Dome and the Cedar Creek Anticline may have some effect upon the location of productive gas accumulations, but are not all-important (Gautier and Rice, 1982).

Hitchon (1984) studied geothermal gradients and hydrodynamic regimes in southeastern Alberta. He noted that recharge areas are the Cypress Hills, the surface-water divide between the South Saskatchewan and Red Deer Rivers, and the Hand Hills. Discharge areas are the major river valleys and Pakowki Lake. Furthermore, formation waters near the base of the Lower Cretaceous strata and near the base of the Upper Cretaceous strata have higher hydraulic heads than those near the top of the Lower Cretaceous. Northwards, this zone of lower hydraulic head moves up-section from the Bow Island Formation into the Second White-Speckled Sandstone. The Milk River Formation and Medicine Hat Sandstone have higher hydraulic heads than underlying or overlying rocks, so formation-water flow is upward from the Milk River Formation into the Pakowki Formation and downward from the Medicine Hat Sandstone into the Lower Cretaceous or the Second White-Speckled Sandstone. The southern side of the Southeast Alberta Gas System occurs where recharging waters from the Cypress Hills change flow direction from northwards to vertically downwards or southwards. The northern limit is similarly defined by changing flow directions of recharge waters from the Hand Hills. Throughout most of the Southeast Alberta Gas System, the hydraulic gradient is low compared to that below the Cypress Hills and the Hand Hills. This hydrodynamic regime, Hitchon (1984) suggested, is clearly the major controlling influence upon the location of the Southeast Alberta Gas System, and is probably a much more important process than one such as exsolution of previously formed biogenic gas from interstitial water, especially as its pattern seems to have remained essentially unchanged since the early Eocene.

Drilling and completion techniques play a most important role in determining initial flow rates and cumulative gas production from wells tapping the extremely water-sensitive, shallow Upper Cretaceous reservoirs of the northern Great Plains (Nyedegger et al., 1979; Black et al., 1981; Evans, 1984).

In general, clear-water drilling fluids containing clay stabilizer (1 dm^3/m^3 3 percent KCl water) or low-fluid-loss, polymer-based muds have effectively reduced drilling times and borehole washouts in southeast Alberta and the Bowdoin Dome area. Clay accounts for 10 to 30 percent of reservoir rocks (Gautier et al., 1983; Evans, 1984), much of it highly expandable mixed-layer illite/smectite, leading to average permeability values that are often less than 0.1 md.

Hydraulic fracturing is needed to improve productivity, which is adversely affected by low permeability and by low reservoir pressure. Evans (1984) recommended two-stage fracturing of the Milk River Formation to increase the thickness of stimulated zones after finding that after-fracture initial flow rates in a sixteen-well Bantry project undertaken by PanCanadian Petroleum Ltd. increased by 91 percent (or appoximately 3600 m^3/day). Production testing continues on these wells to see whether this improved production level is sustained. Evans (1984) considered that three-stage fracturing might lead to further incremental improvements in productivity.

Evans (1984) also summarized improvements in fracture treatment of shallow gas reservoirs, tested in a fourteen-well Medicine Hat - Milk River project in the Cassils Field. Modifications included replacement of the previously used fracture fluid (a KCl-water-Xanthan Gum mixture) by a KCl-water-Hydroxypropyl Guar mixture, and adoption of 20,000 kg of 12/20 sand per fracture treatment instead of 20,000 to 60,000 kg of 10/20 sand (50 percent) and 8/12 sand (50 percent; this sand has the undesirable potential to generate fines when pumped at high rates and high sand concentrations). Pumping rates were the maximum available, and sand concentrations were increased to 1000 kg/m^3 as fast as possible (more than 50 percent of each treatment was pumped at this concentration). A high sand concentration is advantageous because fractures with thin layers of sand proppant tend to heal in these shallow shaly reservoirs. Also, the amount of fluid required to stimulate the reservoir was minimized and clean-up time was reduced (the aid of CO_2 was required because of low reservoir pressure; flow-back rates were controlled so that CO_2 was effectively used to recover the maximum amount of fracturing fluid). Results showed that Medicine Hat initial production rates using the modified fracture treatment improved by 18 percent and those in the Milk River by 130 percent (in combination with two-stage fracturing).

Other stimulation has been attempted, generally without marked economic success, using other fracturing fluids and foams including viscous cross-linked gels, polyemulsions, gelled alcohol/ water mixtures, and nitrogen foam with or without alcohol or carbon dioxide (Nydegger et al., 1979; Black et al., 1981).

Cumulative production figures for wells tapping the three main gas-bearing stratigraphic units in southwestern Saskatchewan are shown in Table 1. They appear to compare closely with production from an average Bowdoin area well, estimated by Nydegger et al. (1979) to be 9 $\times 10^6$ m^3 over a ten-year period. The Little Missouri Field in southwestern North Dakota is of special interest with regard to future exploration targets as it produces entirely from silt-shale reservoir rocks in the uppermost 80 to 100 m of the 300 m thick Gammon Shale. Initial gas flow for one well in the field was reported to be 17,000 m^3/day, achieved by stimulating a 27 m thick zone from a depth of 376 m to 403 m. This zone was selected using data derived from a full suite of porosity logs and an interpretation method described by Nydegger et al. (1979) (Gautier and Rice, 1982). Table 2 shows, for comparative purposes, information about gas reserves in selected Upper Cretaceous strata in the Southeast Alberta Gas System and its eastward extension into Saskatchewan, including smaller gas accumulations in southeast Alberta which are trapped at the same stratigraphic levels but which are located to the south of the main Southeast Alberta Gas System.

Conclusion

Since the 1950s, Upper Cretaceous siliciclastic and argillaceous rocks of the northern Great Plains region of Canada and the U.S. have attracted increasingly close interest from natural gas explorationists because they host, and are sources for, very large accumulations of biogenic methane. Their stratigraphic nomenclature, as currently used in Saskatchewan and Alberta, requires considerable refinement. As formations recognized in Upper Cretaceous strata of north-central and northeast Montana are, for the most part, clearly recognizable on geophysical logs from wells in southwestern Saskatchewan, the applicable stratigraphic nomenclature could usefully be extended into this province.

Table 1 - Natural Gas Production Figures for Selected Wells in Southwestern Saskatchewan

Producing Unit	Well Location	Production Period (days)	Cumulative Gas Production (x 10^6 m^3)	Remarks
Milk River Formation	8-13-16-30W3	4059	7.29	Average production of an older well
	6-5-15-27W3	391	3.33	Completed in upper Milk River
	6-5-15-27W3	392	3.15	Comingled lower Milk River and Medicine Hat production
Medicine Hat Sandstone	6-21-18-29W3	5970	9.47	Below average
	10-31-15-28W3	7020	15.09	Average
	6-5-13-27W3	5442	26.56	Above average
	6-3-14-29W3	6062	51.95	Above average
Second White-Speckled Shale	10-16-14-26W3	1176	27.17	Development started too recently for average production to be calculated
	10-17-14-26W3	1703	27.84	

Table 2 - Reservoir Data for Natural Gas Pools in Selected Upper Cretaceous Strata, Southeastern Alberta and Southwestern Saskatchewan (Energy Resources Conservation Board, 1985; Saskatchewan Energy and Mines, 1986).

Producing Area (name)	Producing Stratigraphic Unit	Mean depth of unit (m)	Mean thickness or thickness range of pay in unit (m)	Producing area (size in hectares x 10^6)	Average Porosity (percent)	Gas Saturation (percent)	Initial Reservoir Pressure (kPa)	Raw Gas in place ($10^6 m^3$)	Producible Raw Gas ($10^6 m^3$)
Southeast Alberta Gas System	Milk River	355.7	1.88 - 10.32	1.37	15.4	55	3,140	165,824	116,121
	Medicine Hat A	487.7	0.55 - 3.88	1.61	17.0	55	4,310	168,450	114,465
	Medicine Hat C	487.7	0.53 - 1.17	0.36	13.9	60	4,450	11,601	5,800
	Medicine Hat D	487.7	0.40 - 1.12	0.27	13.9	60	4,450	9,707	4,854
	Second White-Speckled Shale (A, B, and C)	630.0	0.62 - 4.63	0.60	21.6	60	5,690	59,830	44,769
Fields to south of Southeast Alberta Gas System	Milk River	194.7 to 487.6	0.80 - 4.94	0.005	17.0	60	2,220 - 4,280	374	260
	Medicine Hat	274.0 to 487.7	1.00 - 1.54	0.007	22.0	55	2,590 - 4,500	455	319
	Second White-Speckled Shale	524.3 to 1026.6	0.47 - 3.60	0.013	12.0 to 32.0	40 to 70	3,230 - 5,540	677	487
Southwest Saskatchewan	Milk River	335.0 to 460.0	2.03 - 6.80	0.19	16.0	55	3,450 - 3,630	42,546	26,273
	Medicine Hat Sandstone	477.0 to 520.0	2.80 - 3.26	0.12	16.0 to 21.0	50 to 80	4,310	16,205	12,318
	Second White-Speckled Shale	692.0	3.73	0.027	20.4	70	6,105	12,406	7,823
							TOTAL	448,075	333,489

The potential for substantially increasing known gas reserves in Upper Cretaceous low-permeability shallow reservoirs in southwestern Saskatchewan are excellent, especially southwest of an imaginary line running southeastwards from the Burstall Field on the Saskatchewan-Alberta border to the Bowdoin Field adjacent to the Canada - U.S. boundary. This area probably lay in the outer shelf region on the west side of the Western Interior Seaway for prolonged periods during the Late Cretaceous. High erosion rates in land areas west of the Seaway combined with a wide shallow-water shelf resulted in ideal conditions for widespread depositon of thin (3 cm) sandstone units by storm-related geostrophic currents. These units are locally numerous enough in zones from one to several metres thick and upwards of 200 hectares in area that, if they are saturated with 50 to 65 percent of natural gas (the general range in presently producing fields), they form reservoirs containing ten million cubic metres (or more) methane and start to be of commercial interest. Sand ridges are also characteristically present in many storm-dominated shelf environments, both modern and ancient, and form producing reservoirs in the Shannon Sandstone of southeastern Montana and northwestern South Dakota at a distance of more than 300 km from the Seaway's western shore. Similar sand-ridge reservoirs may be present in Upper Cretaceous strata of southwestern Saskatchewan. Economically viable concentrations of gas may be discovered in siltstone-shale sequences of the Milk River Formation and the Gammon Shale away from producing fields, probably where siltstone is volumetrically dominant over shale in sufficiently thick, widespread areas (as in the Little Missouri Field, southwestern North Dakota).

Natural gas traps in Upper Cretaceous low-permeability rocks of the northern Great Plains are strongly controlled by subtle variations in the abundance of clay-sized particles relative to that of larger particles, in clay mineralogy, and in the size and horizontal continuity of sandstone and siltstone lenses within their argillaceous envelopes. They are essentially stratigraphic traps, but their gas producibility is commonly much improved if suitable closed structures such as the Bowdoin Dome are formed as a result of tectonism, salt solution, or differential sediment compaction. Also, long-established hydrodynamic regimes have probably exerted great influence upon the current geographic and stratigraphic location of northern Great Plains shallow gas fields, and should be accorded due attention during exploration.

Continued refinement of geophysical logging and log-interpretation techniques is required in order to improve further the explorationists' ability to distinguish between productive and nonproductive zones in clay-rich siliciclastic-argillaceous sequences.

During the past few years, improvements in well-drilling and -completion methods in water-sensitive reservoir rocks have led to substantial increases in initial flow rates from northern Great Plains shallow gas wells. If these increases are sustained long enough for cumulative production to be enhanced, significant lateral expansion of producing gas fields into areas outside their current economically viable limits is likely to follow. Also, other gas accumulations, hitherto uneconomic, will attract renewed interest with respect to development.

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